



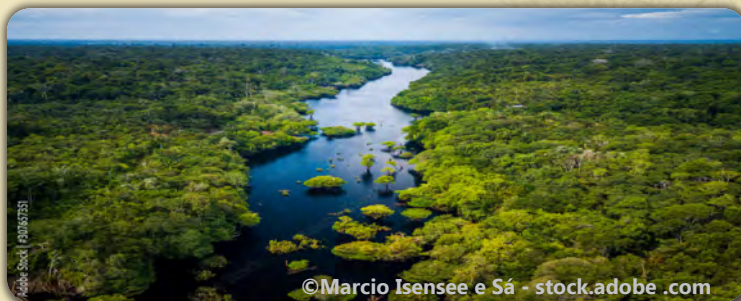
Forest Service
U.S. DEPARTMENT OF AGRICULTURE

Forest Products Laboratory | General Technical Report FPL–GTR–305 | September 2024

Proceedings

23rd International Nondestructive Testing and Evaluation of Wood Symposium

Campinas, São Paulo, Brazil
September 17–21, 2024



Forest Service, Forest Products Laboratory
Universidade Estadual de Campinas
Forest Products Society
International Union of Forest Research Organizations

Abstract

The 23rd International Nondestructive Testing and Evaluation of Wood Symposium was hosted by the School of Agricultural Engineering of the Universidade Estadual de Campinas (FEAGRI/ UNICAMP) and the Brazilian Association of Nondestructive Testing and Evaluation (ABENDI). The symposium was held in Campinas, São Paulo, Brazil, on September 17–21, 2024. This symposium was a forum for those involved in nondestructive testing and evaluation (NDT/NDE) of wood and brought together many international researchers, NDT/NDE users, suppliers, representatives from various government agencies, and other groups to share research results, products, and technology for evaluating a wide range of wood products, including standing trees, logs, structural lumber, engineered wood products, and wood structures. Networking among participants encouraged international collaborative efforts and fostered the implementation of NDT/NDE technologies around the world. The technical content of the 23rd symposium is captured in these proceedings. Full-length, in-depth technical papers for most of the oral presentations and several of the poster presentations, along with abstracts for all the oral and poster presentations, are published herein. Although the authors may have conducted peer reviews for their own papers, the papers were not peer reviewed for the proceedings and are reproduced here as they were submitted by the authors.

Keywords: Nondestructive evaluation, nondestructive testing, wood properties, wood products, logs, trees, wood structures

September 2024

Gonçalves, Raquel; Wang, Xiping; Ross, Robert J., eds. 2024. Proceedings: 23rd International Nondestructive Testing and Evaluation of Wood Symposium. Campinas, São Paulo, Brazil. September 17-21, 2024. General Technical Report FPL-GTR-305. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 309 p.

USDA Forest Service, Forest Products Laboratory
One Gifford Pinchot Drive, Madison, WI, USA 53726
(608) 231-9200
SM.FS.MailroomFPL@usda.gov

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the United States Department of Agriculture (USDA) of any product or service.

Contents

Preface.....	1
General Session.....	4
Session 1—Wood Structure Condition Assessment.....	13
Session 2—In-Forest Wood Quality Assessment.....	44
Session 3—Nondestructive Evaluation of Engineered Wood Products.....	103
Session 4—Urban Tree Inspection and Risk Analysis.....	149
Session 5—Wood Material Characterization	179
Poster Session	238

In accordance with Federal civil rights law and U.S. Department of Agriculture (USDA) civil rights regulations and policies, the USDA, its Agencies, offices, and employees, and institutions participating in or administering USDA programs are prohibited from discriminating based on race, color, national origin, religion, sex, gender identity (including gender expression), sexual orientation, disability, age, marital status, family/parental status, income derived from a public assistance program, political beliefs, or reprisal or retaliation for prior civil rights activity, in any program or activity conducted or funded by USDA (not all bases apply to all programs). Remedies and complaint filing deadlines vary by program or incident.

Persons with disabilities who require alternative means of communication for program information (e.g., Braille, large print, audiotape, American Sign Language, etc.) should contact the responsible Agency or USDA's TARGET Center at (202) 720-2600 (voice and TTY) or contact USDA through the Federal Relay Service at (800) 877-8339. Additionally, program information may be made available in languages other than English.

To file a program discrimination complaint, complete the USDA Program Discrimination Complaint Form, AD-3027, found online at http://www.ascr.usda.gov/complaint_filing_cust.html and at any USDA office or write a letter addressed to USDA and provide in the letter all of the information requested in the form. To request a copy of the complaint form, call (866) 632-9992. Submit your completed form or letter to USDA by: (1) mail: U.S. Department of Agriculture, Office of the Assistant Secretary for Civil Rights, 1400 Independence Avenue, SW, Washington, D.C. 20250-9410; (2) fax: (202) 690-7442; or (3) email: program.intake@usda.gov.

USDA is an equal opportunity provider, employer, and lender.

Proceedings

23rd International Nondestructive Testing and Evaluation of Wood Symposium

**Campinas, São Paulo, Brazil
September 17–21, 2024**

Edited by

Raquel Gonçalves, Professor

Universidade Estadual de Campinas, Campinas, São Paulo, Brazil

Xiping Wang, Research Forest Products Technologist

USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA

Robert J. Ross, Supervisory Research General Engineer, retired; Research Professor; Adjunct Professor

USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA

Michigan Technological University, Houghton, Michigan, USA

Mississippi State University, Starkville, Mississippi, USA

Preface

The International Nondestructive Testing and Evaluation of Wood Symposium Series started in Madison, Wisconsin, USA, in 1963. Since its inception, 22 symposia have been held in various countries around the world, including Brazil, Canada, China, Germany, Hungary, Switzerland, and the United States.

The 23rd International Nondestructive Testing and Evaluation of Wood Symposium was hosted by the School of Agricultural Engineering of the Universidade Estadual de Campinas (FEAGRI/ UNICAMP) and the Brazilian Association of Nondestructive Testing and Evaluation (ABENDI). It was held in Campinas, São Paulo, Brazil, September 17-21, 2024. This symposium was a forum for those involved in nondestructive testing and evaluation (NDT/NDE) of wood and brought together many international researchers, NDT/NDE users and suppliers, representatives from various government agencies, and other groups to share research results, products, and technology for evaluating a wide range of wood products, including standing trees, logs, structural lumber, engineered wood products, and wood structures. Networking among participants encouraged international collaborative efforts and fostered the implementation of NDT/NDE technologies around the world.

The opening ceremony was attended by authorities from UNICAMP, FEAGRI, ABENDI, and the Forest Products Laboratory, and participants were welcomed by the International Committee and the symposium co-chairs, Dr. Raquel Gonçalves and Dr. Robert Ross. The ceremony ended with a performance by the Unicamp choir, Ziper na Boca.

During the symposium's banquet, special recognition awards were presented to Dr. Xiping Wang for his distinguished service in the symposium series and research efforts in the field of nondestructive evaluation and to Dr. Houjiang Zhang for his outstanding research, support of the symposium series, and

excellent teaching efforts in the field of nondestructive evaluation of wood. Dr. Robert Ross and Dr. Peter Niemz, both recently retired, were also honored for the significant contributions they have made throughout their careers to the field of NDT and to the success of the symposium series.

On Tuesday (Sept. 17) before the official symposium, a day-long technical workshop was conducted on “Urban Tree Evaluation and Monitoring – a systemic approach”, followed by the welcome reception in the evening.

An excellent post-symposium tour of São Paulo was held on Saturday (Sept. 21). São Paulo is the largest city in Brazil and one of the largest cities in the world and is Brazil's most important economic center. This dynamic metropolis is a center for finance, commerce, arts, and entertainment, exerting a powerful influence across South America.

The technical content of the 23rd symposium is captured in the following proceedings. Full-length, in-depth technical papers for the oral presentations and several of the poster presentations are published herein. The papers were not necessarily peer reviewed and are reproduced here as they were submitted by the authors.

The organization of the proceedings follows that of the sessions at the 23rd symposium. Technical sessions covered the following topics:

1. Wood Structure Condition Assessment
2. In-Forest Wood Quality Assessment
3. Nondestructive Evaluation of Engineered Wood Products
4. Urban Tree Inspection and Risk Analysis
5. Wood Material Characterization
6. Poster Session

We express our sincere appreciation and gratitude to members of the organizing committee of the International Nondestructive Testing and Evaluation of Wood Symposium Series for their efforts in making this symposium a success:

Dr. Laszlo Bejo, University of West Hungary, Hungary
 Dr. Raquel Gonçalves, University of Campinas, Brazil
 Dr. Francisco Arriaga Martitegui, Universidad Politécnica de Madrid, Spain
 Dr. Robert J. Ross, Forest Products Laboratory, Madison, Wisconsin, USA; Michigan Technological University, Houghton, Michigan, USA; and Mississippi State University, Starkville, Mississippi, USA
 Dr. Udo H. Sauter, Forest Research Institute Baden-Württemberg, Germany
 Dr. C. Adam Senalik, Forest Products Laboratory, Madison, Wisconsin, USA
 Dr. Xiping Wang, Forest Products Laboratory, Madison, Wisconsin, USA
 Dr. Houjiang Zhang, Beijing Forestry University, China

We thank the School of Agricultural Engineering (FEAGRI) of Universidade Estadual de Campinas (UNICAMP), the USDA Forest Service, Forest Products Laboratory (FPL), the Forest Products Society (FPS), and the Brazilian Association on Nondestructive Testing and Inspection (ABENDI) for their support. Thanks also go to the following organizations for providing financial support in the form of sponsorships:

Beijing Forestry University
 Coordination for the Improvement of Higher Education Personnel (CAPES)
 IBRAMEM
 International Union of Forest Research Organizations (IUFRO) - Division 5
 International Wood Culture Society (IWCS)
 Michigan Technological University (MTU)
 NDT net
 PD Instrumentos

RAUTE METRIGUARD

São Paulo Research Foundation (FAPESP)

SUZANO

Teaching, Research and Extension Support Fund (FAEPEX/UNICAMP)

Valora Madeira

A very special thank you to Cinthya Bertoldo (UNICAMP); Brunela Pollastrelli Rodrigues (Clemson University); Rafael Mansini Lorensani (Valora Madeira); Laurice Spinelli Correa (Mississippi State University); Larissa Tiago Volpi, Carolina Kravetz, Karen Christina de Freitas, Chiara Barros Secco, Elidiani Melissa de Moura, Fernando Augusto Franco Batista, Julia Jane Alves Leme, and Paulo Gustavo Krejci Nunes (UNICAMP); and Irani de Oliveira, Maria Daniela Sindeaux, and Valquiria Feitosa Bento (ABENDI) for their outstanding efforts. Without their efforts, this meeting would not have been possible.

We also thank the following staff at the Forest Products Laboratory for their outstanding efforts in preparing these proceedings: Jim Anderson and Barbara Hogan.

A note of thanks to the many individuals who prepared papers for inclusion in the symposium. Your dedication and efforts make this symposium series a success!

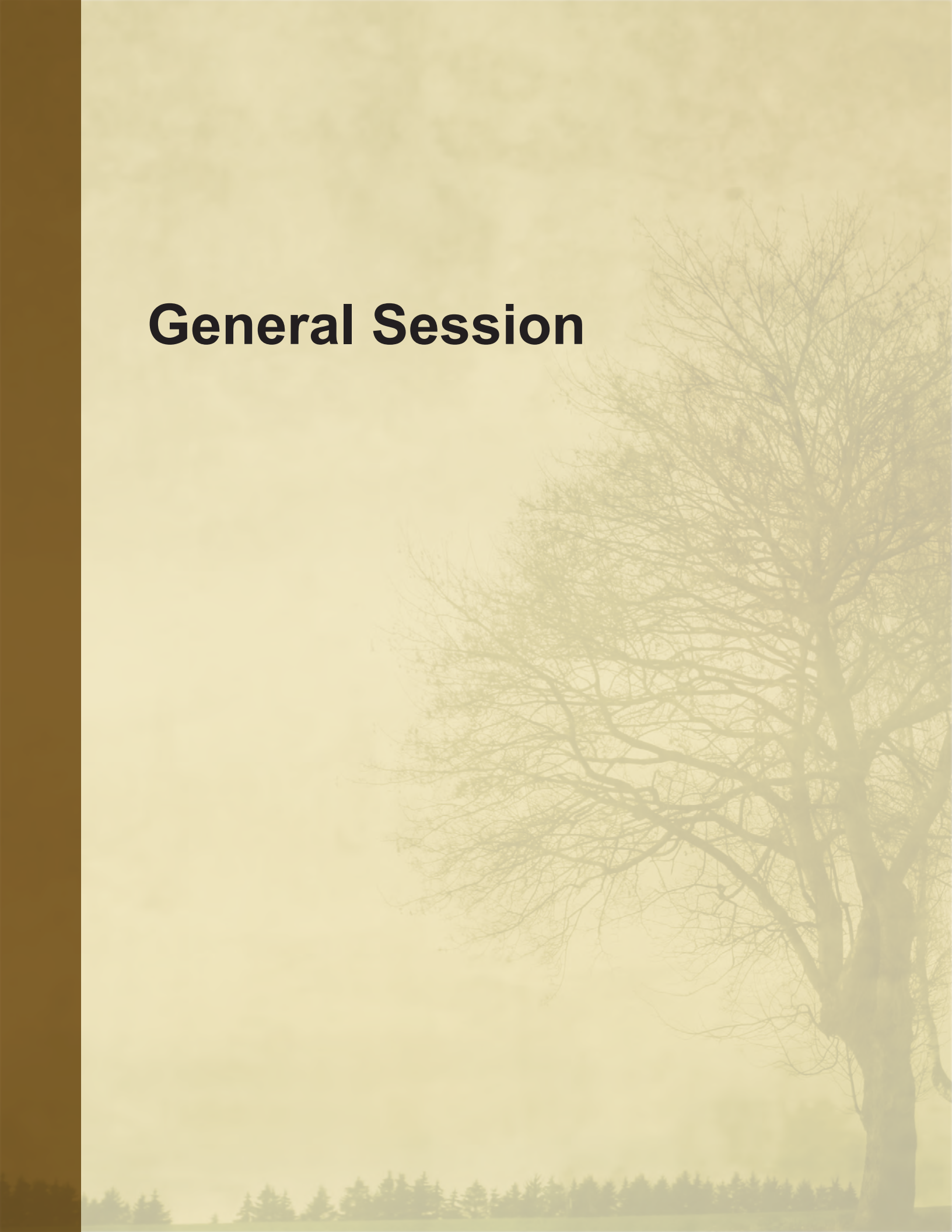
We hope that these proceedings provide inspiration to those who read its papers. And, we welcome new participants into the global wood NDT/NDE family!

Dr. Robert J. Ross, Project Leader (retired), USDA Forest Service, Forest Products Laboratory, USA

Dr. Raquel Gonçalves, Professor, Universidade Estadual de Campinas, Brazil

Symposium Co-Chairs

General Session



Nondestructive Testing and Evaluation of Selected Solid Wood Based Materials—Scientific Advances and Practical Challenges

Peter Niemz

Department of Civil Engineering, Institute for Building Materials, ETH Zurich, Laura- Hentzner Weg 7, CH 8093 Zurich, Switzerland
niemzp@retired.ethz.ch

Jakub Sandak

InnoRenew CoE, Livade 6a, 6310 Izola, Slovenia
jakub.sandak@innornew.eu

Abstract

Wood and wood-based materials (CLT, GLT, LVL) are increasingly being used in multi-story timber construction. Safe and reliable bonding and checking the quality of the bonding are of great importance. In addition to very practical tests such as the tensile shear strength according to EN 302-1 and the delamination test (EN 302-2), non-destructive testing methods are also becoming increasingly important, which concerns: 1) the mechanism of bonding (e.g. penetration of adhesives into the wood using synchrotron radiation, micro-CT, X-ray); 2) The failure mechanism of adhesive joints; and 3) Quality monitoring of the bonded components also during service life. This presentation will provide an overview of the use of important methods of non-destructive testing. These include synchrotron, x-ray tomography, digital image correlation, acoustic emission analysis, NIR spectroscopy as well as functionalized adhesives with variable electrical properties in the state of stress or in the event of large deformation.

Keywords: glulam, CLT, gluing, quality control, x-ray tomography, delamination, ultrasound, NIR-spectroscopy

Introduction

Wood and wood-based materials (CLT, glulam, LVL) are increasingly being used in multi-storey timber construction. The adhesives used, the materials and the production are subject to strict quality control. Depending on the application, special requirements apply to the moisture resistance of the adhesives, and increasingly also to the temperature resistance in the event of fire and the durability of the bonded joint. Conventional methods such as hot water storage (EN 302-1) or the deamination test (EN 302-2) are predominantly used to test moisture resistance. However, non-destructive test methods are increasingly being used in the development of adhesives and the optimization of the material structure. This trend also applies to the monitoring of existing buildings during their use. In addition to random visual and metrological checks such as the opening of adhesive joints, deformation checks and moisture measurements, more and more on-line systems are being developed for this purpose. This applies, for example, to the monitoring of wood moisture and increasingly also the condition of the adhesive joints themselves as well as the deformation of building components.

Used Materials and Influencing Factors on the Properties of Glued Wood

In timber construction, glulam, cross laminated timber and LVL are used in particular. Glulam and cross-laminated timber are predominantly made from softwood, and to a lesser extent from hardwood (often copper beech, ash) for special cases. In Europe, around 3 million m³ (DACH states, Czech Republic, Poland) of glulam and around 1.3 million m³ of cross laminated timber were produced in 2023. The production capacity of cross-laminated timber in particular is constantly increasing. The bonding must be moisture-resistant and also durable (no ageing). Some of the methods used in plywood and glulam production are decades old and were developed, for example, for the development of adhesives in aircraft construction during the Second World War (e.g. Aerodux is still widely used today). Melamine resins and in particular 1C-PUR are increasingly being used for ecological reasons, as this is formaldehyde-free. Intensive work is being done on the development of bio-based systems (Dunky and Niemz 2023). So far, however, only a proportion of bio-based raw materials have been added. Marra (Marra 1992) gives the following equation for the quality of a bonded element.

$$GP = c + \_AC + \_WP + \_SP + \_AA + \_WG + \_PS \text{ (eq. 1)}$$

where GP is the glued product performance, c is a constant, AC is an adhesive composition factor, WP is a wood property factor, SP is a wood surface preparation factor, AA is an adhesive application factor, WG is a wood geometry factor, and PS is a product service factor

Figure 1 shows important factors influencing the bonding quality of solid wood. The bonding itself, as well as the use of bonded elements, is a very complex problem in which many factors have to be taken into account. For example, in addition to the moisture resistance of the glued joints, the question of delamination of joints in a very dry indoor climate is a very important issue today. There are therefore many influencing factors that affect the bonding quality and also the durability of the bond itself. The main thing that is monitored during production is compliance with the specified technology.

Wood	Adhesive	Machining and Technology
specie - grain and ring angle - density/strength - swelling /shrinking - heartwood /sapwood - growth ring structure - extractives - chemical composition - variation from wood properties wood modification - e.g. thermal, chemical, densification	type of adhesive (PRF; MF; MUF; 1 C-PUR; EPI) - chemical and mechanical properties (also variation in a adhesive type) - penetration into wood (viscosity) bondline thickness sorption and mechanical properties from the bondline (MOE, strength, MC) adhesion on wood in dry and wet conditions aging during service and testing	method of preparation and elaboration - planing, surface milling, sanding etc. - surface quality (roughness, waviness etc.) - moisture content from lamellas and variation between lamellas - pretreatment: priming, water, plasma, laser quantity of applied adhesive/accuracy of applied amount pressing conditions - open and closed assembly time, - pressing time - specific pressure - room temperature and air humidity during pressing
	Glulam structure lamella thickness mechanical properties of lamellas properties - variation in and between species, moisture content dimension from glulam beam surface coating - buffering water diffusion, reducing moisture profiles and moisture induced stresses	

Figure 1 Overview of key factors influencing the strength of glue bonded joints (Hänsel et al. 2022)

For materials used in the load-bearing area,

- Adhesives approved by the building inspectorate (e.g. DIBt Berlin/Germany) are required
- The manufacturer must carry out independent quality monitoring and is also monitored by an accredited testing institute.

In Germany, for example, tensile shear tests in accordance with EN 302-1 (storage sequence A1, A4 (boiling), A5 re-drying)) and a delamination test in accordance with EN 302-2 are required. There are also guidelines for testing adhesives and material structures for increased temperature loads (Buchanan and Östmann 2022).

During production, random checks of the bonding quality are carried out (e.g. delamination test, block shear test). The results are often only available a few days after bonding, which can lead to large losses in the event of errors. Faster results are therefore desirable and are being sought. There is great potential here for methods of non-destructive testing of the product and on-line process monitoring of the bonding itself. On-line monitoring of the bonding quality of particle materials has been common practice for decades using ultrasound. Despite various attempts with non-contact coupling (Sanabria 2012) and the pulse-echo method (Hasenstab 2006) or simple measurement of the change in the speed of sound, such methods have not become established for solid wood (Niemz 1995), (Niemz and Sander 1989).

In some cases, random testing is carried out on finger-jointed, longitudinally glued board lamellas for tensile load. Here, the mechanical quality sorting of solid wood (natural frequency measurement, X-ray for knot detection, use of laser (tracheid effect) and the visual quality control of wood (knots, discoloration, etc.) is far behind.

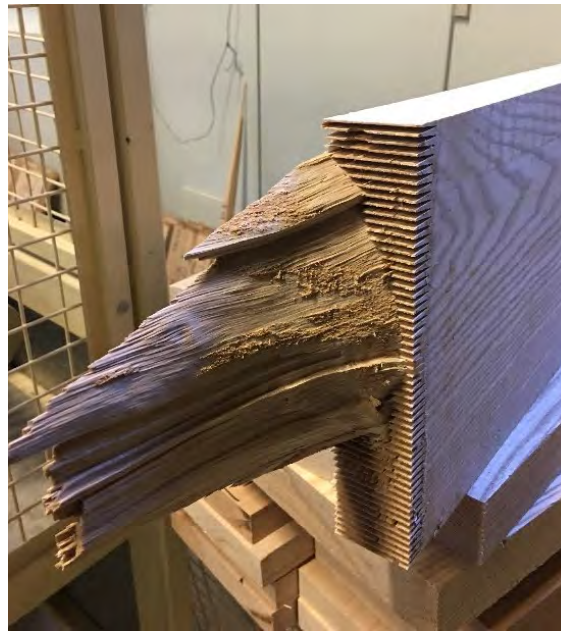


Figure 2 Finger-jointed ash wood, industrially tested for tension (wood failure due to incorrect grain orientation), (random sample inspection in production, neue Holzbau Lungern, Switzerland)

Essentially, only the average wood moisture content is measured on- line using electrical resistance measurement. With 1C-PUR, however, the moisture directly on the surface is relevant for curing. This adapts very quickly to the ambient climate. In winter, when the relative humidity in the production halls is low (20-30% e.g.), additional water is often sprayed onto the surface of the board and the measured average wood moisture content is only of limited relevance for bonding with 1C-PUR.

Monitoring of Structures

In practice, important structures are inspected by trained personnel at certain intervals. This primarily involves selecting buildings that are subject to increased stress or risk, e.g. moisture exposure such as ice halls, swimming pools, bridges, etc. Buildings that have been repurposed with a new orientation are also particularly at risk, as the change in humidity causes additional moisture-induced stresses. In large, heated buildings, damage is increasingly occurring due to the very dry indoor climate in winter (relative humidity up to around 20-30%). This is particularly the case in areas with low outside temperatures in winter (e.g. Scandinavia). In addition, large window areas often cause additional moisture movement due to large temperature differences (see Keylwerth 1969). In this case is not the relative humidity but the temperature difference that is the driving force of the moisture movement.

Various methods are used to check the condition of adhesive joints and structures (Fischer et al. 2004 Pellerin and Ross 2002), (Niemz and Sander 1989).

- Visual inspection (recognizable damage such as cracks, delamination, severe deformations)
- Measurement of wood moisture, condition of glue joints (joint opening, width and depth measurement)
- Selective sampling and testing (only in exceptional cases, sampling with an increment borer)
- Drilling resistance measurement
- In some cases, samples are also taken in the area of the adhesive joint and tested for strength (shear strength)
- Deformation of the structure after application of a defined load (e.g. for bridges)
- Penetration depths using the Pilodyn method (only effective on the surface, no detection of internal damage).

Scientific Methods and Preliminary Works for Industrial Application

Optimization of bonding

Non-destructive testing methods are most frequently used to optimize bonding in the field of research or product development. This concerns the determination of elastic constants on panels using sonic or modal analysis (Gülzow 2008), Czaderski et. al. 2007), Steiger et al. 2012).

Non-destructive testing methods have also been used in many cases for investigations to optimize bonding. One example is the measurement of the penetration behavior of adhesives into the wood using x-ray microtomography or synchrotron light (Hass 2012). Figure 3 shows the penetration of adhesive into beech wood in the area of the glue line for various adhesives (Hass et al. 2012).

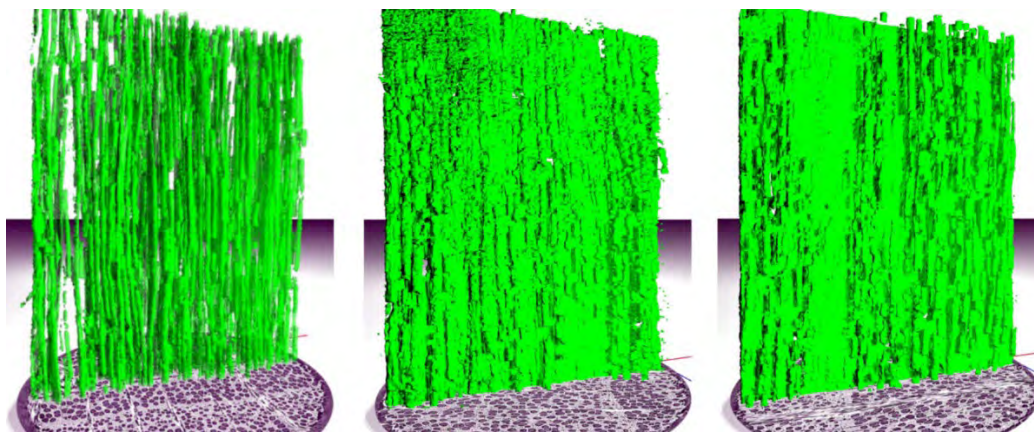


Figure 3 Penetration of various adhesives into beech wood, measured using a synchrotron (Hass et al. 2012)
Left: 1C-PUR prepolymer, center: UF, right: PVAc

Digital image correlation is often used to determine the strain distribution under mechanical or moisture-induced loading (Keunecke, et al. 2012), (Knorz et al. 2016). Figure 4 shows an example. The measurement of moisture accumulation at adhesive joints using neutrons Sonderegger (2011), see fig. 5.

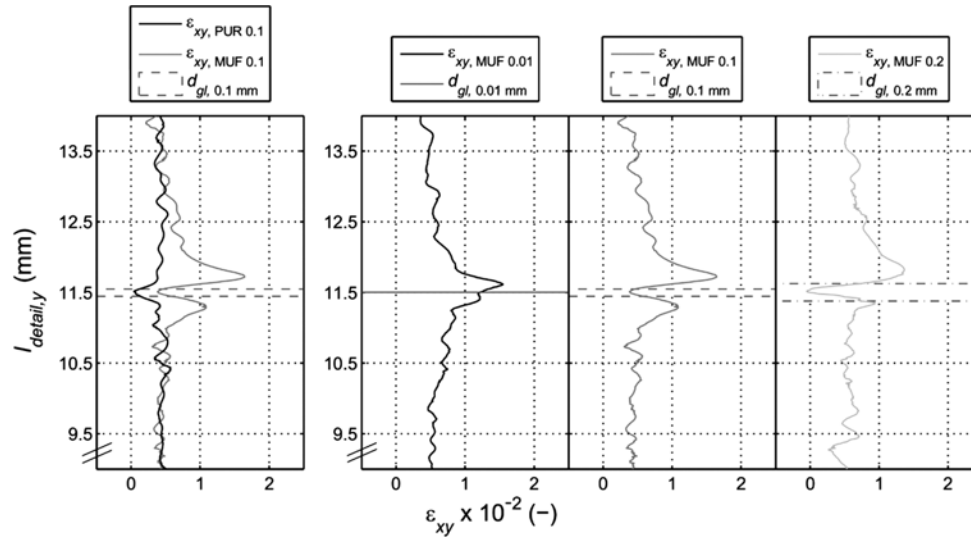


Figure 4 Representative StrD ϵ_{xy} in assemblies with homogenous GL thickness for MUF and PUR (left) and MUF with different bonline thicknesses d_{gl} 0.01, 0.1, 0.2mm (Knorz et al. 2016)

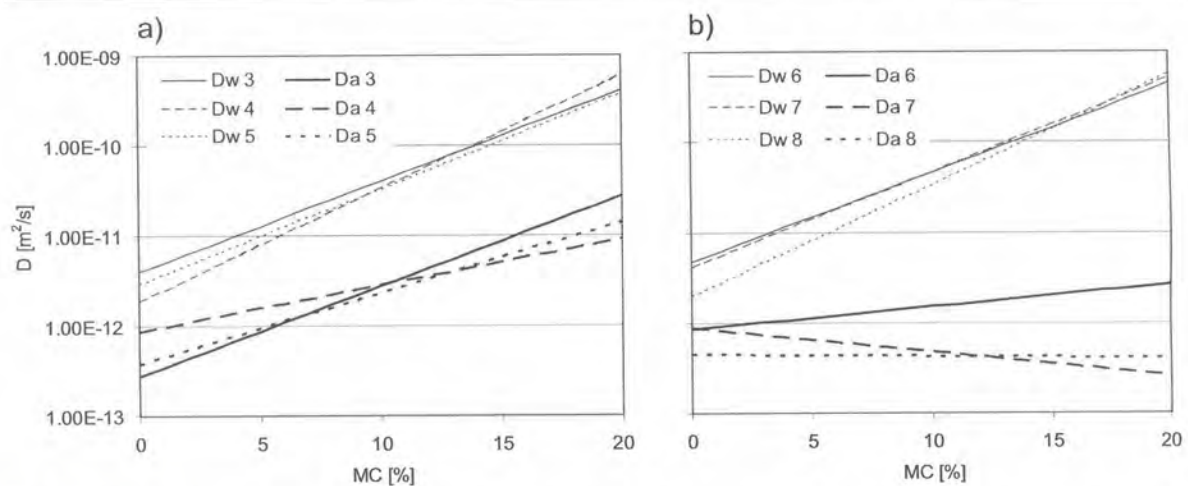


Figure 5 Calculated diffusion coefficients of bulk wood portions (D_w) and adhesive bondlines (D_a) depending on moisture content and number of bondlines (1,2, 5) for UF samples (a) and 1C PUR samples (b) (UF no 3-5) 1C- PUR No 6-8)

Figure 5 shows the diffusion coefficients D for wood and glued joints determined using neutrons (Sonderegger, 2011).

Work was also carried out to measure deformations in the area of glued joints using synchrotron radiation and in situ tests (partly combined with acoustic emission) (Baensch, 2015). Initial tests were also carried out to evaluate the bonding quality using NIR technology. The moisture in the near-surface area, which is important for the curing of 1 C-PUR, can be measured using NIR technology. Correlations between

surface properties and delamination were also examined (Sandak et al. 2021). Certain approaches for industrial implementation are available here and are being worked on.

The question of monitoring the ageing of the adhesive joints is also important; work on this has been carried out by (Clerc et al. 2017) among others, chemical and mechanical analyses.

On-line quality control

During production, only the wood moisture (electrical) is usually measured at around half the thickness of the lamellas, i.e. the average moisture content after drying. On the surface of the freshly planed wood, the wood moisture adapts to the ambient climate within a very short time. In winter, we have low humidity levels in heated rooms, especially in cold regions. The humidity indoors is often only 20%. The wood moisture adapts quickly on the surface of the wood (0.0-0.2 mm), but it takes an extremely long time in the middle of the slats (Fig. 6). Therefore, when bonding with 1C-PUR in dry seasons, additional water is usually sprayed on to maintain the required moisture content for bonding (6-8%). Here, an on-line check could be carried out with an IR device, which is well suited due to the low penetration depth of the radiation (0.1-0.2 mm). Tests in the industry were very successful and showed the differences between electrical resistance measurement and NIR. Work with NIR technology is also running.

The correlation between the surface area properties measured using NIR technology and delamination according to EN 302-2 was also tested (Sandak et al. 2021). The initial results are promising. Other surface properties can also be recorded using this method (e.g. density, growth ring position, extract content). One way would therefore be to check the processed surface. Attempts to detect faulty bonding using non-contact ultrasound have been successfully carried out in the laboratory (Sanabria 2012), but have not yet been implemented in practice. Sensors built into adhesives (adhesive joints) are also a possible approach (Winkler 2021). Another possibility is the comprehensive monitoring of wood moisture in building components (Flexeder et al. 2022). This is becoming increasingly important, especially with the increasing construction of high-rise buildings. Water damage must be detected at an early stage before fungal infestation occurs. Work is being carried out on this as part of an ongoing dissertation at the Technical University of Munich (Flexeder et al. 2022). Deformation measurements on structural components (detection of high deformations) are also being carried out (Pellerin, Ross 2002)

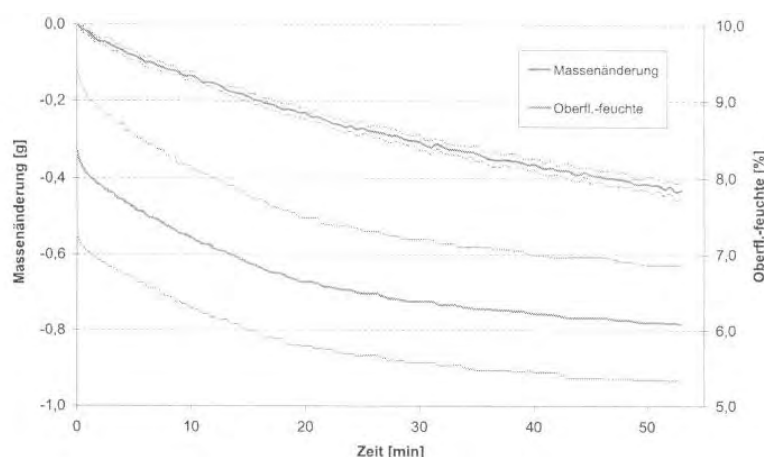


Figure 6 Comparison between surface moisture content and mass change spruce from 20°C/50%RH to 20°C/20%RH (Niemz and Gereke 2009)

Conclusions

Overall, a great deal of work has been carried out and a large number of destructive testing methods have been tested. Many methods have proved very successful in laboratory tests for optimizing the bonding

quality, and progress can also be expected from work on the functionalization of adhesives (installation of sensor functions) and sensor-based monitoring of entire buildings. This work and the installation of systems for monitoring moisture, measuring the deformation of components or the use of functionalized adhesives are very important for monitoring buildings (high-rise buildings). Water damage can very quickly lead to major consequential damage such as fungal infestation.

Literature

- Baensch, F. 2015. Damage evolution in wood and layered wood composites monitored in situ by acoustic emission, digital image correlation and synchrotron based tomographic microscopy. Zürich: Diss., ETH Zürich.
- Buchanan, A.; Östmann, B. (Editors), 2022. Fire Safe Use of Wood in Buildings-Global Design Guide. Boca Raton FL: CRC Press.
- Clerc, G.; Brühlisauer, M.; Affolter, S.; Volkmer, T.; Pichelin, F.; Niemz, P. 2017. Characterization of the ageing process of one-component polyurethane moisture curing wood adhesive. *International Journal of Adhesion & Adhesives* (72): 130–138.
- Czaderski, Ch.; Steiger, R.; Howald, M.; Olia, S.; Gülzow, A.; Niemz, P. 2007. Versuche und Berechnungen an allseitig gelagerten 3-schichtigen Massivholzplatten. *Holz als Roh- und Werkstoff*, (65)5: 383-402.
- Dunky, M. ; Mital, K. 2023. Biobased Adhesives. Chapt. 22: Niemz, P.; Dunky, M: *Bonding of Solid Wood based Materials for Timber Construction*. Beverly, MA 01915-6106, 2023: Skrivener Publishing, Beverly.
- Fischer, A.; Risi, W.; Richter, K. 2004. Zustandsbeurteilung von Klebfugen wetterbeanspruchter Holzbrücken. Sonderdruck aus "bauen mit holz", (106)11: 1-8
- Flexeder, N.; Nouman, A.; Hepf, C., 20.-22.9.2022. Measurement of sorption heat in laboratory and field tests in comparison with hygrothermal simulations. Weimar, Bauhaus Universität Weimar.
- Gülzow, A. 2008. Zerstörungsfreie Bestimmung der Biegesteifigkeiten von Brettsper Holzplatten. Zürich: PhD thesis, ETH Zürich.
- Hänsel, A.; Sandak, J.; Sandak, A.; Mai, J.; Niemz, P. 2022. Selected previous findings on the factors influencing the gluing quality of solid wood products in timber construction and possible developments: A review. *WOOD MATERIAL SCIENCE & ENGINEERING*, (17)3: 221-223.
- Hasenstab, A. G. M. 2006. Integritätsprüfung von Holz mit dem zerstörungsfreien Ultraschallecho-Verfahren. Berlin: PhD thesis, TU Berlin.
- Hass, P. F. S. 2012. Penetration behavior of adhesives into solid wood and micromechanics of the bondline. Zürich: PhD thesis. ETH Zürich.
- Hass, P.; Wittel, F.; Mendoza, M.; Herrmann, H.; Niemz, P. 2012. Adhesive penetration in beech wood: experiments. *Wood Science and Technology*, 46(1-3): 243-256.
- Keunecke, D.; Novosellets, K.; Lanvermann, C.; Mannes, D.; Niemz, P. 2012. Combination of X-ray and Digital Image Correlation for the analysis of moisture-induced strain in wood. opportunities and challenges. *Europ. J. Wood and Wood Products*, (70)4: 407-413.
- Keylwerth, R. 1969. Temperatur- und Feuchtigkeitsgefälle in Holzbauteilen. *Holz als Roh- und Werkstoff*. *Holz als Roh- und Werkstoff*, (27)8: 285-290.
- Klippel, M. 2013. Fire safety of bonded structural elements (PhD thesis). Zurich: ETH Zurich.
- Knorz, M., van de Kuylen, J. W. ; Niemz, P., 2016. Measurement of moisture-related strain in bonded ash depending on adhesive type and glue line thickness. *Holzforschung* (70) 2: 145-155.
- Marra, A. 1992. Technology on Wood Bonding. Principles in Practice. New York: Van Nostrand Reinhold.

- Niemz, P; Gereke, T. 2009. Auswirkungen kurzzeitiger und langzeitiger Luftfeuchteschwankungen auf die Holzfeuchte und die Eigenschaften von Holz. *Bauphysik* (31)6: 381-385.
- Niemz, P. 1995. Bestimmung von Fehlverklebungen mittels Schallaufzeitmessung. *Holz als Roh- und Werkstoff*: (53) 4: 236.
- Niemz, P.; Sander, D (Editors). 1989. *Prozessmesstechnik in der Holzindustrie*. Leipzig: Fachbuchverlag.
- Pellerin, R. F.; Ross, R. J., 2002. *Nondestructive evaluation of wood*. Madison: Forest Products Society.
- Sanabria, S. J. 2012. Air-coupled ultrasound propagation and novel non-destructive bonding quality assessment of timber composites. Zürich: PhD thesis, ETH Zürich.
- Sandak, J; Niemz, P.; Hänsel, A.; Mai, J.; Sandak, A. 2021. Feasibility of portable NIR spectrometer for quality assurance in glue-laminated timber production. *Construction and Building Materials* (308), 25026.
- Sonderegger, W. U. 2011. Experimental and theoretical investigations on the heat and water transport in wood and wood-based materials, Zürich: PhD-thesis, ETH Zürich.
- Steiger, R.; Czaderski, C.; Gülzow, A.; Howald, M.; Niemz, P. 2012. Comparison of bending stiffness of cross-laminated solid timber derived by modal analysis of full panels and by bending tests of strip-shaped specimens. *Europ. J Wood and Wood Products*, (70) 1-3:141–153.
- Winkler, C. 2021. Process and material features influencing piezoresistive wood adhesives (PhD thesis), Wien: Universität für Bodenkultur.

Session 1

Wood Structure Condition Assessment

Condition Assessment of Wood Structure of Jin Zhongdu Watergate Site

Houjiang Zhang

School of Technology, Beijing Forestry University, Beijing 100083, China, hjzhang6@bjfu.edu.cn

Lin Peng

School of Technology, Beijing Forestry University, Beijing 100083, China, 654706069@qq.com

Haoyu Zhou

School of Technology, Beijing Forestry University, Beijing 100083, China, zhy13223926158@163.com

Wenbo Zhang

College of Materials Science and Technology, Beijing Forestry University, Beijing 100083, China, kmwenbo@bjfu.edu.cn

Abstract

Jin Zhongdu watergate site, located in Beijing, China, was built in AD 1152, with 870 years of history. It was a waterway building under the capital city wall for the water in Chinese Jin dynasty. The wood structure, as foundation and main body of the site, play an important role in the whole waterway building. With aim of providing a basis for repair and conservation of the site, we explored detailed composition of the wood structure, and conducted nondestructive testing and evaluated defective situation of wood structural members. Firstly, typical sizes, locations and amounts of three types of wood elements including fixing stone piles, foundation piles and tiebeams, were surveyed. Secondly, according to the respective characteristics of the three wood member types, 236 wood structural members were taken as examples and conducted in situ nondestructive testing and laboratory analysis, including sounding, dimension measuring, moisture content measuring, resistance micro-drilling and wood species identification. Finally, based on information from in situ inspection and laboratory analysis, wood member conditions were rated, and decay distribution regularities were summarized. It was found the overall condition of wood structure of Jin Zhongdu watergate site is severe, and among the three types of wood members, the overall conditions of fixing stone piles are relatively the best, while the overall conditions of the foundation piles are relatively the worst. It is proved that to test and evaluate condition of wood elements of the watergate site by combining sounding, dimension measuring, moisture content measuring and resistance micro-drilling is feasible.

Keywords: Watergate site, wood structure, wood members, decay, nondestructive testing

Introduction

Jin Zhongdu watergate site, located in Beijing, China, was built in AD 1152, with 870 years of history. It served as a water passage for the river beneath the southern city wall of Jin Zhongdu, the capital city of the Jin Dynasty in China. It is the largest surviving site of Jin zhongdu (Ji 2004). The construction of the Jin Zhongdu watergate primarily involved wood and stone structures, with the wood components playing a crucial role as the foundation and main body. The Jin Zhongdu watergate site are fully demonstrated in the wood processing, connection techniques, and the combination of wood and stone structures in

Chinese Jin dynasty, making it a valuable historic and cultural heritage (Shen 2020, Yang 1997, Wang 2020).

The Jin Zhongdu watergate site was discovered and excavated in 1991. Over the past 30 years, deterioration of the wood structure has become severe, with some parts of the site even experiencing deformation and collapse. This poses a certain threat to the preservation of the site. Urgent measures need to be taken to effectively protect and restore the wood structure, especially nondestructive testing and assessment of the defects for the wood members.

Based on the in situ survey results, this study first created a model of the wood structure of Jin Zhongdu watergate site. Various nondestructive testing methods were then applied to detect the defects of the wood members, and information obtained from on-site inspections and laboratory analysis was summarized. The condition of the wood members was classified, and the patterns of decay and defects in the wood members were summarized. The findings of this study not only provide data support for the subsequent protection and restoration of the Jin Zhongdu watergate site, but also have reference value for the nondestructive testing and evaluation of existing underground or semi-underground wood structures.

Inspection Object

Figure 1 shows a photograph and a simplified diagram of Jin Zhongdu watergate site. From plan view (b), it can be observed that the foundation section of the site has a ") (" shape, with a total length of 43.4 meters from north to south. The water passage tunnel is 21.35 meters in length and 7.7 meters in width. The site is mainly composed of three parts: the water passage area, the two compartments of the tunnel section, and the four swing arms on both sides of the inlet and outlet (Shen 2020). The tunnel section can be further divided into the east compartment and the west compartment, while the four swing arms on the sides of the inlet and outlet can be subdivided into the northeast, northwest, southwest, and southeast swing arms. The foundation of the site consists of closely spaced wood piles inserted into the soil layer. On top of the wood piles, wood tiebeams are connected and fixed using mortise and tenon joints, forming a resilient foundation structure. Stone slabs are then laid on the wood structure to create the water passage, compartments, and swing arms.

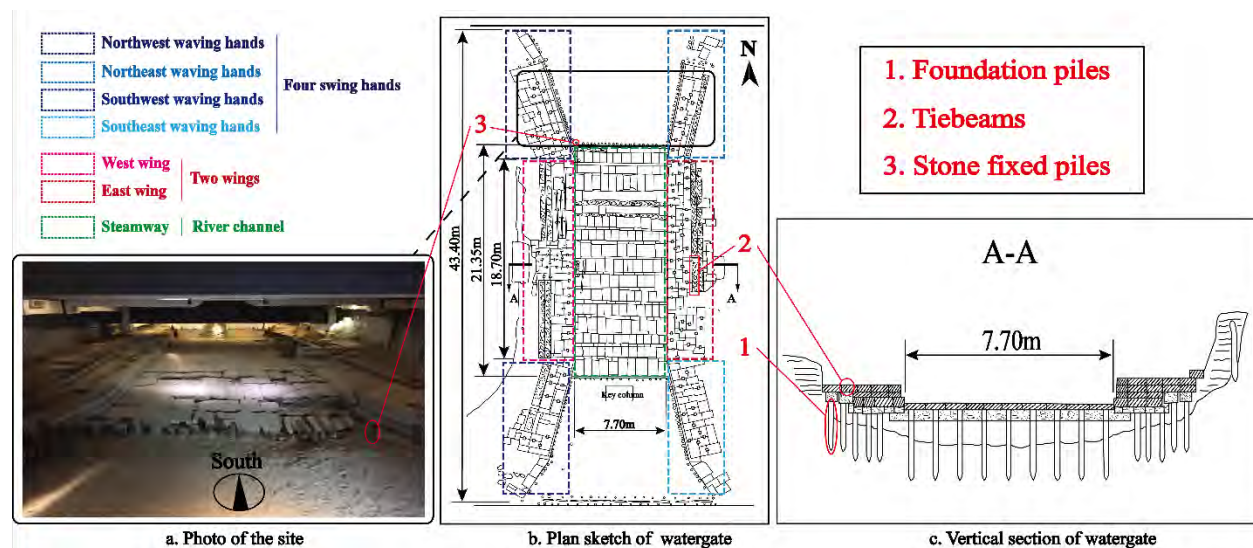


Figure 1—Photograph and structural diagram of the Jin Zhongdu watergate site.

Wood members of the Jin Zhongdu watergate site can be divided into three types based on their own structure, functional characteristics and the surrounding environment: stone fixed piles, foundation piles and tiebeams. The stone fixed piles are wood pillars inserted on the north and south sides of the water channel and at the edges of the four swing arms. They are used to reduce the impact of water flow on the stone slabs. The characteristic of stone fixed piles is that approximately 3/4 of the length of the wood pillar is inserted underground, while about 1/4 is exposed above the ground. Foundation Piles are wood piles inserted into the soil layer, serving to reinforce the foundation and provide support. The characteristic of foundation piles is that the entire length of the wood pillar is inserted underground. Tiebeams are wood beams placed on top of the foundation piles to form a platform for laying stone slabs.

Inspection Method

Map of wood structure model and statistics of wood members

In response to lack of detailed compositional diagrams of wood structure of Jin Zhongdu watergate site, on-site surveys were conducted to record and collect information regarding the positions, quantities, typical dimensions, and interrelationships of wood components such as stone fixed piles, foundation piles and tiebeams. Combining this information with the Song Dynasty's "Commentary and interpretation of the building style" (Li 2018), a diagram illustrating the composition of the wood structure at the site was created, and a statistic of various types of wood components was conducted.

Wood species identification

Different types of wood members are selected from different locations of the watergate site. Samples are taken and brought to the laboratory for wood species analysis and identification.

Defect inspection and evaluation of the wood structure

Working principle

- 1) Excavate one stone fixed pile and one foundation pile, as sampling inspection, exposing their overall height, and conduct to obtain information on their overall defect condition.
- 2) Make full use of exposed parts on the ground of all stone fixed piles and tiebeams to inspect them.
- 3) For some foundation piles, remove the top stone slabs or soil layers and conduct sampling inspection from above.
- 4) For other wood members completely buried in soil or under stone slabs, make speculative evaluations of the conditions based on the previous inspections and grading results of the wood members.

Inspection tools

The instruments used for wood components inspection mainly include Resistograph 650-SC developed by Rinntech in Germany, and YM-50 Wood Moisture Meter made in China. General inspection tools include probes, hammer, tape measure, and screwdriver.

Inspection steps for wood members

- 1) Dig up the soil around one stone fixed pile and one foundation pile, then inspect them.
- 2) Preliminarily judge appearance defects of the wood components through visual inspection, sounding, size measurement and other means.
- 3) Further test wood members with possible internal defects with micro-drilling method, to confirm forms

- and sizes of the internal defects according to the micro-drilling resistance curves.
- 4) Measure moisture contents at different positions of the wood components.
 - 5) Rate wood members into four classes: Grade A wooden members are those in good condition or with minor defects, which have good bearing capacity; Grade B are those with certain defects, which have basic bearing capacity; Grade C wood members are those with large defects that have poor bearing capacity; Grade D are those with huge defects that completely lose bearing capacity.

Results and Analysis

Wood structure model and statistics of wood members

Figure 2 shows the three-dimensional reconstruction model of wood structure for the Jin Zhongdu watergate site, drawn based on the field survey results and a schematic diagram of the site's structure. It is mainly divided into several parts, including the streamway surface, two wings, four hand arms, and southern outer end of the streamway surface.

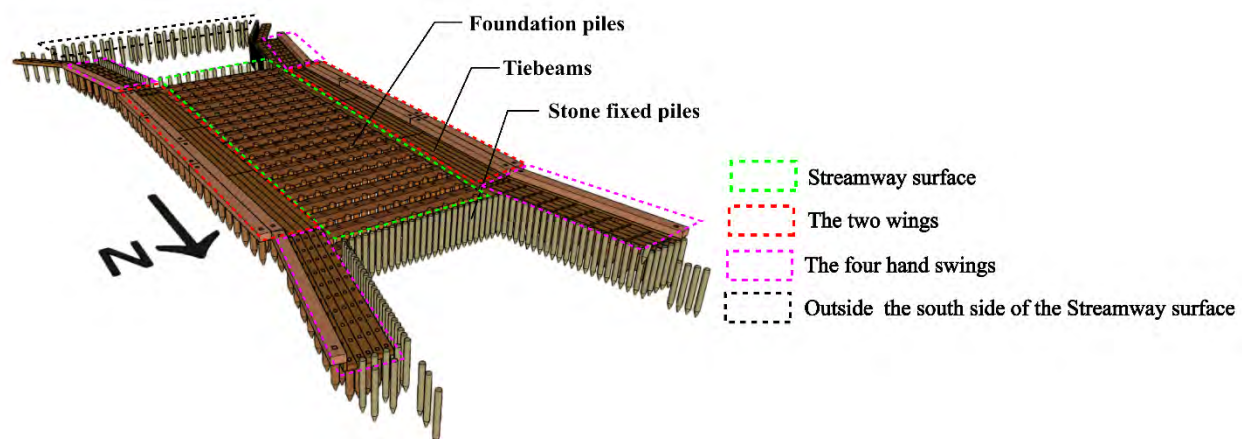


Figure 2—Wood structure model of the Jin Zhongdu watergate site.

Table 1 is a summary table of wood components based on the three-dimensional reconstruction model of the wood structure. There are three main categories of wood components that make up the site's wood structure: stone fixed piles, foundation piles and tiebeams. The quantities are 204, 771, and 92 respectively. The typical dimensions for stone fixed piles and foundation wooden piles are $\Phi 18\text{--}20 \times 200$ cm and $\Phi 20\text{--}22 \times 160$ cm, respectively. The typical dimensions for tiebeams vary based on their location and are approximately $48 \times 30 \times 719\text{--}1017$ cm and $31 \times 30 \times 622$ cm.

Table 1—Summary of position and quantity of each type of wood members

Categories	Quantity (piece)	Typical size (cm)
Stone fixed piles	204	$\Phi 18\text{--}20 \times 200$
Foundation piles	771	$\Phi 20\text{--}22 \times 160$
Tiebeams	92	$48 \times 30 \times 719\text{--}1017$ $31 \times 30 \times 622$

Wood species

Upon conducting tree species identification on the collected 52 wood samples, it was found that the main tree species of the wood members at the Jin Zhongdu watergate site are Larch and Chinese fir. Both of

these wood species are commonly used in ancient architectural timber structures. Among them, Larch accounts for approximately 90.4%, while Chinese fir accounts for approximately 9.6% of the total.

Defect inspection results of the wood structure

The grading results of wood members inspected

Table 2 presents the grading results of wood members inspected at Jin Zhongdu watergate site. Total 236 wood members were taken as examples and conducted in situ nondestructive testing. There are no Grade A wood components among the three categories. Grade B wood components total 117, accounting for 49.6% of the total tested wood components. Grade C wood components total 88, approximately 37.3% of the total tested wood components. Grade D wood components total 31, approximately 13.1% of the total tested wood components.

Table 2—Grating results of inspected wood components at the Jin Zhongdu watergate site

Types of wood members	Grade A	Grade B	Grade C	Grade D	Subtotal
Stone fixed piles	0	114	73	17	204
Foundation piles	0	0	0	13	13
Tiebeams	0	3	15	1	19
Total	0	117	88	31	236
Proportion	0	49.6%	37.3%	13.1%	100%

An inspection example of wood member defect condition

Foundation pile 2-2 is located in northern section of the streamway area. It is connected to the tiebeam above it through a mortise and tenon joint. It has a maximum diameter of approximately 19 cm and a length of about 1.6 m, entire body is buried below the ground surface. The side view excavation of foundation pile 2-2 revealed severe decay, as shown in Figure 3. The pile is overall yellow-brown in color, and resistance micro-drilling testing indicates a complete loss of the timber's basic mechanical properties.



Figure 3—Photos of 2-2 foundation timber pile under the streamway surface.

This foundation pile is completely embedded in the soil and exhibits extensive, sponge-like decay. It has lost all mechanical performance and is prone to causing collapse of the surrounding soil layers once it breaks. In summary, the defect area of foundation pile 2-2 exceeds 80% of its total body, with a length loss exceeding 60%. It has virtually no mechanical performance and is classified as grade D.

Conclusions

1. The prototype of timber structure of the Jin Zhongdu watergate site should consist of 204 stone fixed piles, 771 foundation piles, and 92 tiebeams.
2. The main forms of defects in the wood structure are decay and material loss caused by decay, with minor occurrences of cracks.
3. The overall condition of the wood structure is severely defective, with no wood members classified as grade A. Among the tested 204 stone fixed piles, grades B, C, and D account for 55.9%, 35.9%, and 8.2% respectively. Among the tested 19 tiebeams, grades B, C, and D account for 15.9%, 78.9%, and 5.2% respectively. All 13 tested foundation piles are classified as grade D.
4. The main tree species in the wood structure of Jin Zhongdu watergate site are Larch, with a secondary presence of Chinese fir. The former accounts for approximately 90.4%, while the latter accounts for approximately 9.6%.
5. Practice has proven that it is feasible to detect and assess defect conditions of the wood structure in the watergate site by utilizing techniques such as sounding, dimensional measurement, moisture content measurement, and resistance micro-drilling test.

References

- Ji Heping. 2004. 850 years of vicissitudes of Jin Zhongdu Water Station Ruins - Beijing Liao and Jin City Wall Museum. Architectural Knowledge. (01): 15-18.
- Li Jie. 2018. Commentary and interpretation of the building style. Chemical Industry Press, Beijing, China.
- Shen Yu. 2020. Research on water-pass architecture in ancient Chinese cities. Nanjing Tech University. Ph.D thesis.
- Wang Xiaoying. 2020. A comparative analysis of water gate sites of Jin and Yuan dynasties discovered in Beijing[J]. Beijing Wenbo Series. (02): 40-46.
- Yang Weizhou. 1997. A brief discussion of the Jin Zhongdu and its impact on the Forbidden City camp. Beijing, China.

Condition Assessment of Historic Wooden Ships

C. Adam Senalik *

USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, christopher.a.senalik@usda.gov

Xiping Wang

USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, xiping.wang@usda.gov

Laurice M. Spinelli Correa

Dept. of Sustainable Bioproducts, Mississippi State Univ., Starkville, MS, USA, ls2090@msstate.edu

Rubin Shmulsky

Dept. of Sustainable Bioproducts, Mississippi State Univ., Starkville, MS, USA, rs26@msstate.edu

Robert J. Ross

USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, robert.j.ross@usda.gov

* Corresponding author

Abstract

This paper summarizes work conducted to assess the condition of members in historically significant timber sailing vessels. Four ship assessments are described, the *USS Constitution*, the *USS Cairo*, and the *Wapama*. Launched in 1797, the *USS Constitution* was nicknamed “Old Ironsides” and was a combat vessel used by the US Navy. “Old Ironsides” is a three-masted heavy frigate with a hull primarily constructed of live oak. The *USS Cairo* is a city class ironclad river gunboat. It was built in 1861 and commissioned in January 1862. It was used in combat by Union forces during the American Civil War along the Mississippi River and connected waterways and sunk in December 1862. It remained submerged for 100 years and was recovered in 1964. Currently the *USS Cairo* is on display at the Vicksburg National Military Park. The *Wapama* was launched in 1915 and was used for the Pacific Coast lumber trade and coastal service. It was declared a National Historic Landmark in 1984. It is a wooden steam-powered schooner. Given the historical significance of the vessels, it is important that inspection methods employed do not degrade their conditions. Three categories of nondestructive inspection techniques are employed: acoustic based, moisture detection, and micro-drilling resistance. The specific applications of these techniques for each vessel is described.

Keywords: Wood, ships, nondestructive evaluation, acoustic, moisture, micro-drilling resistance, condition assessment.

Introduction

Deterioration of in-service wood can arise for several reasons. Most common are of biological origin, decay fungi and termites, are frequently the cause of deterioration of wood in a variety of structural systems. In-service wood needs to be inspected on a regular basis to ensure that there has not been a significant loss in load carrying capacity. A thorough inspection is particularly important for main load bearing members. The USDA Forest Products Laboratory (FPL) and cooperators have been developing in-field structural condition assessment techniques for use with wood structures since the 1990’s (White and Ross, 2014). During our work we have had the opportunity to inspect or provide consultation on the condition of a wide range of timber structures including historic ships (Ross et al. 2001). This

manuscript provides a summary of some of the sailing vessels inspected: the *USS Constitution*, the *Wapama*, and the *USS Cairo*. The inspection methods include visual inspection, mechanical inspection by probing, moisture content measurements, stress wave transmission time (SWTT), and micro-drilling resistance.

USS Constitution

The most historically significant ship inspected was *USS Constitution* (Ross et al. 1998; Soltis et al. 1992; Witherall et al. 1992). *USS Constitution*, “Old Ironsides,” was launched on October 21, 1797. She carries the distinction of the oldest commissioned ship afloat in the world because a significant portion of the ship’s underwater structure is original. Included in this original material are the keel, deadwood, floors, lower planking strakes, and several lower frame futtocks. In the 1990s, FPL assisted the U.S. Navy in conducting an intensive condition assessment. The time of flight of stress wave passing through members perpendicular to the grain were measured using a pitch-catch stress wave timing unit (Ross et al. 2005). Mechanical and decay deterioration was observed, which resulted in the replacement of several members.

A unique aspect of this structure was the wood used in its construction. Much of its hull was constructed from oak wood (*Quercus*, sp.), specifically one of species of oak commonly referred to as live oak. Live oak was widely used in early American shipbuilding. Live oak wood is hard, heavy, and difficult to work with, but very strong. In the days of wooden ships, live oaks were the preferred source of the framework timbers of the ship, using the natural trunk and branch angles for their strength. The frame of the *USS Constitution* was constructed from southern live oak (*Quercus virginiana*) wood harvested from St. Simons Island, Georgia, USA. Dry Southern live oak wood has a specific gravity of 0.88 (Forest Products Laboratory 2021), among the highest of North American hardwoods. Another feature of live oak is that the fibers are “interlocked”. Interlocked wood has exceptional strength, specifically perpendicular to the longitudinal axis of the timber.

The density of the wood and its interlocking fiber arrangement allowed it to survive cannon fire, thus earning her the nickname “Old Ironsides”. Because of the trees’ short height and low-hanging branches, timbers from live oak trees were used in curved parts of the frame, such as knee braces (single-piece, L-shaped braces that spring inward from the side and support the deck), making for exceptional strength. Live oaks were not generally used for planking because the curved and often convoluted shape of the tree did not lend itself to being milled to planking of any length. Red oak and white oak were generally used for planking on vessels, because those trees grow straight and tall, with straight trunks long enough for planks. As a consequence of its interlocking fiber alignment, extensive laboratory work was needed to provide baseline sound transmission values for this species of wood (Ross et al. 1998).

Wapama

The historic American ship *Wapama* is the last surviving example of the wooden steam-powered schooners designed for the 19th- and 20th-century Pacific Coast lumber trade and coastal service. Since its launching in 1915, the *Wapama* has had a long and productive life in plying cargo and passengers along the stormy West Coast from Mexico to Alaska. As the sole survivor of the once numerous class, the *Wapama* was declared a National Historic Landmark in 1984. The wood structure of the *Wapama* has significantly deteriorated over the years and currently resides on a barge with internal and external structural supports (Figure 1). Portions of the vessel are unsafe for public access. Assisting in an effort to stabilize and rehabilitate this historic vessel, we conducted a field investigation on the physical condition of the wooden structural members in January 2006 (Wang et al. 2008).

Our investigation focused on the key structural components that provide the structural integrity of the vessel. Structural components tested that provide for longitudinal integrity are the keelsons (rider keelson, main keelson, assistant keelsons), main deck stringers, waterways, bulwarks, and keel. Structural components tested that provide for transverse integrity are the hull assembly (framing timbers, ceiling, clamps, strakes) at three cross-sections and the main deck beams. Due to limited inspection time, the investigation was not intensively focused on individual members, but instead was conducted with relatively large scan intervals or through spot-checking of suspected areas. Stress-wave timing and micro-drilling resistance were the primary methods used in this investigation, coupled with visual inspection and moisture content determination. It was recommended that the roof structure of the main deck be replaced as it was apparent that the current roof did not effectively prevent rainwater intrusion.



Figure 1—Wapama placed on a barge at the Richmond Reserve Shipyard in Richmond, California.

Figure 2 illustrates the distribution of SWTT (in $\mu\text{s}/\text{ft}$) along the length and the mapping of physical conditions of the rider keelson and main keelson. The keelsons deterioration was concentrated between frames 25 and 42, and most severe decay occurred on the main keelson timber between frames 30 and 39. This is also confirmed by micro-drilling resistance tests. Rainwater likely entered this area through the hatch over the years due to failed weather protection and water remained trapped.

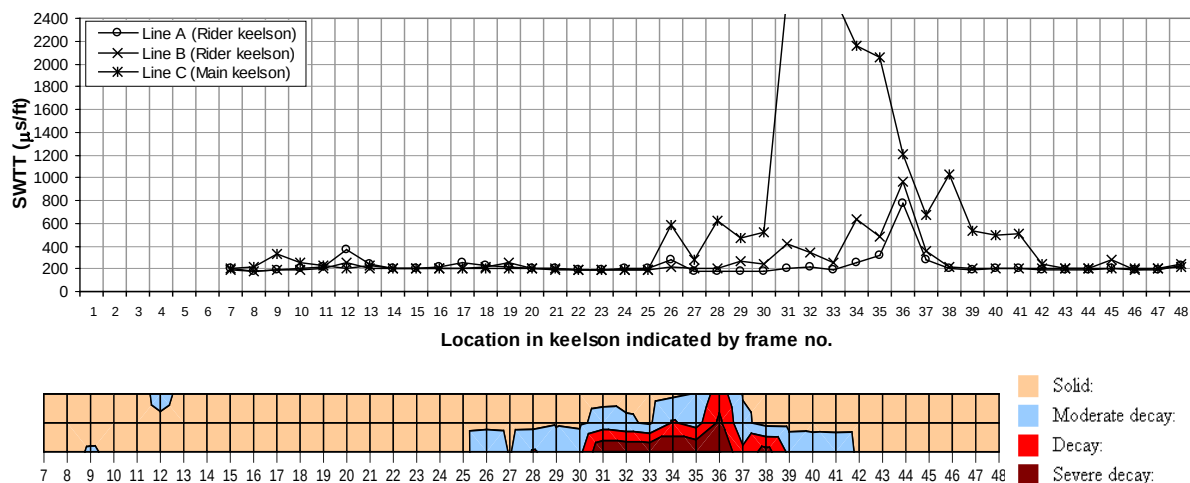


Figure 2—Stress wave transmission time distribution and physical condition map of the keelsons.

Figure 3 is a schematic summary of micro-drilling resistance data collected at hull frame 32. Severe decay was detected at 15 (38%) of the drilling locations, with most of these areas located in the members at the main deck level (stringers and main deck beams) or near the main deck level (clamps, hull frame).

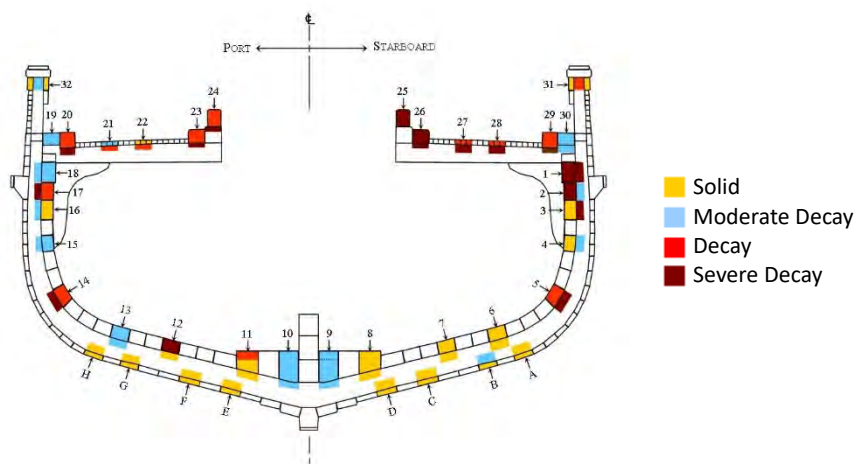


Figure 3—Cross section physical condition map at frame 32 based on micro-drilling resistance.

USS Cairo

The *USS Cairo* was one of a group of Civil War gunboats that were designed specifically to perform in the swift and shallow rivers of the Mississippi River basin. Known as the City Series gunboats, *Cairo* and her six sisters were the first ironclads launched in the Western Hemisphere. Each boat had three keels and flat bottoms that enabled them to glide over the often-shallow rivers. *Cairo* and her sisters were each 175-ft long, 51-ft. wide, and mounted 13 guns. The forward casemate was covered with 2 ½ inches of armor plating which also covered portions of the starboard and port sides. When fully loaded they weighted 880 tons, yet only drafted 6-ft of water. Commissioned on January 15, 1862, *Cairo* had a complement of 175 officers and men and was commanded by Lt. Cmdr. Thomas O. Selfridge, Jr. She was sunk in December 1862 and was salvaged in 1964. In 1980, a covered shelter and mass timber crib structure was built to display and support the *Cairo* (Figures 4a and 4b).



a.



b.

Figure 4—USS Cairo a) Displayed at Vicksburg National Military Park b) Timber crib support

The Forest Products Laboratory (FPL), and Mississippi State University were contacted in 2023 by Vicksburg National Military Park to assist in assessing the condition of a timber crib built to support the *Cairo*. The assessment did not include the *USS Cairo* itself as it is preserved in its current condition because of its historical significance. An inspection utilizing visual, acoustic-based and probing nondestructive testing techniques was conducted on October 24 and 25, 2023 (Senalik et al. 2024). Condition assessment of the *USS Cairo* glulam crib began with a visual inspection to identify obvious areas of decay within the glued laminated (glulam) structure. Overall, the condition of the glulam crib supporting the remains of the *USS Cairo* is in good condition. No areas of surface decay were identified.

The second step of our condition assessment was determination of moisture content (MC) within the wood. Moisture is necessary for wood decay. As moisture content decreases below wood fiber saturation, the likelihood of wood decay decreases. Fiber saturation is species specific, but 20% MC by weight is generally considered below the fiber saturation point. The percentage MC corresponds to the level of concern for the presence or potential of decay. Levels were set at low (below 17%), moderate (17% to 20%), and high (above 20%). At first glance, the underside of glulam beams appeared damp, but it was determined that this was residual oil used in the original pentachlorophenol treatment and moisture readings with a pin-type moisture meter ranged between 8-15% MC, with most values falling within the 10-13% range. These ranges of MC are slightly elevated but still below the 20% and above MC range to promote growth of mold and decay fungi (Forest Products Laboratory 2021). The MC measurements are summarized in Figure 5.

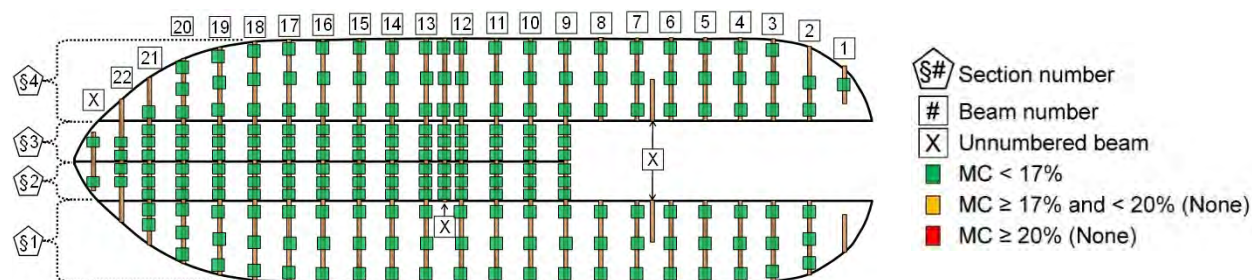


Figure 5—Moisture content of glulam crib underneath the *USS Cairo*. Measurements taken using pin moisture meter. All values fell below 17%. The four sections, left to right, are port, port/center, starboard/center, and starboard. The photograph shows how moisture measurements were taken.

Average moisture content and coefficient of variation (COV) for the four sections of the *USS Cairo* were determined and recorded in Table 1. Overall, moisture content in all four sections was below what is required for decay fungi to grow (>25%). However, there were some instances especially in Section 4 where the moisture barrier between the concrete structure and glulam housing the *USS Cairo* was showing elevated moisture readings (15%). This could be a result of the moisture barrier failing which is allowing elevated moisture readings at these spots. Specific instances of higher moisture readings occurred in Section 1 (port) and Section 4 (Starboard).

Table 1—Average moisture content by section ^a

Section	Average MC (%)	COV (%)
1 (Port)	11.9	10.7
2 (Port/Center)	10.9	9.3
3 (Starboard/Center)	10.8	8.9
4 (Starboard)	11.7	9.9

^a Triplicate readings were measured for each of the glulam structures housing the *USS Cairo*. Average MC was obtained from the entire length of each section.

One area of particular concern is the white oak bulkhead located below the steam pistons attached to the aft paddle wheel assembly. There was evidence of extensive decay and some beginning of structural failure as shown in Figure 6. It is recommended that this area be at a minimum filled with a two-part wood epoxy or similar material to consolidate the member as well as seal off the damage the prevent further biodegradation.

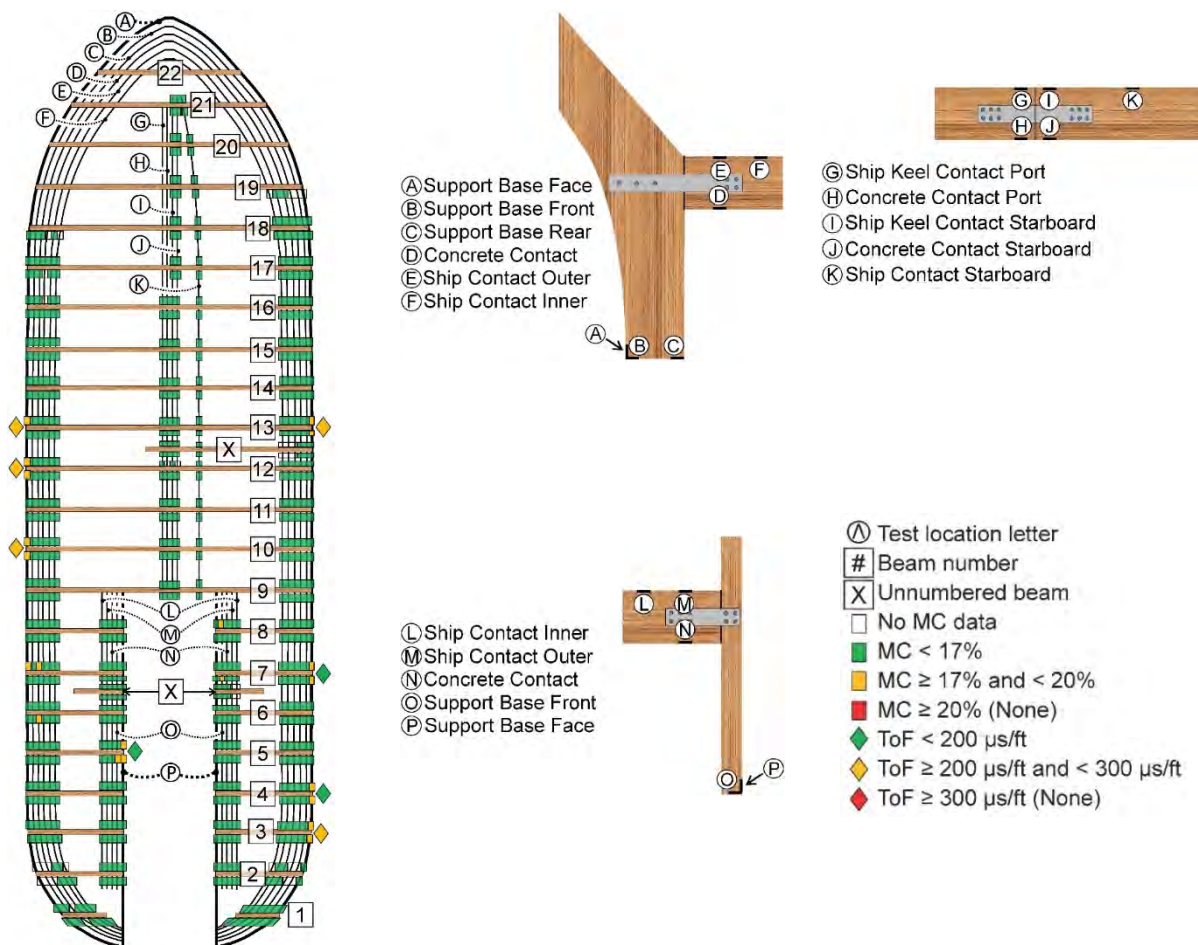


Figure 6—Moisture content (MC) and time of flight (ToF) of glue laminated timber support structure for U.S.S. Cairo. Test locations identified by beam number and location letter provided on diagrams to the right. Locations where MC was at or above 17% were also measured using stress wave ToF. Advanced decay was not found but stress wave ToF revealed locations that should be monitored going forward.

Measurements were taken at contact points between the glulam structure and either the concrete substructure or the historic timbers of the *USS Cairo*. Moisture can become trapped at points of contact and promote wood decay. Wood / concrete contact is particularly prone to decay as the porous concrete absorbs water which is then drawn into wood. Wicking is greatest when the wood end grain is in direct contact with concrete. A thin, barrier layer was placed at each wood-concrete contact point to prevent direct contact between the two materials. The barrier layer minimized transfer of moisture from the concrete to the wood. No areas of MC above 20% were found.

Moderate concern locations (17% to 20% MC) were further tested using stress wave time of flight (ToF). Stress wave time of travel was measured using Fakopp Microsecond Timer from Fakopp Enterprise Bt.

Mechanical waves (sound or mechanical impact) travel faster in sturdy wood than decayed wood. ToF less than 200 μs per foot (μs is a microsecond which is one-millionth of a second) indicate sturdy wood; ToF between 200 $\mu\text{s}/\text{ft}$ and 300 $\mu\text{s}/\text{ft}$ should be monitored; ToF above 300 $\mu\text{s}/\text{ft}$ indicate decay. The Wagner L610 Digital Lumber Moisture Meter and Fakopp Microsecond Timer. No ToF above 300 $\mu\text{s}/\text{ft}$ were observed. Several areas where MC was between 17% and 20% had ToF between 200 and 300 $\mu\text{s}/\text{ft}$.

The following conclusions were drawn from the inspection. Based upon visual inspection, moisture measurement, and time of flight tests it can be concluded that the high humidity and restricted air flow environment have not caused the development of advanced decay. Areas of moderate concern were identified and should be regularly monitored for the development of advanced decay. Increasing air flow around the contact between the glulam supports and the concrete substructure will reduce absorption from standing water. The high humidity environment will continue to be a source of moisture that can potentially lead to the development of advanced decay.

Acknowledgments

The inspection work reported in this paper was conducted through research collaboration between the Forest and Wildlife Research Center, Mississippi State University and the USDA Forest Service Forest Products Laboratory (FPL).

References

- Forest Products Laboratory. 2021. Wood handbook—wood as an engineering material. General Technical Report FPL-GTR-282. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 543 p
- Ross, R.J.; Kirchner, J.; Wang, X.; Forsman, J. 2001. Inspection of keel and mizzenmast on C.A. Thayer. Report to San Francisco Maritime National Park, San Francisco, CA.
- Ross, R.J.; Pellerin, R.F. 1995. Review of nondestructive evaluation of timber. Proceedings, Conference on Technical Aspects of Maintaining, Repairing, and Preserving Historically Significant Ships. Naval Historical Center Detachment Boston, USS Constitution Maintenance and Repair Facility, Charlestown, MA. p. 78-91.
- Ross, R.J.; Soltis, L.A.; Otton, P. 1998. Assessing wood members in the USS Constitution using nondestructive evaluation methods. APT Bulletin 29(2): 21-25.
- Ross, R.J.; X. Wang; B.K. Brashaw. 2005. Detecting decay in wood components. In: Inspection and Monitoring Techniques for Bridges and Civil Structures, Woodhead Publishing Limited, Cambridge, England. pp. 100-114.
- Senalik, C.A.; Ohno, K.; Kirker, G.; Martin, W.A.; Winschel, T.; Spinelli Correa, L.M.; Shmulsky, R.; Ross, R.J.; Shelton, T.G. 2024. Condition Assessment of the Timber Frame Supporting USS Cairo, Vicksburg National Military Park, Vicksburg, Mississippi.
- Soltis, L., A. Baker, L. Ferge, M. Knaebe, T. Kuster, K. McDonald, R. Ross, V. Schwandt, T. Wilkinson, S. Williams. 1992. USS Constitution: Inspection and Evaluation Procedures for Live and White Oak Members. Unpublished research report submitted to U.S. Navy, Maintenance and Repair, USS Constitution, Boston Naval Shipyard, Charlestown, MA. October 1992.
- Wang X., J.P. Wacker, R.J. Ross, B.K. Brashaw; 2008. Condition assessment of the main structural members of historic steam schooner Wapama. Res. Pap. FPL-RP-649. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 29 p.

White, R.H. and R.J. Ross. 2014. Wood and Timber Condition Assessment Manual. Second Edition. General Technical Report. FPL-GTR-324. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 102 p.

Witherall, P.W.; Ross, R.J.; Farris, W.R., 1992. Using today's technology to help preserve USS Constitution. Naval Engineers Journal 104(3): 24-134.

New Ultrasound Transducers Employing Wireless Technology for Large Range of Wood Quality Assessment Applications

Yann Benoit*

Technology & Services, CBT SA, Saint-Sulpice, Switzerland, benoit@cbs-cbt.com

Jean-Daniel Gasser

IT, CBT SA, Saint-Sulpice, Switzerland, gasser@cbs-cbt.com

Jean-Luc Sandoz

CBS, Choisy-le-Roi, France, sandoz@cbs-cbt.com

* Corresponding author

Abstract

CBT SA, based in Switzerland and in collaboration with the Ecole Polytechnique Fédérale de Lausanne (EPFL), launched its first equipment in 1985: the Sylvatest. This device, designed for wood diagnostic applications from the forest to built-up areas, has collected a wealth of data worldwide over its 30-year history. Of course, different versions of the device have evolved over the years, with the Sylvatest Duo, then Trio, before the latest generation of devices was launched in 2022: the Sylvatest 4. The main challenge of this latest version was to remove the cables between the probes and the measurement box, to make interventions faster, more didactic and more ergonomic. Controlled by an application installed on a smartphone, the ultrasonic probes communicate with each other via Bluetooth protocol. This simple technology, widely used today for everyday electronic products, nevertheless requires a great deal of fine-tuning to clock in and out and measure km/s (speed observed in wood) in a wide variety of industrial environments.

The aim of this article is to present this new generation of devices which, in addition to measuring the propagation time of low-frequency ultrasonic waves, can also collect the signal envelope for a better understanding of the quality measured. The software application developed for smartphones is more didactic and facilitates the work of experts, even if it means guiding them step by step according to the cases studied. Examples of the device's use are also presented in this article, demonstrating the wide range of applications covered by this non-destructive technology.

Defect Rating of Wooden Columns Embedded in Walls of Ancient Building Based on Multi-Source Data Fusion and Machine Learning

Yufeng Li *

School of Technology, Beijing Forestry University, Beijing, China, lyf1996@bjfu.edu.cn

Yangwu Ou

School of Technology, Beijing Forestry University, Beijing, China, oywbfu@gmail.com

Shuqi Sun

School of Technology, Beijing Forestry University, Beijing, China, ssq_1105@163.com

Houjiang Zhang *

School of Technology, Beijing Forestry University, Beijing, China, hjzhang6@bjfu.edu.cn

Wenbo Zhang

College of Materials Science and Technology, Beijing Forestry University, Beijing, China, kmwenbo@bjfu.edu.cn

Dian Zhang

The Palace Museum, Beijing, China, zhangdian126@126.com

* Corresponding author

Abstract

Ancient wooden buildings in China rely on wooden columns as their main load-bearing elements. However, these columns within walls are prone to biodeterioration, insect attack, and various forms of damage. Timely inspections through nondestructive testing (NDT) are essential to assess their condition and ensure preservation of these historic structures. This study aims to integrate NDT techniques to detect defects in wooden columns embedded in walls of ancient structures and develop artificial neural network models for rapid and accurate defect assessment. We first collected defect images and micro-drilling resistance data from the wooden columns in walls. Then we synthesized the surface and internal defect information of the columns and employed machine learning to rate defects. The datasets from various sources were individually augmented, and multi-source features were fused to construct defect classification models using various neural networks. Among the neural networks evaluated, the radial basis function (RBF) neural network model yielded best results. We further optimized the RBF neural network model using grey wolf optimizer (GWO) to improve defect rating. The results indicated that the defect rating based on micro-drilling resistance data outperformed the defect rating based on defect images of wooden columns. Furthermore, the defect rating from multi-source data fusion was more accurate than that from single-source data. The rating accuracy of the optimized GWO-RBF neural network model reached 98.0%. The defect rating method we developed in this study has a potential for use in real-world condition assessment of wooden columns, providing rapid and effective assessment of wooden columns for preservation of ancient wooden buildings.

Keywords: ancient building, wooden columns, defect classification, multi-source data fusion, machine learning, neural network.

Introduction

Wooden columns play a crucial role as load-bearing elements in wood-framed ancient buildings. They are responsible for carrying vertical loads and transferring them to the foundation. However, as a type of biological material, wooden columns undergo light aging and dry-wet cycles over hundreds of years in the natural environment. This process is accompanied by fungi, bacteria, insects, and other biological attacks (Xin et al. 2022). As a result, the surface and interior of the columns are prone to various defects, leading to the deterioration of the wood properties. This poses a threat to the safety of ancient buildings.

According to the relationship with the walls of ancient buildings, wooden columns can be categorized as exposed columns, semi-exposed columns, and embedded columns (Yu et al. 2022). Semi-exposed columns and embedded columns are partially or completely embedded in walls. When the humidity of the environment in which they are located is high, it is easy to promote biological erosion, exacerbating the development of defects in wooden columns. Missing material, insect infestation, internal cracks and cavities, surface and internal decay, and even overall deformation of wooden columns can seriously threaten the stability of ancient buildings, potentially leading to the collapse of the structures.

Defect detection and rating of wooden columns are crucial aspects of safety inspections for ancient buildings. A variety of nondestructive or micro-destructive testing methods and techniques (Niemz and Mannes 2012) can be used for the inspection of wooden cultural relics, including visual inspection, hammering detection, micro-drilling resistance detection (Rinn et al. 1996), stress wave tomography (Xu et al. 2021), ultrasonic detection (El Najjar and Mustapha 2021), infrared thermography detection methods (Kandemir-Yucel et al. 2007), etc. Though there are numerous methods for detecting defects in wooden columns, each method and technique has its own applicable scenarios and limitations. Therefore, on-site detection of wooden columns in ancient buildings often requires a combination of various nondestructive testing methods based on the different conditions of the wooden columns. Due to the cumbersome detection steps and high labor intensity, specialists find it challenging to promptly and accurately assess the defects of wooden columns in ancient buildings based on detection data. This difficulty leads to significant inconvenience in on-site defect rating.

In order to enhance the efficiency of defect rating and promptly present the defect rating results, considering the limited operating space for the wooden columns embedded in walls, this study was based on surface defect images and internal micro-drilling resistance data of wooden columns with various defect grades. Expert defect ratings were used as labels, neural network models were trained, evaluated and optimized for rapid and precise defect rating of wooden columns in ancient buildings.

Research Objects

The objects of the research are the wooden columns embedded in the walls of an ancient building, the cross-section of which is shown in Figure 1(a). Part or all of the wooden column is embedded in the wall, and there are air vents used for the ventilation of the wooden columns. These vents help to remove some of the humidity from the columns. In the long-term service life, the original ventilation system may become blocked. This, combined with various environmental, biological factors, and other influences, can lead to defects of varying degrees in the wooden columns. As an example, the wooden columns in Figure 1(b), embedded in the northwest corner of the building, were found to have more serious defects because of the shady and damp environment, posing a threat of decay and pests.

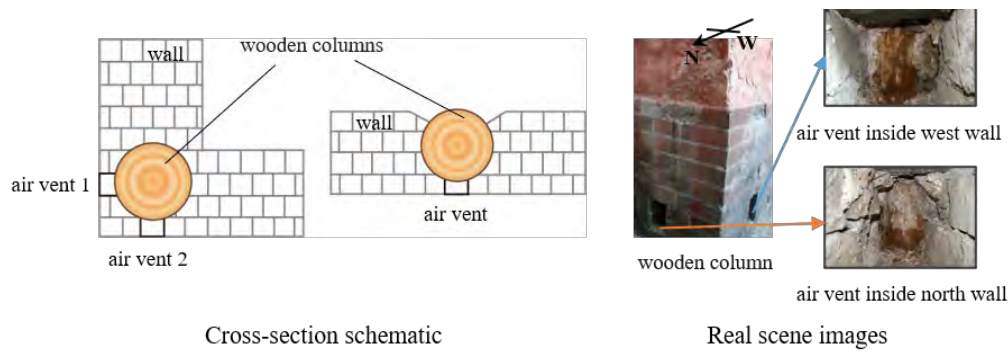


Figure 1—Wooden columns embedded in walls

Research Method

Nondestructive testing and expert defect rating of wooden columns

Nondestructive testing

As shown in Figure 2, the overall condition of the wooden columns was first visually observed through the air vents. Probes and measuring tapes were used to detect the location, shape, and size of defects on the column surface. The dimensions of the missing parts of the wooden columns were recorded. Secondly, a digital camera was used to capture images of column surfaces, and a moisture content meter was utilized as an auxiliary testing device to measure the moisture content of ancient architectural columns. The initial assessment of the internal defect condition of the wooden columns was conducted through hammering detection to determine the presence of defects like decay, hollow areas, and so on. Finally, for columns with potential internal defects, Resistograph 650-SC developed by Rinntech, Germany, was utilized to detect the micro-drilling resistance in the columns through the air vents. Based on the resistance of the drilling needle through the wood, combined with knowledge of wood science, the type, size, and distribution of internal defects were determined.

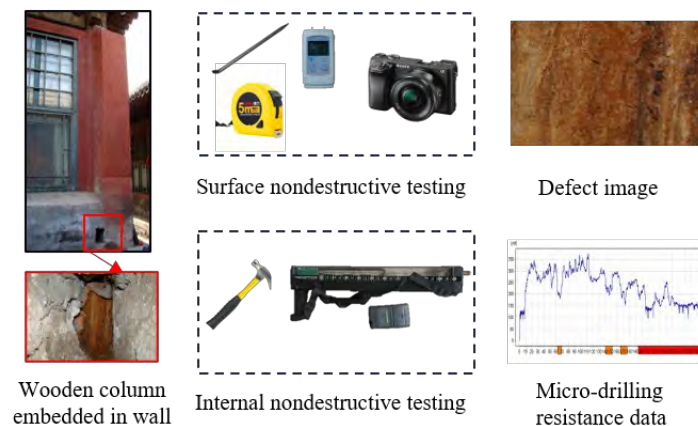


Figure 2—Nondestructive testing of wooden columns

Expert defect rating

According to the Chinese national standards GB/T 50165-2020, GB/T 13942.2-2009, DB11/T 1190.1-2015, and reference (Zhang et al. 2022), the evaluation of wooden columns was based on the external defect area proportion coefficient k , internal defect area proportion coefficient p , crack length proportion

coefficient m , and crack depth proportion coefficient n , as listed in Table 1. The wooden columns were classified into four defect grades: grade A columns were in good condition and did not require intervention; grade B columns were defective and did not require immediate intervention but needed to be reviewed periodically; grade C columns were defective and needed to be appropriately reinforced; and grade D columns were not suitable for continued use and were recommended to be replaced or pier-jointed.

Table 1—Defect rating criteria for wooden columns

Defect types	Proportion coefficient	Rating criteria			
		Grade A	Grade B	Grade C	Grade D
External defect	k	$k \leq 0.05$	$0.05 < k \leq 0.25$	$0.25 < k \leq 0.45$	$k > 0.45$
Internal defect	p	$p = 0$	$0 < p \leq 0.08$	$0.08 < p \leq 0.15$	$p > 0.15$
Crack	m	$m \leq 0.1$	$0.1 < m \leq 0.4$	$0.4 < m \leq 0.8$	$m > 0.8$
	n	$n \leq 0.1$	$0.1 < n \leq 0.4$	$0.4 < n \leq 0.8$	$n > 0.8$

Multi-source dataset augmentation and fusion

Due to the inherent value and scarcity of ancient buildings, making it difficult to detect hundreds or thousands of wooden column samples, it is essential to augment the dataset. The multi-source dataset augmentation mainly focused on two aspects: the augmentation of defect images and micro-drilling resistance data.

The image dataset was augmented by injecting noise, performing linear transformation, and applying image enhancement. Invalid data not related to wood columns were removed from the original micro-drilling resistance data and some missing data were added. Furthermore, the length of the micro-drilling resistance data was adjusted to ensure consistent features. The micro-drilling dataset was then augmented by recombining sub-regions and adding random errors to obtain new micro-drilling resistance data for rating wooden column defects.

The image data of the wooden column surface defects was fused with the micro-drilling resistance data after supplementing the missing parts. This process resulted in obtaining a multi-source fusion data related to the defects of the wood columns embedded in walls. As shown in Figure 3, image data comprised of 10,000 features, micro-drilling resistance data had 30,000 features, and multi-source fusion data contained 40,000 features.

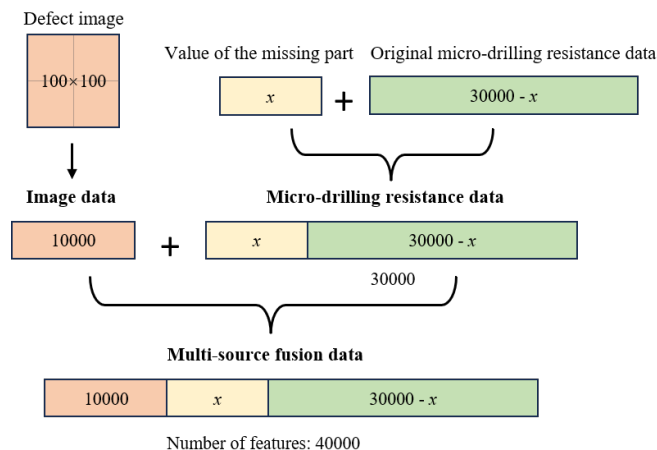


Figure 3—Feature fusion of multi-source data

Machine learning based defect rating

Based on three existing datasets of image dataset, micro-drilling dataset, and multi-source fusion dataset of wooden columns embedded in walls with different defect grades, neural network classification models such as convolutional neural network (CNN) (LeCun et al. 2010), long short-term memory (LSTM) network (Hochreiter and Schmidhuber 1997), radial basis function (RBF) network (Hwang and Bang 1997), and extreme learning machine (ELM) (Bao et al. 2018) were trained and tested using the expert defect ratings as labels. The grey wolf optimizer (GWO) (Mirjalili et al. 2014) simulated the leadership hierarchy and hunting mechanism of grey wolves to achieve the optimal solution by searching for the prey, surrounding and attacking it. This optimizer was utilized to enhance the neural network classification model, aiming to further improve the defect rating effect and accuracy.

The performance of neural network classification models for rating wooden column defects was evaluated using accuracy *Accuracy* (Zhang and Pan 2022) as shown in the following formula.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$

Where, *TP*, *TN*, *FP*, and *FN* denote true positives, true negatives, false positives, and false negatives in machine learning classification, respectively. *Accuracy* indicates the proportion of samples whose defect grades are correctly classified out of the total number of samples.

Results and Analysis

Nondestructive testing and expert defect rating of wooden columns

According to the defect rating criteria of wooden columns shown in Table 1, the results of the defect rating were 26 grade A, 24 grade B, 14 grade C and 21 grade D wooden columns in the ancient building. Grade C and D wooden columns, which needed to be reinforced and replaced, accounted for 41.18% of the detected wooden columns embedded in walls.

Machine learning based defect rating

Multi-source dataset augmentation and segmentation

Table 2 presents the original datasets of surface defect image data and internal micro-drilling resistance data of wooden columns with various defect grades, along with the sample sizes of their augmented datasets, which also include the multi-source fusion dataset. As shown in Table 2, the sample sizes of the augmented datasets were both 760. The training datasets and the test datasets were randomly segmented in a proportion of 4:1 for training and testing the machine learning models, respectively.

Table 2—Sample size of augmented datasets for machine learning

Type of dataset (features)		Defect grade				Total
		Grade A	Grade B	Grade C	Grade D	
Original datasets	Image dataset (10,000)					
	Micro-drilling dataset (30,000)	27	24	20	24	95
Augmented datasets	Image dataset (10,000)					
	Micro-drilling dataset (30,000)	216	192	160	192	760
	Multi-source fusion dataset (40,000)					

Defect rating results of different neural network classification models

Our research compared the performance of CNN, LSTM, RBF, and ELM neural network classification models in image dataset, micro-drilling dataset, and multi-source fusion dataset for defect rating of wooden columns in ancient building. All the neural network models had an accuracy close to 100% in the training datasets, indicating that the prediction results of different defect grades were in good agreement with the labels.

Figure 4 displays the defect rating performance in the test datasets. The defect rating performance of all neural network models in image dataset, micro-drilling dataset, and multi-source fusion dataset exceeded an accuracy of 83.4%. This indicated that these models were suitable for general defect inspection of wooden columns embedded in walls of ancient buildings. CNN, LSTM, RBF, and ELM neural network classification models achieved higher defect rating performance in the multi-source fusion dataset than in the micro-drilling dataset and image dataset. Evidently, the defect rating from multi-source data fusion was more accurate than that from single-source data. Defect rating based on micro-drilling resistance data outperformed that based on defect images of wooden columns. In the multi-source fusion dataset, the RBF neural network model achieved an accuracy of 97.35%, demonstrating superior performance in classifying the defect condition of wooden columns compared to other neural network models.

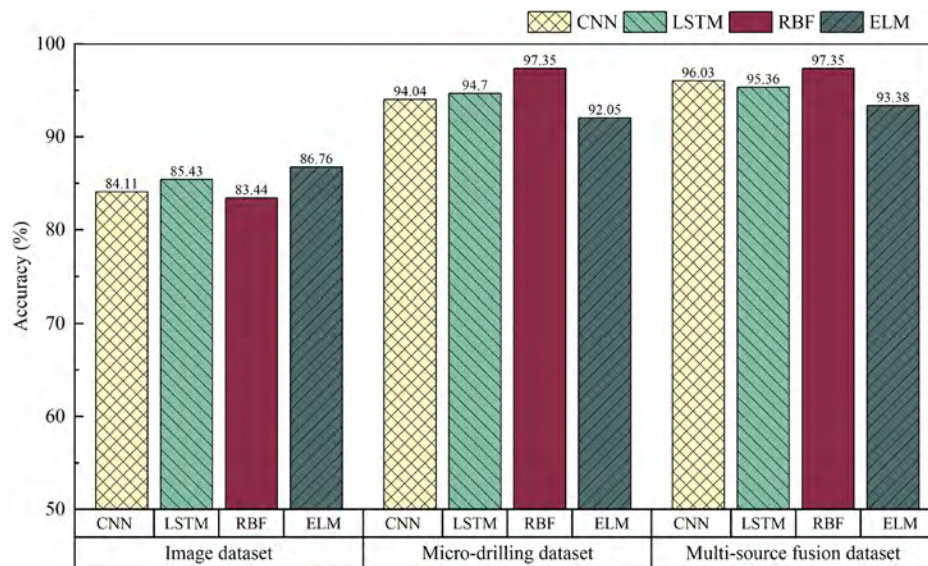


Figure 4—Evaluation of defect rating performance of different neural network classification models

The optimized GWO-RBF neural network classification model for defect rating

The RBF neural network optimized using GWO algorithm was tested in multi-source fusion dataset as shown in Figure 5. The optimized GWO-RBF neural network model had an accuracy of 98.68% in predicting the defect grades of wooden columns, which was 1.33% higher than the traditional RBF neural network model. After re-segmenting the training and test datasets of the multi-source fusion dataset, the accuracy of the prediction results of GWO-RBF neural network model was 98.01%. It can be found that the GWO-RBF neural network model can accurately classify most of the wooden column defect samples and performs very well on the test data.

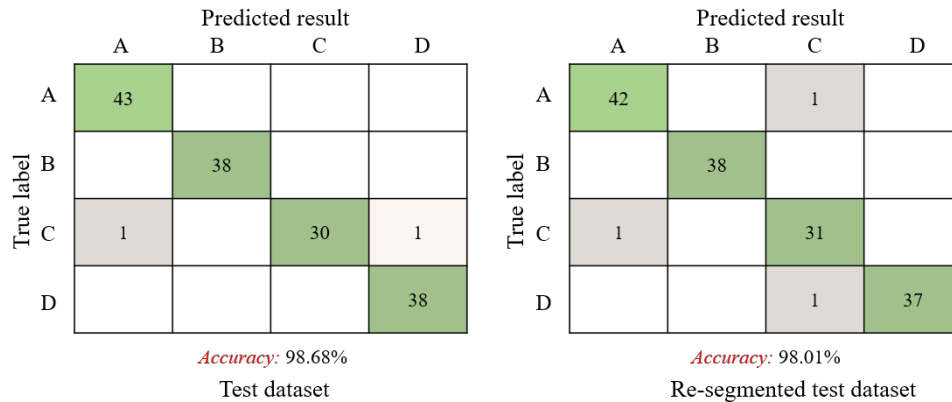


Figure 5—Defect rating of GWO-RBF neural network model in multi-source fusion dataset

Conclusions

In this study, the surface and internal defect information of the wooden columns embedded in walls of an ancient building was obtained through visual inspection, hammering detection, micro-drilling resistance detection, and other nondestructive testing methods. The detection and expert assessment of wooden column defects were conducted. Based on the surface defect image data, internal micro-drilling resistance data, and multi-source fusion data of ancient architectural wooden columns with different defect grades, neural network models were trained, evaluated, and optimized using the expert defect rating results as labels. This approach achieved a fast and accurate defect rating of wooden columns. The results can offer quick and effective scientific references for subsequent maintenance, restoration, and reinforcement. The main conclusions of this study are as follows:

- 1) The accuracy of CNN, LSTM, RBF, and ELM neural network models for defect rating of wooden columns in image dataset, micro-drilling dataset, and multi-source fusion dataset was greater than 83.4%. Neural network models evaluated can be utilized for general defect inspection of wooden columns in ancient buildings.
- 2) The defect rating performance in the multi-source fusion dataset was higher than that in the micro-drilling dataset and the image dataset. The RBF neural network achieved the highest accuracy of 97.35% for defect rating for wooden columns in multi-source fusion dataset.
- 3) The optimized GWO-RBF neural network model improved the accuracy by 1.33% compared to the traditional RBF neural network model. After re-segmenting the training dataset and test dataset, the GWO-RBF neural network achieved an accuracy of over 98.0% in the test dataset. This enables accurate and rapid identification of the defect condition and efficient rating of wooden column defects.

References

- Bao, R.; Chen, W.; Tang, G. [and others]. 2018. Classification of fresh and processed strawberry cultivars based on quality characteristics by using support vector machine and extreme learning machine. *Journal of Berry Research* 8, 81–94.
- El Najjar, J.; Mustapha, S. 2021. Condition assessment of timber utility poles using ultrasonic guided waves. *Construction and Building Materials* 272, 121902.
- Hochreiter, S.; Schmidhuber, J. 1997. Long short-term memory. *Neural computation* 9, 1735–1780.

Hwang, Y.-S.; Bang, S.-Y. 1997. An efficient method to construct a radial basis function neural network classifier. *Neural Networks* 10, 1495–1503.

Kandemir-Yucel, A.; Tavukcuoglu, A.; Caner-Saltik, E.N. 2007. In situ assessment of structural timber elements of a historic building by infrared thermography and ultrasonic velocity. *Infrared Physics & Technology* 49, 243–248.

LeCun, Y.; Kavukcuoglu, K.; Farabet, C. 2010. Convolutional networks and applications in vision. In: *Proceedings of 2010 IEEE International Symposium on Circuits and Systems*, Paris, France, pp. 253–256.

Mirjalili, S.; Mirjalili, S.M.; Lewis, A. 2014. Grey wolf optimizer. *Advances in Engineering Software* 69, 46–61.

Niemz, P.; Mannes, D. 2012. Non-destructive testing of wood and wood-based materials. *Journal of Cultural Heritage* 13, S26–S34.

Rinn, F.; Schweingruber, F.-H.; Schär, E. 1996. RESISTOGRAPH and X-Ray Density Charts of Wood. Comparative Evaluation of Drill Resistance Profiles and X-ray Density Charts of Different Wood Species. *Holzforschung* 50, 303–311.

Xin, Z.; Fu, R.; Zong, Y. [and others]. 2022. Effects of natural ageing on macroscopic physical and mechanical properties, chemical components and microscopic cell wall structure of ancient timber members. *Construction and Building Materials* 359, 129476.

Xu, P.; Guan, C.; Zhang, H. [and others]. 2021. Application of nondestructive testing technologies in preserving historic trees and ancient timber structures in China. *Forests* 12, 318.

Yu, Y.; Guan, C.; Zhang, H. [and others]. 2022. Numerical simulation on the influence of wall wood column defects on the safety of ancient building. *Journal of Beijing Forestry University* 44, 132–145.

Zhang, H.; Xin, Z.; Yu, Y. [and others]. 2022. Nondestructive evaluation of the concealed wood columns in historic buildings. In: *Proceedings of the 22nd International Nondestructive Testing and Evaluation of Wood Symposium*, Quebec City, Canada, pp. 293–300.

Zhang, L.; Pan, Y. 2022. Information fusion for automated post-disaster building damage evaluation using deep neural network. *Sustainable Cities and Society* 77, 103574.

A Fusion Algorithm to Detect the Internal Defects of Timbers Based on GPR Data

Xi Wu*

The Engineering Technology Training Center, Nanjing Vocational University of Industry Technology, Nanjing, Jiangsu Province, China, wuxiyilange2010@163.com
School of IoT Engineering, Jiangnan University, Wuxi, Jiangsu, China,

Xiaoyun Zhang

The Engineering Technology Training Center, Nanjing Vocational University of Industry Technology, Nanjing, Jiangsu Province, China, xyzhang531@163.com

James Wacker

USDA Forest Products Laboratory, Madison, Wisconsin, USA, james.p.wacker@usda.gov

Christopher Adam Senalik

USDA Forest Products Laboratory, Madison, Wisconsin, USA, christopher.a.senalik@usda.gov

* Corresponding author

Abstract

Traditionally, timber structures are inspected using visual, sounding, coring and mechanical drilling methods which are time-consuming and labor-intensive. Ground penetrating radar (GPR), as a non-destructive detection method, has great potential for fast assessment of the physical conditions of timber structures and for health monitoring of urban trees. The evaluation of bridge timbers using GPR data is an upfront basis of this research. Most of the data of this research was generated from at least 10 groups of simulated timber models (different material properties and conductive properties) in the GprMax environment. This research presents the application of GPR as a field inspection method and develops a fusion algorithm based on signal processing and machine learning to detect the internal defects of the timbers. The results showed that the fusion algorithm was effective in identifying internal damages in the existing timber structures.

Keywords: Ground penetrating radar (GPR), timber, defect detection.

Introduction

There are numerous wooden structure bridges both domestically and internationally. The internal serious defects and imbalance of the structure caused by long-term disrepair would make a significant threat to the people's lives and public property. The traditional methods to detect the ancient wood structures always rely on the manual experience. The manual methods for detecting ancient wood structures have limited reliability and accuracy. Therefore, the high-precision non-destructive testing technology is the mainstream direction of the future research. Ground Penetrating Radar (GPR) is commonly used to detect objects buried in different materials as sand, timber, and concrete. The internal reflection of the radar signal brings the information of the targets, such as the dielectric, the position, the size, and so on.

Cardimona et al. (2000) measured the carriageways of 11 Bridges. The results show that the GPR can provide an accurate estimate of deterioration after the comparison. Cimadevila et al. (2010) explored the various uses of GPR in forestry by utilizing antennas with 900 MHz and 1 GHz. Their initial findings indicated differences in wave velocity and relative permittivity. Muller (2002) concentrated on the efficacy and applications of GPR in the assessment of the bridge timbers by detecting the internal flaws using non-destructive method. Maï et al. (2014) detailed the application of the GPR by evaluating the timber structures after measuring the relative permittivity on the spruce and pine using resonance technology with 1.26 GHz and a GSSI SIR 3000 system with 1.5 GHz antenna. The results displayed a strong correlation between relative permittivity and water content in diverse wood samples. Because of the dependence of the dielectric constant on the moisture content, there is a correlation between the hyperbolic echo and the moisture content of the wood. Kravitz et al. (2019) conducted ground penetrating radar experiments in a tunnel. They researched the selection of the antenna frequency to get the best resolution on the penetrate in the reinforced segment.

In order to enrich the data types and datasets that get a better understanding of the complexed distribution of targets inside of the plates, the constant proportional numerical simulation of actual samples was necessary. The finite-difference time-domain (FDTD) method is known to be a method for calculating discretized values in the electromagnetic field (Lu et al. 2020). Dr. Antonis. Giannopoulos created the GprMax simulation environment in 1966. GprMax is a simulated environment for the GPR model based on FDTD theory. In this environment, users could simulate models of the GPR reflection with different parameters, such as the medium parameters, the parameters of the radar emission source, the boundary conditions, and so on. In the simulation environment of GprMax, parameters such as root diameter roughness, burial depth, and scanning angle are simulated. Wang et al. (2020) simulated the reflection of the tree root based on the ground penetrating radar methods. They discussed the influences of different parameters to the simulation, such as root diameter roughness, burial depth, and scanning angle. They found that the target was easier to be detected with a scan angle that was above 45 degrees and a smaller buried depth.

There is little research about the methods of defect identification of wooden bridges. The researches mainly focuses on the analysis of raw data combined with machine learning methods. And the selected methods usually require big data sets. The data used sometimes has limited species or invalid data. Therefore, data preprocessing becomes particularly important. The preprocessing methods of radar signals include several ways, such as the removal of direct wave, the noise removal of background signal, trace shifting, Hibbert transform, offset and so on. Dou et al. (2017) proposed a new suitable technique for real-time field applications. After the preprocessing of the B-Scan data, the areas of the targets were separated from the background information by a threshold segmentation method.

Al-Nuaimy et al. proposed an automatic system to detect the buried objects. The methods trained a three-layer fully connected feed-forward perception neural network with a backpropagation neural network and identified the Welch spectral to realize the estimation of the density of buried targets. Wu Yutong (2020) studied the methods to locate and identify the root automatically among the GPR data. They realized the identification and location of the simulated data in the GprMax environment based on the Faster R-CNN model and Principal Component Analysis (PCA).

Materials and Methods

In the previous study of the PhD study, the target recognition faced some hurdles. The reasons are as follows: the sample size is small; the sample contains a few types of defects; the defects in the sample are densely distributed and the signal has a large mutual influence.

In order to enrich the data types and datasets of ground penetrating radar, and to better understand the distribution of complex targets inside the wood timber, the simulation of the GPR scanning was necessary. These internal defects of the timber were intricate and diverse with a wide variety of types.

In order to locate and classify the regions, a fusion method combining image processing and machine learning methods was proposed based on the simulated data.

In the 1996, Dr. Edinburgh Antonis Giannopoulos, from the University of Edinburgh, created the GprMax simulation environment. GprMax is an environment for the simulation of the GPR signal based on the FDTD theory.

Therefore, the simulated model with an equal scale was performed on the actual samples in the GprMax environment. The detection depth differs depending on the emission frequency. The range of detection depth corresponding to different antenna frequencies were shown in the Table 1. The frequency of the simulation was chosen according to the parameter in the machine that used in the real scan of the samples.

Table 1—The range of detection depth corresponding to different antenna frequencies

The frequency of the transmitting antenna (MHz)	The depth of the detection (m)
2000	0.3-0.6
1000	0.6-1
900	0.75-1.5
500	1.5-3
300	3-6
200	2
100	7

The simulated process of the scanning was shown in Figure 1. The refined parameter of the simulation was shown in the Table 2. The simulated data consists of multiple files (*.out). By integrating these files, the entire files (*.out) for one whole scan path can be obtained. The data results can be A-Scan data and B-Scan data.

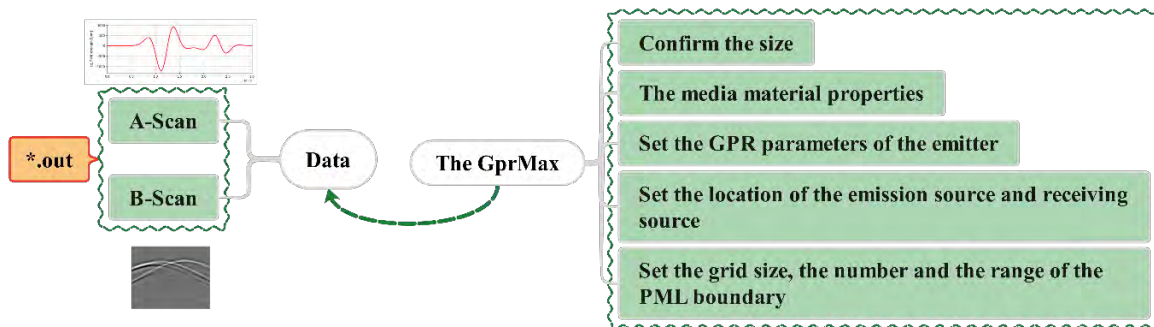


Figure 1—This figure showed the process of the simulation.

Table 2—The parameters of simulation under GprMax environment

The type of Parameters	Values
Size(m*m*m)	0.3048×0.1016×0.1
Grid-step size (m*m*m)	0.00254×0.00254×0.1
Time-window(ns)	3.79
The start position of the transmitting antenna (m)	0.025, 0.1016, 0
The start position of the receiving antenna (m)	0.035, 0.1016, 0
Antenna step (m)	0.01

The processing process includes a total of 6 steps. The evidence shows that the direct wave was greatly disturbed. For example, some region of the targets in the B-Scan data are covered by direct waves due to the proximity to the surface. To address the above issues, the background wave of the echo data was removed using the removal methods. There are various direct-wave remove methods, among that the median filtering was the best one.

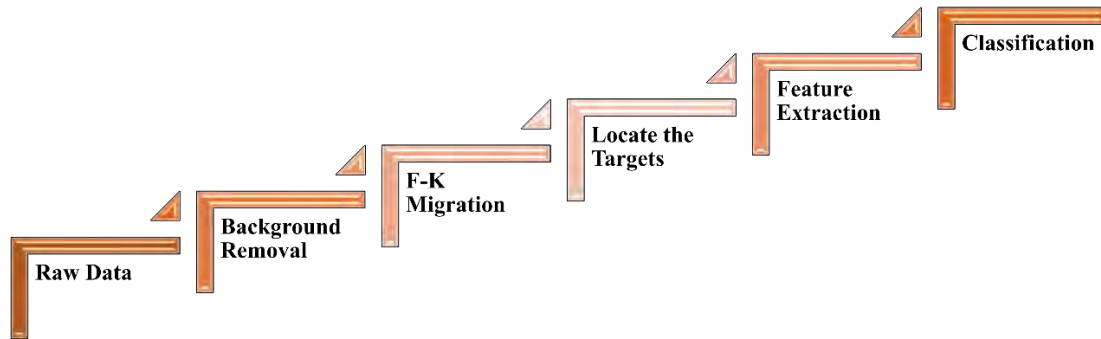


Figure 2—This figure showed the process of the simulation.

DTW (Dynamic Time Warping) is a method of measuring the similarity between two time series with different lengths. This method is a typical optimization problem that uses time warping functionality to demonstrate the temporal correspondence between test templates and reference templates. The similarity analysis was conducted on the pre-processed of the data, then the region with the local maximum value could be found on the metric curve.

A migration processing method combining with different sliding window was proposed, which was based on the wavelength of the simulated emission source and the width of the hyperbolic waves. The size of the sliding window needs to be set greater than a half of the echo's wavelength. There are two modes for the sliding window, one is to scan from 40 cells on the left of the target to 50 cells on the right with a moving step of 10 cells, and the other is 90 cells to scan from left to right with a sliding step of 10 cells.

The results of the above two sliding windows could get a set of echo targets. But there are also some cases which were not the target need to be located. In order to improve these situations, a point updated method based on image segmentation and image morphology analysis was proposed. The successful check of the target areas achieved the localization of the targets.

Then, a 16×16 cell size was selected for target regions and the histogram of oriented gradient features of these areas were collected. Finally, these features were fed into the classifier to achieve the classification of complex internal targets in the simulated samples.

Results

It is well known that, objects with high differences in dielectric properties are more obvious in the GPR image. It is easier to determine the category and size of some single-target region. The experimental data in this research mainly focused on the simulation data with the units of 0.3048 meters. Some signal noise would be caused during the actual scanning process by the testing ways and the testing environment. But for the simulated model, the medium was isotropic materials. The data was not affected by external noises. The maximum number of internal targets for each sample was 8. The small distance between multiple targets caused superposition of reflected waves, and also resulting in higher energy in concentrated area. Therefore, the preprocessing part of the data focuses on the removal of direct waves. The B-Scan after background removal and direct-wave removal could be seen in the Figure 3.

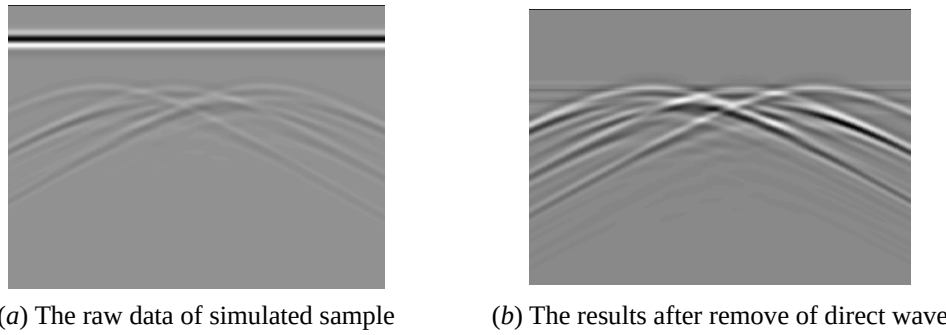


Figure 3—Comparison chart of direct wave removal of No.62 simulation data

By performing overall migration process on the B-Scan image, it can be seen that the signal of the targets area was affected by the surrounding complied echoes. In response to this situation, the following process was adopted, using the mean subtraction method to enhance the energy of the target region and decrease the similarities between the targets (Figure 4(b)). There are some regions around the targets contained some similar information that may be misjudged as the interested area. In this situation, the error targets with similar coordinates and repetitive confirmation were successfully deleted using the method we proposed as shown in the Figure 4(d). The analysis shown that the misjudge of the target was often generated because of the position. For example, the peak of the echo was covered by the left or the right waves of the other nearly echo (Figure 4 (a)). For this situation, the data correction by processing the center distance, intersection rate, and the signal entropy were not suitable. Therefore, establish a series of constraints. Firstly, calculate the slope of the bone line in the target area, and remove the point if the value exceeds a certain range; Secondly, check the whole points, deleting the meaningless areas based on the morphology analysis on the image; Finally, eliminating the error points based on the distribution of the maximum kurtosis of the channel. The final results could be seen in the Figure 4(d).

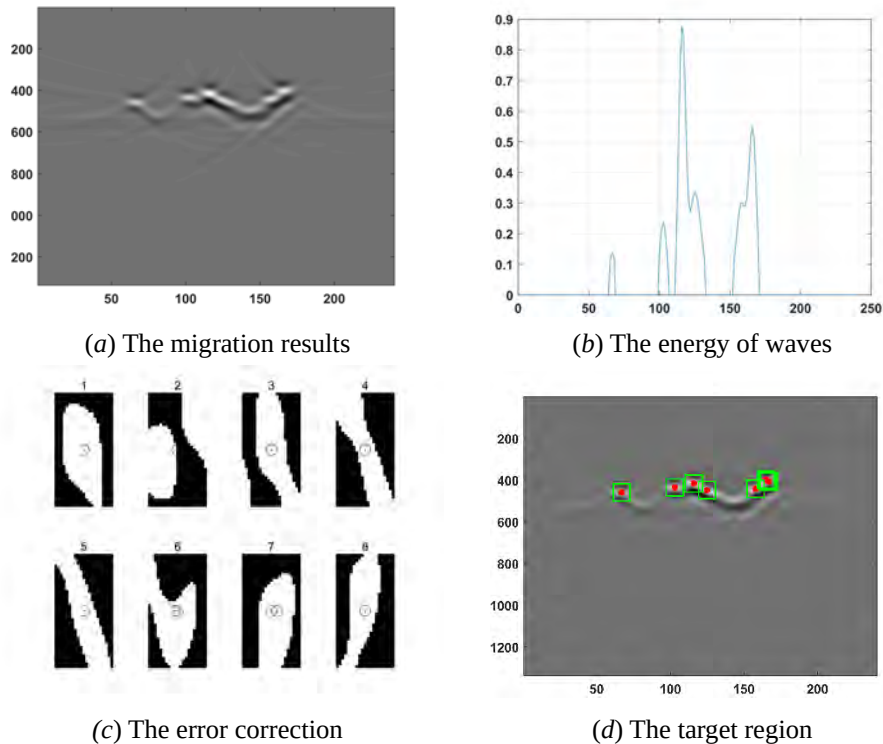


Figure 4—The results of the processing

Selecting three sets of samples as the test data, and the rest of the data were the training data. Setting the metal sample as the positive sample and the hole as the negative sample. Feeding multiple types of features into the classifier and using the Linear Kernel.

Conclusions

This study demonstrated the effectiveness of using a fusion method to locate and classify the internal defects of wood material. We tried to build different simulated models according to the real situation of the wooden timber. We proposed a self-adaption method based on the migration to get the preparation of the positioning. We put forward a method to correct the misjudged points on the B-Scan image. For the complex distribution of the targets, the method we generated was effective to locate each region. After these processing, the accuracy of the classification for these small data set with intricate targets under some classifiers was above 90%.

Acknowledgments

This study was supported by the Scientific Research Start-up Foundation for the Talents (Nanjing Vocational University of Industry Technology, YK22-14-03).

References

- Cardimona, S.; Willeford, B.; Webb, D.; Lippincott, T.; Wenzlick, J.; Anderson, N. 2000. Ground penetrating radar survey of interstate 70 across Missouri. 13th EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems.
- Cimadevila, H.L.; Gracia, M.; Novo, A.; Armesto, J. 2010. Forestry applications of ground-penetrating radar. *Forest Systems*. 19(1): 5-17.
- Muller, W. 2002. Trial of ground penetrating radar to locate defects in timber bridge girders. Institute of Public Works Engineering Australia Queensland Division, State Conference, Noosa Lakes, Queensland, Australia.
- Maï, T.; Sbartaï, Z.; Bos, F.; Razafindratsima, S.; Demontoux, F. 2014. Nondestructive evaluation of timber structures using GPR technique. *Proceedings of the 15th International Conference on Ground Penetrating Radar*, Brussels, Belgium. 218-
- Kravitz, B.; Mooney, M.; Karlovsek, J.; Danielson, L.; Hedayat, A. 2019. Void detection in two-component annulus grout behind a pre-cast segmental tunnel liner using Ground Penetrating Radar. *Tunnelling & Underground Space Technology*. 83: 381-392.
- Lu, Y.; Peng, S.; Cui, X.; Li, D.; Wang, K.; Xing, Z. 2020. 3D FDTD anisotropic and dispersive modeling for GPR using rotated staggered grid method. *Computers & Geoscience*. 136: 104397.
- Wang, M.K.; Li, W.B.; Wen, J. 2020. Study on Recognition Technology of Coarse Roots Using Ground — Penetrating Radar. *Forest Engineering*. 36(3):21-27.
- Dou, Q.; Wei, L.; Magee, D. R.; Cohn, A. G. 2017. Real-time hyperbola recognition and fitting in GPR data. *IEEE Transactions on Geoscience and Remote Sensing*. 55(1): 51-62.

Al-Nuaimy, W.; Huang, Y.; Nakhkash, M.; Fang, M, T, C.; Nguyen, V, T.; Eriksen, A. 2000. Automatic detection of buried utilities and solid objects with GPR using neural networks and pattern recognition. *Journal of Applied Geophysics*. 43(2-4): 157-165.

Yutong, Wu. 2020. Research on Faster-rCNN Based Root Scanning Image Location and Recognition.

Session 2

**In-Forest Wood
Quality Assessment**

Influence of Edaphoclimatic Variations on Growth and Non-Destructive Parameters Obtained in *Eucalyptus* sp. Clone Trees

Carolina Kravetz *

Laboratory of Nondestructive Testing – LabEND, College of Agricultural Engineering – FEAGRI – UNICAMP, Campinas, São Paulo, Brazil, carolinakra.12@gmail.com

Cinthya Bertoldo

Laboratory of Nondestructive Testing – LabEND, College of Agricultural Engineering – FEAGRI – UNICAMP, Campinas, São Paulo, Brazil, cinthyab@unicamp.br

Rafael Mansini Lorensani

Valora Madeira Ltda, Campinas, São Paulo, Brazil, rafael@valoramadeira.com

Fernanda Trislitz Perassolo Guedes

Sylvamo do Brasil, Mogi Guaçu, São Paulo, Brazil, fernanda.guedes@sylvamo.com

* Corresponding author

Abstract

The objective of this work was to verify whether edaphoclimatic variations interfere in the results of resistance tests, implemented in standing trees. Field trials were carried out in two regions, analyzing three clones of *Eucalyptus*, at three ages. The tests were carried out over a period of 1 year. The parameters collected were height, diameter at 1.30m above the ground, drilling amplitude, penetration depth, and edaphoclimatic parameters, which were analyzed through multivariate analysis of variance. As a result, it was found that among the edaphoclimatic variables, the highest temperature in region 2 favored an increasing in resistance to perforation, while the greater water storage capacity in the soil, presented by region 1, can be considered responsible for the highest values of resistance to penetration of the clones grown in this location. In this way, the interference of edaphoclimatic parameters in non-destructive resistance tests carried out on trees was evident.

Keywords: non-destructive tests, penetrograph, pilodyn.

Introduction

The pulp and paper sector is always looking for more efficient ways to evaluate its plantations. A more effective way to monitor the development of *Eucalyptus* clones is through non-destructive tests, which have great advantages such as: shorter time for data collection, low cost, and the possibility of evaluating a large number of samples (Gouvêa et al., 2011). Among the equipment that can be used for this purpose are the penetrograph and the pilodyn, with which several studies have already been carried out and significant results have been discovered, mainly in predicting the basic density of wood from different clones of *Eucalyptus* genus (Lima et al., 2006; Gomes, 2007; Gonçalves et al., 2007; e Gouvêa et al., 2011).

The penetrograph can record variations in torque demand as structural variations occur in the wood cells, and also due to the effects of tree growth conditions (Rinn et al., 1996). From this, the records are obtained in the form of resistance to perforation, which is called drilling amplitude and provided as a percentage. The pilodyn consists of a metal pin that is directed into the interior of the tree with a certain force. The depth that the steel pin penetrates the wood is indicated on the equipment itself. This does not present an estimate of the real density of the wood tested, however it provides an estimate of the relative density, making it possible to use it to classify genetic units, which are related to the density of the wood, such as clones, families, seed lots and origins (Hansen, 2000).

Therefore, significant results can be obtained from non-destructive tests to evaluate wood properties. However, these properties can be influenced throughout the development of plantations by climatic conditions, forest management and genetic material (Câncio, 2003; Gomes, 2007; Foelkel, 2015). These variations are responsible for changes in the physical, chemical, anatomical and mechanical characteristics of wood, causing changes that can interfere with the quality of the material produced and in industrial processes.

The interference of climatic conditions in characteristics linked to wood quality has been the focus of several studies with different hybrids of *Eucalyptus* sp. Almeida et al. (2019), Costa et al. (2019) and Rocha et al. (2020), through destructive analyses, identified the occurrence of significant influences on the average annual increase and basic density due to different environmental variations, such as temperature and precipitation. Balasso et al (2021) identified variations in growth in diameter and height, in addition to the basic density and dynamic elastic modulus of *Eucalyptus nitens* plantations, due to differences in precipitation, temperature and soil characteristics in the studied locations.

Thus, knowing the potential of non-destructive tests to infer about the properties of wood, and that these properties can be altered by the environmental conditions that these trees are subjected to, this work aimed to identify whether edaphoclimatic variations interfere with the parameters obtained through non-destructive resistance tests, carried out on standing trees.

Methodology

Characteristics of the areas studied

The individuals evaluated are present in two regions. Region 1 (R1) is located close to the city of Mogi Guaçu, in the interior of the state of São Paulo. According to the Köppen classification, the climate is humid subtropical with dry winters and hot summers (Cwa), where rainfall is significant throughout the year, with a rainy period from november to march, and a dry period from june to august. The predominant soil in the region is the latosol.

Region 2 (R2) is located close to the city of Tambaú, state of São Paulo. According to Köppen, the climate in this region is humid subtropical with dry winter and temperate summer (Cwb), with a rainy period from december to february, and the dry season varies from may to september. The predominant soil in this region is neosol.

Field trials

For this work, three clones of *Eucalyptus* sp were used, cultivated in two regions (R1 and R2), with basic densities of 0.48 g/cm³ - A, 0.43 g/cm³ - B and 0.37 g/cm³ - C. For the research, 30 individuals were selected from each clone (A, B and C), age (1, 3 and 4 years) and region (R1 and R2), totaling 540 specimens, which had their development monitored for the period of 12 months. Perforation resistance and penetration resistance tests were carried out, in addition, data were obtained on the diameter at 1.30

meters from the ground (DBH), the height of the tree and the soil and climate characteristics during the period considered for the tests. The trials took place in the months of may/21 (reading 1), august/21 (reading 2), december/21 (reading 3) and march/22 (reading 4).

To obtain the perforation resistance in trees, a penetrometer (IML Resi, PD Series 500, Germany) was used, taking diametrical measurements in perpendicular positions at a height of 1.30 m from the ground, using the methodology described by Isik & Li (2003), from this test, the drilling amplitude was obtained, which is directly related to the resistance that the wood offers to the penetration of the 3 mm thick needle. Measurements were also carried out to obtain resistance to penetration using the pilodyn (6J, PROCEQ, USA), with which two measurements were made per tree, one in relation to the north face and the other in relation to the south face. Pilodyn was used only in may/21 (reading 1) and march/22 (reading 4) trials, due to equipment availability.

The height of the trees in the field was measured using a hypsometer (Vertex IV, Haglöh, Switzerland) and the gain in tree diameter was monitored using a measuring tape at a height of 1.30 m above the ground (DBH).

The forestry company associated with the study periodically collects climate data from different sources and provided us with information regarding the period of non-destructive testing in the field. Among the data collected are average temperature, monthly accumulated precipitation, global radiation, pressure deficit, real evapotranspiration, water storage in the soil and water deficit.

Thus, the parameters obtained from field trials were evaluated through multivariate analysis of variance with the aim of verifying the existence of statistical differences in different conditions: regions, clones, ages and readings.

Results and Discussion

For each parameter obtained from the field tests (drilling amplitude, penetration depth, DBH and height) multivariate analyzes of variance were carried out considering the different factors (region, clone, age and reading). In all analysis results, the p-value was less than 0.05, which indicates that there were statistically significant differences in the field parameters in relation to the conditions evaluated, with 95% reliability.

Firstly, analyzing the drilling amplitude, differences between clones can be observed, with the highest resistance values being associated with clone A (Figure 2a), which also presents the highest basic density, similar to what was also found in other studies (Gouvêa et al., 2011; Lima et al., 2006; Isik & Li, 2003).

Over time, trees are expected to increase in density (Vidaurre et al., 2020) and, therefore, older individuals should present greater amplitude values. Thus, perforation resistance values increased in relation to age and in relation to the chronological order in which field tests were carried out (Figures 2b and 2c).

When analyzing the difference in the parameter obtained for trees located in the two regions, it was found that the highest values were found in specimens from region 2, therefore they can be considered trees with greater drilling amplitude (Figure 2d). Therefore, edaphoclimatic differences influenced the perforation resistance values presented by trees grown in different regions.

When evaluating the penetration depth data, it is clear that there was a difference between the clones, with clone A presenting the lowest values for penetration depth (Figure 3a). According to Gouvêa et al. (2011), the denser the wood, the lower the depth value of the equipment pin, therefore, clone A can be considered the densest in relation to the clones studied, followed by clones B and C, respectively (Figure 3a), matching the basic density presented by each clone as well as the result of penetration resistance (Figure 2a).

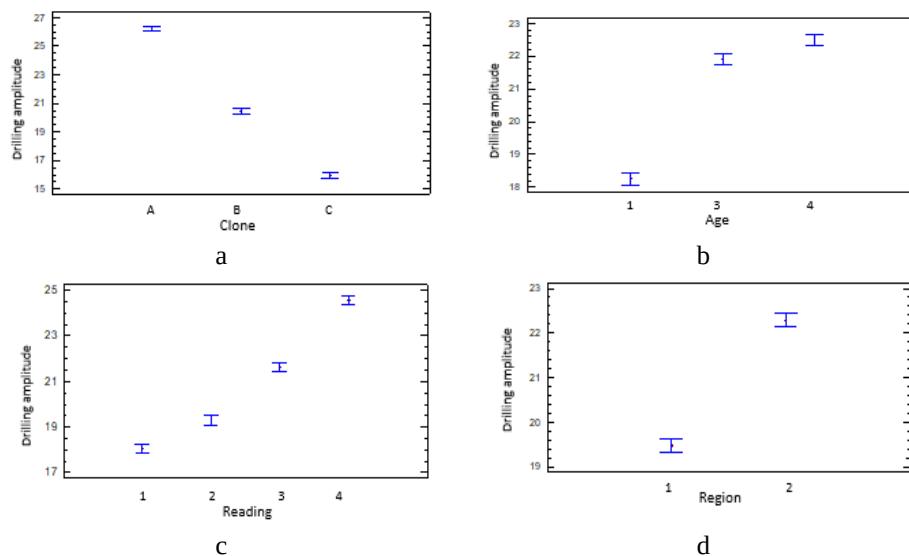


Figure 2. Graph of confidence intervals of the mean drilling amplitude as a function of the type of clone (a), age (b), reading performed (c) and region (d).

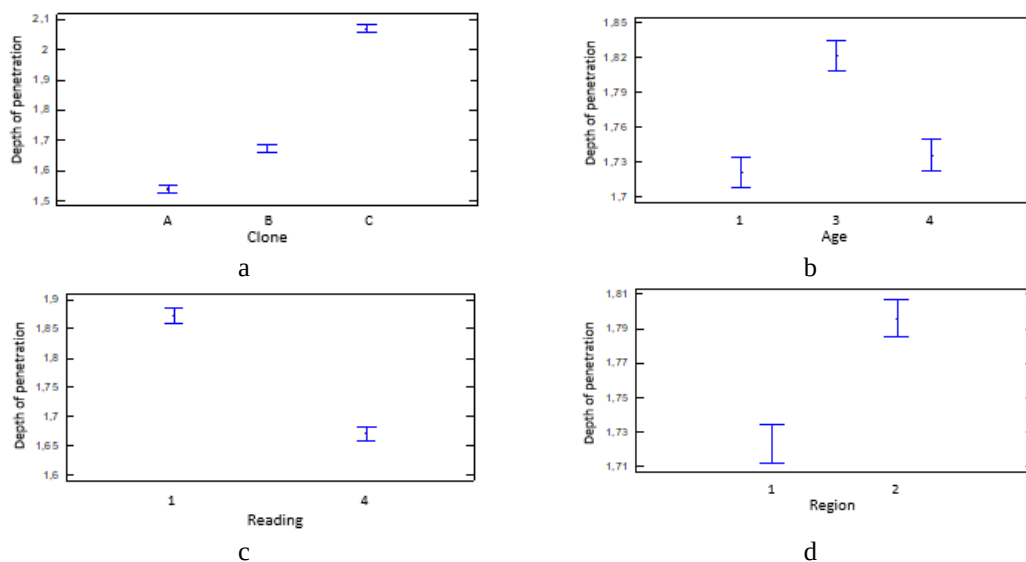


Figure 3. Graph of confidence intervals of the mean depth of penetration as a function of the type of clone (a), age (b), reading performed (c) and region (d).

A gradual increase in basic density is expected as the tree ages and, consequently, a lower value obtained by pilodyn. However, when evaluating this parameter in relation to the age of the trees, the penetration depth showed no statistical difference for the ages of 1 and 4 years, presenting higher values only for the 3-year-old specimens (Figure 3b). This could be explained by the fact that the tests were carried out on different trees for each age. Because, when analyzing the sequence of readings carried out, they presented the expected pattern, with decreasing values for the depth of penetration over time, thus reading 4 (march/2022) presented the lowest values for the parameter (Figure 3c).

When analyzed in relation to the region, the highest values for the parameter were found for region 2, and, therefore, individuals from this location can be considered less resistant to penetration than individuals from region 1 (Figure 3d). In this way, it can be seen that the edaphoclimatic conditions of the regions influenced the values of resistance to penetration, as well as the values of resistance to perforation.

When analyzing tree growth in relation to DBH, it was observed that the average diameter was greater in clone C, while clones A and B presented statistically equal and lower values when compared to the DBH presented by Clone A (Figure 4a).

In relation to age, individuals aged 3 and 4 had no statistical difference in their diameter, most likely due to the fact that the tests were carried out on different specimens at each age (Figure 4b). The tree diameter values as a function of readings taken at different times throughout the year showed the expected pattern, with an increase in the DBH value over time, therefore in reading 1 the lowest DBH values were detected while that in reading 4, the highest values for the parameter were obtained (Figure 4c).

When analyzed in relation to the region, the highest DBH values were found for the trees in region 2, therefore the edaphoclimatic differences between the regions influenced their growth (Figure 4d).

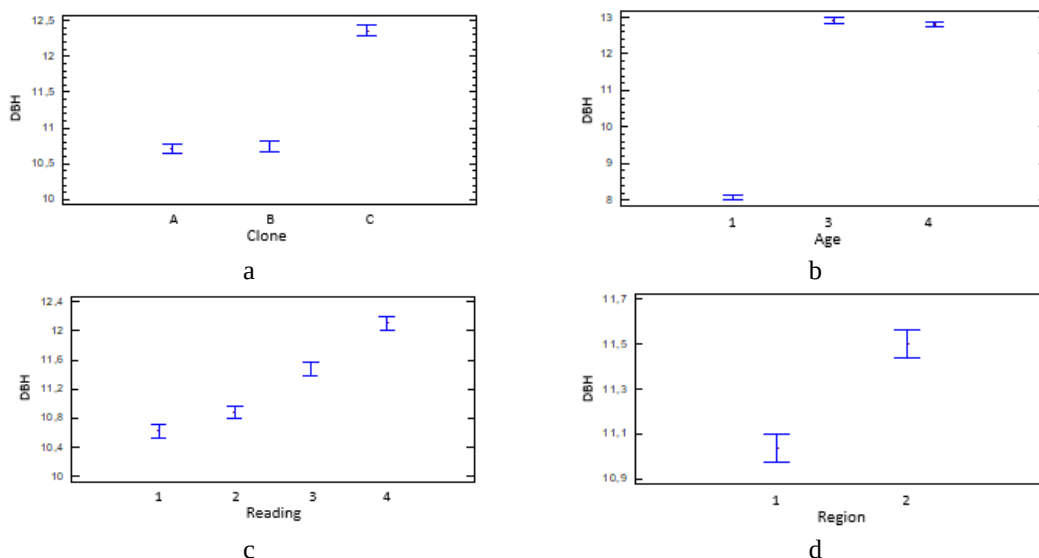


Figure 4. Graph of confidence intervals of the mean diameter at 1.30 meters from the ground as a function of the type of clone (a), age (b), reading performed (c) and region (d).

Regarding the growth in height of the trees, it is observed that the clone with the greatest height is C, while clone A had the shortest trees, with clone B having an intermediate height between clones A and C (Figure 5a).

The behavior of height in relation to the age of the trees was similar to what occurred when DBH was evaluated in relation to age, with 3 and 4 year old individuals showing no statistical difference in their height (Figure 5b), for the same justification given previously. The order of readings, on the other hand, presented the expected pattern, with this value increasing throughout the year (Figure 5c).

When analyzing the height of the trees in relation to the planting region, it is observed that the specimens grown in region 2 were higher in height than the specimens in region 1, which indicates, once again, that the differences in the edaphoclimatic conditions of the regions influenced tree growth (Figure 5d).

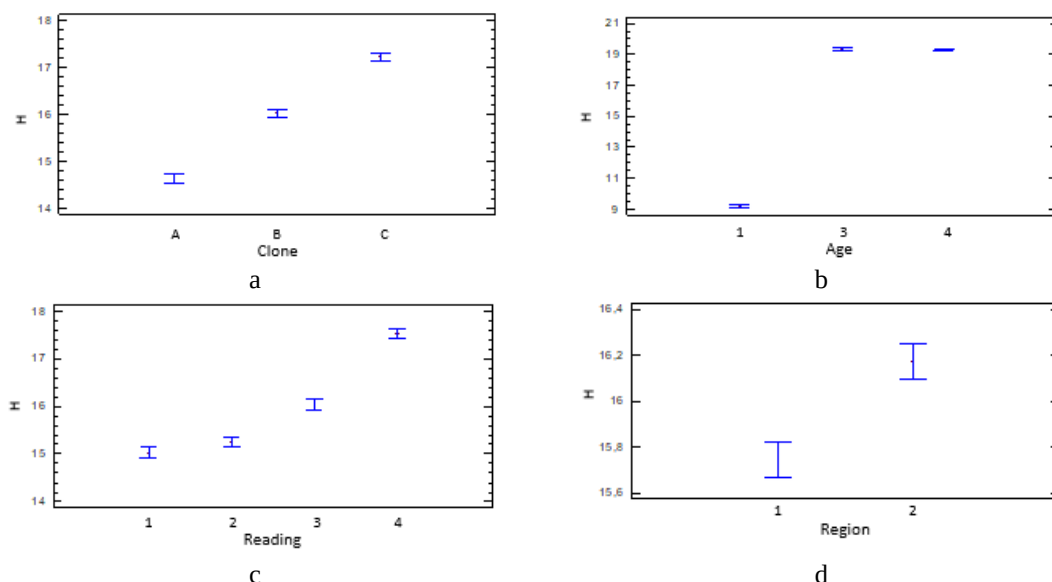


Figure 5. Graph of confidence intervals of the mean height as a function of the type of clone (a), age (b), reading performed (c) and region (d).

In general, the differences in tree resistance and growth parameters between clones, ages and readings were within what is expected and described in the literature. However, the parameters showed differences for the two tree growth regions (Figures 2d, 3d, 4d and 5d). When evaluating the results of the p-value of the edaphoclimatic parameters, obtained from the multivariate variance analysis, it was observed that only the average temperature and water storage in the soil were statistically different between the two regions, as they presented the lowest p-value than 0.05 (Table1).

Table 1. Results of the analysis of edaphoclimatic parameters

Parameters	P-value
Average temperature	0.0076
Monthly accumulated precipitation	0.0563
Global radiation	0.3075
Pressure deficit	0.0556
Actual evapotranspiration	0.1287
Soil water storage	0.0130
Water deficit	0.2802

Analyzing the average temperature of the two regions during the study period (2021 and 2022), region 2 presented a value of 23.4 °C, while region 1 presented a value of 22.7 °C (Figure 6). According to Flores et al. (2016), the average annual temperature required by *Eucalyptus grandis*, one of the most planted species in Brazil, is between 15 and 22 °C, therefore the two regions presented adequate temperature conditions for the growth of individuals.

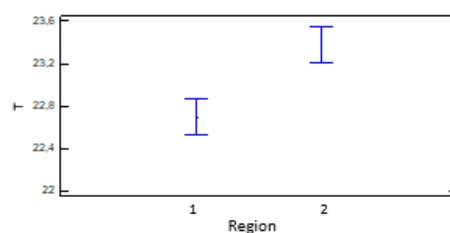


Figure 6. Graph of confidence intervals of average temperature for the two tree growing regions.

In relation to water storage in the soil, region 1 presented higher values for the parameter (Figure 7), this result is justified by the difference in the characteristics of the typical soils of each region. In region 1, the predominance is latosols, which are soils formed by smaller particles due to the high intensity of weathering (Lepsh, 2011) and, because these particles are smaller, they have greater water adhesion on their surface, which allows the soil has a greater water storage capacity. While in region 2 the predominant soil is neosol, which is a more sandy soil, made up of larger particles (more resistant to weathering) and, due to the size of these particles, water flow is greater, therefore, they have a low storage capacity of water (Lepsh, 2011).

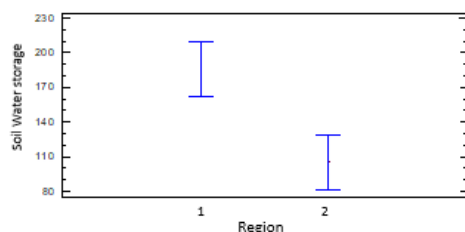


Figure 7. Graph of confidence intervals of soil water storage for the two tree growing regions.

The two planting regions have adequate conditions for the development of trees, however, in region 2 the individuals had greater growth in both height and DBH. Therefore, the growth of the trees in this study was more influenced by temperature than by the availability of water in the soil.

Regarding resistance parameters, trees grown in region 2 showed greater resistance to perforation, while trees grown in region 1 showed greater resistance to penetration. Variations in the penetrometer result occur due to variations in the structures of wood cells and the effects of growth, considering the entire diameter of the tree (Rinn et al., 1996), whereas the penetration depth of the pilodyn is related only to the structure of the outermost cells of the cambium (Hansen, 2002). Variations in cell structures are also related to the availability of water in the environment, in the work of Câmara et al. (2020), in environments with greater water restriction, the xylem vessels were wider, with thicker walls, but with a lower vessel density. These characteristics contribute to a greater basic density (Vidaurre et al., 2020), which explains the greater resistance to drilling of trees in region 2.

In general, in eucalyptus, density increases in the pith-bark direction (Vidaurre et al., 2020), and the pilodyn result corresponds only to the density of the external wood, which is more mature, and therefore may overestimate this characteristic (Hansen, 2002).

Conclusion

In this work, penetrometer and pilodyn tests were carried out on three clones of the genus *Eucalyptus* (A, B and C), at different ages (1, 3 and 4 years), located in two regions with different soil and climate characteristics, carrying out tests every 3 months over a period of 1 year, with the aim of identifying whether edaphoclimatic variations interfere with the parameters obtained through these non-destructive resistance tests, carried out on standing trees. Through multivariate analysis of variance, the parameters of drilling amplitude, penetration depth, DBH and height showed the expected behavior given the differences in clone, age and readings. When analyzing the differences between regions, it was identified that the higher temperature in region 2 favored the growth of trees and they presented greater resistance to drilling. While in region 1, trees showed higher penetration resistance values, possibly influenced by the greater availability of water in the soil in this region. Therefore, the interference of edaphoclimatic parameters in non-destructive resistance tests carried out on trees was evident.

Acknowledgments

We are grateful to the support of the Laboratory of Nondestructive Testing (LabEND), the employees of forest research from Sylvamo do Brasil and to the financial support from the National Council for Scientific and Technological Development (CNPQ).

References

- ALMEIDA, M.N.F.; VIDAURRE, G.B.; PEZZOPANE, J.E.M. [and others]. 2019. Heartwood variation of *Eucalyptus urophylla* is influenced by climatic conditions. **Forest Ecology and Management**, 458.
- BALASSO, M.; HUNT, M.; JACOBS, A.; O'REILLY-WAPSTRA, J. 2021. Characterisation of wood quality of *Eucalyptus nitens* plantations and predictive models of density and stiffness with site and tree characteristics. **Forest Ecology Management**. 491.
- CÂMARA, A. P.; VIDAURRE, G.B.; OLIVEIRA, J.C.L. [and others]. 2020. Changes in hydraulic architecture across a water availability gradient for two contrasting commercial *Eucalyptus* clones. **Forest Ecology and Management**, 474.
- CÂNCIO, O. N. 2003. **Qualidade da madeira de eucalipto para produção de celulose e sua influência na formação de florestas industriais**. Monografia: Mestrado Lato Senso em Tecnologia de Celulose e Papel – Universidade Federal de Viçosa.
- COSTA, S. E. L. 2019. **Efeito de ambientes contrastantes sobre a densidade básica e o incremento médio anual da madeira de clones de Eucalipto**. Dissertação (Mestrado em Ciências Florestais) – Unidade Acadêmica Especializada em Ciências Agrárias – Universidade Federal do Rio Grande do Norte. Macaíba, p. 56.
- FLORES, T. B.; ALVARES, C. A.; SOUZA, V. C.; STAPE, J. L. 2016. **Eucalyptus no Brasil – Zoneamento climático e guia para identificação**. 448 p.
- FOELKEL, C. 2015. Qualidade da Madeira do Eucalipto – Reflexões acerca da utilização da densidade básica como indicador de qualidade da madeira no setor de base florestal. **Eucalyptus Online Book & Newsletter**, capítulo 41.
- GOMES, A.de F. 2007. **Avaliação das características da madeira e da polpa de Eucalyptus mediante a aplicação de métodos não destrutivos na árvore viva**. Dissertação: Mestrado em Engenharia Florestal – Universidade Federal de Lavras.
- GONÇALVES, F.G.; OLIVEIRA, J.T.da S.; TOMAZELLO FILHO, M.; REZENDE, G.D.S.P. 2007. Estimativa da densidade básica da madeira de um híbrido clonal de *Eucalyptus urophylla* x *Eucalyptus grandis* por método não destrutivo. **Revista Cerne** (Nota Técnica). v. 13, p. 119-128.
- GOUVÊA, A.de G.; TRUGILHO, P.F.; GOMIDE, J.L. [and others] 2011. Determinação da densidade básica da madeira de eucalyptus por diferentes métodos não destrutivos. **Revista Árvore**. v. 35, n. 2, p. 349-358.
- HANSEN, C. P. 2000. **Application of the pilodyn in Forest tree improvement**. Denmark: Danida Forest seed Centre, (Series of Technical Notes, 55).
- ISIK, F. and LI, B. L. 2003. Rapid assessment of wood density of live trees using the Resistograph for selection in tree improvement programs. *Canadian Journal of Forest Research*. 33(12), 2426-2435.

LEPSH, I. F. 2011. **19 lições de pedologia**. Oficina de Textos. São Paulo.

LIMA, J.T.; HEIN, P.R.G.; TRUGILHO, P.F. SILVA, J. R. M. da. 2006. Adequação do resistograph para a estimativa da densidade básica da madeira de Eucalyptus. **Madeira: Arquitetura e Engenharia**, v. 7, n. 18.

RINN, F.; SCHWEINGRUBER, F. H.; SCHAR, E. 1996. Resistograph and X-ray density charts of wood comparative evaluation of drill resistance profiles and X-ray density charts of different wood species. **Holzforschung**, Berlim, v. 50, n. 4, p. 303-311.

ROCHA, S.M.G; VIDAURRE, G.B.; PEZZOPANE, J.E.M. [and others] 2020. Influence of climatic variations on production, biomass and density of wood in eucalyptus clones of different species. **Forest Ecology and Management**, 473.

VIDAURRE, G. B.; SILVA, J. G. M. Da; MOULIN, J. C.; CARNEIRO, A. de C. O. 2020. Qualidade da madeira de eucalipto proveniente de plantações no Brasil. **EDUFES**. Vitória, ES. 221 p.

Use of Non-Destructive Technologies for Detection of Compression Wood in *Pinus taeda* Standing Trees

Ana Paula Coelho-Duarte *

Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay, paula.coelho@fagro.edu.uy

Stephany Arrejuría

Latitud Fundación LATU, Montevideo, Uruguay, sarrejuría@latitud.org.uy

Andrés Baietto

Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay, abaietto@fagro.edu.uy

Fernando Bonfiglio

Latitud Fundación LATU, Montevideo, Uruguay, fbonfig@latitud.org.uy

Verónica Casaravilla

CENUR Noreste, Universidad de la República, Montevideo, Uruguay, casaravillav@gmail.com

Noelia Franco

Latitud Fundación LATU, Montevideo, Uruguay, nfranco@latitud.org.uy

Paula Guzzetti

Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay, paula.guzzetti@gmail.com

Luciana Ingaramo

LUMIN, Rivera, Uruguay, luciana.ingaramo@lumin.com

Daniela Malates

FYMNSA, Rivera, Uruguay, dmalates@fymnsa.com.uy

Carlos Mantero

Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay, cmantero@fagro.edu.uy

Miguel Oñate

Agroempresa Forestal, Montevideo, Uruguay, monate@af.com.uy

Carla Padilla

FYMNSA, Rivera, Uruguay, cpadilla@fymnsa.com.uy

Diego Passarella

CENUR Noreste, Universidad de la República, Montevideo, Uruguay, diego.passarella@cut.edu.uy

Juan Pedro Posse

INIA, Tacuarembó, Uruguay, jposse@inia.org.uy

Ludmila Profumo

CENUR Noreste, Universidad de la República, Montevideo, Uruguay, lprofumo@cur.edu.uy

Luis Reina

CENUR Noreste, Universidad de la República, Montevideo, Uruguay, luis.reina@cut.edu.uy

Fernando Resquin

INIA, Tacuarembó, Uruguay, fresquin@inia.org.uy

Lucía Revetria

Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay,
luciarevetriamartinez@gmail.com

Julia Sáenz

Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay, jsaenz@fagro.edu.uy

Agustín Sarries

Arboreal SA, Tacuarembó, Uruguay, agustin.sarries@arboreal.com

Paula Vener

Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay, paulamvener@hotmail.com

Silvia Böthig

Latitud Fundación LATU, Montevideo, Uruguay, sbothig@latitud.org.uy

* Corresponding author

Abstract

Compression wood (CW) is produced in gymnosperms as a biomechanical mechanism to adapt to environment, with negative impact on the sawmill industry. Detecting the presence of CW in standing trees can prevent this material from reaching the mill. The aim of this research was to evaluate non-destructive testing (NDT) for the early detection of CW in a *Pinus taeda* stand. Eighteen trees were selected according to their phenotypic characteristics and divided into two groups: high and low likelihood of presence of CW. Measurements were carried out using acoustic technologies, sonic tomography, ultrasonic and resistography, followed by physical properties determination and visual assessment of the presence of CW. It was found that resistography preceded by acoustic tomography has a significative detection capacity, concluding that combination of semi-destructive methods is promising for the early detection of CW. Further studies should be carried out to look for the best NDT combination.

Keywords: reaction wood, acoustic tomography, ultrasonic tomography, resistography, pine trees

Introduction

The main commercial destination of *Pinus taeda* in Uruguay is to obtain solid wood products through industrial processing. There are several factors that affect the industrial quality, among which is severe compression wood (CW). This type of wood causes defects in the products, such as abnormal warping and reduction of strength in boards or cracking of peeled veneers, which, in addition to hindering the production process (causing misalignment and even breakage in the machines), reduces the yield and quality of the final products. Although the incidence rate has not yet been precisely quantified, it has been estimated to be around 5-10% at certain sites, making it a significant economic problem. However, there are very few studies on this issue at the national level.

CW is a type of reaction wood found in gymnosperms. It has peculiar characteristics that are notoriously different from those of normal wood, where its physical, chemical, and mechanical properties are altered (Duncker 2014). The color of CW is different from that of normal wood (NW). It has a dark reddish-brown

color, that is produced because its cells have wide, well-lignified walls similar to latewood cells. This greater amount of lignin at the cell wall produces the dark color characteristic of CW (Diaz-Vaz 2003). The most obvious physical characteristic of CW is the increase in basic density (Tomazello Filho and Silva 1987). Diaz-Vaz et al. (2009) indicated that the density values in CW are 8% higher compared to NW for *Pinus radiata*. This increase in density is mainly due to thicker cell walls (Timell 1986). The strength properties and modulus of elasticity of CW are lower than expected, and it can be explained by the fact that the microfibril angle (MFA) in CW is large compared to that in normal wood (Gardiner et al. 2014).

CW occurs with different level of severity (i.e., severe, moderate, low), and the CW properties vary significantly depending on the level. There are also differences between the CW of juvenile wood and mature wood, and there are even differences between earlywood and latewood CW (Diaz-Vaz 2007).

In South Africa, it appeared as a problem in *P. taeda* species in the 1980s, and it was called as "abnormal" CW, and differentiated it from "normal" CW mainly by its mode of occurrence. While CW occurs in leaning trees, "abnormal" CW occurs even in straight trees and without having been exposed to conditions that would normally form CW (Malan and Kassier 2002). Although the anatomical properties of "abnormal" CW are somewhat different from those of "normal" CW (Herman 1988), their physical properties and behavior characteristics are almost the same.

Because CW has different physical and mechanical properties from NW and based on previous researches (Hamm and Lam 1986; Bucur 2010; Brancheriau et al. 2012; Arciniegas et al. 2014; Palma et al. 2018), the hypothesis of this work is that nondestructive technologies capable of estimating wood density and modulus of elasticity would be able to also detect CW in standing trees. The objective of this research was to build a decision tree regression with resistograph, sonic tomograph and ultrasound variables to predict the presence of MC, in order to propose methodologies for the early detection of MC in *Pinus taeda* plantations.

Methodology

Site and stand characteristics

The pine stand belonging to the company Lumin S.A., which had a significant history of CW years ago. It is located in the department of Rivera (31°01'11.37 "S 55°31'55.81 "W), Uruguay. The trees were close to the end rotation age (23 years old).

A total of 120 trees were pre-selected with the following excluding criteria: a) not on the edge; b) without direct exposure to wind; c) a clear balance in the crown structure; d) without bifurcation; e) with a slope of no more than 6%; and f) without symptoms of disease. The selection was based on three diameter classes, according to the inventory —35 to 40cm, 40.1 to 45cm and 45.1 to 50cm—, and 40 trees were selected from each class.

After prior analysis, a total of 36 trees were then selected, 12 from each class. The following measurements were taken: a) diameter at 1.10 m and diameter at the base; b) diameter at breast height (DBH) maximum and DBH at 90°; c) total height, height at first live branch, height at first dead branch; d) major and minor crown diameter; e) crown balance; f) trunk shape record at 1.10m (circular, ellipse or irregular); g) branch thickness (visual categorization: 1 thin 2 intermediate 3 thick); h) branch insertion angle (visually); i) curvature present and at what height of the tree (visually); j) tree lean measurement at 1m height; k) tree location within the stand; l) distance to the nearest tree and distance to the edge; m) slope measurement. The data from the 36 trees were studied, generating indicators of probability of CW occurrence and then finally 18 trees were selected in total (6 trees per class).

NDT measurements

Measurements with nondestructive testing (NDT) were performed in the following order: acoustic tomograph ArboSonic 3D – drilling resistance Resistograph PD Series – ultrasonic Sylvatest (Figure 1).

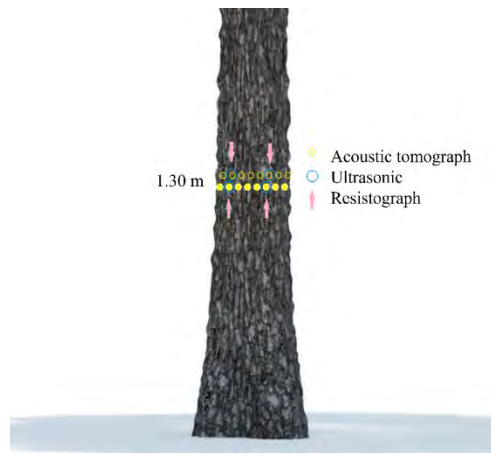


Figure 1—Position of NDTs in pine trees, based on acoustic tomograph sensors position around the trunk circumference.

Measurements were made with acoustic tomograph using 16 sensors plus 16 Ludwig, where sensor 1 was always positioned at the North and the others followed in a counterclockwise direction. Distance measurements were taken with the caliper, following the software instructions. The measurements were set for tapping the head sensors five times, with 5% deviation and difference between routes less or equal to three. Based on the hypothesis that the presence of CW could result in areas of low velocities, after the tomogram was obtained, a print screen was taken, and the CW suspected areas were marked. Then, the team that was using the resistograph could take the position of the pith and the directions as a reference (Figure 2).

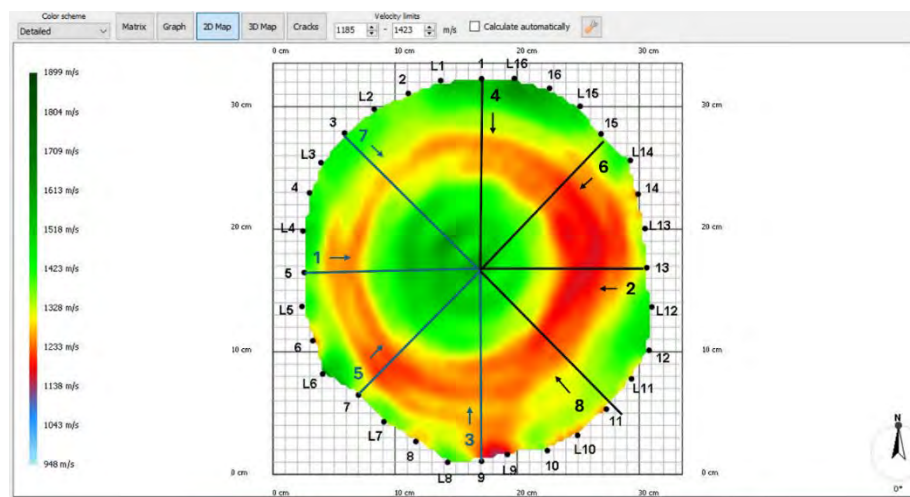


Figure 2—Example of tomogram with resistograph directions proposed. The arrows indicate the drilling direction, and the numbers indicate the drilling order.

Resistograph measurements were taken at a distance of approximately 5 cm below the acoustic tomograph measurement line (Figure 1), with a total of eight measurements per tree. The real needle exit positions were identified on the tree for future drill graphs reading and fitting. In cases where the needle

exited in a position far from the planned position (due to excessive deviation, e.g. caused by a knot) or if the needle returned due to overheating, the measurement was repeated and this observation was noted, which could help in the interpretation of the results. For all measurements the combination of feed speed of 150 cm/min and rotational speed of 2500 r/min, which had been previously tested and fitted, was used.

The measurements with the ultrasonic device were performed at the same height as the acoustic tomogram, taking advantage of the previous sensor holes. Eight transverse measurements were taken per tree, per pair of sensors —1-9, 2-10, 3-11, 4-12, 5-13, 6-14, 7-15 and 8-16 (Ludwigs were not considered)— and then 4 measurements were repeated at the same positions of the opposite pairs of drillings. Three readings were taken for each measurement point.

Destructive analysis

Two discs of 3 to 4 cm thickness were cut from each tree, considering the tomograph and resistograph area. After cutting, four sensors were remarked to maintain the identification of the measurements. The discs containing the tomograph measurements were used to make samples for basic density determination. For this, the discs were cut into 16 parts, according to the position of the sensors (without considering the Ludwigs).

The discs containing the resistograph measurements were used for visual assessment of the CW. For these assessments, they were also divided into 16 sectors, but without cutting them. Annual ring growth was measured in four radii (considering the largest diameter and its perpendicular). Then, for each sector, all rings were evaluated, subdivided into earlywood and latewood. The assessment considered the absence and presence of CW. At the end of this assessment, the actual needle paths of the resistograph were marked.

Data process

The directions of the resistograph measurements were used as a reference to assemble the database and, considering that the discs were divided into sectors corresponding to the acoustic tomograph sensors, the following describes how the data were processed for each NDT and for the visual assessment (Figure 3).

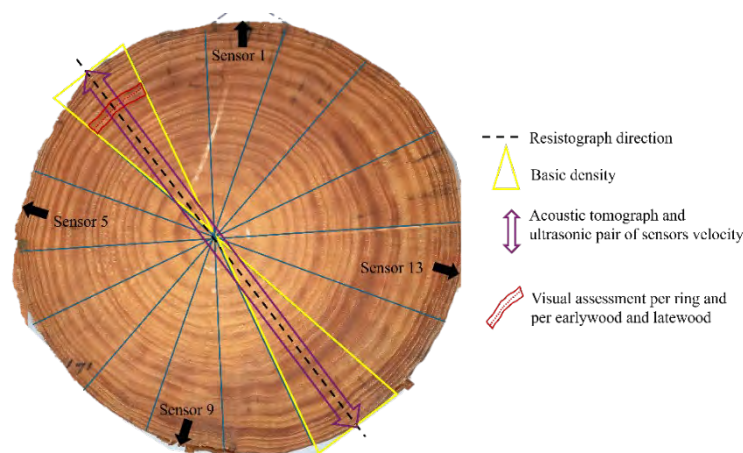


Figure 4—Database scheme for NDT measurements and visual assessment.

a) Resistograph: Depth x Feed Amplitude data were downloaded. For each annual ring, six peak indicators were generated (Figure 4), based on slenderness, shape factor and asymmetry.

- Slenderness 1: $F_{max}/(x_f - x_i)$

- Slenderness 2: $F_{max}/(X_d[0.75F_{max}] - X_{iz}[0.75F_{max}])$
- Shape factor 1: $(X_d[0.75F_{max}] - X_{iz}[0.75F_{max}])/x_f - x_i$
- Shape factor 2: $(X_d[0.8F_{max}] - X_{iz}[0.8F_{max}])/(X_d[0.6F_{max}] - X_{iz}[0.6F_{max}])$
- Peak Asymmetry: $(x_f - x_i) / (x_f - x_i)$

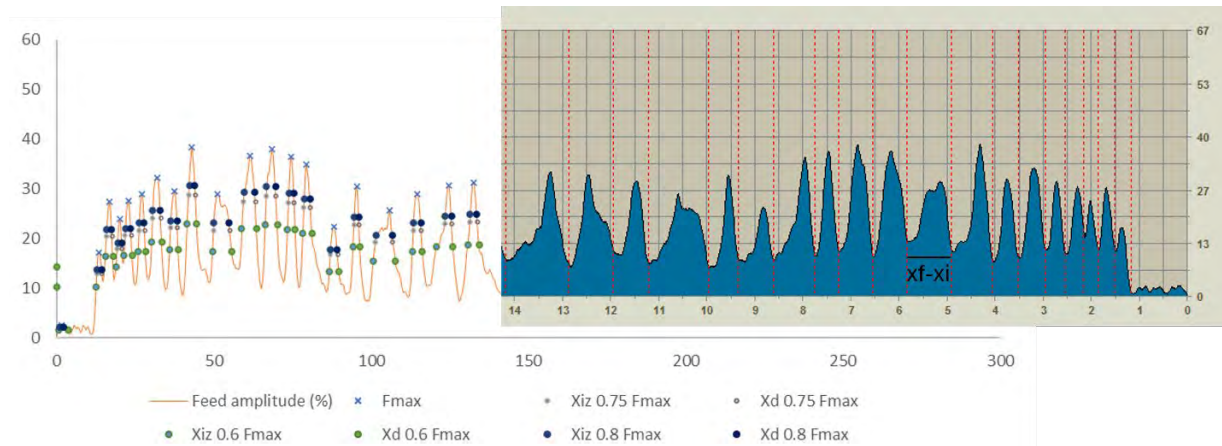


Figure 4—Resistograph peak indicators. Fmax: Maximum Feed Amplitude; iz and d: left and right.

- b) Tomograph: The velocity matrices resulting from the software reports for each tree were used. From the matrix, radial velocity data were extracted, i.e., those corresponding to opposite sensors that coincided with the directions of the resistograph measurements.
- c) Ultrasonic: velocity data between the pairs of sensors corresponding to the same directions of the resistograph measurements were used.
- d) Basic density: the basic densities of the eight sectors through which the resistograph was measured were used.
- e) Visual assessment: Binary classification data were used, separated into earlywood and latewood, and then unified as a single data per ring (presence was considered if at least in one of the ring parts was present).

Statistical analysis

A correlation between all variables of NDT and visual assessment of CW was used for exploratory analysis. For predicting the presence of CW, a decision tree was build using the function “rpart” in R program (Therneau and Atkinson, 2019). The data set were randomly split into a training set (70%) and a test set (30%). The training set (1915 observations) was used to pick the optimal regression tree model, and this model was used on the test set (821 observations) to appraise its performance accuracy. First, all variables were used in the model. After analysis of importance, a set of variables was defined, and the tree decision was rebuilt. The variable importance of the final model, the effect of each taxa abundance on the decision model, was visualized in the taxonomic tree. The accuracy, precision and recall were calculated for both training and test sets. The accuracy of the model was estimated from confusion matrix, overall accuracy, recall and precision.

Results and Discussion

Slenderness was the variable most highly correlated with the presence of CW (Table 1). This correlation was negative, i.e., lower slenderness was associated with higher presence of CW. The high correlation

between basic density and feed amplitude was expected (Rinn et al. 1996), as well as that the high correlation between acoustic tomography and ultrasound velocities (Arciniegas et al. 2014).

Table 1—Correlation matrix for NDT variables and basic density. E1: Slenderness 1 x Feed Amplitude; Fm: Maximum Feed Amplitude; D: Basic density; AS: Pick Asymmetry; E2: Slenderness 0.75 x Feed Amplitude; FF1: Shape factor 0.75 x Feed Amplitude; VT: Sonic Tomography Velocity; VS: Ultrasonic Velocity; FF2: Shape factor 0.8/0.6 Feed Amplitude. Coefficients in bold: p-value<0.0001.

	Fm	E1	E2	FF1	FF2	AS	VT	VS	D
Fm									
E1	0,20								
E2	0,46	0.53							
FF1	-0,03	0.42	-0.12						
FF2	0,04	0.02	-0.22	0.09					
AS	0,05	0.49	0.02	0.41	0.06				
VT	-0,14	-0.07	-0.05	-0.02	-0.03	-0.003			
VS	-0,08	0.01	-0.01	0.04	-0.04	0.06	0.43		
D	0,54	0.13	0.14	0.06	-0.004	0.12	-0.13	0.13	
CW	0,16	-0.36	-0.21	-0.08	-0.001	-0.11	-0.01	0.05	0.14

For the decision tree model, it provides information about the relative importance of different NDT variables that could predict CW (Figure 5). Overall, the relative importance of variables related to resistograph is higher than that of sonic and ultrasonic devices. The slenderness E1 and the Feed Amplitude had the highest relative importance, whereas both shape factor indicators and both sonic and ultrasonic velocities had the lowest relative importance.

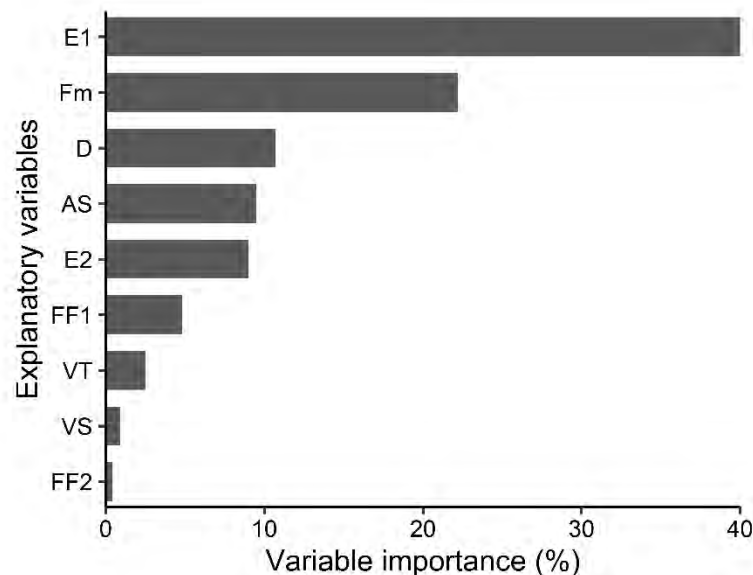


Figure 5—Variable importance of NDT indicators predicting presence of CW. E1: Slenderness 1 x Feed Amplitude; Fm: Maximum Feed Amplitude; D: Basic density; AS: Pick Asymmetry; E2: Slenderness 0.75 x Feed Amplitude; FF1: Shape factor 0.75 x Feed Amplitude; VT: Sonic Tomography Velocity; VS: Ultrasonic Velocity; FF2: Shape factor 0.8/0.6 Feed Amplitude.

The final decision tree was built with the three most important variables —Slenderness, Feed Amplitude and Basic density— (Figure 6). When the slenderness is greater than or equal to 3, there is 29% of CW absence in 63% of dataset test, and slenderness lower than 3 there is 62% of CW presence in 37% of this dataset. The following node is the maximum feed amplitude, where slender and low peaks had probability of CW absence. On the other hand, peaks between 3 and 6.4 with a Feed Amplitude greater than 25 have 53% probability of having CW. Adding to that path the basic density, there is 76% probability of having CW. When the slenderness is less than 3, there is 62% probability of having CW and, of these, if the density is greater than 0.42 g/cm³, there is 67% probability of having CW. The operational restriction of this analysis is that it is also supported on a destructive determination, basic density.

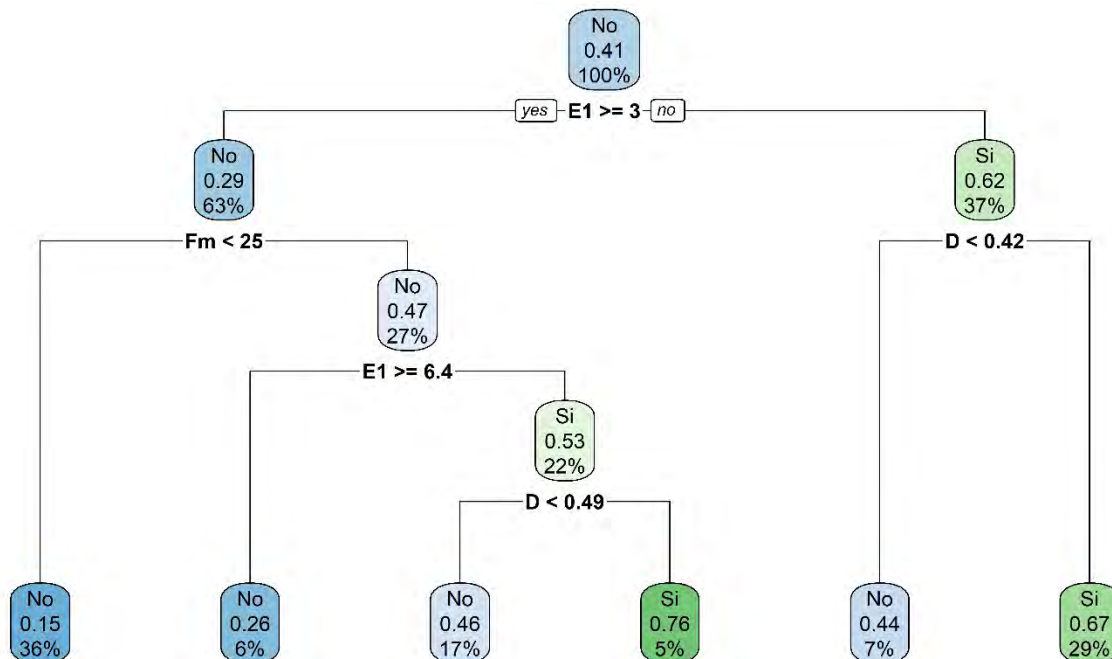


Figure 6—Decision tree predicting presence of Compression Wood. E1: Slenderness 1 x Feed Amplitude; Fm: Maximum Feed Amplitude; D: Basic density.

Regarding the statistical model indicators (Table 2), the accuracy indicates that the model correctly classifies 71% of all instances in the test data set. According to the precision, the model has a 26% of having false positives, estimating that it has CW when it does not. In turn, the probability of having a false negative is the worst scenario, since in this case it would estimate that there is no CW when there is, and this causes material with undesirable characteristics to reach out the industry. This indicator is given by the recall, and in the model it was 19%.

Table 2—Results of model performance.

	Accuracy	Precision	Recall
Train data	0.711	0.728	0.814
Test data	0.716	0.743	0.814

Conclusions

The results of the decision tree model showed that variables related to the resistograph measurements are the most influential factor in predicting the presence of CW. Among these variables, the slenderness has the highest level of importance, followed by maximum feed amplitude and density. Variables related to acoustic tomograph and ultrasonic NDT presented very low importance in predicting CW. Since drilling

resistance is good predictor of density, it seems likely that the resistograph is the more suitable equipment for detecting CW in standing trees. Nevertheless, the tomograms obtained from the acoustic testing were fundamental for reference and for deciding where to drill in the tree. Further studies with samples containing a greater amount of CW should be carried out to validate this model and look for the most feasible and effective NDT combination.

Acknowledgments

Our thanks to the funding agency National Agency for Research and Innovation (ANII) (Proyecto ART_X_2021_1_170389) and all companies that strongly collaborated in this research (FYMNSA, LUMIN, ARBOREAL SA, AGROEMPRESA FORESTAL).

References

- Arciniegas, A., Prieto, F., Brancheriau, L., Lasaygues, P. 2014. Literature review of acoustic and ultrasonic tomography in standing trees. *Trees*, 28, 1559-1567. <https://doi.org/10.1007/s00468-014-1062-6>
- Brancheriau, L., Saadat-Nia, M. A., Gallet, P., Lasaygues, P., Pourtahmasi, K., Kaftandjian, V. 2012. Ultrasonic Imaging of Reaction Wood in Standing Trees. *Acoustical Imaging*, 31, 399-411. https://doi.org/10.1007/978-94-007-2619-2_38,
- Bucur, V. 2010. Acoustic Tomography for Tension Wood Detection in Eucalypts. En *Delamination in Wood, Wood Products and Wood-Based Composites*. Springer. https://doi.org/10.1007/978-90-481-9550-3_13
- Díaz-Vaz, J.E. 2003. *Anatomía de Maderas*. Marisa Cúneo Ediciones, Chile 151 p.
- Díaz-Vaz, J. E., Ananías, R. A., Rodríguez, S., Torres, M., Fernández, A., Poblete, W. H. 2009. Compression wood in *Pinus radiata* II: Density and chemical composition. *Maderas: Ciencia y tecnología*, 11(2), 139-151.
- Díaz-Vaz, J. E., Fernandez, A., Valenzuela, L., Torres, M. 2007. Madera de compresión en *Pinus Radiata* D. Don: I, características anatómicas. *Maderas. Ciencia y tecnología*, 9(1), 29-43.
- Duncker, P. 2014. Detection and Grading of Compression Wood. In *The Biology of Reaction Wood* (pp. 201-224). Springer, Berlin, Heidelberg.
- Gardiner, B., Barnett, J., Saranpää, P., Gril, J. (Eds.). 2014. *The Biology of Reaction Wood*. Springer Berlin Heidelberg. <https://doi.org/10.1007/978-3-642-10814-3>
- Hamm, E. A., Lam, F. 1986. Compression wood detection using ultrasonics II. Project No. 04-55-43-008. 22 p.
- Herman, B. 1988. Abnormal wood formation in *Pinus taeda*. *South African Forestry Journal*, 144(1), 23-29.
- Herman, B. 1988. Effects of 1—Naphthaleneacetic Acid (NAA) and Gibberellin A3 (GA3) on Abnormal Wood Formation in *Pinus taeda*. *South African Forestry Journal*, 144(1), 30-32.

Malan, F. S., Kassier, H. W. 2002. Abnormal compression wood in *Pinus taeda*: A review of current knowledge and proposed future strategy. *The Southern African Forestry Journal*, 194(1), 43-51.

Palma, S. S. A., Gonçalves, R., Trinca, A. J., Costa, C. P., Reis, M. N., Martins, G. A. 2018. Interference from Knots, Wave Propagation Direction, and Effect of Juvenile and Reaction Wood on Velocities in Ultrasound Tomography. *BioResources*, 13(2), 2834-2845.

Rinn, F., Schweingruber, F.-H., Schär, E. 1996. Resistograph and X-Ray Density Charts of Wood. Comparative Evaluation of Drill Resistance Profiles and X-ray Density Charts of Different Wood Species. *Holzforschung*, 50, 303-311. <https://doi.org/10.1515/hfsg.1996.50.4.303>

Timell, T. 1986. Fundamental factors causing compression wood. In *Compression Wood in Gymnosperms* (pp. 983-1090). Springer-Verlag, Berlin.

Therneau, T., Atkinson, B. 2019. Rpart: Recursive partitioning and regression trees. R package version 4.1-15. <https://CRAN.R-project.org/package=rpart>

Tomazello Filho, M., Silva, D. D. 1987. Formation and characterization of compression wood in *Pinus caribaea* var. *hondurensis*.

Influence of Resin Extraction in the Effectiveness of Nondestructive Evaluation of The Forestry Industry

Mônica Ruy

Structural Wood Engineering Platform (PEMADE), University of Santiago of Compostela (USC), Lugo, Lugo, Spain, m.ruy@usc.es

María Portela Barral

PEMADE, USC, Lugo, Lugo, Spain, maria.portela.barral@usc.es

Inés Seoane Conde

PEMADE, USC, Lugo, Lugo, Spain, ines.seoane.conde@rai.usc.es

José Antonio Lorenzana

PEMADE, USC, Lugo, Lugo, Spain, joseantonio.lorenzana@usc.es

Maria Belen Feijoo Lombao

PEMADE, USC, Lugo, Lugo, Spain, mbelen.feijoo@usc.es

Manuel Guaita Fernandez

PEMADE, USC, Lugo, Lugo, Spain, m.guaita@usc.es

Abstract

Integrating high-quality timber production with ancillary forestry activities like resin extraction has gained traction recently. While resin extraction offers potential socioeconomic advantages for forest communities, its impact on wood quality and its implications for non-destructive techniques as quality control tools remain uncertain. This study aimed to evaluate the viability of using non-destructive techniques to assess the quality of *Pinus pinaster* timber from trees subjected to resin extraction. Non-destructive (stress wave/analysis of vibration) tests were conducted on trees and sawn timber. Density and dasometric parameters were measured for tree samples while bending tests were conducted on beams. Statistical analysis indicated no significant differences in dasometric, non-destructive parameters, strength, or modulus of elasticity between resined and control samples (trees and sawn timber). Despite the study's limited sample size, these findings suggest that non-destructive techniques can effectively serve as quality control tools for wood sourced from forests first intended for resin production.

Keywords: conference, paper, instructions, template

Introduction

Pinus pinaster is pivotal in supplying the processing industry across the Atlantic arc. In Galicia, these plantations primarily cater to the timber sector, forming an extensive network involving various stakeholders along the production chain, benefiting from sustainable practices (Rodríguez Soalleiro et al. 2007). Integrating complementary activities alongside wood exploitation not only enhances mountain management and conservation but also fosters regular economic activities, creating added social value for local communities (Picos et al. 2019). As outlined in Decree 73/2020, resin tapping on three pine species, including *Pinus pinaster* Ait., *Pinus radiata* D. Don, and *Pinus nigra* Arnold, is recognized as one such

complementary activity in Galicia. This initiative aims to incorporate resin extraction as an ecosystem service, augmenting the management of Galician forests, initially designated for timber use.

Pinus pinaster stands out as the most suitable Spanish species for resin tapping owing to its high productivity and ease of extraction. Resin tapping has historically been a significant rural activity in Spain. Despite its potential value addition to mountain regions, resin tapping remains relatively underutilized in Galicia, limited to small areas. Various challenges hinder the sector's development, between them the forest owner's reluctance due to concerns over wood quality and industry apprehension regarding technical handling issues (Camacho Rios 2013). Over the decades, several studies have evaluated the compatibility of resin tapping with wood production.

In recent years, non-destructive techniques have emerged as critical tools for assessing wood quality in forestry. The methodology's accuracy stems from extensive research and global findings, continuously analyzing potential influences encountered during its application. Hence, this study aims to analyze the impact of resin tapping on the efficacy of non-destructive techniques for wood quality assessment, spanning from standing trees to material classification for structural purposes.

Material and Methods

A total of 24 trees from two distinct planted forests (Samples A and B) were analyzed. 12 trees were selected in each forest: 6 specimens previously subjected to resin extraction and 6 control specimens. Dasometric parameters (diameter at the base, breast height, crown diameters, crown height, and tree height) were measured for each tree. Additionally, stress wave testing was carried out through Microsecond Timer (MST) equipment from Fakopp (Hungary), and samples were collected using an increment borer to determine the density of each tree.

After field measurements, the identified trees were cut and passed through a sawing process to obtain pieces of structural dimensions.

238 pieces of sawn wood were tested in the Laboratory of PEMADE (Structural Wood Engineering Platform). The sample was divided into two groups: 118 specimens from resin-tapped trees and 120 specimens from control trees. Before conducting the non-destructive and bending tests, the pieces were conditioned in a standard environment of $(20 \pm 2)^{\circ}\text{C}$ and $(65 \pm 5)\%$ relative humidity until they reached a constant mass.

The non-destructive and bending tests were performed on rectangular section specimens with nominal dimensions of 40x110x2500 mm.

Two non-destructive techniques were employed: stress wave testing using the Microsecond Timer, and natural frequency testing with the Mechanical Timber Grader (MTG) from Brookhuis (The Netherlands). The velocities derived from both equipment datasets were associated with material density values to calculate the Indicator Property – IP – (EN 14081-2) utilized in the statistical procedures for wood species classification.

Bending tests were conducted following the procedures outlined in UNE-EN 408 (2011). After the bending tests were completed, the density and humidity of the specimens were determined using a slice extracted from each piece in accordance with the UNE 13183-1.

Each test piece's moisture content (MC) was utilized to adjust the parameters of the indicator property, modulus of elasticity, and density to the reference condition (12% MC) defined by the standard.

The dasometric, acoustic, and density parameters of resined and control trees were compared through statistical analysis. Likewise, a comparison analysis was carried out for the results obtained for sawn timber. Linear regression models were utilized to establish correlations between the non-destructive methodologies and the parameters employed in timber classification, specifically the modulus of elasticity and strength in bending and density.

Results and Discussion

Table 1 displays the results obtained from the comparison analysis between dasometric parameters (diameter at the base, diameter at breast height, crown diameter, tree height, crown height), stress wave propagation velocity, and density of resined and control trees. Confidence intervals containing zero indicate data sets with no statistically significant differences between their means.

Table 1. Confident intervals obtained for the comparison of dasometric parameters (diameter at the base – D_b , diameter at breast height – DBH, crown diameter – D_{crown} , tree height – H , crown height, H_{crown}), stress wave propagation velocity (V_{MST}), and density of resined and control trees.

Parameter	Sample	Confident Interval
D_b	A	[-5.31; 3.31]
	B	[-6.98; 3.65]
DBH	A	[-5.24; 3.57]
	B	[-8.02; 5.68]
D_{crown}	A	[-2.19; 1.38]
	B	[-2.68; 0.99]
H	A	[-2.44; 2.17]
	B	[-3.48; 1.45]
H_{crown}	A	[-2.98; 1.78]
	B	[-4.93; 0.23]
V_{MST}	A	[-185.87; 319.09]
	B	[-48.95; 620.83]
Density	A	[-128.71; -3.24]
	B	[-82.87; 6.85]

The results in Table 1 indicate no statistically significant differences between the means of dasometric parameters and stress wave propagation in resined and control trees, suggesting that resin extraction does not affect these parameters. However, significant differences in average densities were observed in one of the samples analyzed.

Table 2 presents the values of descriptive (mean, standard deviation and coefficient of variation) and normality (Skewness and Kurtosis) statistics of the Indicator Property (IP) data, obtained in tests with non-destructive techniques (MST and MTG); the modulus of rupture (MOR) and modulus of elasticity (MOE_{GLOBAL} and MOE_{LOCAL}), obtained in the bending tests; and density (ρ) of the resin sample. The values of Skewness and Kurtosis within the range of -2 and +2 indicate that the data of analyzed present a normal distribution and validate the use of parametric statistical tests for the analysis of the results.

Table 2. Statistical values of mean, standard deviation, coefficient of variation (COV), skewness and kurtosis for bending data (MOE_{GLOBAL} , MOE_{LOCAL} , MOR), density and Indicator Property (IP) obtained by tests with wave vibration technology (IP_{MTG}) and of tension waves (IP_{MST}) of the resinated sample.

	IP_{MST}	IP_{MTG}	MOE_{GLOBAL}	MOE_{LOCAL}	MOR	density
Mean	12780	11069	9776	10400	46	558
Standard Deviation	2148	2100	1930	2249	13	30
COV	17%	19%	20%	22%	28%	5%
Skewness	-0.47	0.50	1.05	-0.04	-0.01	-0.60
Kurtosis	-1.16	-0.85	-1.38	-0.92	-1.08	0.84

Table 2 presents the values of descriptive statistics (mean, standard deviation and coefficient of variation) and normality (Skewness and Kurtosis) of the Indicator Property (IP) data obtained in tests with non-destructive techniques (MST and MTG); of strength (MOR) and modulus of elasticity (MOE_{GLOBAL} and MOE_{LOCAL}) obtained in the bending tests; and density of the boards from the test feet. Skewness and Kurtosis values within the range of -2 and +2 indicate that the data from IP_{MST} , IP_{MTG} , MOE_{GLOBAL} , MOE_{LOCAL} and density of the sample of control tables present normal distribution. However, the resistance data (MOR) did not present a normal distribution: Skewness value were out from the -2 and 2 range. Therefore, Outliers values of MOR were identified and eliminated to proceed with the proposed analyses.

Table 3. Statistical values of mean, standard deviation, coefficient of variation (COV), skewness and kurtosis for bending data (MOE_{GLOBAL} , MOE_{LOCAL} , MOR), density and Indicator Property (IP) obtained by tests with wave vibration technology (IP_{MTG}) and of tension waves (IP_{MST}) of the control sample.

	IP_{MST}	IP_{MTG}	MOE_{GLOBAL}	MOE_{LOCAL}	MOR	density
Mean	12456	10884	9581	9843	49	546
Standard Deviation	2177	2117	1806	2003	11	38
COV	17%	19%	19%	20%	23%	7%
Skewness	-1.22	-0.96	-0.26	0.28	-3.14	-1.51
Kurtosis	-1.84	-1.32	-1.46	-1.08	0.27	0.18

In general, the values obtained for the two samples are within the same order of greatness. As expected, the Indicator Properties are numerically larger than the modulus of elasticity obtained in flexure. The global moduli of elasticity were also expected to be lower than the local moduli. This behavior was confirmed in both samples (resined and control specimens). Regarding strength, the control sample presented a mean value slightly (6%) higher than the sample from resinated trees.

Table 4 presents the results obtained from the comparison analysis between indicator properties obtained by non-destructive techniques (IP_{MST} and IP_{MTG}), bending data (MOE_{GLOBAL} , MOE_{LOCAL} , MOR) and density of resinated and control trees. Confidence intervals containing zero indicate data sets with no statistically significant differences between their means.

Table 4. Confident intervals obtained for the comparison of bending data (MOE_{GLOBAL} , MOE_{LOCAL} , MOR), density and Indicator Property (IP) of sawn timber from resined and control trees.

Parameter	Sample	Confident Interval
IP_{MST}	A	[-462.86; 863.40]
	B	[-786.14; 757.19]
IP_{MTG}	A	[-424.25; 943.75]
	B	[-680.33; 944.21]
MOE_{GLOBAL}	A	[-340.60; 893.63]
	B	[-638.93; 810.79]
MOE_{LOCAL}	A	[-156.369; 1250.85]
	B	[-249.41; 1342.32]
MOR	A	[-5.05; 3.06]
	B	[-7.88; 1.52]
Density	A	[-9.61; 10.91]
	B	[7.80; 35.06]

The results in Table 4 indicate no statistically significant differences between the means of non-destructive and bending data, suggesting that previous resin extraction activity does not affect the mechanical quality of wood. However, the statistical analysis showed significant differences between the average densities of pieces from Sample B.

Considering the similarity between the distribution of the data obtained for the two samples (resinated and control trees) and that, in general, there are no statistical differences between them, the possibility of proposing a statistical analysis for mechanical classification (correlation between methodologies) was considered, considering all the pieces as a single sample. The analyses presented below, therefore, refer to a sample of 238 *Pinus pinaster* specimens from resinated and control trees.

Table 3 presents the values of descriptive statistics (mean, standard deviation, and coefficient of variation) and normality (Skewness and Kurtosis) of the Indicator Property (IP) data, obtained in tests with non-destructive techniques (MST and MTG); of strength (MOR) and modulus of elasticity (MOE_{GLOBAL} and MOE_{LOCAL}), obtained in the bending tests; and density of all the specimens under study (control and resinated trees). The values of Skewness and Kurtosis within the range of -2 and +2 indicate that the IP_{MTG} , MOE_{GLOBAL} , MOE_{LOCAL} data of all the tables in the sample present a normal distribution. However, the IP_{MST} , MOR and density data did not present a normal distribution: Skewness value out from the range of -2 and 2. For these parameters, outliers were identified and eliminated to proceed with the proposed analyses.

Table 5. Statistical values of mean, standard deviation, coefficient of variation (COV), skewness and kurtosis for bending data (MOE_{GLOBAL} , MOE_{LOCAL} , MOR), density and Indicator Property (IP) obtained by tests with wave vibration technology (IP_{MTG}) and of tension waves (IP_{MST}) of all sample (resin and control).

	IP_{MST}	IP_{MTG}	MOE_{GLOBAL}	MOE_{LOCAL}	MOR	densidad
Mean	12617	10976	9677	10118	48	552
Standard Deviation	2164	2106	1867	2142	12	35
COV	17%	19%	19%	21%	26%	6%
Skewness	-1.21	-0.34	0.70	0.41	-2.03	-2.42
Kurtosis	-2.06	-1.48	-1.90	-1.34	-1.08	1.33

For mechanical classification of wood for structural purposes, EN 14081-2 defines a series of statistical procedures that correlate non-destructive variables with the mechanical and physical properties of the material (strength, modulus of elasticity and density). The first procedure defined by the document (EN 14081-2) is to obtain linear regressions between the Indicator Properties (IP) and bending and density parameters. Table 4 presents the P-value, correlation coefficient (R), coefficient of determination (R^2), standard estimation error and the step equations obtained by linear regression analysis between the Indicator Properties (IP) obtained by the two techniques (MST and MTG) – and the density and bending parameters (MOE_{GLOBAL} , MOE_{LOCAL} and MOR).

Table 6. Statistical parameters – P-Value, correlation coefficient (R), coefficients of determination (R^2), standard estimation error, and equations - obtained in the linear regressions between the indicator properties (IPMST and IPMTG) and density and bending properties.

		P-Value	R	R^2	Error	Ecuación
IP_{MST}	MOE_{GLOBAL}	0.00	0.82	67%	1077	MOE_{GLOBAL} = 843.503 + 0.700795* IP_{MST}
	MOE_{LOCAL}	0.00	0.72	51%	1493	MOE_{LOCAL} = 1193.93 + 0.707902* IP_{MST}
	MOR	0.00	0.44	19%	11	MOR = 16.8689 + 0.00244931* IP_{MST}
	density	0.00	0.34	11%	32	ρ = 484.884 + 0.00535725* IP_{MST}
IP_{MTG}	MOE_{GLOBAL}	0.00	0.93	86%	688	MOE_{GLOBAL} = 764.948 + 0.813973* IP_{MTG}
	MOE_{LOCAL}	0.00	0.83	68%	1199	MOE_{LOCAL} = 1036.78 + 0.830371* IP_{MTG}
	MOR	0.00	0.61	38%	10	MOR = 9.31988 + 0.00352245* IP_{MTG}
	density	0.00	0.42	17%	30	ρ = 479.133 + 0.00658405* IP_{MTG}

In relation to the models presented in Table 4, there is a statistically significant relationship between the parameters analyzed with a confidence level of 95.0%, for all cases (P value <0.05).

R values greater than 0.70 indicate that the properties obtained with non-destructive equipment strongly correlate with the modulus of elasticity (global and local) in bending. Although the standard (EN 14081-2) defines that linear regressions must be obtained between Indicator Properties (IP) and all the resistance variables of the material (modulus of elasticity, strength, and density), it is expected that the modulus of elasticity correlates better (higher R^2) with non-destructive methods.

The graphs (Figure 2) show the linear regressions between the bending properties (MOE_{GLOBAL} , MOE_{LOCAL} , MOR and density) and the indicator properties (IP) obtained by the tests with non-destructive equipment (MST and MTG) in the total *Pinus pinaster* sample. The red points of the graph refer to the resined sample and the blue ones refer to the control sample.

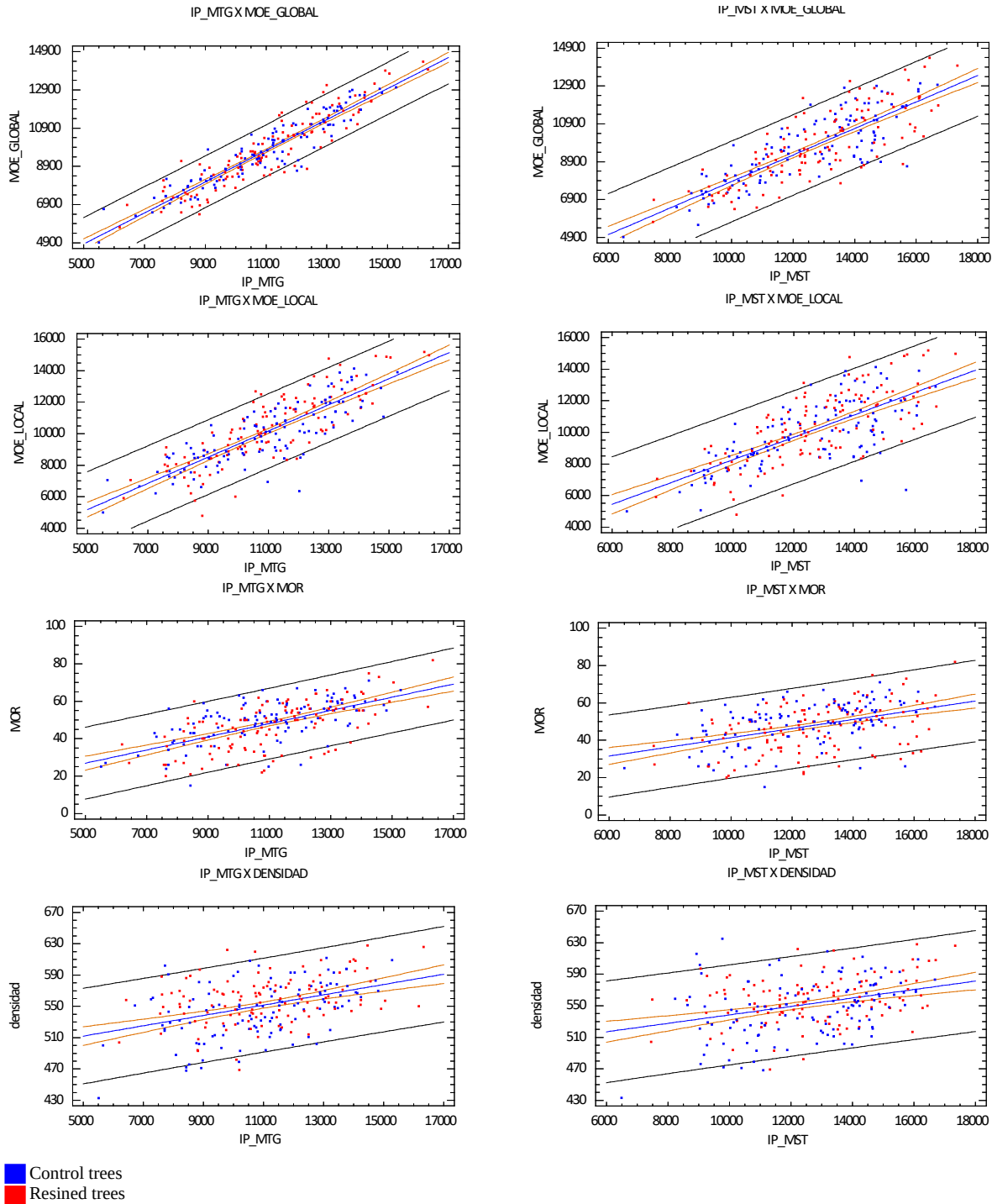


Figure 1. Linear regressions between mechanical properties (MOE_{GLOBAL}, MOE_{LOCAL}, MOR) obtained in bending and density and the indicator properties (IP) obtained by non-destructive tests (MST and MTG) in the total sample of *Pinus pinaster* specimen.

The graphs show the trend lines of the regressions (blue) and two sets of limits for each regression. The inner limits (red lines) establish 95% confidence intervals for the mean values of Y at any selected X. Since the relationships are linear, these limits indicate how well the trend lines have been estimated. The

outer (black) lines are the 95% prediction limits for new observations. It is estimated that 95% of the additional observations, similar to those in the sample, would be within those limits.

The linear regression graphs show that the distribution of the data from the resinated (red points) and controls (blue points) trees is very similar, which indicates that the resin activity does not affect the efficiency of the non-destructive technique for classifying *Pinus pinaster* wood.

Conclusions

Overall, the data obtained from the mechanical classification of wood from resinous trees show minimal numerical and distribution differences compared to non-resinous trees.

The dasometric and acoustic parameters used to predict wood quality from standing trees did not exhibit differences between resined and control trees. However, the density of the resined trees is slightly higher than that of the control ones.

Regarding mechanical classification, the correlation coefficient values (R^2) between the indicator properties (IP_{MTG} and IP_{MST}) and the resistance properties (MOE_{GLOBAL} , MOE_{LOCAL} , MOR, and density) obtained for the entire sample of specimens fall within expected limits. The result suggests that acoustic parameters and their effectiveness in controlling the quality of wood remain unaffected by resin activity.

Acknowledgments

The authors thank the Ministry of Agriculture, Fishing and Food for the project funding within the framework of the National Rural Development Program 2014-2020, which was €561,719.17. It was financed with FEADER funds at 80% and AGE at 20%.

References

- Camacho Rios, P. (2013). Impulso del sector resinero en el medio rural: Proyecto de Cooperación "Resina y Biomasa". *II Simposio Internacional de Resinas Naturales*. (pp. 144-151) 16 al 18 de abril. Coca. Segovia.
- EN 408: 2010+A1:2012. Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties. European Committee of Standardization (CEN), Brussels, Belgium.
- EN 13183-1: 2002. Moisture content of a piece of sawn timber - Part 1: Determination by oven dry method. European Committee of Standardization (CEN), Brussels, Belgium.
- EN 14081-2: 2019. Timber structures - Strength graded structural timber with rectangular cross section - Part 2: Machine grading; additional requirements for type testing. European Committee of Standardization (CEN), Brussels, Belgium.
- Picos Martín, J., & Rodríguez Soalleiro, R. (2019). Retos para la selvicultura de *Pinus pinaster* Ait. en Galicia. *Fundación HAZI Fundazioa*. País Vasco.
- Rodríguez Soalleiro, R. J., & Madrigal Collazo, A. (2007). Selvicultura de *Pinus pinaster* subesp. Atlantica. *Compendio de Selvicultura Aplicada*. INIA, 367-398.

Tree Inspection: Experience from Around the World—Australia

Vilius Gendvilas *

Forest Research Institute, University of the Sunshine Coast, Sippy Downs, Queensland, Australia,
vgendvilas@usc.edu.au

David Lee

Forest Research Institute, University of the Sunshine Coast, Sippy Downs, Queensland, Australia,
dlee@usc.edu.au

Geoff Downes

Forest Quality Pty Ltd., Franklin, Tasmania, Australia, geoff.downes@forestquality.com

* Corresponding author

Abstract

Drilling resistance is a semi-non-destructive method used for the mechanical characterization of natural stone, concrete, and wood. In Australia, the drilling resistance method using an IML-RESI Power Drill instrument designed to measure the drilling resistance of wood is rapidly becoming a routine method among forest plantation growers for wood quality assessments. The major driver in the commercial uptake of drilling resistance is its speed, cost-effectiveness, and sufficient precision for commercial use, especially when data are processed through a user-friendly, web-based processor. Drilling resistance can be utilized for both basic density and stiffness predictions for standing trees. It can also assess wood properties radially. Unlike other non-destructive wood testing techniques, drilling resistance is not affected by moisture above the fibre saturation point. Furthermore, in an open forest, 40 trees per hour can be assessed for drilling resistance, compared to 27 trees with the ST-300 and 4 trees using coring methods. To ensure drilling resistance works effectively, we need to account for friction effects, needle wear, how the operator and instrument affect drilling resistance, needle diameter, potential instrument battery effects, and how different feed speeds and RPMs affect drilling resistance values. These factors have been quantified to optimize drilling resistance measurements in pine and eucalypt trees in Australia.

Keywords: resistance drilling, IML-RESI Power Drill, instrument related variance, drill bit wear, drill bit diameter, feed speed and RPM settings, battery effect.

Acoustic Evaluation of Wood Properties of Fire-Damaged Ponderosa Pines on the Plumas National Forest

Frederico Jose Nistal Franca *

Department of Sustainable Bioproducts, Mississippi State University, Starkville, MS, USA,
fn90@msstate.edu

Xiping Wang

USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, xiping.wang@usda.gov

Thomas L. Eberhardt

USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, thomas.l.eberhardt@usda.gov

Rubin Shmulsky

Department of Sustainable Bioproducts, Mississippi State University, Starkville, MS, USA,
rs26@msstate.edu

Michael C. Stambaugh

School of Natural Resources, University of Missouri, Columbia, MO, USA, StambaughM@missouri.edu

* Corresponding author

Abstract

Wildfires on the forest landscape can negatively affect both wood quality and merchantable volume. Prescribed fires, although set with intent as a key management tool, can inadvertently lower the quality of the wood, particularly that near a fire scar. To date, forest managers have relied on visual inspections of standing fire-damaged trees to assess volume losses; however, these visual assessments do not directly relate to wood quality. Novel commercially available nondestructive evaluation (NDE) technologies have recently been developed that can determine the quality of wood in standing timber. The objective of this study is to assess the impact of fire treatments on hard pine wood properties through field NDE testing of standing hard pine trees, coupled with laboratory tests of wood samples. In the first phase of field testing, we conducted nondestructive testing on 56 ponderosa pine trees on the Plumas National Forest, located near Quincy, California, USA. The sample trees tested were from 9 plots across various treatments (control – no burn, one burn, two burns, and three burns). Acoustic time-of-flight (TOF) data was collected from the sample trees in both transverse and longitudinal directions. Transverse acoustic velocity was found to consistently decrease as the fire condition changed from no burn to one, two, and three burns. There was a significant reduction in transverse acoustic velocity in 2 burn and 3 burn conditions when compared with the control. However, no significant differences were found in the measured longitudinal velocity among the different fire conditions.

Keywords: acoustic measurements, ponderosa pine, time-of-flight, wood quality, wood property.

Introduction

A century of wildfire suppression in fire-adapted forest ecosystems across the United States has eroded forest resilience, compounding the primary issue of fuel loads exceeding historical levels (Donovan and Brown 2007, Ryan et al. 2013). Thinning operations can help mitigate wildfire severity; however, they are not sufficient alone in restoring fire-adapted ecosystems nor the threat of catastrophic wildfires (Prichard et al. 2021). Barriers to using prescribed fire to restore fire-adapted landscapes include permitting issues, lack of resources (e.g., equipment, funding, labor), and public perceptions (Huber-Sterns et al. 2021). For hardwood ecosystems in the eastern United States, studies have shown that the merits of prescribed fires can be accompanied by tree wound, tree (wood) quality degradation, and tree mortality (Saunders et al. 2021; Dey and Schweitzer 2018; Kinkead et al. 2017; Marschall et al. 2014). Far fewer studies have focused on the application of prescribed fire to hard pine forests, and these have been more concerned about creating conditions favoring forest regeneration, resilience, and the restoration of forest attributes of fire-adapted ecosystems (Stambaugh et al. 2019; Tepley et al. 2020). Little attention has been given to address impacts that prescribed fire may have on wood quality.

To date, forest managers have often relied on visual inspections of standing fire-damaged trees to assess volume losses (Dey and Schweitzer 2018); however, these visual assessments do not directly relate to wood quality. Novel commercially available nondestructive evaluation (NDE) technologies have recently been developed that can determine the quality of wood in standing timber (Gao et al. 2017; Schimleck et al. 2019; Wang 2021). In this study, we investigated the feasibility of using NDE technologies to assess the impact of fire treatments on hard pine wood properties.

This research is part of a broader study on quantifying fire effects on Sierra Nevada pine wood properties from tree to stand scale and evaluating multi-benefit outcomes including wood quality, volume production, and ecosystem values. In this paper, we report preliminary results of field NDE testing conducted on ponderosa pine trees across varied burn histories on the Plumas National Forest near Quincy, California, USA. In the future, field NDE tests will also be conducted in other national forests and the field NDE data will be paired with laboratory test results of wood samples to gain a better understanding of fire effects on wood properties of residual merchantable trees.

Materials and Methods

Study site, plot conditions, and tree samples

The study site is on the Plumas National Forest, located near Quincy, California, USA. A total of 74 plots were selected for the overall study covering vegetation types of ponderosa pine, Jeffrey pine, and Sierra mixed conifer forests (Stambaugh et al. 2023). All plots had known burn histories and included areas of no burn (control plot), burned once, twice, and three times in the past four decades. In this study, we focused on testing ponderosa pine trees. Our field work started in the summer of 2023. We worked with the research team at the University Missouri on the tree sampling process; 9 plots were selected across four fire conditions, including no burn (control), one burn, two burns, and three burns. Our initial sampling target was 15 trees per condition. The actual number of trees sampled ranged from 11 to 17 trees per condition, resulting a total of 56 ponderosa pine trees (17 trees in control, 13 trees in one-burn, 15 trees in two-burn, and 11 trees in three-burn). We plan to sample additional trees for NDE data collection in the summer of 2024.

Field nondestructive testing on tree samples

Wood quality, in terms of mechanical and physical properties, was assessed in the field on selected tree samples using various NDE techniques. Transverse and longitudinal acoustic velocities of a tree provide measures of the soundness and stiffness (dynamic modulus of elasticity) of wood; micro-drilling resistance provides measures of wood density variation, growth pattern, and decay if present. Calibrations of field acoustic data will involve the destructive sampling of a limited number of trees from which tree disks and bole sections will be processed to determine parameters of moisture content, wood density, acoustic velocity, and wood stiffness (e.g., mechanical testing of small clear specimens in the laboratory).

Transverse acoustic measurements were conducted on the tree samples using the Fakopp Microsecond Timer (Fakopp Enterprise Inc., Sopron, Hungary), coupled with a pair of sensor probes (Figure 1). This test measures the acoustic wave transmission time across tree's diameter, which indicates the internal conditions of the tree trunk. In general, acoustic waves travel faster in sound and high-quality wood than in deteriorated or low-quality wood. Internal defects such as decay or internal fire scars could slow the wave propagation. By measuring acoustic wave transmission time across a tree's stem, it is anticipated that internal fire damage in the trees could be identified and/or quantified. Measurements were made at the breast height (dbh) across trunk's diameter in the north-south and east-west directions. Three time-of-flight (TOF) readings were recorded for each direction.

Different from the transverse acoustic measurement, the longitudinal acoustic measurement measures the time-of-flight of acoustic waves along the tree stem, which is then used to determine the acoustic velocity of trees. Longitudinal acoustic velocity in trees can be used to predict important wood properties such as stiffness (MOE) and micro-fibril angle (MFA). We used a Fakopp Microsecond Timer with two spike-sensor probes inserted into a tree trunk, each at a 45-degree angle, over a span of 1.2 meter, and aligning in a vertical line on the north face (Figure 2). An acoustic wave was introduced into the tree trunk by impacting the lower sensor-probe with a hand-held hammer. The resulting signals were received by start and stop sensor-probes and recorded on the Fakopp Microsecond Timer. Three TOF readings were recorded for each tree. Acoustic wave velocity was then calculated by dividing the test span L by the averaged TOF.

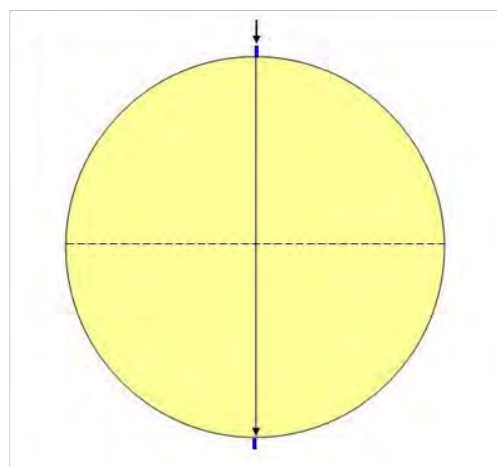


Figure 1. Transverse acoustic measurement conducted at the breast height of a tree sample in two perpendicular directions: north-south and west-east.

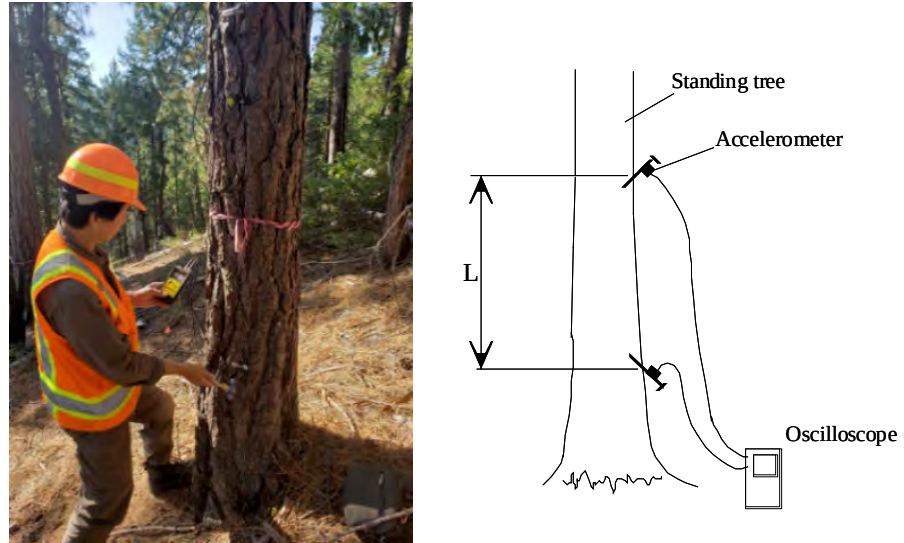


Figure 2. Longitudinal acoustic measurement conducted on a tree sample over a span of 1.2 m.

Results and Discussion

Figure 3 shows the box plot of diameter at breast height data from the ponderosa pine trees we sampled in different fire conditions. The dbh of the sample trees varied greatly overall, ranging from 27 cm to 97 cm. The average dbh was 43.1, 47.1, 56.9, and 75.5 cm for the control, one burn, two burn and three burn plots respectively. The study plots in the two-burn and three-burn conditions exhibited the largest dbh variations. The dbh variation among fire conditions is not related to the burn frequency, but the results of different stand ages and stand conditions which need to be looked into in future analysis.

Table 1 summarizes the basic statistics of measured acoustic velocities of the ponderosa pine trees. Transverse acoustic velocity ranged from 1315 to 2072 m/s and the longitudinal acoustic velocity ranged from 2263 to 4336 m/s. Figure 4 shows the box plot of the measured transverse acoustic velocity of ponderosa pine trees in different fire conditions. Transverse acoustic velocity consistently decreased as the fire condition changed from no burn to one, two, and three burns. The trees in no-burn condition (control) exhibited the highest average velocity (1808 m/s), in contrast, the trees in the three-burn condition had the lowest average velocity (1579 m/s). Statistical analysis indicated significant reduction in transverse acoustic velocity in two-burn and three-burn condition comparing with the control. It is possible that the velocity reduction was caused by the damage from repeated fires, which could be the internal fire scars from past fires, the external physical damage directly caused by fire, or the wood deterioration following the severe fire burns. We will further examine the fire damages of the sampled trees in the next phase.

Table 1—Statistics of the measured acoustic velocities of ponderosa pine trees in different fire conditions.

Group	Acoustic Velocity (m/s)							
	Transverse				Longitudinal			
	Average	Min	Max	COV (%)	Average	Min	Max	COV (%)
No Burn	1808	1539	2072	6.07	3292	2263	4022	14.70
1 Burn	1782	1562	1982	5.71	3711	3250	4040	7.63
2 Burns	1635	1467	1825	6.26	3247	2392	4176	15.55
3 Burns	1579	1315	1877	9.18	3471	2813	4336	13.70

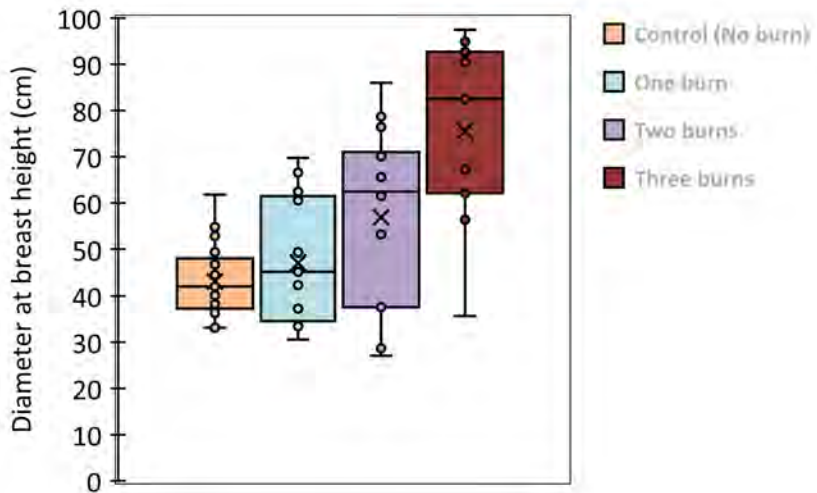


Figure 3. Diameter at breast height (dbh) of the ponderosa pine tree samples in different fire conditions.

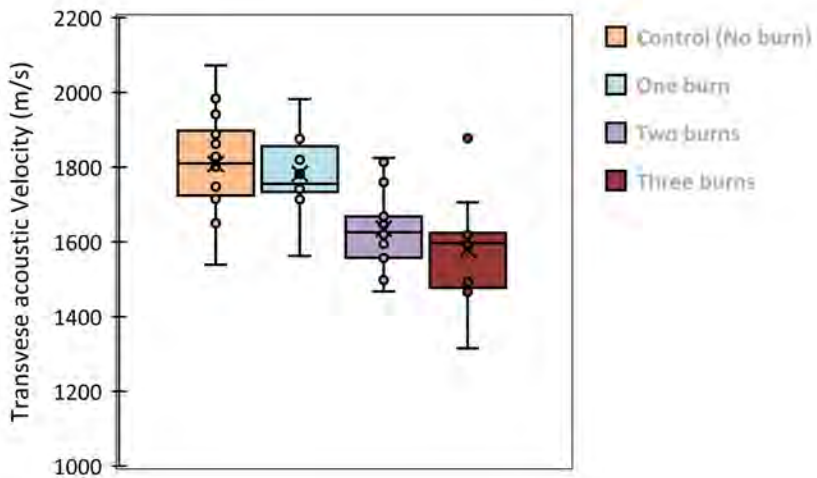


Figure 4. Transverse acoustic velocity of ponderosa pine trees in different fire conditions.

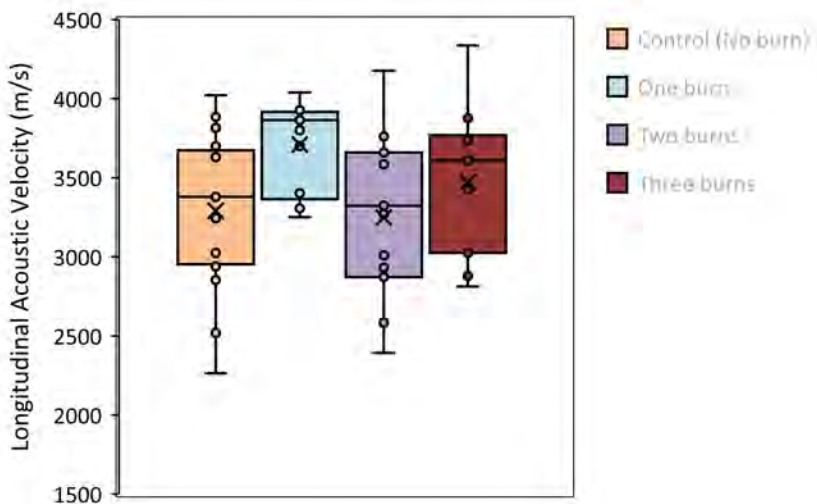


Figure 5. Longitudinal acoustic velocity of the ponderosa pine tree samples in different fire conditions.

Figure 5 shows the box plot of the measured longitudinal acoustic velocity of ponderosa pine trees in different fire conditions. No significant differences were found in the measured longitudinal velocity among different fire conditions. It should be pointed out that the measured longitudinal acoustic velocity of trees needs to be calibrated against log acoustic velocity. Previous studies have found the measured tree velocity is often deviated from log velocity due to diameter effect. We will develop a calibration model by measuring the log acoustic velocity after felling a subset of the sample trees. This work is under planning.

During the field testing, we noticed that ponderosa pine trees have thick barks and the thickness of the barks varied from plot to plot. Trees in older stands had barks up to 1.5 – 2 in thick, which created difficulties when inserting the sensor probes into the tree stem. The Fakopp sensor probes we used were only 2.5-in long, and not long enough for testing ponderosa pine trees with their thick barks. The Hitman ST300 tool has much longer probes than Fakopp sensors and is better suited to this study. We plan to use Hitman ST300 tool for future tree testing.

Another observation we made is that the actual fire damage of the trees can vary greatly within the same plot or within the same fire condition. In Figure 5, we see more variations in acoustic velocity within the same fire conditions than those among the different fire conditions. With limited tree samples (11 to 17 trees) within each fire condition, it is difficult to make meaningful comparisons based on measured tree velocity in terms of fire impact. To determine the impact of fire condition on wood properties, we need focus on examining within-tree wood property variations, particularly in the radial direction.

Conclusions

This paper reports the preliminary results of nondestructive testing conducted on ponderosa pine trees across varied burn histories. Transverse acoustic velocity was found to consistently decrease as the fire condition changed from no burn, to one, two, and three burns. There was a significant reduction in transverse acoustic velocity in two-burn and three-burn conditions comparing with that in the control (no burn). However, no significant differences were found in the measured longitudinal velocity among different fire conditions.

Acknowledgments

This research was funded by the USDA Forest Service through the Bipartisan Infrastructure Law and the research agreement (23-JV-1111134-028) between the Mississippi State University and the USDA Forest Service Forest Products Laboratory (FPL). Special thanks to Joseph Marschall, Joshua Yantis, and Owen Steins of School of Natural Resources at the University of Missouri for their supports in field testing.

References

- Dey DC, Schweitzer CJ. 2018. A review on the dynamics of prescribed fire, tree mortality, and injury in managing oak natural communities to minimize economic loss in North America. *Forests*. 9:461.
- Donovan GH, Brown TC. 2007. Be careful what you wish for: The legacy of Smokey Bear. *Frontiers in Ecology and the Environment* 5(2):73-79.

Gao S, Wang X, Wiemann MC, Brashaw BK, Ross RJ, Wang L. 2017. A critical analysis of methods for rapid and nondestructive determination of wood density in standing trees. *Annals of Forest Science* 74:27.

Huber-Stearns HR, Santo AR, Schultz CA, McCaffrey SM. 2021. Network governance in the use of prescribed fire; roles for bridging organizations and other actors in the Western United States. *Regional Environmental Change* 21:118.

Kinthead CS, Stambaugh MC, Kabrick JM. 2017. Mortality, scarring, and growth in an oak woodland following prescribed fire and commercial thinning in the Ozark Highlands. *Forest Ecology and Management* 403:12-26.

Marschall JM, Guyette RP, Stambaugh MC, Stevenson AP. 2014. Fire damage effects on red oak timber product value. *Forest Ecology and Management* 320:182-189.

Prichard SJ, Hessburg PF, Hagmann RK, Povak NA, Dobrowski SZ, Hurteau MD, Kane VR, Keane RE, Kobziar LN, Kolden CA, North M, Parks SA, Stafford HD, Stevens JT, Yocom LL, Churchill DJ, Gray RW, Huffman DW, Lake FK, Khatri-Chhetri P. 2021. Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological applications* 31(8):e02433.

Ryan KC Knapp EE, Varner JM. 2013. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. *Frontiers in Ecology and the Environment* 11(1):e15-e24.

Saunders MR, Mann DP, Stanis S, Wiedenbeck, JK, Dey DC, Schuler TM. 2023. Prescribed fire causes wounding and minor tree quality degradation in oak forests. *Forests* 14:227.

Schimleck L, Dahlen J, Apiolaza LA, Downes G, Emms G, Evans R, Moore J, Pâques L, Van den Bulcke J, Wang X. 2019. Non-destructive evaluation techniques and what they tell us about wood property variation. *Forests* 10:728.

Stambaugh MC, Marschall JM, Abadir ER, Jones BC, Brose PH, Dey, DC Guyette RP. 2019. Successful hard pine regeneration and survival through repeated burning: An applied historical ecology approach. *Forest Ecology and Management* 437:246-252.

Stambaugh MC, Marschall JM, Dey DC. 2023. Fire scar injury characteristics across varied burn histories and severities on the Plumas National Forest, California, USA. 10th International Fire Ecology and Management Congress, December 4-8, 2023, Monterey, California. Poster presentation.

Tepley AJ, Hood SM, Keyes CR, Sala A. 2020. Forest restoration treatments in a ponderosa pine forest enhance physiological activity and growth under climatic stress. *Ecological Applications* 30(8):e2188.

Wang X. 2021. Recent advances in nondestructive evaluation of wood: In-forest wood quality assessments. *Forests* 12:949.

Influence of Climatic Conditions on the Propagation Speed of Ultrasound Waves in Forest Trees

Cinthy Bertoldo*

Laboratory of Nondestructive Testing – LabEND, College of Agricultural Engineering – FEAGRI of University of Campinas - UNICAMP, Campinas, São Paulo, Brazil, cinthyab@unicamp.br

Carolina Kravetz

Laboratory of Nondestructive Testing – LabEND, College of Agricultural Engineering – FEAGRI of University of Campinas - UNICAMP, Campinas, São Paulo, Brazil, carolinakra.12@gmail.com

Rafael Mansini Lorensani

Valora Madeira Ltda, Campinas, São Paulo, Brazil, rafael@valoramadeira.com

Fernanda Trislitz Perassolo Guedes

Sylvamo do Brasil, Mogi Guaçu, São Paulo, Brazil, fernanda.guedes@sylvamo.com

* Corresponding author

Abstract

The aim of the work was to evaluate whether the propagation velocity of ultrasound waves is influenced by the period of the year in which the test is carried out on the tree. To achieve this goal, ultrasound tests were carried out on 540 trees from three different eucalyptus clones (A, B and C), with three different ages (1, 3 and 4 years), located in two regions (R1 and R2). The tests took place at four different times over twelve months, with a reading being carried out every 3 months on all tree individuals. The results of the research allowed us to conclude that the propagation velocity of ultrasound waves in trees is dependent on the period in which the tests are carried out, with higher velocity values are obtained after a longer period of drought and lower velocity values are obtained after a period of greater rainfall.

Keywords: radial velocity, longitudinal velocity, eucalyptus clones

Introduction

In companies in the forestry sector there is a need to monitor and anticipate knowledge of the quality of plantations efficiently. Therefore, more agile methods are needed, which allow decision-making and quick actions to maintain the expected development. An important tool for evaluating wood is non-destructive testing, which can be used by industries to improve process quality control through greater uniformity in the raw material and its derivatives (Erikson et al., 2000).

Non-destructive testing aims to obtain information about the properties of materials, such as physical and mechanical properties, without changing their usability (Pellerin & Ross, 2002). These tests have advantages such as: low cost, agility and the possibility of evaluating the structure without the need for its

removal (Oliveira, Campos and Sales, 2002). The ultrasound technique deserves to be highlighted in determining the properties of wood, as it has the ability to test and predict the properties of the material, based on tests on the standing tree or on test specimens (Bertoldo, 2011; Gonçalves et al, 2013; Wang, 2013; Bertoldo, 2014) and also in access to information about its quality (Wang et al, 2007; Bertoldo et al., 2009; Bertoldo et al., 2011; Batista, 2012; Bertoldo, 2014).

However, it is essential to know the environmental conditions in which the analyzed material is found, as factors such as temperature and humidity influence the parameters of the ultrasound waves (Bucur & Bohnke, 1994). In the work of Llana et al (2014), specimens of *Pinus sylvestris* were subjected to different temperature and humidity conditions, in the laboratory, and as a result they identified that with increased humidity there was a decrease in ultrasound speed, while in regarding temperature, only below 0 °C were there significant changes in speed.

Brazilian forest plantations are found in different locations, and each region has a specific climate, with variations in temperature and precipitation over the months. These variations are expected, but it is not common to determine a specific period for field trials to occur. However, knowing the behavior of ultrasound in different temperature and humidity conditions, it is important to understand the performance of field tests on Eucalyptus clones, used by the Brazilian forestry sector.

Thus, knowing the potential of non-destructive tests to access information about wood properties, and considering that forest plantations end up being subjected, mainly, to recurrent changes in precipitation and temperature rates throughout the year, it is important to understand how these changes may affect tests carried out in the field. Therefore, this work aimed to evaluate whether the propagation speed of ultrasound waves is influenced by the period of the year in which the tree test is carried out in the field.

Methodology

Characterization of the areas

The trees that were part of this study are found in two regions. Region 1 is located close to the city of Mogi Guaçu- SP, has a humid subtropical climate with dry winters and hot summers (Cwa), according to the Köppen classification, where rainfall is significant throughout the year, presenting a rainy period from november to march, and dry period from june to august (Figure 1). The characteristic soil of the region is the latosol, with greater water storage in the soil. Region 2 is close to the city of Tambaú – SP, and according to Köppen, the climate in this region is humid subtropical with dry winter and temperate summer (Cwb), with a rainy period from december to february, and the dry season varies from may to september (Figure 2). The characteristic soil of the region is nitisol, with a greater proportion of sand.

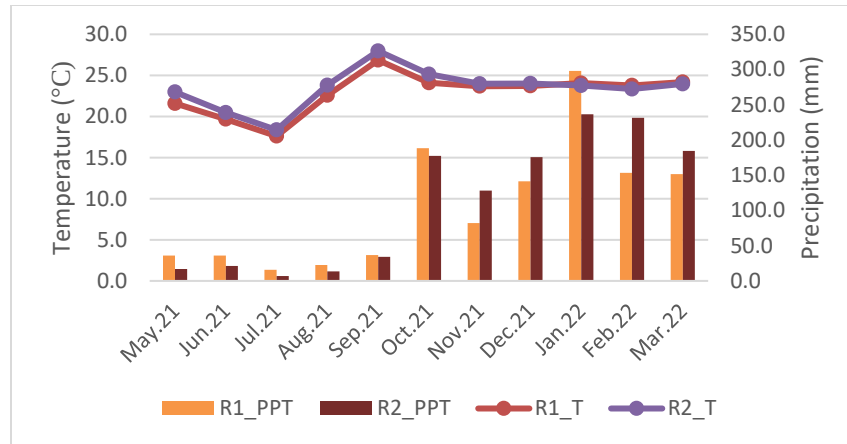


Figure 1. Temperature (T) and precipitation (PPT) from may/2021 to march/2022 for the two tree growing regions R1 and R2).

Field trials

For this work, three clones of *Eucalyptus* sp with different densities were used (A - 0.48 g/cm³, B - 0.43 g/cm³, C - 0.37 g/cm³), which were evaluated at three ages (1, 3 and 4 years) and cultivated in the two regions (R1 and R2) described previously. For each clone, age and cultivation region, 30 trees were selected, which had their development monitored from may/2021 to march/2022, with tests that were repeated every 3 months. Therefore, with the aim of evaluating the influence of climate variations on ultrasound speed results, tests were carried out on selected trees in the months of may/21 (reading 1), august/21 (reading 2), december/21 (reading 3) and march/22 (reading 4).

To obtain the wave propagation speed in the trees, ultrasound equipment (USLab, Valora Madeira, Brazil) and exponential face transducers of 45 kHz frequency were used. The ultrasound tests on trees were carried out at a height of 1.30 m, indirectly, with the transducers inclined at 45°, positioned on the same side of the trunk, with a distance of 50 cm between them (Figure 3a) and directly, with the transducers positioned on opposite sides of the trunk, therefore the distance between the transducers varied according to the diameter of the tree (Figure 3b). For each tree, three propagation time readings were taken, and the average of these values was taken into account for the calculations.



Figure 2. Ultrasound tests being carried out on trees with indirect measurements (transducers positioned on the same face) (a) and direct measurements (transducers on opposite faces) in the radial direction (b).

To calculate the speed, Equation 1 was applied, which uses the propagation time of the waves, obtained from the equipment and the distance between the transducers during the test. Therefore, longitudinal

velocity values were calculated from indirect measurements and radial velocity from direct measurements.

$$V = \frac{\Delta s}{\Delta t} \quad (1)$$

Onde: Δs is the distance between the transducers when carrying out the tests (m) and Δt is the wave propagation time identified by the equipment (μs).

In addition to ultrasound measurements, tree growth was monitored by measuring tree height and diameter at breast height (DBH). The height of the trees in the field was measured using a hypsometer (Vertex IV, Hagl f, Switzerland) and the gain in tree diameter was monitored using a measuring tape at a height of 1.30 m above the ground (DBH).

Thus, the parameters obtained from the field trials were evaluated through multivariate analysis of variance with the aim of verifying the existence of statistical differences considering the different factors (regions, clones, ages and readings) with a 95% confidence level.

Results and Discussion

Considering the results of the multivariate analyzes of variance, the p-value was less than 0.05 for all factors considered in the research, indicating that there were significant statistical differences in velocities in relation to clones, ages, regions and readings performed (Figures 4 and 5).

The results of the longitudinal velocity in the different clones showed that clone B presented the highest value for this parameter, while clone C had the lowest value. When the ultrasound test is performed in the longitudinal direction, the waves travel in the same direction as the fibers and, according to the study by Duong et al. (2018), fiber length has a positive correlation with velocity, indicating that these clones probably differ in relation to fiber characteristics, with the longer the fiber length, the greater the longitudinal velocity.

When evaluating the results of longitudinal velocity as a function of the age of the trees tested, there is an increase in the values of this parameter as age passes. This occurs because, as the trees grow, the wood acquires characteristics of an adult tissue, such as longer fibers and thicker cell walls (Vidaurre et al, 2020) and, thus, the ultrasound velocity tends to propagate better, resulting in higher speeds (Bucur, 2006).

Considering the different ultrasound readings in the longitudinal direction carried out throughout the year, it is observed that, contrary to what was expected, the speed did not increase over time (from reading 1 to reading 4), there is a variation in the speed values that coincided with the availability of water given by the volume of precipitation. Reading 2, which occurred in a period of lower precipitation (august 2021), presented the highest average speed values, while reading 4, which occurred in a period of greater water availability (may 2022), presented the lowest velocity values (Figure 4c). In the study by Pe a and Grace (1986), a reduction in ultrasound velocity was observed after a period of water stress; this reduction in speed was justified, by the authors, due to the effects of cavitation on xylem cells.

When comparing the longitudinal ultrasound velocities of trees grown in the two regions, it appears that this presented values, on average, 4% lower for specimens from region 1 than for trees grown in region 2 (Figure 4d). As region 1 has soils with greater water storage capacity, the greater availability of water probably influenced the decrease in speed values for trees grown in this region.

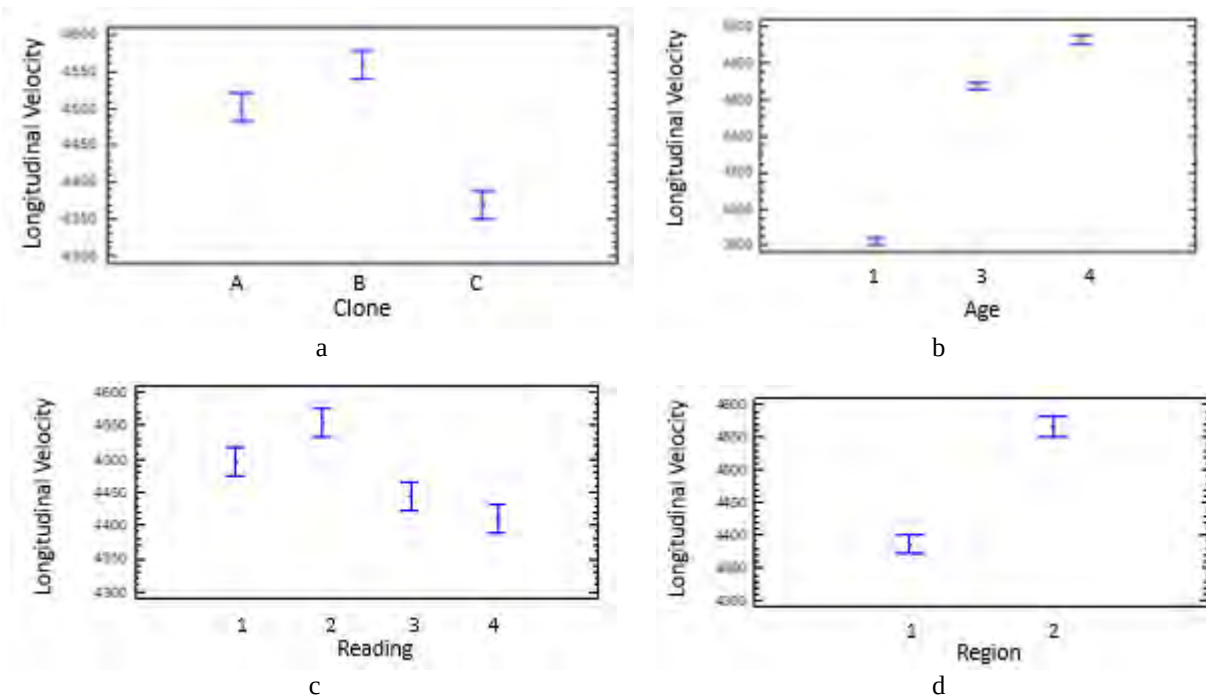


Figure 3. Graph of confidence intervals of the mean longitudinal velocity as a function of clone (a), age (b), reading performed (c) and cultivation region (d).

When we evaluated the radial velocity in the different clones used in the research, we found that clone A presented values, on average, 8.4% higher than clone B, while the latter presented average radial velocity values 13% higher than clone C. When waves propagate in the radial direction, they move through the cell walls, and their thickness has a direct relationship with the propagation speed of ultrasound waves (Bucur, 2006), as well as with the density of the wood (Vidaurre et al, 2020). Thus, the result of radial velocity in the different clones is in line with the basic density values presented by them (A - 0.48 g/cm³, B - 0.43 g/cm³ and C - 0.37 g/cm³).

Over the years, tissues mature (Vidaurre et al, 2020) and, therefore, it is expected that ultrasound velocities will be greater as the age of the trees advances, just as occurred for longitudinal velocity (Figure 4b). However, the same did not occur for radial velocity in the case of this research, where 1-year-old trees presented higher values when compared to 3 and 4 year-old trees, and for these last two ages it was possible to observe the values crescents (Figure 5b).

Regarding the radial velocity values, considering the different readings taken throughout the year, they showed the same behavior presented by the longitudinal velocities, where reading 2, in the driest period, presented the highest average values, and reading 4, in the rainiest period, the lowest speeds (Figure 5c).

When evaluating the differences in radial velocity of trees grown in the two regions, it appears that specimens grown in region 1 presented higher values for the parameter than those grown in region 2 (Figure 5d). To justify this result, it is important to jointly evaluate the difference in the growth of trees in these two regions, where there is greater growth both in relation to DBH and in relation to height for trees grown in region 2 (Figure 6). Faster-growing trees have different anatomical and physical wood characteristics than slower-growing trees (Dewi et al., 2022). Generally, fast-growing trees have low wood density (Nguyen et al. 2014), which is influenced by several anatomical structures, such as fiber length, lumen diameter, and cell wall thickness (Dewi et al., 2022). Therefore, the trees that grew in region 1, due to their lower growth (given by DBH and height), produced fibers with greater thickening of

the cell wall, thus justifying the higher values for radial velocity for cultivated trees in this region (Figure 5d).

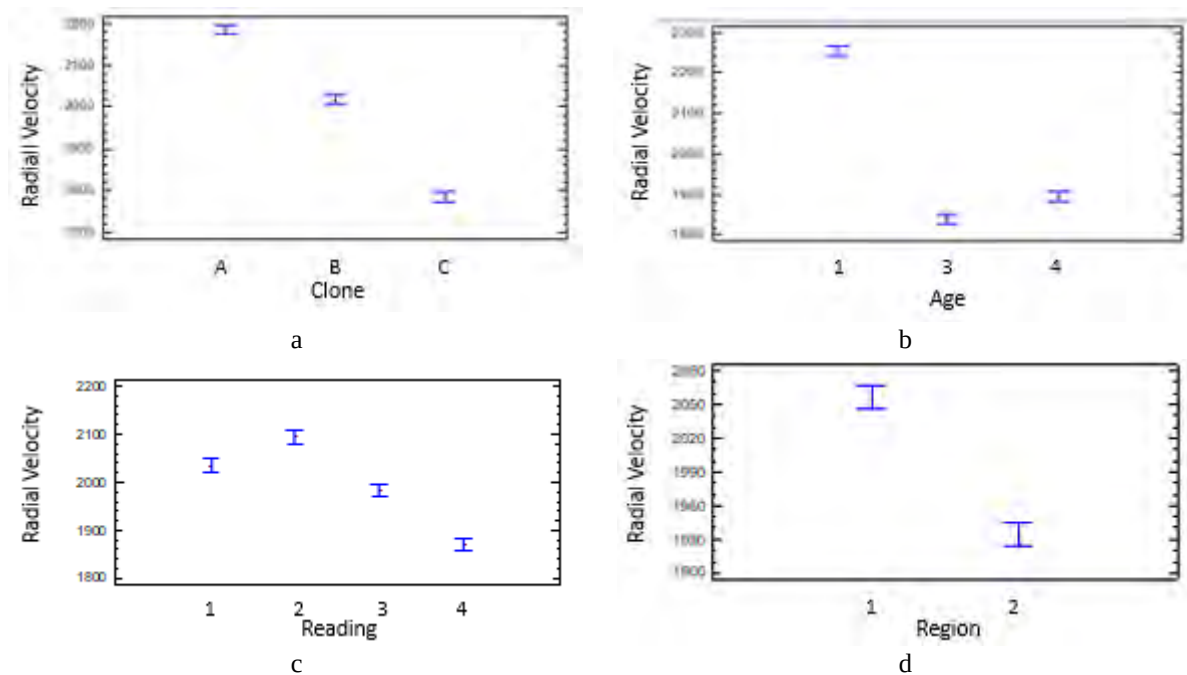


Figure 4. Graph of confidence intervals of the average radial velocity as a function of clone (a), age (b), reading performed (c) and cultivation region (d).

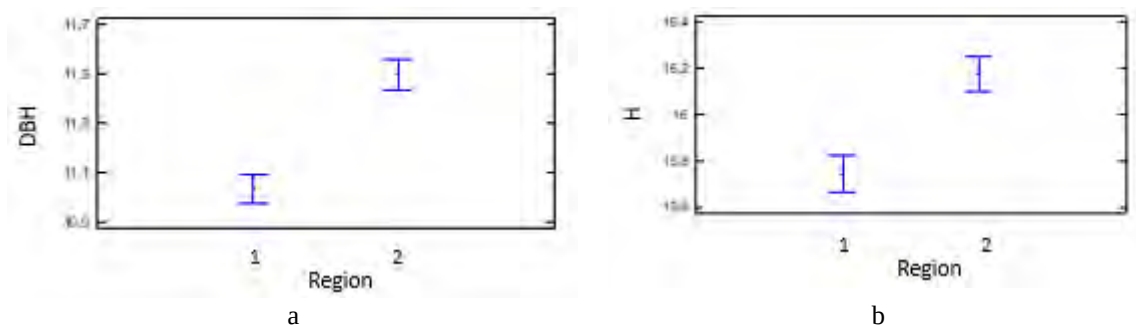


Figure 5. Graphs of confidence intervals for the average DBH (a) and average height (H) (b) of trees grown in the two growing regions.

Conclusion

Ultrasound tests were carried out every 3 months during a period of 1 year, on three clones of the genus *Eucalyptus* (A, B and C), at different ages (1, 3 and 4 years), located in two regions with edaphoclimatic characteristics different, with the aim of evaluating whether the propagation speed of ultrasound waves is influenced by the period of the year in which the test is carried out on the tree. For this, multivariate variance analyzes were carried out, and thus it was observed that through the ultrasound velocity results there was a distinction between the clones and the ages studied, possibly due to anatomical characteristics, but when analyzing the test periods (readings), as well as regions, the influence of environmental characteristics on the results can be seen. Therefore, it is concluded that the propagation speed of ultrasound waves in trees is dependent on the period in which the tests are carried out, with

higher speed values being obtained after a longer period of drought, and lower speed values obtained after periods of greater precipitation.

Acknowledgments

We are grateful to the support of the Laboratory of Nondestructive Testing (LabEND), the employees of forest research from Sylvamo do Brasil and to the financial support from the National Council for Scientific and Technological Development (CNPQ).

References

- BERTOLDO, C. 2014. **Propriedades de Resistência e de Rigidez da madeira obtidas a partir da avaliação acústica na árvore**. Tese: Doutorado em Engenharia Agrícola - Universidade Estadual de Campinas, Fundação de Amparo à Pesquisa do Estado de São Paulo.
- BERTOLDO, C.; GONÇALVES, R.; BATISTA, F.; SECCO, C. B. 2011. Velocity of ultrasonic waves in live trees and in freshly-felled logs. In: 17th International Nondestructive Testing and evaluation of wood symposium WoodNDT, 2011, Sopron, Hungria, **In Proceedings...** Vol. 1, pp.1-3.
- BERTOLDO, C.; GONÇALVES, R.; MASSAK, M. V.; SECCO, C. 2009. Assessment of Wood Quality by Tree Evaluation Using Ultrasound. In: XIII Congresso Florestal Mundial, 2009, Buenos Aires. v. 1. p. 304-304.
- BUCUR, V. 2006. Acoustics of wood. **Springer**. 2nd edition.
- BUCUR, V. & BOHNKE, I. 1994. Factors affecting ultrasonic measurements in solid wood. **Ultrasonics**. 32 (5). p. 385-390.
- DEWI, A. P.; TIHURUA, E. F.; WULANSARI, T. Y. I. 2022. Trachea features and fiber dimensions of fast-growing tree: A casr study on wood samples from eastern Indonesia. 2nd International Conference on Tropical Wetland Biodiversity and Conservation.
- DUONG, D. V.; HASEGAWA, M.; MATSUMURA, J. 2018. The relations of fiber length, wood density, and compressive strength to ultrasonic wave velocity within stem of *Melia azedarach*. **Indian Academy of Wood Science**.
- GONÇALVES, R.; BATISTA, F.; LORENSANI, R. M. 2013. Selecting Eucalyptus Clones Using Ultrasound Test on Standing Trees. **Forest Products Journal**, v. 63, p. 112-118.
- LLANA, D. F.; INIGUEZ-GONZALEZ, G.; ARRIAGA, F.; NIEMZ, P. 2014. Influence of temperature and moisture content on non-destructive measurements in scots pine wood. **Wood Research**. 59 (5). p. 769-780.
- LORENSANI, R. G. M. 2017. **Antecipação do conhecimento de propriedades da madeira utilizando ensaios em mudas**. Tese: Doutorado em Engenharia Agrícola - Universidade Estadual de Campinas.
- NGUYEN, H.; FIRN, J.; LAMB, D. HERBOHN, J. 2014. Wood density: A tool to find complementary species for the design of mix species plantations. **Forest Ecology and Management**. 334, 106-113.

OLIVEIRA, F. R.; CAMPOS, J. A. O.; SALES, A. 2002. Ultrasonic measurements in Brazilian hardwood. **Materials research**, v.5, n.I, p.51-55.

PELLERIN, R. F. & ROSS, R. J. 2002. Nondestructive Evaluation of Wood. Forest Products Society, Madison, USA.

PEÑA, J. & GRACE, J. 1986. Water relations and ultrasound emissions of *Pinus sylvestris* L. before, during and after a period of water stress. **The New Phytologist**. 103, 515-524.

WANG, X. 2013. Acoustic Measurements on Trees and Logs: a Review and Analysis. **Wood Science and Technology**. 47: 965-975.

WANG, X.; ROSS, R. J.; CARTER, P. 2007. Acoustic Evaluation of Wood Quality in Standing Trees. Part 1. Acoustic Wave Behavior. **Wood Science and Technology**, p. 28-38.

VIDAURRE, G. B.; SILVA, J. G. M. da; MOULIN, J. C.; CARNEIRO, A. de C. O. 2020. Qualidade da madeira de eucalipyo proveniente de plantações no Brasil. **EDUFES**. Vitória, ES. 221 p.

Non-Destructive Evaluation Methods for Wood Traits in Norway Spruce Genetics and Breeding

Hong T.H. Nguyen *

Department of Forest Tree Breeding and Biotechnology, Forest Science Institution of South Vietnam, Ho Chi Minh, Vietnam, hong.nguyen@vafs.gov.vn

Zhi-Qiang Chen

Department of Forest Genetics and Plant Physiology, Swedish University of Agricultural Sciences, Umea, Sweden, zhiqiang.chen@slu.se

Anders Fries

Department of Forest Genetics and Plant Physiology, Swedish University of Agricultural Sciences, Umea, Sweden, Anders.Fries@slu.se

Mats Berlin

Department of Tree Breeding, Forest Research Institute of Sweden, Uppsala, Sweden, Mats.Berlin@skogforsk.se

Henrik R. Hallingbäck

Department of Tree Breeding, Forest Research Institute of Sweden, Uppsala, Sweden, Henrik.Hallingbäck@skogforsk.se

Harry X. Wu

Department of Forest Genetics and Plant Physiology, Swedish University of Agricultural Sciences, Umea, Sweden, Harry.wu@slu.se

* Corresponding author

Abstract

Knowledge of wood properties is important for decision-making and production management in the wood processing industries. Non-destructive evaluation methods have been widely used to inspect the properties of wood and wood products on standing tree at early ages to accelerate the processes of selection and genetic improvement of a species and improves forest management that aims to produce high quality timber. The objectives of this study were to estimate genetic parameters for growth, wood quality traits from the 27-year-old full-sib clonal trial and genetic relationship among them which aimed to effectively develop optimal breeding programs for timber production of Norway spruce. Time-of-flight stress wave technique (Hitman), Pilodyn penetration depth (Pilo), microdrilling resistance (Resi) and wedge grain angle gauge (GA) were used to improve wood properties of living trees for future breeding program of Norway spruce. The results of this study indicated wood quality traits (i.e. Resi, Pilo, AV, MOE and GA) had generally higher heritability than growth traits. Genetic correlations among observed traits were generally higher than phenotypic correlations. Wood density measured indirectly by Resi and Pilo, and MOE showed moderate and unfavourable genetic correlations with diameter at breast height (DBH) but weak correlations with height. The predicted genetic gain of clonal deployment of the best replicated tested clones (CRC) was the greatest, followed by clonal deployment of best individual trees (CIN) and the deployment of seedlings from open-pollination of the best individuals (SOP). Under selection of the best 5% clones, genetic gains for DBH were estimated to obtain 14–17% from (CRC). This corresponds to a relative improvement of 22–46% over deployment of CIN and 58–179% over SOP deployment. For wood traits at the same selection intensity, clonal deployment of CRC indicated a relative improvement of 11–31% over CIN and 18–140% over SOP.

Keywords: non-destructive methods, wood traits, Norway spruce, genetics, breeding

Machine Learning Algorithms and Non-Destructive Methods for Inference Properties of Planted Forest Trees

Rafael Gustavo Mansini Lorensani*

Valora Madeira, Campinas, São Paulo, Brazil, rafael@valoramdeira.com

Stella Stopa Assis Palma

Valora Madeira, Paulínia, São Paulo, Brazil, stella@valoramadeira.com

Raquel Gonçalves

Laboratory of Nondestructive Testing – LabEND, College of Agriculture Engineering – FEAGRI – UNICAMP, Campinas, São Paulo, Brazil, raquelg@unicamp.br

Abstract

Inferring the properties of forest is essential for timber industries, enabling the monitoring, anticipation of knowledge, and optimized management. For these goals the nondestructive methods are adequate tools. With significant advancements in data analysis propelled by the introduction of machine learning algorithms, there has been a true revolution in this field. In this research the sample comprised 492 eucalyptus trees planted in the state of São Paulo, Brazil, ranging from 3 to 7 years old. Data collected from forest inventory were augmented with ultrasound, drilling resistance, sclerometric impact, and penetration resistance tests. Five machine learning algorithms were applied on data, aiming to identify the most effective model in predicting tree basic density. The Random Forest algorithm presented better results with coefficient of determination (R^2) of 81% and root mean square error (RMSE) of 12.9 kgm^{-3} indicating the potential of this analysis tool.

Keywords: basic density, planted forests, ultrasound, drilling resistance.

Introduction

Despite advancements in genetic engineering and cloning, the properties of wood are still influenced by various factors (climate, soil, altitude, etc.) related to the development of trees. These influences result in significant variability in the wood produced in the forest, making it difficult to establish important reference values for the production line of forest companies linked to pulp and paper, wood-based products (fiberboards and particleboards), as well as roundwood or processed wood used in solid or engineered forms (glued laminated timber or cross-laminated timber) in construction.

The determination of tree properties in the forest has been a recurring topic in both national and international publications, with non-destructive techniques being a viable alternative to this challenge. By not affecting the material, these techniques allow tests to be repeated during the tree's growth. They can be performed directly on standing trees, and since no sampling or tree cutting is required, they are more economical, simple, and quick, enabling increased sampling.

Thus, several research groups have been developing studies using various non-destructive techniques aimed at inferring properties such as wood density (basic or apparent) and stiffness (Gendvilas et al., 2021; Nickolas et al., 2020; Gonçalves et al., 2019; de Pádua et al., 2019; Kharrat et al., 2019; Liu et al., 2019;

Gonçalves et al., 2018; Downes et al., 2018; Fundova et al., 2018; Carrillo et al., 2017; Soriano et al., 2015; Sandoz, 1999). These non-destructive methods include those that use wave propagation (ultrasound and stress waves), resistance to drilling, resistance to penetration, mass spectrometry, among others. Regardless of the type of equipment or technique used, the focus of the research is to correlate the measured parameters in trees with wood properties, with statistical modeling being the tool typically used to obtain the relationship between variables to predict results. Classical statistical tools are no longer the most suitable when the volume of data is very large, and machine learning algorithms are currently recommended for such cases.

The literature review indicated that in Brazil, studies related to machine learning are more strongly focused on estimating tree volume (Aragão et al., 2018; Lima et al., 2017; Cordeiro et al., 2015; Binoti et al., 2014, and Leite et al., 2016). In other countries, the works of Demertiz et al. (2017) and Iliadis et al. (2013) were the closest to our objective, as the authors studied different machine learning algorithms in inferring density, with results superior to those obtained using classical multiple regression. In field trials, Demertiz et al. (2017) and Iliadis et al. (2013) used dendrometric measurements of trees (height and diameter at breast height (DBH), NDT techniques (stress wave propagation and resistance to drilling (only Demertiz et al. (2017), and extracted cores with an increment borer for density measurement using X-ray densitometry.

The general objective of this research was to evaluate whether machine learning algorithms, using data obtained from standing trees (inventory and non-destructive inspections), provide adequate results in predicting wood basic density.

Materials and Methods

The sampling comprised 492 eucalyptus trees planted in the state of São Paulo, Brazil, aged between 3 and 7 years. In addition to the data collected in the conventional inventory of the partnering company (diameter at breast height, total height, and pycnometric penetration), data from ultrasonic wave propagation tests in the longitudinal and radial directions, drilling resistance, sclerometric impact, and sample retrieval with the Pressler probe were added (Figure 1). From each plot, 3 trees were chosen according to their DBH class and cut for determination of basic density in the laboratory of the partnering company. The data were compiled into a single database, containing the inventory results and additional tests, to which 5 machine learning algorithms were applied, selected with the aim of predicting basic density from the other variables, following a sequence of steps (Figure 2). The basic density of the trees that were not cut was estimated using a model adopted by the partnering company.



(a)



(b)



(c)



(d)

Figure 1 – Ultrasonic wave propagation test in the longitudinal direction (a), drilling resistance test (b), sclerometric impact test (c), and sample retrieval by Pressler probe (d).



Figure 2 – Sequence of steps performed during the modeling of machine learning algorithms.

The step of determining the training and testing sets is carried out so that the models are trained with different databases in each training round, increasing their generalization capacity and reducing the occurrence of overfitting. The normalization step is important so that dimensional differences in variables are not incorporated by the models. Some models work optimally with normalized data.

All data mining methods were set up according to Plas (2016) and McKinney (2012) regarding the configuration of hyperparameters. Individual adjustments were made, model by model, to avoid overfitting or overfitting. Overfitting occurs when a model fits the training data very well but is unable to predict new data. Underfitting occurs when the model cannot find relationships between the variables available in the training set and therefore the process is interrupted, even before confronting the test set. Since this is ongoing research, with data from a company, the code cannot be disclosed.

After the prediction step, each model was evaluated according to the following metrics: coefficient of determination (R^2), adjusted coefficient of determination (adjusted R^2), MAE (Mean Absolute Error), and RMSE (Root Mean Squared Error).

Results and Discussion

Some parameters do not have a normal distribution because skewness and/or kurtosis values are outside the expected range of -2 to 2 for this type of distribution (Table 1). For evaluations involving conventional parametric statistics, it would be necessary to attempt transformations. However, the algorithms used in this research do not require the sample distribution to be normal.

Table 1 – Mean values, standard deviation, coefficient of variation, skewness, and kurtosis of the parameters.

Parameters	Mean	Stand. Dev.	C.V.	Skewness	Kurtosis
DBH [cm]	13.86	3.4	24.53%	1.031	0.457
H [m]	21.71	5.18	23.86%	-1.048	-3.688
VL [m.s^{-1}]	4317.61	566.7	13.13%	-4.367	2.101
VR [m.s^{-1}]	1946.18	278.91	14.33%	1.849	10.786
SI [%]	26.51	5.95	22.44%	5.777	31.211
DR [%]	24.3	3.35	13.79%	-1.311	-0.498
BdSU [kg.m^{-3}]	441.9	32.24	7.3%	3.622	-3.341
BdV [kg.m^{-3}]	386.34	34.12	8.83%	3.063	-0.407
VITCC [m^3]	0.165	0.108	65.45%	9.664	4.362
VITCCR [m^3]	231.24	93.32	40.36%	-0.961	-5.416
IMATCC [$\text{m}^3/\text{ha.year}$]	46.28	8.66	18.71%	-3.551	-1.945

Note: DBH = diameter at breast height, H = height, VL = longitudinal ultrasonic pulse velocity, VR = radial ultrasonic pulse velocity, SI = sclerometric impact, DR = drilling resistance, BdSU = basic density provided by Suzano, BdV = basic density obtained by borer, VITCC = total volume with bark, VTCCR = total volume of the production unit, IMATCC = annual mean increment.

Considering the model fit metrics (R^2 , adjusted R^2) and prediction errors (RMSE), Random Forest was the model with the best results (Table 2).

Comparing the mean absolute errors (MAE) as a percentage of the mean basic density obtained from laboratory tests, values range from 1.85% to 4.38% (Table 2), indicating low estimation errors when compared to the coefficient of variation of basic density. This result suggests that the model adequately captures the data variability and provides accurate predictions relative to the dispersion of actual values.

Table 2 – Evaluation metrics of the assessed algorithms

Algorithm	MAE	RMSE	R ²	R ² adj
KNN (K-Nearest Neighbor)	14.9	20.39	0.55	0.53
Decision Tree	8.19	13.87	0.79	0.78
Random Forest	8.26	12.92	0.82	0.81
Gradient Boosting	9.01	13.66	0.79	0.79
Xtreme Gradient Boosting	9.12	14.14	0.78	0.77
SVM (Superior Vector Machine)	19.37	24.29	0.36	0.34
ANN (Artificial Neural Network)	18.3	22.82	0.44	0.42

In addition to the metrics, two graphs were generated for each model, one showing the dispersion of observed responses versus adjusted responses, and the other showing the dispersion of residuals (Figures 3a and 4b). It can be observed from the graph in Figure 3a that the points are concentrated around the 45° line, indicating a close proximity between the estimated and actual values. The analysis of data representation through a model can be considered adequate when the residuals are randomly distributed, i.e., they do not show a trend, and this behavior was observed in the calculations with the algorithm (Figure 3b).

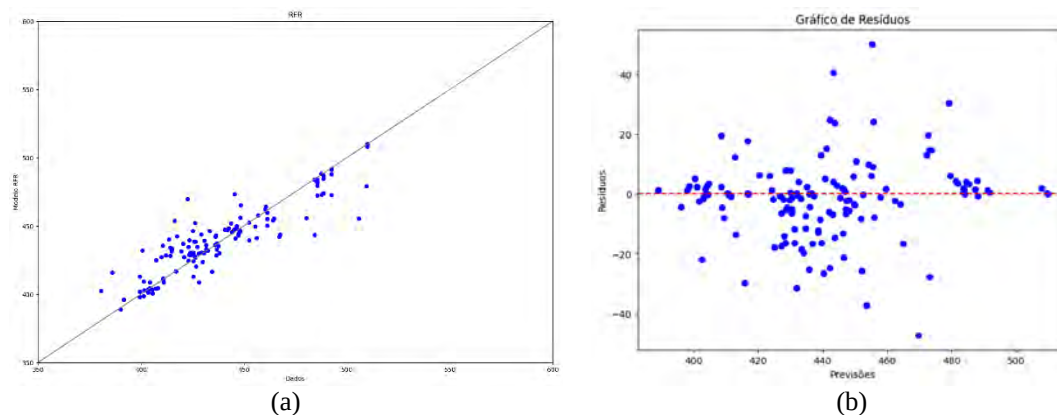


Figure 3 – Results predicted vs observed graph (a) and residuals graph (b) for the Random Forest algorithm.

Leite et al. (2016) obtained higher R² values than those obtained in this research (Table 1); however, they directly used the height (H) and diameter at breast height (DBH) variables in the model, which are autocorrelated, leading to multicollinearity effects in the models and overestimating the fits. Considering the importance of these variables, it is necessary to combine them into a new variable, such as H/DBH, to use them in the model.

For species different from those studied in this research (Douglas-fir, fir hybrids, acacias, and species from the Brazilian cerrado), with ages ranging from 32 to 50 years, and using different types of algorithms and architectures (ANN, CART, and SVM), literature reports R² values ranging from 0.50 to 0.80 (Demertzis et al., 2017; Iglesias et al., 2017; Iliadis et al., 2013; Silva et al., 2018), which are closer to those obtained in this research, with a range of 0.36 to 0.82 (Table 1).

Conclusions

Machine learning algorithms, applied to databases obtained from measurements taken on standing trees, allow for the creation of suitable models for inferring the wood basic density of the tree. However, for this tool to be effective, analyses should be based on a deep understanding of the technique and, whenever possible, on interpretation tools, as many of the algorithms are presented as black boxes.

Acknowledgments

We thank the pulp and paper company Suzano for the logistical support and supply of eucalyptus clones for this research, and the Laboratory of Nondestructive Testing – LabEND for the assistance with field and laboratory trials.

References

- Aragão, M. DE A.; Santos, J. S.; Da Silva, M. L. M. Técnica de mineração de dados aplicada a estimação de volume de árvores de eucalyptus. 5a Semana de Engenharia Florestal da Bahia. Anais...Vitória da Conquista: mar. 2018.
- Binoti, M. L. M. DA S. et al. Redes neurais artificiais para estimação do volume de árvores. Revista Árvore, v. 38, n. 2, p. 283–288, abr. 2014.
- Carrillo, I.; Valenzuela, S.; Elissetche, J. P. Comparative evaluation of Eucalyptus globulus and E. nitens wood and fibre quality. IAWA Journal, v. 38, n. 1, p. 105–116, 2017.
- Cordeiro, M. A. et al. Estimativa do volume de Acacia mangium utilizando técnicas de redes neurais artificiais e máquinas vetor de suporte. Pesquisa Florestal Brasileira, v. 35, n. 83, p. 255, 30 set. 2015.
- De Pádua, F. A. et al. Recommendation of non-destructive sampling method for density estimation of the Eucalyptus wood. Maderas: Ciencia y Tecnologia, v. 21, n. 4, 2019.
- Demertzis, K. et al. Machine learning use in predicting interior spruce wood density utilizing progeny test information. Neural Computing and Applications, v. 28, n. 3, p. 505–519, 1 mar. 2017.
- Downes, G. M. et al. Application of the IML Resistograph to the infield assessment of basic density in plantation eucalypts. Australian Forestry, v. 81, n. 3, p. 177–185, 3 jul. 2018.
- Fundova, I.; Funda, T.; Wu, H. X. Non-destructive wood density assessment of Scots pine (Pinus sylvestris L.) using Resistograph and Pilodyn. PLoS ONE, v. 13, n. 9, 1 set. 2018.
- Gendvilas, V. et al. Friction correction when predicting wood basic density using drilling resistance. Holzforschung, v. 75, n. 6, p. 508–516, 1 jun. 2021.
- Gonçalves, R. et al. Evolution of acoustical, geometrical, physical, and mechanical parameters from seedling to cutting age in Eucalyptus clones used in the pulp and paper industries in Brazil. Forest Products Journal, v. 69, n. 1, p. 5–16, 2019.
- Gonçalves, R. et al. Modeling of wood properties from parameters obtained in nursery seedlings. Canadian Journal of Forest Research, v. 48, n. 6, p. 621–628, 2018.

IGLESIAS, C. et al. Influence of heartwood on wood density and pulp properties explained by machine learning techniques. *Forests*, v. 8, n. 1, 1 jan. 2017.

Iliadis, L. et al. Predicting Douglas-fir wood density by artificial neural networks (ANN) based on progeny testing information. *Holzforschung*, v. 67, n. 7, p. 771–777, 1 out. 2013.

Kharrat, W. et al. Intra-ringwood density and dynamic modulus of elasticity profiles for black spruce and jack pine from X-ray densitometry and ultrasonic wave velocity measurement. *Forests*, v. 10, n. 7, 1 jul. 2019.

Leite, H. G. et al. Redes Neurais artificiais para a estimação da densidade básica da madeira. *Scientia Forestalis/Forest Sciences*, v. 44, n. 109, p. 149–154, 1 mar. 2016.

Lima, E. de S. et al. Classificação do desenvolvimento inicial do eucalipto utilizando técnicas de mineração de dados. *Cerne*, v. 23, n. 2, p. 201–208, 2017.

Liu, F. et al. Use of time-of-flight ultrasound to measure wave speed in poplar seedlings. *Forests*, v.10, n. 8, 2019.

Nickolas, H. et al. Application of resistance drilling to genetic studies of growth, wood basic density and bark thickness in *Eucalyptus globulus*. *Australian Forestry*, v. 83, n. 3, p. 172–179, 2 jul. 2020.

Plas, J. V. *Python Data Science Handbook*. 2016. Disponível em:
<<https://jakevdp.github.io/PythonDataScienceHandbook/>>.

McKinney, W. 2012. *Python for data analysis* (3rd. ed.). O'Reilly Media, Inc.

Sandoz, J. L. Standing Tree Quality Assessments Using Ultrasound. *Acta Horticulturae*, n. 496, p. 269–278, set. 1999.

Soriano, J.; Da Veiga, N. S.; Martins, I. Z. Wood density estimation using the sclerometric method. *European Journal of Wood and Wood Products*, v. 73, n. 6, p. 753–758, 1 nov. 2015.

Applicability of Using the Penetrograph as a High-Performance Tool for Wood Characterization

Fernanda Trislitz Perassolo Guedes *

Sylvamo do Brasil Ltda, Mogi Guaçu, São Paulo, Brazil, fernanda.guedes@sylvamo.com

Tania Cristina Castroviejo

Pd Instrumentos para Pesquisa e Desenvolvimento Ltda, Jarinu – SP, taniam@pdinstrumentos.com.br

* Corresponding author

Keywords: wood quality, wood variability, Eucalyptus wood

Abstract

Eucalyptus wood is a sustainable and economically relevant raw material. One of the factors that corroborates is planting of genetic materials suitable for the final product. This depends on a large quantity of materials with characterized wood, an expensive and complex process. In this context, the penetrometer emerges as an alternative tool with high potential as it makes it possible to obtain information in an uncomplicated and quick way about the stiffness of wood, a characteristic correlated with the basic density, one of the characteristics of greatest industrial interest. To evaluate the feasibility of using the penetrometer to characterize Eucalyptus wood, 450 trees from 3 clones were analyzed. The clones were planted in the same location and date, under the same fertilization and spacing pattern. Preliminarily, tests were carried out with different penetrometer configuration patterns. Then, perforations were made in the transverse direction of the trunk, parallel and perpendicular to the planting line, at a standardized height. The equipment configuration had a significant impact on the result, but with the appropriate configuration, the equipment showed precision and sensitivity in detecting variations in wood stiffness. Using only the average stiffness per tree, it was possible to detect a difference between the clones, but this difference became more evident when analyzing their variation pattern. With this analysis, differences were detected in the homogeneity of wood between clones and between trees of the same clone. It was also possible to verify that, with regard to wood stiffness, the clones respond differently to the aging of the cambium. The precision, sensitivity and speed in obtaining data using a penetrometer validate its application for large-scale phenotyping to select new clones and quickly better characterize the wood and thus differentiate and qualify clones for the industry.

Introduction

Wood is a versatile, renewable, and environmentally sustainable material with a wide range of utilization (Fundova et al. 2018). Wood properties is constantly evolving mainly influenced by tree growth, environmental factors and genetics modifying which directly affects its quality and, consequently, its performance according to its use (Vlad et al., 2022).

To determine the appropriate final use of wood from a particular tree species, it is first necessary to know its properties (Tomczak et al., 2022). The identification of a wood analysis method for screening large numbers of trees is highly important. In general, we distinguish between destructive methods, which interfere with the trunk structure, and non-destructive methods (Tomczak et al., 2022). Independent of the method, an important component of wood and fiber quality analysis, whether by non-destructive tool or traditional method, is the sampling efforts (Schimleck et al., 2019).

The traditional methods are very time-consuming and require a great deal of manual work, including large amount of each sample, weighing, drying and measuring the samples while non-destructive methods are robust, easy to use in the field, and rapidly provide data (measurement time in minutes) have emerged on the market in response to demand from the forestry sector (Schimleck et al., 2019). Non-destructive methods may be more effective and much faster, thanks to the use of advanced technologies (Tomczak et al., 2022). Owing to the wide range of non-destructive methods options available and reasons for forest sampling, it can be difficult to determine which approach to employ for a given project (Fundova et al. 2018). Studies carried out with different species provided evidences that the microdrilling device has a great deal of potential to assess standing-tree wood density (Tomczak et al., 2022).

The penetrograph is an alternative tool with high potential as it makes it possible to obtain information in an uncomplicated and quick way about the stiffness of wood, a characteristic correlated with the basic density, one of the characteristics of greatest industrial interest (Fundova et al. 2018). And studies carried out with different species provided evidences that the microdrilling device has a great deal of potential to assess standing-tree wood density (Tomczak et al., 2022; Vlad et al., 2022).

This tool measured the resistance of the drilled material based on the energy input when drilling at a constant speed (Tomczak et al., 2022). The device is drilled into a cross-section of a tree at any height, using a thin needle that is a few millimetres in diameter and (Tomczak et al., 2022). The resistance drill's results depend on many variables such as moisture content, rotation, speed, friction, angle of drilling and species (Tomczak et al., 2022).

In this context, this work aims to analyze the potential of a microdrill device for characterizing wood in terms of resistance to microdrilling with the potential for ranking different clones based on this characteristic.

Materials and Methods

The study was conducted in commercial clonal plantations of a paper industry company, planted in the same location, on the same date under identical planting and forest management conditions. Three clones were selected, each classified within a known range of wood density, ranging between 510 and 380kg/m³. Within this range, clones A, B and C are classified by the company respectively as being of high, medium and low density.

For each clone, 150 trees without phytosanitary or other issues such as leaning or excessive curvature were analyzed. To collect the data, an IML-RESI PowerDrill device was used. Tests were conducted with different advice configuration settings. Subsequently, perforations were made in the transverse direction of the trunk, both parallel and perpendicular to the planting line, at a standardized height.

Preliminarily, tests were conducted on 5 trees from each of the 3 clones with different drill rotation speeds and penetration velocities to determine the optimal configuration.

Measurements were taken over a 3-day interval in August when climatic conditions are most stable, with insignificant temperature and humidity variations in the region where the plantations are located.

The data were processed to eliminate records not related to the material, such as those generated by the start of data recording before contacting the trunk, after passing through the trunk, or due to friction with sawdust generated during drilling.

Basic statistical descriptors (average, variance, standard deviation) were used to identify the difference between clones and different configurations of the advice.

Results and Discussions

The IML-Resi PowerDrill device allows adjustments to be made in penetration speed and drill rotation. These adjustments affect the range of resistance since it is the result of the equipment's effort to maintain the speed and rotation of the drill determined at the beginning of the perforation. Thus, the lower the effort, the smaller the range. The first result of the test was that among the different possible combinations of

adjustment between penetration speed and drill rotation, only 7 of several tests could be used, and most of the tested combinations could not be equally applied to all clones because they required very low drill effort to the point where the range data were very close to zero, or because they generated an overload on the equipment. These 7 combinations that were successfully applied to all 3 clones are presented in Figure 1 and were called C1, C2, C3, C4, C5, C6, and C7.

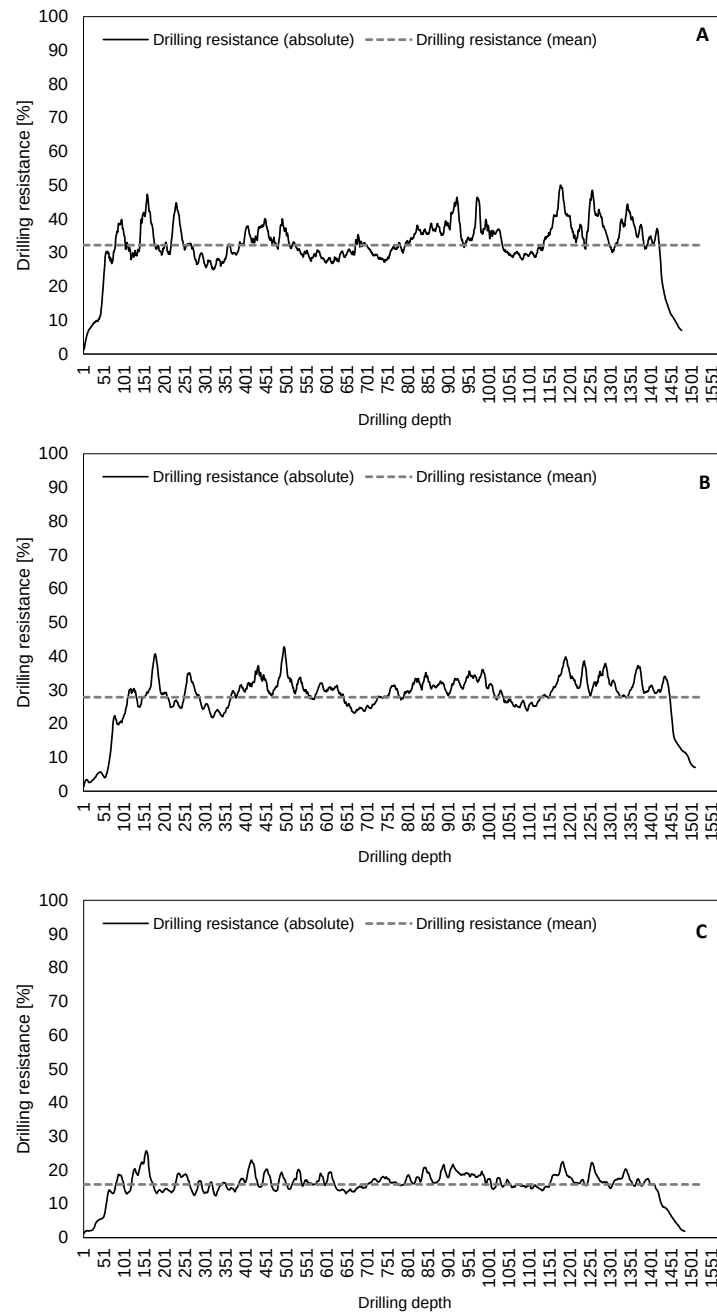


Figure 1 – Drilling resistance profile for the 3 different clones analyzed with different penetration speed and drill rotation settings. 1A – Clone A, configuration C1; 1B – Clone A, configuration C2; 1C - Clone A, C3 configuration; 1D - Clone b, configuration C1; 1E - Clone B, C4 configuration; 1F - Clone B, C5 configuration; 1G - Clone C, C1 configuration; 1H - Clone C, configuration C6; 1I - Clone C, configuration C7.

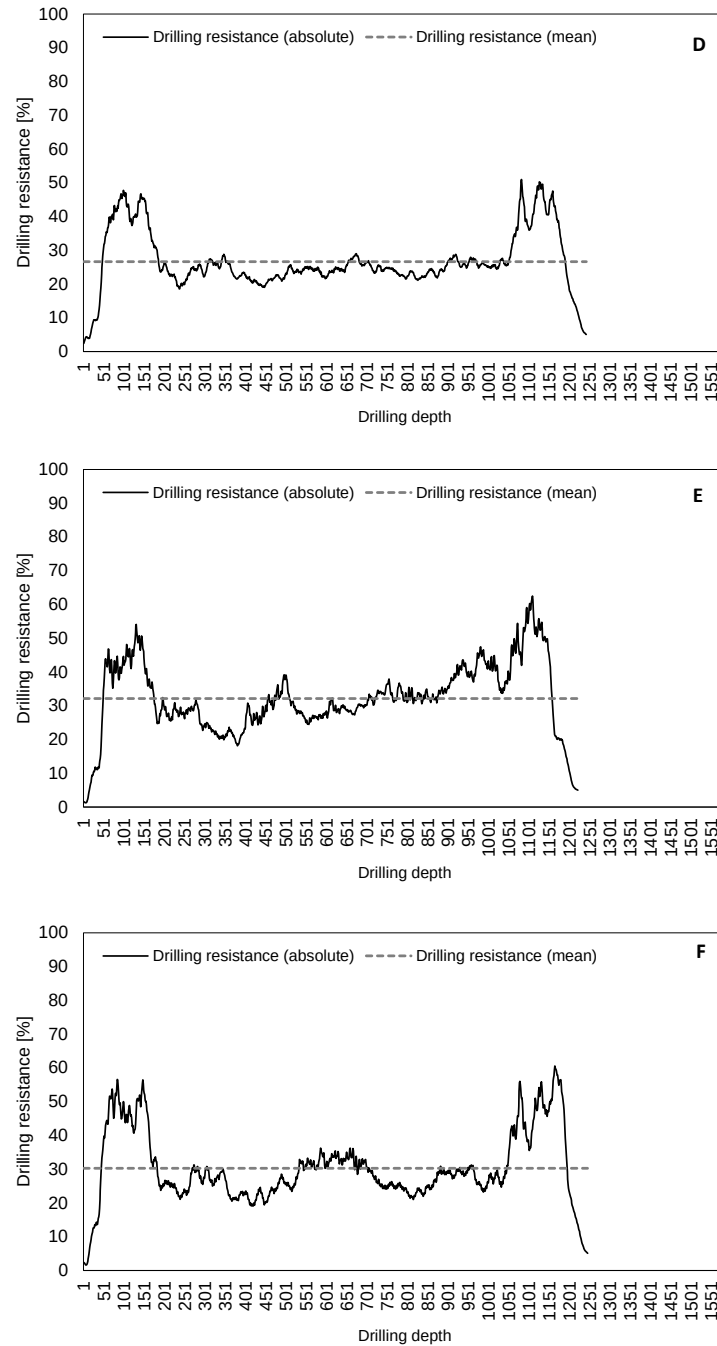


Figure 1 – cont.

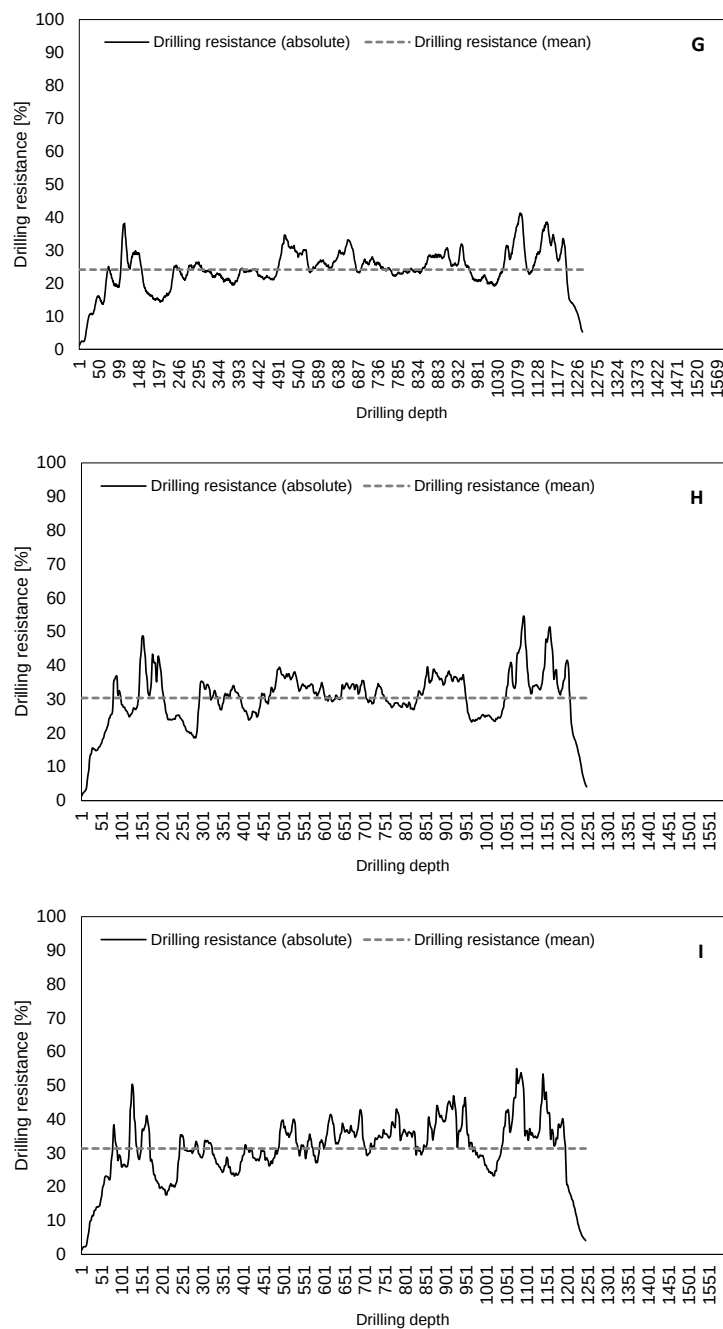


Figure 1 – cont.

However, despite the profiles maintaining a standard format for each clone, we observed that the values vary depending on the clone analyzed and the adjustment of penetration speed and drill rotation. These changes in amplitude values become evident when comparing the absolute values of the profiles with the mean, and we can observe the shift in the position of the mean. These alterations could be captured with simple statistical parameters (Table 1).

Table 1 – The general statistical parameters for drilling resistance (%)

Statistic parameters	Clone A			Clone B			Clone C		
	C1	C2	C3	C1	C4	C5	C1	C6	C7
Average	14.6	24.7	32.3	26.0	28.6	28.9	22.5	29.5	28.5
Variance	25.8	78.3	103.9	118.0	155.9	167.4	76.1	146.7	128.5
Standard deviation	5.1	8.8	10.1	10.8	12.5	12.9	8.7	12.1	11.3

Observing the results, we have 2 different configurations that yielded the same outcome for different clones: C4 for clone B and configuration C7 for clone C, with amplitude averages of 28.6 and 28.5, respectively. This result clearly highlights the importance of selecting the adjustment of penetration speed and drill rotation for ensuring comparable results when the objective is the ranking of clones based on micro-drilling resistance.

Among the configurations tested, configuration C1 was set as the standard for evaluating all selected trees, and it is the average of the results of these measurements that is presented for this specific configuration. When the clones were compared based on the results generated by the equipment with the standard configuration, we noticed that the average amplitude is capable of differentiating the three clones, despite the density amplitude being only 130 kg/m³, which also highlights the equipment's sensitivity to this type of wood characteristic.

Although the average amplitude of micro-drilling resistance is an interesting parameter for differentiating clones, when we analyze the profiles, we notice that the clones have very characteristic patterns of variation in drilling resistance, which possibly reflect other anatomical and chemical composition peculiarities of the wood cell wall. Clone A exhibits a more stable resistance pattern across the diameter, which may reflect greater wood homogeneity for other characteristics as well. Clones B and C show an increase in micro-drilling resistance closer to the bark, with resistance more pronounced in clone B. In addition to the resistance profile pattern, the standard deviation corroborates with the observations.

Conclusions

IML-Resi PowerDrill device has a great deal of potential to assess standing-tree wood resistance to microdrill, and as some studies presented evidence that it is highly correlated with wood density, it has also a great potential to assess standing-tree wood density, especially when a significant quantity of samples needs to be analyzed in a specific project. One of the advantages of these types of methods is the reduction in data acquisition time and the obtaining of information in a more agile manner, with less need for data processing.

Acknowledgements

We thank Sylvamo do Brasil Ltda and Pd Instrumentos para Pesquisa e Desenvolvimento Ltda for all the support.

References

- Funova, I.; Funda, T.; Wu, H. X. 2018. Non-destructive wood density assessment of Scots pine (*Pinus sylvestris* L.) using Resistograph and Pilodyn. PlosOne [13] (9)
- Schimleck, L.; Dahlen, J.; Apiolaza, L. A.; Downes, G.; Emms, G.; Moore, J.; Pâques, L.; Bulcke, J. V., Wang, X. 2019. Non-Destructive Evaluation Techniques and What They Tell Us about Wood Property Variation. [10]: 728
- Tomczak, K.; Tomczak, A.; Jelonek, T. 2022. Measuring Radial Variation in Basic Density of Pendulate Oak: Comparing Increment Core Samples with the IML Power Drill. Forests. [13]: 589.
- Vlad, R.; Pei, G.; Sidor, C. G.; Cuciurean, C.; Ispranavic, A. and Stefan, G. 2022. Assessing Standing-Tree Wood Density by Microdrilling in Tending Forestry Work Carried Out on Norway Spruce (*Picea abies* (L.) H. Karst) Stands. Forests. [13]: 1450

Exploring Hoop Pine (*Araucaria cunninghamii*) Wood Properties

Vilius Gendvilas *

Forest Research Institute, University of the Sunshine Coast, Sippy Downs, Queensland, Australia, vgendvilas@usc.edu.au

David Lee

Forest Research Institute, University of the Sunshine Coast, Sippy Downs, Queensland, Australia, dlee@usc.edu.au

Dominic Kain

HQPlantations, Toolara Forest, Gympie, Queensland, Australia, dominic.kain@hqplantations.com.au

Geoff Downes

Forest Quality Pty Ltd., Franklin, Tasmania, Australia, geoff.downes@forestquality.com

Chandan Kumar

Queensland Government Department of Agriculture and Fisheries, Forest Products Innovation, Salisbury Research Facility, Salisbury, Queensland, Australia, chandan.kumar@daf.qld.gov.au

* Corresponding author

Abstract

Hoop pine (*Araucaria cunninghamii* (Mudie)) stands out as one of the few endemic rainforest species that has been successfully domesticated for timber production, with over 44,300 hectares of plantations in Queensland, Australia. Hoop pine trees thrive across various sites characterized by differing environmental conditions such as latitude, precipitation, temperature, and elevation. In this study, two separate thinning trials were assessed, each consisting of five stocking treatments (100, 200, 300, 500, and 750 trees per hectare), on stands aged 31 to 35 years (mid-rotation). The drilling resistance (IML-RESI PD 500) method was used for the assessment of standing tree basic density, including the variation in radial basic density. The lower stocking treatments had an increase in tree size; however, there was only a minor change in basic density relative to the higher stocking treatments. This implies that trees can be grown at a faster rate without compromising wood quality. In addition to the thinning trials, assessments were carried out across ten sites within the estate of harvest-aged hoop pine trees ranging from 51 to 63 years old. These sites were categorized into three classes (i) wetter, (ii) drier, and (iii) dry, colder sites at higher elevations. Significant variations in basic density were observed across the classes, with distinct radial basic density trends being identified. These findings offer valuable insights for hoop pine growers regarding their resources based on wood quality. Furthermore, when compared to younger trees in thinning trials, the older trees exhibited only slightly higher basic density and tree size. This suggests that the rotation of hoop pine could potentially be shortened without sacrificing growth and wood quality.

Keywords: resistance drilling, *Araucaria cunninghamii*, thinning, basic density, mid-rotation and mature stands, site effects.

Session 3

**Nondestructive
Evaluation of
Engineered Wood
Products**

Nondestructive Testing of Mechanical Properties of Reinforced Oak Wood Elements by Carbon and Glass Fibres Composite

Andrija Novosel*

University of Zagreb, Faculty of Forestry and Wood Technology, Svetošimunska 23, HR 10000 Zagreb, Croatia, anovosel@sumfak.unizg.hr

Luka Lučić

University of Zagreb, Faculty of Forestry and Wood Technology, Svetošimunska 23, HR 10000 Zagreb, Croatia, lucic007@gmail.com

Dean Čizmar

University of Applied Science, Department of Civil Engineering, Av.Većeslava Holjevca 15, HR 10000 Zagreb, Croatia, deancizmar@gmail.com

Tomislav Sedlar

University of Zagreb, Faculty of Forestry and Wood Technology, Svetošimunska 23, HR 10000 Zagreb, Croatia, tsedlar@sumfak.unizg.hr

Hrvoje Turkulin

University of Zagreb, Faculty of Forestry and Wood Technology, Svetošimunska 23, HR 10000 Zagreb, Croatia, hturkulin@sumfak.unizg.hr

Vjekoslav Živković

University of Zagreb, Faculty of Forestry and Wood Technology, Svetošimunska 23, HR 10000 Zagreb, Croatia, vzivkovic@sumfak.unizg.hr

* Corresponding author

Abstract

Using natural fibre as reinforcements may significantly improve the mechanical properties of wood-based building elements. A study of the effect of reinforcements made of carbon fibre-reinforced polymer (CFRP) and glass fibre-reinforced polymer (GFRP), glued with two different commercial adhesives, to oak-wood model beams laminated in two directions, was performed to improve stiffness in the elastic region and bending strength. Fibres were introduced in the model beams' tensile and compression zones, glued with epoxy resin and polyurethane adhesives. As oak wood is more challenging for gluing than softwoods, which are dominantly used for laminations, the suitability of different types of adhesives was analysed. Carbon and glass fibres producers recommend the usage of epoxy in combination with wood. Conversely, PUR adhesives have been most commonly used for glulam for nearly two decades. They have been standardized (according to EN 15425 and related standards), but their ability to be combined with GFRP or CFRP is still not fully proven. CFRP and GFRP were glued into the laminated beams with epoxy resin (ER) and polyurethane adhesives (PUR) and subjected to testing. Displacements and deformations were tested in elastic region using DIC method and four-point bending with aim to select the optimum combination of reinforcement and adhesive. The average load in elastic region for the samples glued with PUR adhesives are comparable to those glued with epoxy resin (up to 5 % lower). On the other hand, implants glued with PUR adhesives exhibit a displacement reduction of up to 5%. Slightly lower mechanical properties of the beams laminated with polyurethane (PUR) adhesive, on one side, and very challenging utilization of epoxy adhesive in industrial conditions on the other side set PUR as an adequate alternative for bonding wood to CFRP and GFRP reinforcements.

Keywords: Laminated timber, oak–wood, four-point bending, reinforced polymer, DIC

In-Field Inspection of Wooden Utility Poles Using Nondestructive Technology—Study Cases for Softwood and Hardwood

Yann Benoit*

Technology & Services, CBT SA, Saint-Sulpice, Switzerland, benoit@cbs-cbt.com

Jean-Daniel Gasser

IT, CBT SA, Saint-Sulpice, Switzerland, gasser@cbs-cbt.com

Jean-Luc Sandoz

CBS, Choisy-le-Roi, France, sandoz@cbs-cbt.com

* Corresponding author

Abstract

The companies managing overhead networks in the fields of telecommunications or electricity are striving to reduce the costs of pole replacement while ensuring a high level of safety for their lines. Even though many countries, especially in Europe, are investing in underground networks, overhead lines still exist, and wooden poles are a preferred component due to their high mechanical performance and durability.

Several million wooden poles are still in use, but their expertise is delicate compared to that of steel, concrete, or composite poles, for which a simple visual inspection is generally sufficient. To assist network managers, CBT SA, in collaboration with the Swiss Federal Institute of Lausanne (EPFL) in Switzerland, developed a non-destructive measurement device to assess the remaining condition of wooden poles—the Polux device (early 1990s).

In 2020, CBT SA launched the latest generation of the device, Polux 5: more compact, lighter, and much easier to use. Polux 5 has become the market standard and is used on all five continents to provide a reliability diagnosis for wooden poles, whether softwood or hardwood.

This article introduces the Polux 5 device, its measurement sensors, and its results in different configurations. It demonstrates how wooden poles can remain a preferred component in overhead line networks, allowing managers to control maintenance objectively and ensure optimal safety while saving costs.

Keywords: wood-poles, nondestructive assessment, overhead lines, asset management

Case Study: Classification of the Modulus of Elasticity of Wood Obtained through Non-Destructive Testing for the Manufacture of Glued Laminated Timber (GLT) Beams with the Aim of Meeting Structural Requirements of an Executed Structure

Melissa Lago de Jesus S. Silva*

Rewood, Taboão da Serra, São Paulo, Brazil, melissa.eng@rewood.com.br

Carlito Calil Neto

Rewood, Taboão da Serra, São Paulo, Brazil, calil@rewood.com.br

* Corresponding author

Abstract

Glued Laminated Timber (glulam) is an engineered product capable of enabling the use of rapidly growing plantation woods, as its production process allows for the selection of pieces to position lamellae according to their mechanical classification. For this purpose, non-destructive testing methods are used to obtain the mechanical characterization of the piece before its manufacture. Through the structural design specified in the project, it is possible to produce pieces with the same cross-sectional area but with different mechanical resistance capacities by evaluating the modulus of elasticity non-destructively and the visual classification. The objective of this work was to demonstrate the method of classification of the modulus of elasticity through non-destructive testing applied to a case executed using the MTG equipment, ensuring not only larger spans with greater slenderness but also enabling the project in terms of architectural configuration and optimizing costs. It can be concluded that the non-destructive classification method for qualifying pieces ensures physical and mechanical characterization in their use, as well as enabling the use of reforestation woods and allowing the material to be utilized to its fullest potential.

Keywords: glulam, MOE, mechanical classification

Introduction

Laminated glued timber (GLT) results from the gluing of lamellas with the grain direction parallel to the longitudinal axis of the final piece through an industrialized process. The conception of LGT provides a highly effective utilization of raw materials, and it can be manufactured in various shapes, sizes, and configurations (Sandak et al. 2021).

Products derived from mass timber, such as glued laminated timber (GLT), can have most of their important mechanical properties estimated through analytical and numerical models to be subsequently used in the structural design process. Such characteristics require a considerable degree of accuracy to be utilized in project execution, as an inadequate classification system can result in significant variation in the mechanical properties of the final product (Derikvand et al. 2019).

According to Sandak et al. (2021), the manufacturing of GLT follows rules indicated in national or European codes that have predefined strength classes. The appropriate class is defined by the strength of the wood to be used, as well as its position within the cross-section. The results of the strength and stiffness values of the strength classes are determined according to the current standard.

The assignment of mechanical properties to wood is extremely important for its use as a structural material, obtained through visual or mechanical classification, which must be carried out according to standards (Moltini et al., 2022). The Brazilian standard NBR 7190 (ABNT, 2022) guides that the lamellas must be classified into strength classes through visual and mechanical classification based on the modulus of elasticity. This process results in data that will characterize and evaluate the lamella for the sizing of the piece.

Thus, based on the lamella classification, it is possible to select pieces that are suitable for the demands and load capacity required by the structural design. Therefore, the lamella is positioned according to its visual and mechanical classification, making it possible to produce pieces with the same cross-section but different mechanical resistance capacities.

Therefore, the aim of this study was to demonstrate the method of classifying the modulus of elasticity through non-destructive testing applied to a case carried out by Rewood - Engineered wood structural solutions, ensuring not only larger spans with greater slenderness but also making the project viable in terms of architectural configuration and optimizing costs.

Materials and Methods

The case study (Figure 1) is in Angra dos Reis - RJ. The architectural project was designed by Jacobsen Arquitetura. With a projected area of 1160 m², the development features 110 m³ of GLT, which was designed, manufactured, and executed by the company Rewood. The type of wood used was pine, with an average density of 550 kg/m³.



Figure 1 - Case of study. Source: Jacobsen Arquitetura (2024).

Rewood is responsible for the project (Figure 2), fabrication, and assembly of engineered wood structures. In the architectural project conception process, the company seeks to guide development with the aim of optimizing the material and its appropriate use.

Among the services offered are pre-sale consulting, structural analysis, product planning, production, logistics, transportation, assembly, installation, warranty, and post-installation support throughout Brazil.

Each project undergoes a specific logistics analysis, as the entire process of material arrival at the destination is monitored and ensured.

In this case study, logistics were complex to enable the arrival of the material on the island of Angra dos Reis. The entire process began to be analyzed from the project stage, mainly due to the presence of long pieces.

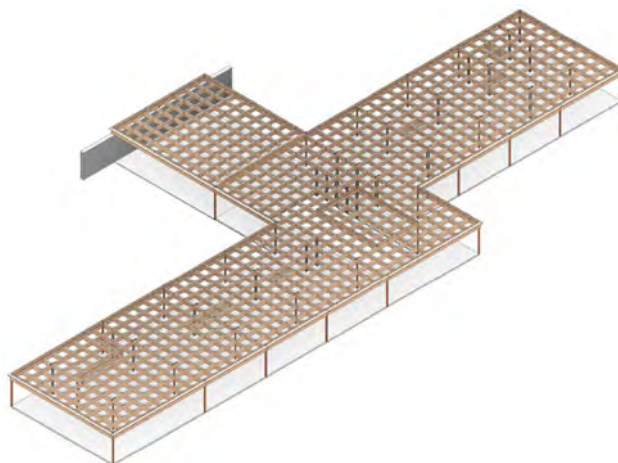


Figure 2 – Case of study. Source: Rewood (2021).

The structural solution was designed to accommodate modular spans of 7500 mm and a maximum span of 12560 mm, ensuring that the cross-section remained consistent for all beams. Such a condition would not be possible without the classification of the wood, necessitating a larger volume with larger sections to accommodate the longer spans. The project consisted of primary, secondary, and tertiary beams, joists, and stringers in LVL, as well as metal columns.

To maintain the cross-section and already knowing which pieces would be most requested, a selection and visual classification were carried out, along with the elasticity module, in order to map the material for manufacturing, meeting the physical and mechanical characteristics required by the project. For this purpose, the Timber-Grader (MTG) (Figure 3) was used, which is an ergonomic measuring instrument with an LCD display that is placed against the wooden piece. When the trigger button is pressed, a sound wave is sent through the beam in the longitudinal direction of the piece. The Stress Wave Detector receives this reflected impulse and sends it wirelessly to a computer. Therefore, the Timber Grader software converts the sound waves into measurement results.



Figure 3 – Timber Grader MTG.

The design of each structural element was carried out according to the guidelines of NBR 7190 (ABNT, 2022), which describes that the modulus of elasticity should be considered as a reference for the

composition process of the pieces, so that the classification should group an upper subplot that is above the representative average (E_m) of the species used, as well as a lower subplot with boards below this average.

Therefore, the lamellas belonging to the upper subplot must be allocated to compose the outermost quarters away from the neutral axis of the GLT piece, while those from the lower subplot must be part of the composition of the central half of the cross-section of this piece.

Figure 4 illustrates the combination of lamellas based on the modulus of elasticity.

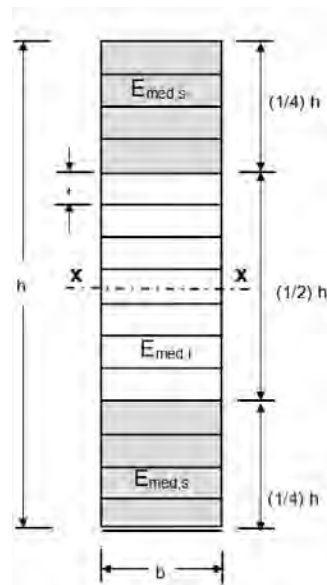


Figure 4 - Cross-section with the combination of lamellas with different modulus of elasticity.
Source: (ABNT NBR 7190, 2022)

Thus, the flexural stiffness was calculated using the transformed section method, considering the modulus of elasticity of each lamella composing the GLT piece, as the piece was made from a combination of lamellas with higher modulus of elasticity values used in the lower part of the beam (Class A). Since Rewood performed the classification and assembly, it was possible to control the position of each lamella, with 25% of the lamellas with above-average modulus positioned in the lower part of the beam.

The wood batch used for manufacturing was 130 m³, consisting of pieces measuring 150 mm x 50 mm x 3000 mm, totaling 5778 pieces, with a utilization rate of 85%, resulting in 110 m³ of glued laminated timber. The laminates were classified into Classes A, B, and C, with Class A lamellas placed in the lower fourth, Class B in the upper fourth, and Class C in the central half of the cross-section.

Results and Discussion

From the characterization and classification of the lamellas, the structural pieces were dimensioned and produced following a cross-section of 120 mm x 450 mm for all primary beams, enabling the spanning of a clear span of 12560 mm to meet the architectural purpose, which did not allow for pillars, while also meeting the requested physical and mechanical characteristics.

Thus, out of the batch of 110 m³ of glued laminated timber produced, 27.5% consisted of lamellas with superior modulus of elasticity (Class A), positioned in the lower part of the beam (112.5 mm), as illustrated in Figure 5.

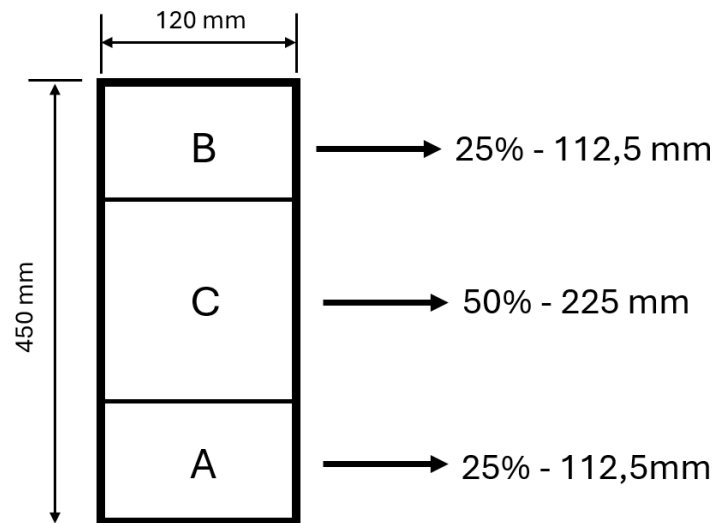


Figure 4 – Illustration of the distribution of lamellas according to the height of the cross-section.

In the conducted classification, the maximum value found for the modulus of elasticity was 16353 MPa and the minimum value was 7546 MPa. The normal distribution curve (Figure 6) represents the distribution of the values found in a sample, correlating with the classifications of the wood - Classes A, B, and C.

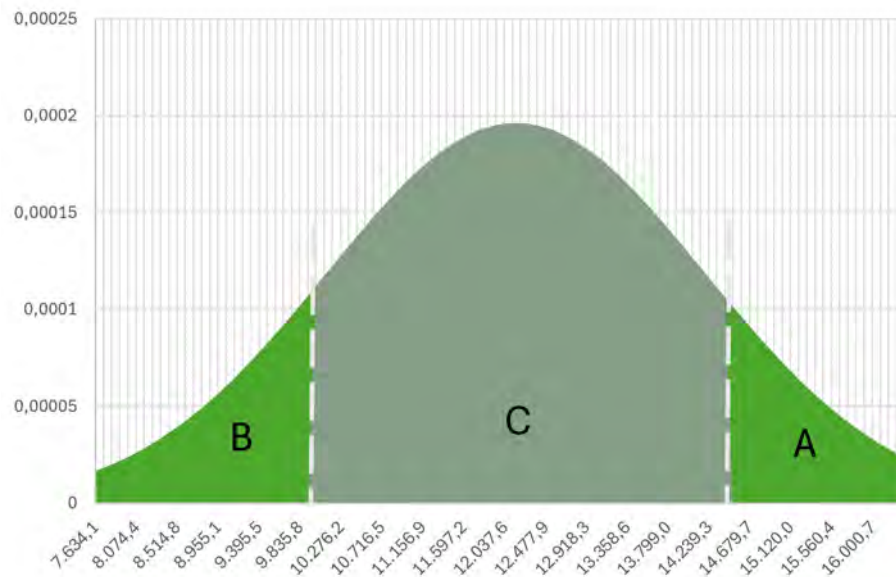


Figure 5 – Normal distribution of the modulus of elasticity.

Figure 7 depicts the assembly sequence of the structure, starting with the installation of the metal pillars, followed by the assembly of the main (primary) beams. Subsequently, the secondary beams were assembled, followed by the joists, tertiary beams, and stringers.

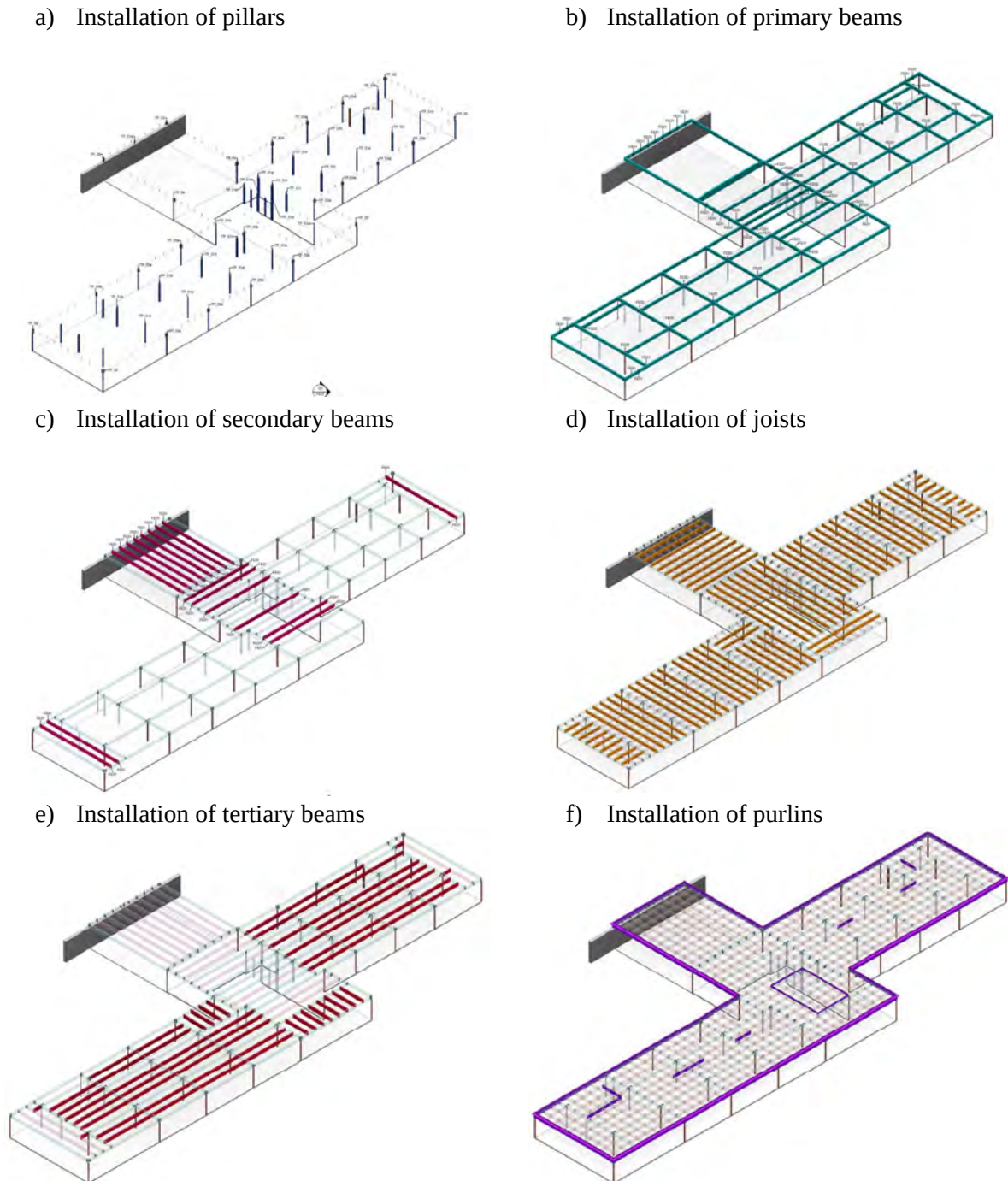


Figura 6 – Assembly sequence.

Establishing the same section for all beams in the project to accommodate different spans was only possible through the mechanical classification of lamellas based on modulus of elasticity and visual classification. In a scenario without prior classification, it would not be possible to meet the requirement of larger spans with the same section and cubic meterage. Thus, it was possible to use wood rationally, adapting and integrating its properties into the proposed use, with the classification enabling structural spans by simply changing the way of working with wood. Therefore, the importance of engineering wood can be understood, not only rationalizing, and optimizing the use of the material but also catering to various architectural configurations. Furthermore, the financial relevance of engineered wood is justified.

Figure 8 presents the floor plan of the main beams, illustrating the modulation ranging from 7000 mm to 12560 mm. All beams had the same section, as did the joists.

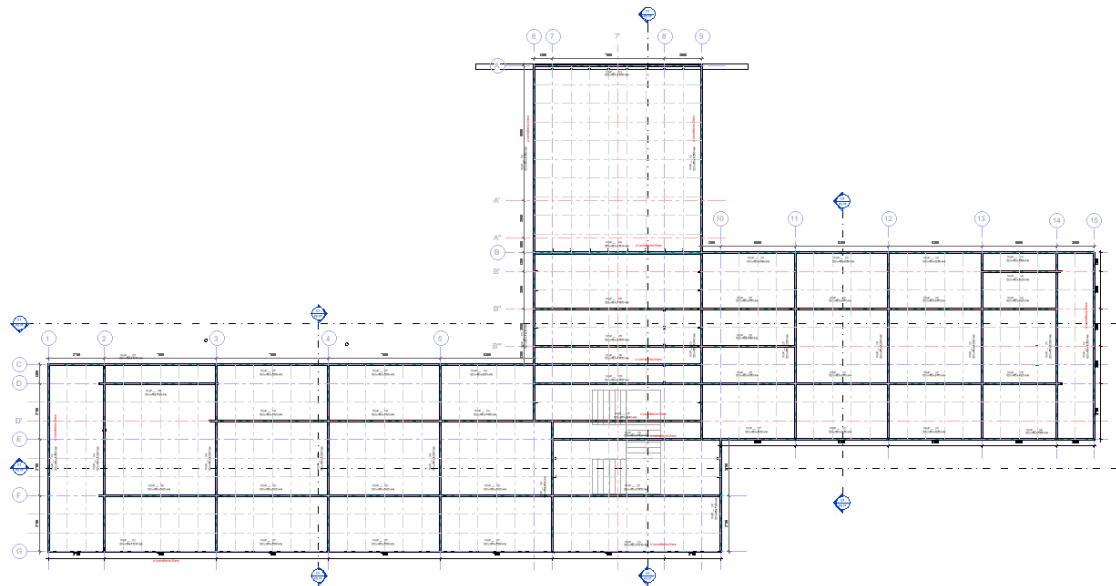


Figure 7 – Floor plan of the main (primary) beams.

Figures 9, 10, and 11 below present the executed project.

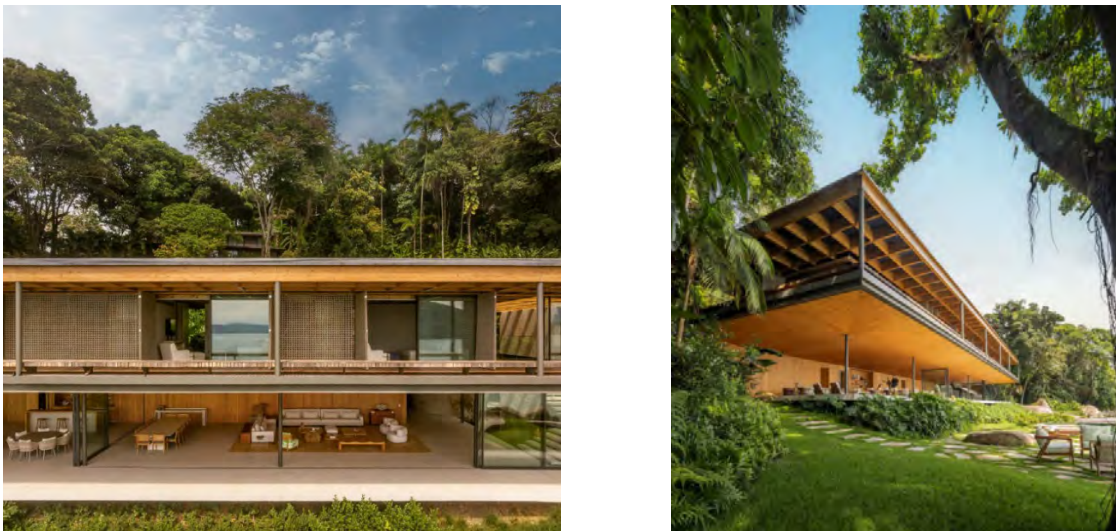


Figure 8 – Project executed. Source: Jacobsen Arquitetura (2024)

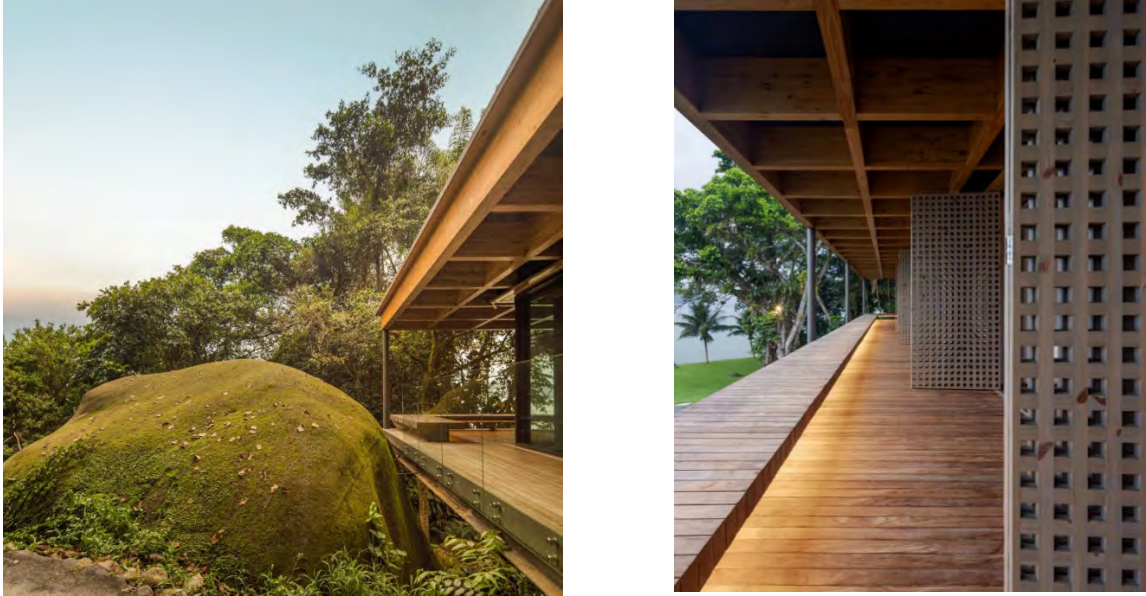


Figure 9 – Project executed. Source: Jacobsen Arquitetura (2024)

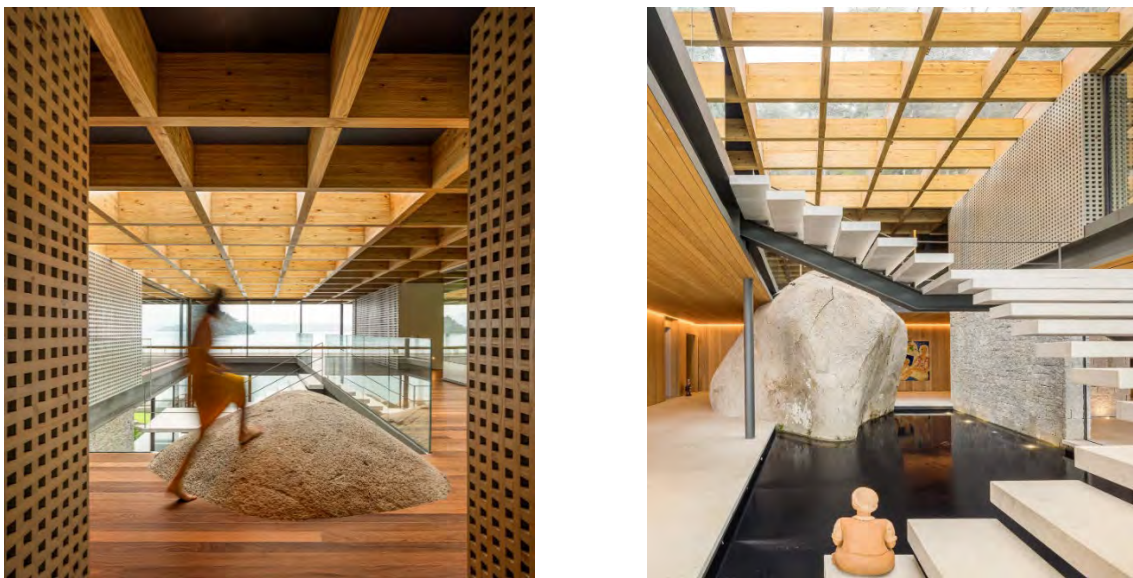


Figure 10 – Project executed. Source: Jacobsen Arquitetura (2024)

Conclusions

Glued laminated timber (GLT) enables structural barriers to be created to meet architectural demands that require larger clear spans while maintaining the cross-section throughout the project. It is possible to optimize the design of structural elements through non-destructive classification methods to categorize and map the pieces based on modulus of elasticity. Through the case study, it was possible to apply these concepts to ensure the physical and mechanical characteristics of the material in its use, enabling the use of reforested woods and allowing the material to be utilized to its full potential. It can be concluded that when properly classified, wood meets specific structural requirements without altering the cubic meterage, only adapting the manufacturing process, and optimizing usage through its properties. This process enables engineered wood to overcome technical barriers while also making the product financially viable.

References

Brazilian Association of Technical Standards. NBR 7190-1: Design of timber structures - Part 1: Design criteria. 1st ed. Rio de Janeiro: ABNT, 2022. 81 p.

Brazilian Association of Technical Standards. NBR 7190-2: NBR7190-2: Design of timber structures - Part 2: Test methods for visual and mechanical classification of timber structural elements. 1st ed. Rio de Janeiro: ABNT, 2022. 15 p.

Derikvand, Mohammad; Kotlarewski, Nathan; Lee, Michael; Jiao, Hui; Chan, Andrew; Nolan, Gregory. 2019. Short-term and long-term bending properties of nail-laminated timber constructed of fast-grown plantation eucalypt. *Construction and Building Materials*. v. 211, p. 952-964. Elsevier BV. <http://dx.doi.org/10.1016/j.conbuildmat.2019.03.305>.

Hänsel, Andreas; Sandak, Jakub; Sandak, Anna; Mai, Juana; Niemz, Peter. 2021. Selected previous findings on the factors influencing the gluing quality of solid wood products in timber construction and possible developments: a review. *Wood Material Science & Engineering*. v. 17, n. 3, p. 230-241. Informa UK Limited. <http://dx.doi.org/10.1080/17480272.2021.1925963>.

Jacobsen Arquitetura. **AEA HOUSE**. Disponível em: https://jacobsenarquitetura.com/en/projects/aea-house/?fbclid=PAaAbzhmUh9r7pXh9-sfrSoKOn9hqx7MTVYxWkoquW0GrDw-ROMnMNC6UMI0_aem_AbpLZIYwkh6WXqBLd9XztIjjD22Q7w-tzmGe-Zg-1y5QyPgLe3qq7wjDXfR1HQFAX9Y. Acesso em: 20 abr. 2024.

Moltini, Gonzalo; Íñiguez-González, Guillermo; Cabrera, Gonzalo; Baño, Vanesa. 2022. Evaluation of Yield Improvements in Machine vs. Visual Strength Grading for Softwood Species. *Forests*. v. 13, n. 12, MDPI AG. <http://dx.doi.org/10.3390/f13122021>.

Sandak, Jakub; Niemz, Peter; Hänsel, Andreas; Mai, Juana; Sandak, Anna. 2021. Feasibility of portable NIR spectrometer for quality assurance in glue-laminated timber production. *Construction and Building Materials*. v. 308. Elsevier BV. <http://dx.doi.org/10.1016/j.conbuildmat.2021.125026>.

Influence of Finger Joints on the Propagation of Acoustic Waves

Maria Portela Barral

Structural Wood Engineering Platform (PEMADE), University of Santiago of Compostela (USC), Lugo, Lugo, Spain, maria.portela.barral@usc.es.

Mônica Ruy *

Structural Wood Engineering Platform (PEMADE), University of Santiago of Compostela (USC), Lugo, Lugo, Spain, m.ruy@usc.es.

Manuel Guaita Fernandez

Structural Wood Engineering Platform (PEMADE), University of Santiago of Compostela (USC), Lugo, Lugo, Spain, m.guaita@usc.es.

Raquel Gonçalves

College of Agricultural Engineering (FEAGRI), Laboratory of Nondestructive Testing (LabEND), University of Campinas (UNICAMP), Campinas, São Paulo, Brazil, raquelg@g.unicamp.br.

* Corresponding author

Abstract

Finger joints are usually used to join pieces of wood to produce large structural pieces. Nondestructive techniques are increasingly used for the mechanical classification of wood, for direct use, or to compose engineered products. Generally, this classification is carried out on solid material before industrial processes that can cut and join pieces of different origins and characteristics. Therefore, this work aimed to evaluate whether finger joints influence wave propagation and whether this influence differs depending on the technique used to classify the wood. The measurements were carried out on *Quercus robur* beams from natural forests. The pieces were previously visually evaluated to avoid the presence of singularities that could affect the results. Nondestructive tests were carried out on each origin beam using three techniques (stress wave, ultrasound, and vibration). Then, the pieces were cut and joined with finger joints, and the nondestructive tests were performed again. For the wave propagation tests (ultrasound and stress wave), the velocity and stiffness coefficient values were numerically lower in the original (solid) pieces than in the pieces with finger joints. In contrast, an opposite behavior was found for the vibration technique. In the case of wave propagation (ultrasound and stress wave), the propagation passes through the adhesive, which has a higher velocity than the wood, explaining the behavior obtained. In the case of vibration, the connection constitutes a weakness, reducing velocity. Despite the statistical difference in behavior between the results obtained with the ultrasound and vibration tests, the regression analysis indicates significant correlations ($R^2 > 0.98$) between them. Furthermore, for both tests, there were significant differences between results on solid pieces and those with joints, indicating sensitivity to be used to classify the pieces. On the other hand, stress wave propagation tests did not result in significant differences between solid pieces and those with joints.

Keywords: finger joints, wood classification, engineered products

Evaluating Ultrasound as a Method for Estimating the Static Modulus of Elasticity and Strength of *Apuleia leiocarpa*

Suelem Maurício Fontes Macena

School of Architecture and Urbanism, University of Sao Paulo, São Paulo, São Paulo, Brazil,

suelemmacena@usp.br

Institute for Technological Research of the State of Sao Paulo, São Paulo, São Paulo, Brazil,

sumacena@ipt.br

Fabiana Lopes de Oliveira

School of Architecture and Urbanism, University of Sao Paulo, São Paulo, São Paulo, Brazil,

floliveira@usp.br

Takashi Yojo

Institute for Technological Research of the State of Sao Paulo, São Paulo, São Paulo, Brazil, yojos@ipt.br

Cassiano Oliveira de Souza

Institute for Technological Research of the State of Sao Paulo, São Paulo, São Paulo, Brazil,

cassianos@ipt.br

Abstract

Non-destructive methods are crucial for evaluating the mechanical properties of wood in heritage buildings. This study aims to assess the ultrasound method for obtaining the stiffness coefficient and compare it with the static modulus of elasticity parallel-to-grain obtained according to ABNT NBR 7190:2022. Additionally, it was sought to compare the static modulus of elasticity obtained from the conventional parallel-to-grain compression test with that obtained from the ultrasound result and to verify the correlations between these parameters and crushing strength. The evaluation was conducted using the species *Apuleia leiocarpa*. The result obtained for the stiffness coefficient was 1.31 times higher than that of the reference test, and among the evaluated parameters, these presented the best correlation. The result of the comparison between the conventional method and ultrasound for obtaining the static modulus of elasticity showed statistical equivalence; therefore, this technique has enormous potential for assessing historic wooden structures.

Keywords: non-destructive methods, ultrasound, stiffness coefficient, dynamic modulus of elasticity, static modulus of elasticity, heritage building

Introduction

Heritage buildings have immeasurable cultural and historical value to humanity. Therefore, proper maintenance of these constructions is highly relevant for their preservation. Much of this heritage includes wooden structures, which are themselves highly complex materials requiring specific care to ensure durability.

Non-destructive methods applied to wood for determining mechanical properties have proven to be important tools, especially in the evaluation of components with structural functions. This is particularly

relevant in the case of historical heritage structures, where the principle of minimal intervention must be followed.

Considering that inspections of historical heritage wooden structures are still predominantly conducted qualitatively (Van Roy *et al.* 2018), the application of ultrasound as a non-destructive technique for measuring mechanical properties would bring significant improvement to assessments of this nature.

In this regard, several studies have shown the potential of non-destructive techniques such as ultrasound to estimate mechanical properties of wood.

Balarin and Nogueira (2005) showed that for mature *Pinus taeda* wood, the dynamic modulus of elasticity is 34% higher than the static modulus of elasticity, and regarding juvenile wood, this difference is 40%, with determination coefficients ranging from 89% to 94%, respectively.

Birinci (2023) used *stress wave* in samples of *Fagus orientalis* species and found a difference of 26% between these parameters. In addition, there is also a correlation between the modulus of elasticity and the mechanical strength of the wood (Josifovski *et al.* 2023; Carrasco *et al.* 2020; Melo R.F. *et al.* 2021; Lemke *et al.* 2023; Balarin and Nogueira 2005; Baar *et al.* 2015). Obtaining these parameters non-destructively can significantly aid in the evaluation of wooden structural elements, contributing to decision-making regarding the need for intervention.

Thus, this study aims to evaluate the relationship between the static modulus of elasticity - obtained through the conventional testing method according to ABNT NBR 7190-3 (2022) - and the stiffness coefficient in the longitudinal direction obtained using ultrasound. Furthermore, there is also a pursuit to compare the static modulus of elasticity obtained from the conventional compression parallel-to-grain testing and that obtained from ultrasound results, as well as to verify the correlations between these parameters and crushing strength.

Wood Properties

Evaluating the inspection object efficiently, it's necessary to know its material, behavior, as well as its characteristics and peculiarities.

The wood is a hygroscopic material due to its ability to exchange moisture with the environment, and its moisture content depends on the temperature and relative humidity conditions. Furthermore, this parameter strongly influences its physical and mechanical properties (Glass and Zelinka 2021). Another important property of this material is density, which, according to these authors, is defined as the ratio of mass to volume, expressed in kilograms per cubic meter, according to the International System of Units. Additionally, density is highly sensitive to changes in moisture content.

As a natural material, wood is susceptible to variations in temperature and relative humidity, and it also exhibits significant variability in its properties due to variations in soil conditions and growing space, even when free from defects (Senalik and Farber 2021).

The wood is an anisotropic material but can be considered as orthotropic (Bodig and Jayne, 1993; Senalik and Farber 2021) since it exhibits distinct behavior in each of the principal directions, namely longitudinal (parallel-to-grain), radial (normal to the growth rings), and tangential (tangential to the growth rings).

The modulus of elasticity is a stiffness parameter that indicates the material's ability to deform under load and recover its shape when unloaded. The wood has twelve elastic constants, nine of which are independent (Senalik and Farber 2021). The static modulus of elasticity is conventionally obtained from compression testing (Senalik and Farber 2021). Regarding the stiffness coefficient, it can be obtained through non-destructive methods such as *stress wave* and ultrasound. In the present study, the stiffness coefficient and the static modulus of elasticity were determined, both in the longitudinal direction, based on the premise

that the material is orthotropic for the analysis of the results. The ultrasound method was also used to obtain the stiffness coefficient. The density and moisture content of the sample were also determined.

Several studies have concluded that there is a good correlation between the static and dynamic modulus of elasticity. Carrasco *et al.* (2017), in a study to evaluate wood characteristics using impulse excitation on 29 wood species, showed a correlation between static and dynamic modulus of elasticity with an R^2 of 97.5%. Lemke *et al.* (2023) demonstrated a correlation between static and dynamic modulus of elasticity with an R^2 of 0.50 for birch and spruce species.

Balarin and Nogueira (2005), in their study on *Pinus taeda* wood modulus of elasticity using ultrasound, found a correlation between static and dynamic modulus of elasticity with R^2 ranging from 0.89 to 0.94. Baar *et al.* (2015) used *Azelia bipindensis*, *Intsia bijuga*, *Millettia laurentii*, *Astronium graveolens*, and *Microberlinia brazzavillensis* species in their study and presented a correlation between dynamic modulus of elasticity obtained by ultrasound and static modulus obtained from bending test with R of 0.83. Acuña *et al.* (2023) used *Populus euramericana*, *Fagus sylvatica* L., *Quercus pyrenaica* L., *Paulownia elongata*, and *Pinus sylvestris* L. species in their study and found an R^2 of 95.9% with dynamic modulus of elasticity obtained from induced vibration technique and an R^2 of 93.7% through ultrasound.

Carrasco *et al.* (2020), in a study to determine elastic constants of *Caryocar Villosum* species, showed a correlation between static and dynamic modulus with an R^2 of 97.3%. Carvalho *et al.* (2023) conducted a study to estimate static modulus of elasticity of *Eucalyptus sp.* species using dynamic modulus obtained from *stress wave* and ultrasound techniques, obtaining determination coefficients of 0.52 for the first method and 0.55 for the second.

In addition to the correlation between modulus of elasticity, other studies also show a correlation between modulus of elasticity and the mechanical strength of wood. Lemke *et al.* (2023) correlated bending strength with static modulus of elasticity and obtained an R^2 of 0.41, as well as, between bending strength and dynamic modulus of elasticity with an R^2 of 0.33. Meanwhile, Baar *et al.* (2015) demonstrated that static modulus of elasticity and bending strength have a correlation with an R of 0.73. Josifovski *et al.* (2023), in a study on *in situ* evaluation of wood structures using non-destructive methods such as ultrasound and X-ray, showed a correlation between compression strength and dynamic modulus of elasticity with an R^2 of 0.58 and a correlation between bending strength and dynamic modulus of elasticity with an R^2 of 0.60. Carrasco *et al.* (2017) demonstrated a correlation between dynamic modulus and crushing strength, tensile strength, and shear strength with R^2 of 74.5%, 55.6%, and 56.8%, respectively.

The stiffness coefficient is referred to in the cited papers as the dynamic modulus. In this work, the term stiffness coefficient was adopted.

Stiffness coefficient and static modulus of elasticity

To calculate the longitudinal stiffness coefficient in the direction parallel-to-grain (C_{11}) and the static modulus of elasticity E_1 (corrected value) using ultrasound, the equations presented by Bucur (2006) were employed, based on the stiffness matrix for the case of orthotropic material considered in the research, as shown in Equation 1:

$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \quad (1)$$

Considering wave propagation aligned with the axis of symmetry and phase angle for an orthotropic material, Equation 2 derived from the *Christoffel* equation is applied:

$$\begin{bmatrix} \Gamma_{11} - \rho V^2 & 0 & 0 \\ 0 & \Gamma_{22} - \rho V^2 & 0 \\ 0 & 0 & \Gamma_{33} - \rho V^2 \end{bmatrix} = 0 \quad (2)$$

From the previous equation, it is possible to obtain a longitudinal wave and two transverse waves. In the present study, only the longitudinal direction is considered, as shown in Equation 3:

$$\Gamma_{11} - \rho V^2 = 0 \quad (3)$$

Where Γ_{11} is an element of the Christoffel matrix, ρ is the material density, and V is the wave propagation velocity in the fiber Direction.

Thus, the stiffness coefficient in the longitudinal direction (C_{11}) is given by Equation 4:

$$C_{11} = \rho V^2 \quad (4)$$

The compliance matrix S (Equation 5) is the inverse of the stiffness matrix, expressed with engineering constants:

$$S = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{12}}{E_2} & -\frac{\nu_{13}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{21}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{23}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{31}}{E_1} & -\frac{\nu_{32}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \quad (5)$$

Considering the terms presented in Equation 5, the modulus of elasticity in the longitudinal direction can be determined using (Equation 6):

$$C_{11} = (1 - \nu_{23}\nu_{32})[E_2E_3S]^{-1} \quad (6)$$

Where S is given by Equation 7:

$$S = [1 - \nu_{12}\nu_{21} - \nu_{23}\nu_{32} - \nu_{13}\nu_{31} - 2\nu_{21}\nu_{32}\nu_{13}].(E_1E_2E_3)^{-1} \quad (7)$$

Where ν_{12} , ν_{21} , ν_{23} , ν_{32} , ν_{13} and ν_{31} are the Poisson's ratios in the longitudinal radial, radial longitudinal, radial tangential, tangential radial, longitudinal tangential, and tangential longitudinal directions, respectively. E_1 , E_2 , and E_3 are the static modulus of elasticities in the longitudinal, radial, and tangential directions, respectively.

Naming the term in brackets as “ k ”, it has Equation 8:

$$k = 1 - \nu_{12}\nu_{21} - \nu_{23}\nu_{32} - \nu_{13}\nu_{31} - 2\nu_{21}\nu_{32}\nu_{13} \quad (8)$$

By appropriately manipulating the equations presented with the equation for the stiffness coefficient, Equation 9 is obtained for calculating the static modulus of elasticity.

$$E_1 = \frac{C_{11}}{(1 - \nu_{23}\nu_{32})} k \quad (9)$$

The Poisson's ratios could not be measured in the laboratory; therefore, the coefficients from the literature (Bertoldo *et al.* 2023) for the same species, with density very close to the analyzed sample, were adopted.

Materials and Methods

For the tests, forty wooden specimens of *Apuleia leiocarpa* species were prepared with dimensions of (150 x 50 x 50) mm³, oriented in the longitudinal, radial, and tangential orthogonal directions, respectively. To ensure the orthotropic behavior of the sample, the maximum fiber inclination criterion of 6° was followed, as recommended in the ABNT NBR 7190-1 standard (2022) for visual classification of the specimens used in strength determination.

The tests for determining density, moisture content, and compression strength and modulus of elasticity parallel-to-grain (Figure 1) were conducted according to ABNT NBR 7190-3 (2022) standard. Figure 1 also shows the application of the *Pundit Lab*® ultrasonic equipment on the same sample.

Prior to the ultrasonic measurements, the equipment was calibrated using the reference time of the standard block of 25.4 μ s.

Transducers with a frequency of 150 kHz were used, following the ABNT NBR 15521 (2007) standard, considering that the dimension of the piece should be equivalent to at least three wavelengths λ .

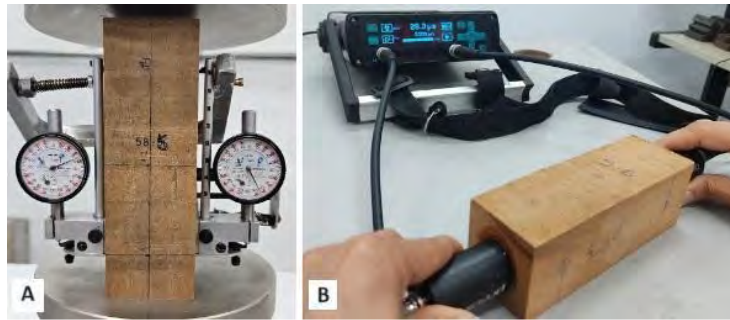
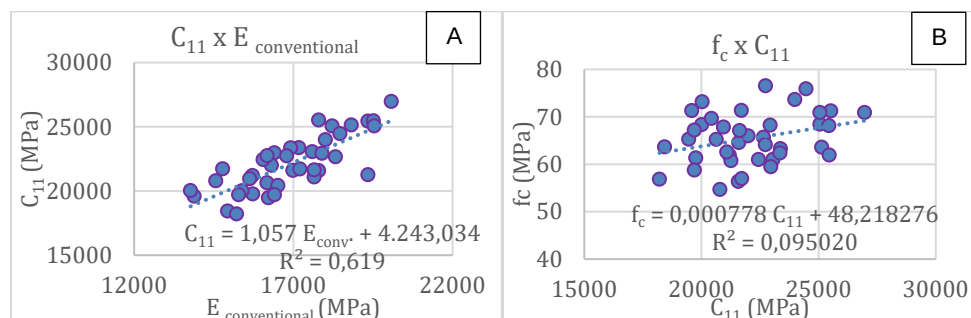


Figure 1—Conventional test for determining the modulus of elasticity in compression parallel-to-grain (A). Ultrasonic test for measuring ultrasonic velocity with *Pundit Lab*® equipment from Proceq (B). (Source: Authors)

For data analysis, the *Shapiro-Wilk* normality test, *Student's t*-test for comparing means of the results, and correlation coefficient test were conducted.

Results and Discussion

The results of density, moisture content, stiffness coefficient in the longitudinal direction (parallel-to-grain), conventional modulus of elasticity parallel-to-grain, ultrasound modulus of elasticity, and crushing strength parallel-to-grain are presented in Table 1.



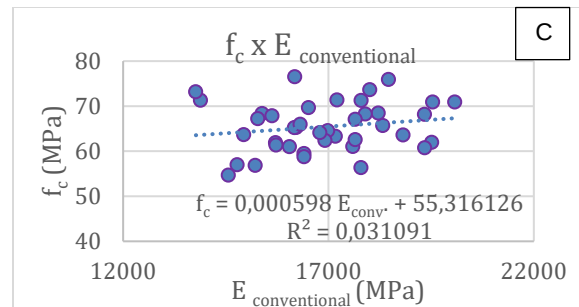


Figure 2 – A - Correlation between the longitudinal stiffness coefficient (C_{11}) and the conventional static modulus of elasticity ($E_{\text{conventional}}$). **B**- Correlation between crushing strength (f_c) and the longitudinal stiffness coefficient (C_{11}). **C**- Correlation between crushing strength and the conventional modulus of elasticity ($E_{\text{conventional}}$). (Source: Authors).

Table 1—Results of density, moisture content (MC), stiffness coefficient C_{11} , modulus of elasticity E_{us} , modulus of elasticity conventional $E_{\text{conventional}}$ and crushing strength f_c .

Test piece (n)	Density (kg/m ³)	MC (%)	C_{11} (MPa)	E_1 (MPa)	$E_{\text{conventional}}$ (MPa)	f_c (MPa)
1	777	12,5	23058	17913	17596	61
2	794	12,6	23371	18156	17172	63
3	761	12,4	21597	16778	16987	65
4	763	12,6	22652	17597	18324	66
5	838	11,8	19462	15119	16218	65
6	893	10,8	23986	18633	18010	74
7	794	11,2	20637	16031	16176	65
8	789	11,8	21198	16467	15717	62
9	811	10,8	19590	15219	13887	71
10	777	12,6	25138	19528	18821	64
11	823	12,5	25063	19470	18218	68
12	833	14,4	23355	18143	16917	62
13	861	11,8	26964	20947	20080	71
14	860	11,6	24465	19005	18467	76
15	864	12,3	25441	19763	19344	68
16	848	9,6	19761	15352	15725	61
17	822	13,3	20794	16153	14567	55
18	937	10,8	22935	17817	17901	68
19	874	12,8	20014	15548	15389	68
20	826	12,1	20945	16271	15631	68
21	790	12,5	22965	17840	16408	59
22	800	11,7	21994	17086	16315	66
23	812	11,8	20432	15872	16516	70
24	802	12,5	18432	14319	14938	64
25	845	12,7	25459	19777	19517	62
26	772	13,6	21579	16764	17796	56
27	744	14,9	18211	14147	15220	57
28	806	12,6	22441	17433	16053	61
29	874	12,5	25525	19829	17798	71
30	809	12,6	19702	15305	16409	59
31	865	8,7	22741	17666	16182	77
32	861	12,4	25059	19467	19541	71
33	892	11,7	20033	15563	13771	73
34	896	11,4	19702	15305	15283	67
35	760	13,6	21262	16517	19347	61
36	745	12,3	22734	17661	16793	64
37	840	12,2	21710	16865	17212	71
38	781	13,6	21085	16380	17656	63
39	801	12,3	21719	16872	14782	57
40	817	11,7	21632	16805	17656	67
Mean	821	12,2	22121	17185	16909	65
Sd (%)	46	1,1	2145	1667	1597	5
C.V.(%)	6	9,3	10	10	9	8

Sd is the standard deviation and C.V. is the coefficient of variation

The *Shapiro-Wilk* normality test was performed for C_{11} and E_1 , resulting in a W of 0.967 for both. For $E_{\text{conventional}}$, a W of 0.976 was obtained, and for f_c , the W obtained was 0.979. All values were greater than the critical W value of 0.940, considering a significance level of 5%, and thus, they have a normal distribution.

The average value of the static modulus of elasticity resulted in 16909 MPa, and the longitudinal stiffness coefficient in 22121 MPa, showing a $C_{11}/E_{\text{conventional}}$ ratio of 1.31, which is close to 1.34, as evidenced by Ballarin and Nogueira (2005). Figure 2 presents the correlation between the longitudinal stiffness coefficient (parallel-to-grain) and the static modulus of elasticity obtained from the conventional method, between crushing strength and the longitudinal stiffness coefficient, and between crushing strength and the conventional static modulus of elasticity.

At a significance level of 5%, the correlation coefficient tested with *Student's* t-test with 38 degrees of freedom between C_{11} and $E_{\text{conventional}}$ resulted in 7.866, between f_c and C_{11} resulted in 1.997, and between f_c and $E_{\text{conventional}}$ resulted in 1.104. Comparing the means of parameters E_1 and $E_{\text{conventional}}$ with a significance level of 5%, considering samples with a *Student's* t-distribution with 78 degrees of freedom, a t-value of 0.757 was obtained, which compared to the critical t-value of 1.665 resulted in statistically equivalent values. Furthermore, the difference between the two results was 1.6%.

Conclusions

The comparison results between the conventional method and ultrasound for obtaining the static modulus of elasticity showed statistical equivalence, demonstrating that the non-destructive method is viable for material characterization and can replace the conventional method. Among the correlation analyses between the evaluated parameters, the longitudinal stiffness coefficient and the conventional static modulus showed the best result, followed by the crushing strength in relation to the stiffness coefficient. However, the analysis between crushing strength and the conventional modulus of elasticity resulted in no correlation. This can be explained by the study being conducted with only one species with low variability in the modulus of elasticity.

A relationship between the stiffness coefficient and the conventional static modulus of elasticity and the equivalence of this result with the one obtained from the ultrasound method, combined with the other results presented, confirm the effectiveness and potential of this method for use in assessing structural elements of wood in historical buildings.

References

- ACUÑA, L.; MARTÍNEZ, R.; SPAVENTO, E. [and others]. 2023. Modulus of elasticity prediction through transversal vibration in cantilever beams and ultrasound technique of different wood species. *Construction And Building Materials*, v. 371. Elsevier BV: 327-345.
- ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. 2022. NBR 7190-1: Projeto de estruturas de madeira. Parte 1: Critérios de dimensionamentos. 1 ed. Rio de Janeiro. 36 p.
- ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. 2022. NBR 7190-3: Projeto de estruturas de madeira. Parte 3 Métodos de ensaio para corpos de prova isentos de defeitos para madeiras de florestas nativas. 1 ed. Rio de Janeiro. 36 p.
- ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. 2007. NBR 15521: Ensaio não destrutivo - Ultrassom - Classificação mecânica de madeira serrada de dicotiledôneas. 1 ed. Rio de Janeiro. 7 p.

BAAR, J.; TIPPNER, J.; RADEMACHER, P. 2015. Prediction of mechanical properties-modulus of rupture and modulus of elasticity-of five tropical species by nondestructive methods. *Maderas. Ciencia y tecnología*, v. 17, n. 2, p. 239-252.

BALLARIN, A. W.; NOGUEIRA, M. 2005. Determinação do módulo de elasticidade da madeira juvenil e adulta de *Pinus taeda* por ultra-som. *Construções Rurais e Ambiente: Engenharia Agrícola*, v. 25, n. 1, p. 19-28.

BERTOLDO, C.; PEREIRA, G. A.; GONÇALVES, R. 2023. Effect of Reducing the Size and Number of Faces of Polyhedral Specimen on Wood Characterization by Ultrasound. *Materials*, Basel, v. 16, n. 13, p. 1-15.

BİRİNCİ, E. 2023. Determination of the relationship between static and dynamic modulus of elasticity in beech wood. *Mobilya Ve Ahşap Malzeme Araştırmaları Dergisi*, v. 6, n. 1, p. 47-54.

BODIG, J; JAYNE, B.A. 1993. *Mechanics of wood and wood composites*. Malabar: Krieger.

BUCUR, V. 2006. Theory of and Experimental Methods for the Acoustic Characterization of Wood. In: BUCUR, Voichita. *Acoustics of Wood*. 2. ed. Vienna, Springer: 39-104. Chapter 4.

CARRASCO, E. V. M.; VARGAS, C. B.; SOUZA, M. F. [and others]. 2017. Avaliação das características mecânicas da madeira por meio de excitação por impulso. *Matéria (Rio de Janeiro)*, v. 22, n. 1.

CARRASCO, E. V. M.; ALVES, R. C.; VON KRÜGER, P. G. [and others]. 2020. Determination of constant elastic of pequi wood using ultrasound. *Mix Sustentável*, Florianópolis, v. 6, n. 4, p. 139-144.

CARVALHO, R. A.; SILVA, G. F.; PINHEIRO, C. J. G. [and others]. 2023. Predição do módulo de elasticidade estático de *Eucalyptus* sp. por meio de duas técnicas não destrutivas. *Ciência Florestal*, v. 33, n. 3. Universidade Federal de Santa Maria.

GLASS, S. V.; ZELINKA, S. L. 2021. Moisture Relations and Physical Properties of Wood. In: Forest products Laboratory (ed.). *Wood handbook: Wood as an engineering material*. Madison: USDA Forest Service, Forest products Laboratory, p. 4.1-4.4. Chapter 4.

JOSIFOVSKI, A.; TODOROV, N.; MILOSEVI, J. [and others]. 2023. An Approach to In Situ Evaluation of Timber Structures Based on Equalization of Non-Destructive and Mechanical Test Parameters. *Buildings*, Basel, v. 1405, n. 13, p. 1-16.

LEMKE, U.; JOHANSSON, M.; ZIETHÉN, R. [and others]. 2023. New criteria for visual strength grading of sawn timber from birch grown in Sweden. In: *World Conference on Timber Engineering*, 13th, 2023, Oslo. *Proceedings [...]*, Oslo: WCTE, 2023. 10 p.

MELO, R. R. et al. 2021. Ultrasound to determine physical-mechanical properties of *Eucalyptus camaldulensis* wood. *Wood Material Science & Engineering*, v. 16, n. 6, p. 407-413.

SENALIK, C. A.; FARBER, B. 2021. Mechanical Properties of Wood. In: Forest products Laboratory (ed.). *Wood handbook: Wood as an engineering material*. Madison: USDA Forest Service, Forest products Laboratory, p. 5.1-5.3. Chapter 5.

VAN ROY, N.; VERSTRYNGE, E.; VAN BALEN, K. 2018. A preventive conservation approach for historical timber roof structures. *Journal Of Cultural Heritage Management And Sustainable Development*, v. 8, n. 2, p. 82-94.

Correlation between the Visual Quality, Acoustic and Mechanical Properties of the Logs of Four Different Tree Species Collected at a Public Auction of Valuable Logs

Jure Žigon *

Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, Ljubljana, Slovenia, jure.zigon@bf.uni-lj.si

Aleš Straže

Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, Ljubljana, Slovenia, ales.straze@bf.uni-lj.si

* Corresponding author

Abstract

The mechanical and physical properties of wood obtained from visually graded logs are often a matter of question. In this study, we aimed to investigate the correlation between the acoustic properties of the logs with their quality classes (A, B and C) and the corresponding prices. The logs of four different tree species collected at public auction of valuable logs were examined: Norway spruce (*Picea abies*), Common beech (*Fagus sylvatica*), European oak (*Quercus robur*, *Quercus petraea*) and sycamore maple (*Acer pseudoplatanus*). For the non-destructive evaluation of the logs, longitudinal and bending vibration resonance methods were used in several vibration modes. As expected, the correlation between the visually determined better quality of the logs and their higher price was confirmed. The quality grades of the logs were associated with the acoustic characteristics. Higher stress wave velocity and specific modulus of elasticity (E/ρ) determined in the longitudinal direction of the logs were associated with lower damping ($\tan\delta$) and higher quality of the logs. In addition, the specific modulus of elasticity and relative acoustic conversion efficiency (RACE) determined during the bending vibration of the logs were positively correlated with their higher price. In some cases, however, the acoustic characteristics of the logs could not adequately explain the grading quality. The prices given to some logs depended not only on their visual quality, but also on the requirements and needs of individual buyers.

Keywords: auction, logs, properties, quality, vibration

Pilodyn for Rapid Field Assessment of Decay in Hardwood Trailer Deck Boards Exposed to Deep Tropical Jungle Environments

Xinfeng Xie *

College of Forest Resources and Environmental Science, Michigan Technological University, Houghton, Michigan, USA, xinfengx@mtu.edu

Yunxiang Ma

College of Forest Resources and Environmental Science, Michigan Technological University, Houghton, Michigan, USA, yma2@mtu.edu

Xiping Wang

USDA Forest Service Forest Products Laboratory, Madison, Wisconsin, USA, xiping.wang@usda.gov

* Corresponding author

Abstract

The Pilodyn, a nondestructive testing device originally designed for assessing wood decay in utility poles, has become invaluable in evaluating the physical and mechanical properties of wood in the field. Its application has extended to assessing the density of standing trees and the structural integrity of timber components by measuring the penetration depth of a standard strike pin fired with a consistent impact energy. This study utilized Pilodyn to assess the condition of some commercial hardwood trailer decking boards which have been exposed in the tropical jungle environment for 3 years. The results from the Pilodyn tests were compared with visual assessments based on the American Wood Protection Association (AWPA) standard scales. These tests collectively evaluated the condition of the decking boards, highlighting the potential of Pilodyn for rapid on-site evaluation of the condition of hardwood trailer deck boards.

Keywords: Nondestructive test, on-site evaluation, trailer decking

Introduction

The Pilodyn, originally developed for assessing wood decay in utility poles, has emerged as a versatile tool for evaluating the physical and mechanical properties of wood in various applications. Its utility has expanded beyond its initial purpose to encompass assessing the density of standing trees and determining the structural integrity of timber components. This evolution in its application has prompted researchers to explore its efficacy in diverse environments and contexts. One such context is the evaluation of commercial hardwood trailer decking boards, particularly in challenging environments such as tropical jungles. The durability and performance of these boards in such conditions are crucial for the efficiency and safety of transportation operations. However, assessing the condition of these boards after prolonged exposure to such environments poses challenges, necessitating the use of efficient and reliable testing methods.

Tropical hardwoods, which includes endangered species, such as *Dipterocarpus* spp, have been used for open-bed trailers and trucks as decking materials in North America. Harvesting of such tropical hardwood has resulted in destruction of tropical rainforests. At the meantime, the supply chain issue is also adding extra pressure to the stakeholders. Thus, finding a North America sourced hardwood replacement for the tropical hardwoods would be in favor of environmental and economical concerns. As a result, a system of pressure-treated commercial North America oak-based trailer decking product is under development. The durability of the product was evaluated with field exposure in the jungles of South America based on the American Wood Protection Association (AWPA) E16 standard (AWPA 2022) and AWPA E7 (AWPA 2021). To be specific, the exposure test was conducted following E16, and the samples were visually inspected and graded following E16 for decay, and E7 for insect attack.

This paper focuses on utilizing the Pilodyn as a nondestructive testing device to evaluate the condition of commercial hardwood trailer decking boards exposed to the tropical jungle environment for an extended period. By measuring the penetration depth of a standard strike pin fired with consistent impact energy, the Pilodyn offers insights into the structural integrity of the boards. These findings are then compared with visual assessments based on established standards, particularly those defined by the American Wood Protection Association (AWPA) E16 and E7. The objective of this study is to assess the feasibility and effectiveness of Pilodyn in rapidly evaluating the condition of hardwood trailer decking boards on-site, providing valuable insights for maintenance and decision-making processes. By combining quantitative Pilodyn measurements with qualitative visual assessments, this research aims to enhance the efficiency and accuracy of the condition assessment of hardwood trailer decking boards, thereby contributing to the optimization of transportation operations in challenging environmental conditions.

Method and Materials

The field exposure was conducted in rainforest of Afobaka, Suriname. The site has an annual precipitation of 2309 mm (90.9 inch), mean annual temperature of 25.9° C (78.6° F) and mean relative humidity of 88.4%, which can represent the extreme working condition of trailer decks. The decking board samples were 305 mm (12-in) wide and 3355 mm (11-ft) long. Three replicates were included in each sample group. The parameters of the sample groups, including the species and treatment, are listed in Table 1. The treatment was a copper-based oil-borne wood preservative pressure treatment. Primarily red oak and some white oak were used in the groups of mixed oak.

Table 1 Sample Species and Treatment Conditions
Board Types
1, untreated mixed oak, no coating
2, treated mixed oak, no coating
3, treated mixed oak, top and bottom coating
4, treated mixed oak, bottom FRP reinforced
5, treated white oak, bottom coating
6, treated white oak, no coating
7, treated red oak, no coating
8, treated sugar maple lumber boards
9, untreated Apitong

The inspection was conducted after 13 months, 25 months and 37 months of exposure. The assessment of decay and insect attack on each board was visually conducted using the rating scales outlined in AWPA standards E7 and E16. In accordance with these standards, a rating of 10 indicates that the sample is in sound condition, while a rating of 0 implies functional failure. To provide clarity, ratings between these

extremes are further delineated: a score of 9.5 denotes the presence of trace attack, 9 indicates slight attack with up to 3% of the area affected, 8 represents 3-10% area affected, 7 implies 10-30% area affected, 6 indicates 30%-50% affected area, and 4 implies 50-75% area affected. These defined criteria facilitate an overall evaluation of the extent of decay and insect infestation on the examined boards.

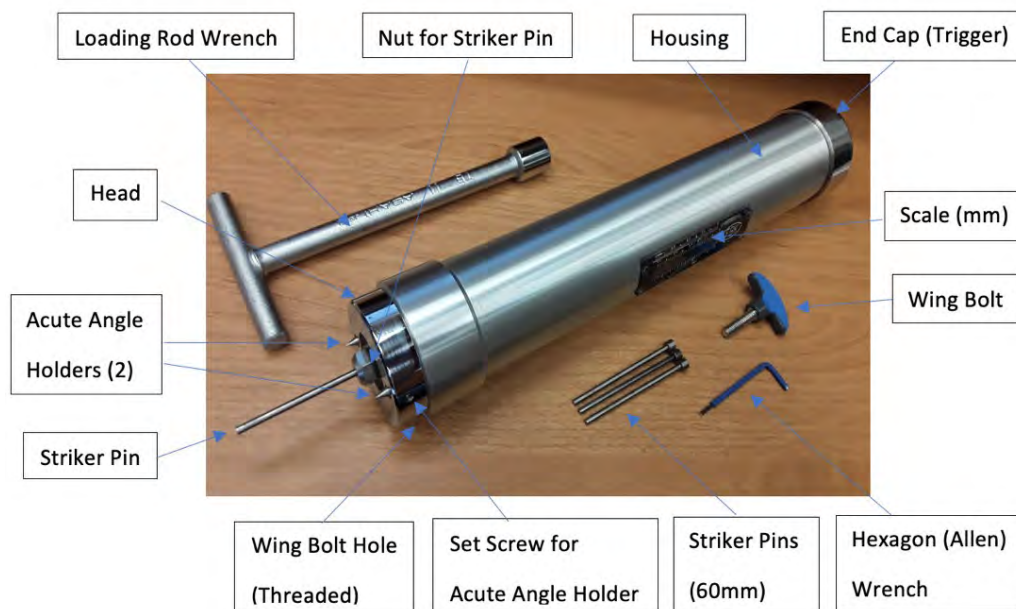


Figure 1 Pilodyn, the surface hardness tester

As shown in Figure 1, Pilodyn is a non-destructive tester that measures the penetration depth of a standard strike pin fired with a consistent impact energy. The depth of the penetration then serves as an indication of the surface hardness of the evaluated wood. It was designed to detect soft rot wood decay in utility poles, evaluation the density of standing trees, and determine the condition of structural timbers. In this study, one Pilodyn data point was taken at the center of every foot of each board, which resulted in 11 datapoints for each sample board at each evaluation period. An extra set of data was obtained before exposure for reference.

In order to eliminate the effect of moisture content (MC) on the Pilodyn penetration depth, a series of laboratory tests were conducted on the wood specimens with different species and MC. The specimens included northern red oak (*Quercus rubra*), white oak (*Quercus alba*), sugar maple (*Acer saccharum*), and Apitong (*Dipterocarpus* spp.) to cover the species included in the full-size decking exposure field test. A total of 24 measurements were taken on 6 specimens with the specific gravity within 5% of the average specific gravity of the species. Based on the lab testing results, the Pilodyn penetration depth of the samples with different MC were converted to the equivalent penetration depth with the same MC, which will minimize the effects of MC included in the Pilodyn penetration results.

Result and Discussions

The results of the lab testing of Pilodyn penetration on wood specimens of different species with a variety of MC are as shown in Figure 2. The results indicate that for all the four species, the Pilodyn penetration was dependent on MC in the range between 7% to 31%, while the change was relatively small when the MC increased beyond the Fiber Saturation Point (FSP).

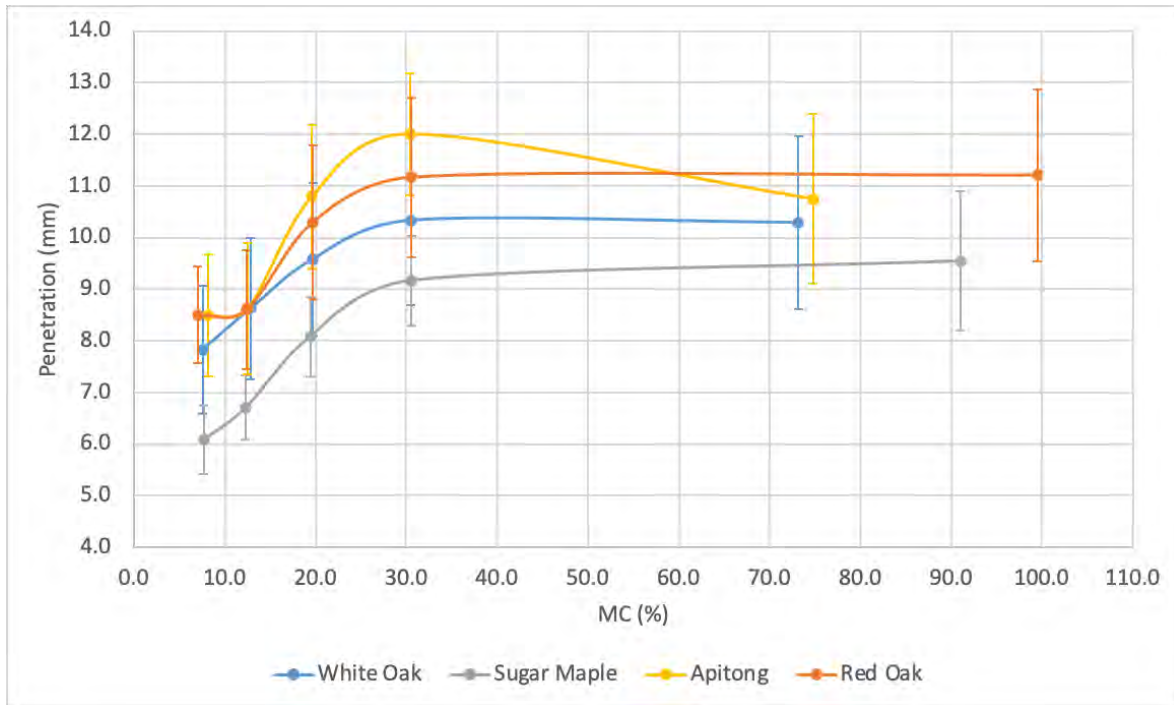


Figure 2 The effects of MC on Pilodyn penetration into different wood species

To be specific, the correlation between the Pilodyn penetration and MC at the range of 7% to 31% is approximately linear. As shown in Figure 3, the linear regression equations for each species were derived accordingly. The R^2 of all the four equations are above 93%, which indicates the equations can approximately represent the correlation.

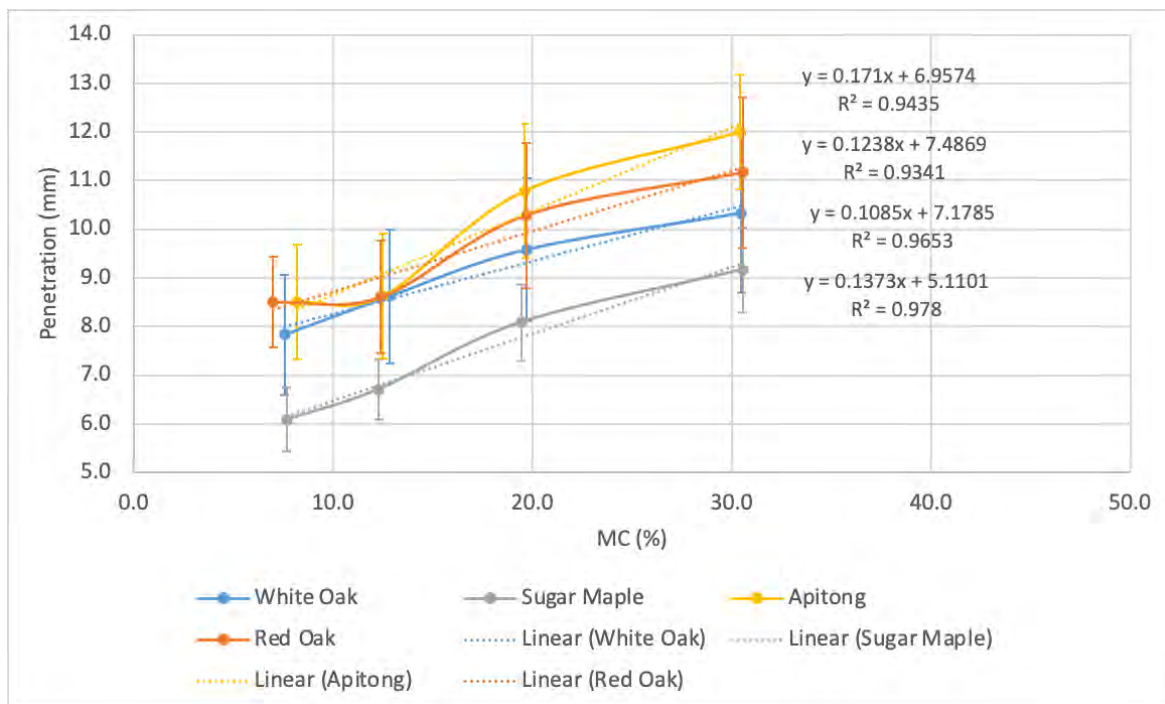


Figure 3 The effects of MC on Pilodyn penetration into different wood species

The Pilodyn penetration results of the trailer decking boards with different MC were calculated based on the regression equations to the equivalent penetration depth at 30%MC. The average penetration (P) of each board type and the adjusted penetration depth (P_{adj}) are listed in Table 2. The change of penetration depth indicated the change of surface hardness of the boards. The change in the surface hardness showed continuous overall deterioration of all the boards. The pressure treated oak boards (type 2-7) has less changes in the surface hardness, indicating less overall deterioration than the untreated oak boards (type 1), which have been functional failed at 37 months.

Table 2 Pilodyn penetration (P) and adjusted penetration (P_{adj}) at each exposure time

Board Type	No Exposure			13 Months Exposure			25 Months Exposure			37 Months Exposure		
	MC (%)	P (mm)	P_{adj} (mm)	MC (%)	P (mm)	P_{adj} (mm)	MC (%)	P (mm)	P_{adj} (mm)	MC (%)	P (mm)	P_{adj} (mm)
1	7.9	8.5	11.4	30.2	13.9	13.9	22.3	16.9	18.5	-	-	-
2	-	8.5	11.4	30.8	11.4	11.4	23.6	11.6	12.5	12.4	10.6	12.8
3	7.4	8	10.7	30.4	15.0	15.0	24.7	15.4	16.4	25.1	18.2	18.8
4	7.4	8.1	10.9	31.7	13.1	13.1	27.6	13.5	13.9	24.3	12.9	13.6
5	8.1	7.6	10.0	32.0	12.0	12.0	31.3	12.2	12.2	29.2	10.9	11.0
6	-	7.6	10.0	32.0	12.8	12.8	31.4	13.2	13.2	21.3	10.4	11.3
7	7.0	8.5	11.4	32.0	11.2	11.2	29.4	12.9	13.0	20.4	9.3	10.5
8	7.7	6.1	9.3	27.1	8.7	9.1	15.9	9.6	12.2	14.2	8.2	10.4
9	8.2	8.5	12.6	29.6	9.9	10.0	19.7	12.6	14.8	20.9	13.1	14.7

The difference of adjusted penetration depth (D_p), the decay rating (D_{decay}) and the insect attack rating (D_{insect}) are listed in the Table 3 to compare the different assessment approaches. Overall, the increase of penetration depth was observed along with the decreasing of the ratings. Out of the two ratings, decay was more severe than the insect attack. Similar to what indicated by the penetration depth results, the pressure treated oak (type 2-7) is shown to be more durable than the untreated oak (type 1). Moreover, the untreated apitong (type 9) and the treated maple (type 8) also appear to be less durable than treated oak boards (type 2-7), which were not captured by the Pilodyn penetration test.

Since the visual grading rating is qualitative rather than quantitative, the direct numerical correlation between the penetration depth changes and the change of visual grading rating was not conclusive. One factor hindering the direct correlation between the penetration assessment and the rating might be that the Pilodyn assesses local properties while the visual grading assesses the overall appearance. For the mixed oak decking with top and bottom coating (type 3), the increase of penetration depth is higher than all other boards, while the rating changes are not as much as treated maple (type 8) and untreated apitong (type 9). After looking into the raw data (Appendix 1), it turns out that one of the samples in that group is having much deeper (26.1 mm) penetration compared to the other two in the same group (13 mm and 15.4 mm) after 37 months' exposure. Meanwhile, 3 out of 7 treated maple samples (type 8) and 5 out of 10 untreated apitong samples (type 9) failed at the end of the 37 months. The failed samples were not included in the Pilodyn penetration test, which resulted in the overestimation of the groups' average surface hardness.

As a result, while Pilodyn penetration test provides valuable perspective of local mechanical properties, the overall visual grading is still necessary. The combination of the two assessments will provide a more thorough understanding of the degradation of the wood samples, catching both locally individual weaknesses and overall durability. When visual grading is not applicable or limited, it is recommended to sample more locations with Pilodyn to assess the overall condition of the wood product.

Table 3 Differences of adjusted penetration depth (D_p), decay rating (D_{decay}) and insect attack rating (D_{insect}) of each exposure time period comparing with the unexposed status.

Board Type	13 Months Exposure			25 Months Exposure			37 Months Exposure		
	D_p	D_{decay}	D_{insect}	D_p	D_{decay}	D_{insect}	D_p	D_{decay}	D_{insect}
1	22.0%	2.7	3.0	62.3%	5.0	6.7	-	10.0	10.0
2	0.0%	1.0	0.3	9.7%	3.0	0.0	12.1%	3.0	1.0
3	39.8%	0.8	0.0	52.9%	3.3	2.0	75.3%	4.7	2.3
4	20.6%	0.8	0.0	28.0%	3.0	1.3	25.3%	4.7	2.0
5	20.1%	0.7	0.0	22.1%	2.0	0.3	10.0%	3.0	2.7
6	28.1%	0.8	0.0	32.1%	2.0	0.0	13.6%	2.3	2.0
7	-1.7%	0.5	0.0	14.1%	2.0	0.0	-8.0%	3.7	2.0
8	-1.9%	0.7	1.0	31.6%	3.3	3.3	11.8%	7.0	5.6
9	-20.6%	1.6	0.7	17.5%	5.5	1.9	16.3%	7.5	4.4

Conclusions

From the field exposure test with combined assessment method, it is found that decay was the major deteriorating factor for the trailer decking boards exposed in the South America rainforest condition. The treated oak boards were showing better durability than the untreated oak, as well as the untreated apitong and treated maple. The comprehension of results indicated that Pilodyn can provide an additional perspective of wood product durability. The combination of AWPAs prescribed visual evaluation method and Pilodyn can provide complementary assessments of the conditions of trailer decking boards, including both localized quantitative and overall qualitative perspectives. To improve the field evaluation method, further study on the calibration of penetration depth-MC correlation is needed. More sampling is also recommended for future Pilodyn test practices.

Acknowledgment

This study was conducted through a cooperative research agreement (FS 19-JV-111111064) between Michigan Technological University (MTU) and the USDA Forest Products Laboratory (FPL) and was partially funded by the U.S. Army Ground Vehicle Systems Center (GVSC). Technical support in the field exposure tests was provided by the U.S. Army Yuma Proving Ground Tropical Regions Test Center.

References

- AWPA, American Wood Protection Association. 2021. "Standard Field Test for Evaluation of Wood Preservatives to be Used in Ground Contact (UC4A, UC4B, UC4C)." In. Birmingham, AL USA.
- . 2022. "Standard Field Test for Evaluation of Wood Preservatives to be Used Above Ground (UC3B)." In. Birmingham, AL USA.

Appendix

Appendix 1 MC, Pilodyn penetration and visual grading result of each sample after different exposure time

Platform	Species	Specimen			Sept' 21 (13 mos.)				Sept' 22 (25 mos.)				Sept' 23 (37 mos.)			
		Treated	Coating	"M" Tag #	Ave. MC(%)	Ave. Hardness (mm)	Decay	Termite	Ave. MC(%)	Ave. Hardness (mm)	Decay	Termite	Ave. MC(%)	Ave. Hardness (mm)	Decay	Termite
1	Mixed Oak	No	No	9450	29.4	12.3	8	7	22.6	17.5	4	0	---	---	TF	0
				9449	30.2	15.8	7	7	21.8	20.9	4	0	---	---	0	0
				9451	32.0	13.5	7	7	22.4	12.5	7	10	---	---	TF	0
			Mean Values:		30.5	13.9	7.3	7.0	22.3	16.9	5.0	3.3	---	---	TF	0.0
		Yes	No	9441	30.1	11.3	9	10	25.7	12.2	7	10	12.3	10.5	7	9
				9440	32.0	11.6	9	9		Broken			14.4	10.8	7	9
				9439	30.3	11.4	9	10	21.4	11.1	7	10	10.6	10.4	7	9
			Mean Values:		30.8	11.4	9.0	9.7	23.6	11.6	7.0	10	12.4	10.6	7.0	9.0
2	Mixed Oak		Top and Bottom	9427	27.9	14.1	9.5	10	19.6	14.4	7	10	22.1	13.0	6	10
				9428	32.0	15.7	9	10	26.6	14.6	7	10	23.9	15.4	6	9
				9429	31.1	15.3	9	10	28.1	17.2	6	4	29.3	26.1	4	4
		Yes	Mean Values:		30.3	15.0	9.2	10	24.7	15.4	6.7	8.0	25.1	18.2	5.3	7.7
			Bottom Reinforced	9432	32.0	14.2	9.5	10	30.3	14.0	8	10	24.9	14.0	6	9
				9431	31.0	12.9	9	10	26.5	13.3	7	10	20.4	13.4	6	8
				9430	32.0	12.1	9	10	26.0	13.2	6	6	27.6	11.2	4	7
			Mean Values:		31.7	13.1	9.2	10	27.6	13.5	7.0	8.7	24.3	12.9	5.3	8.0
3	White Oak		Bottom Coating	9433	32.0	11.7	9.5	10	31.1	12.3	8	10	29.6	11.7	7	8
				9434	32.0	12.7	9	10	30.8	12.0	8	10	28.0	10.8	7	7
				9435	32.0	11.6	9.5	10	32.0	12.3	8	9	29.9	10.1	7	7
		Yes	Mean Values:		32.0	12.0	9.3	10	31.3	12.2	8.0	9.7	29.2	10.9	7.0	7.3
			No Coating	9438	32.0	13.3	9	10	32.0	13.5	8	10	25.1	11.8	8	8
				9437	32.0	11.9	9	10	32.0	12.5	8	10	24.7	9.1	7	8
				9436	32.0	13.2	9.5	10	30.2	13.7	8	10	14.1	10.3	8	8
			Mean Values:		32.0	12.8	9.2	10	31.4	13.2	8.0	10	21.3	10.4	7.7	8
4	Red Oak	Yes	No Coating	9421	32.0	11.1	9.5	10	27.4	13.0	8	10	18.3	8.6	6	8
				9422	32.0	11.1	9.5	10	30.8	12.3	8	10	25.1	9.0	6	8
				9423	32.0	11.3	9.5	10	29.9	13.5	8	10	17.9	10.3	7	8
			Mean Values:		32.0	11.2	9.5	10	29.4	12.9	8.0	10	20.4	9.3	6.3	8
	Apitong	No	No Coating	---	32.0	10.3	7	8	29.7	16.7	0	9	20.7	---	DF	0
				---	32.0	10.0	9	10	25.1	14.7	6	8	19.1	12.1	4	7
				---	32.0	11.5	8	9	18.9	13.8	7	10	26.7	19.8	4	7
				---	32.0	9.3	9.5	10	20.6	10.5	8	10	24.3	10.4	4	7
	Sugar Maple			---	32.0	10.4	8	9	17.8	11.6	4	7	21.4	---	0	0
			Mean Values:		32.0	10.3	8.3	9.2	22.4	13.5	5.0	8.8	22.4	14.1	3.0	4.2
				9442	26.4	6.9	9	7	25.0	11.1	6	6	---	---	0	0
				9443	27.6	6.5	10	10	17.2	12.9	7	6	---	---	0	0
	Apitong	No	No Coating	---	28.0	9.8	9	10	15.9	10.8	7	10	15.6	11.7	4	8
				---	28.4	9.1	8	8	18.4	12.1	0	6	22.6	---	0	DF
				---	25.7	9.1	9	10	13.6	10.3	6	6	23.7	---	0	6
			Mean Values:		24.2	8.5	8	9	18.2	12.9	0	7	15.7	---	0	DF
5	Apitong			---	27.3	9.5	8.6	9.4	17.0	11.6	4.0	7.4	19.4	12.1	2.0	7.0
				---	30.2	10.9	9	10	18.8	11.9	7	8	19.3	12.5	6	7
				---	28.0	9.8	9	10	15.9	10.8	7	10	15.6	11.7	4	8
				---	28.4	9.1	8	8	18.4	12.1	0	6	22.6	---	0	DF

The Influence of Fibre Reinforcements to Stability of Oak-Wood Panels between Different Climates

Vjekoslav Živković*

University of Zagreb, Faculty of Forestry and Wood Technology, Svetošimunska 23, HR 10000 Zagreb, Croatia, vzivkovic@sumfak.unizg.hr

Josip Miklečić

University of Zagreb, Faculty of Forestry and Wood Technology, Svetošimunska 23, HR 10000 Zagreb, Croatia, jmiklecic@sumfak.unizg.hr

Hrvoje Turkulin

University of Zagreb, Faculty of Forestry and Wood Technology, Svetošimunska 23, HR 10000 Zagreb, Croatia, hturkulin@sumfak.unizg.hr

Andrija Novosel

University of Zagreb, Faculty of Forestry and Wood Technology, Svetošimunska 23, HR 10000 Zagreb, Croatia, anovosel@sumfak.unizg.hr

* Corresponding author

Abstract

The main objective of this research was to study the stability of the form of laminated oak-wood panels during exposure between two different climates (interior and exterior). Cross-woven fibre reinforcements were introduced and glued with epoxy resin below the top veneer on both sides of the wood panel. Laminated but unreinforced oak-wood reference panels were compared with reinforced variants. Each specimen was produced as a flat panel and installed as the entrance doors on the opening of the conditioning chamber which was put in the laboratory. Panels in the form of door leaves were continuously exposed to the standard indoor climate (23°C, 50% RH) on the interior side and simulation of changing conditions in the exterior. Exterior conditions consisted four weeks of extra humidity (23°C, 85% RH) followed by extra dry conditions (23°C, 30% RH) for another four weeks. Displacements and deformations on the tested panels were continuously monitored all over the panel and additionally at 11 identical locations on each tested panel using a non-contact optical stereometric system and the digital image correlation method (DIC). Door panels without reinforcements exhibited up to 7 mm bow during exposure. Fibre-reinforcements were shown to significantly improve the stability of the tested panels - deformations of reinforced leaves were reduced up to 75 % compared to the unreinforced reference element. This confirms not only the stabilization effect, but the possibility of industrial application of experimental results, demonstrating the high effectiveness of carbon and glass fibre reinforcements in improving the stability of oak wood panels that might be used for entrance pedestrian doors.

Keywords: external doors, form stability, oakwood, fibre-polymer reinforcements, glass fibres, carbon fibres

Impact of Time-on-Ground of Felled Pine Trees on Quality of Mass Timber

Laya Khademibami*

Assistant Research Professor. Department of Sustainable Bioproducts, Mississippi State University, MS 39762-9820. USA. Email: lk475@msstate.edu

Rubin Shmulsky

Department head and Warren S. Thompson Professor, Department of Sustainable Bioproducts, Mississippi State University, MS 39762-9820. USA. Email: rs26@msstate.edu

Frederico Jose Nistal Franca

Assistant Professor. Department of Sustainable Bioproducts, Mississippi State University, MS 39762-9820. USA. Email: fn90@msstate.edu

Robert J Ross

Supervisory Research Gen. Engineer (retired), USDA Forest Service Forest Products Laboratory, United States Department of Agriculture, Wisconsin State, WI 53726-2398. USA. Email: Robert.j.ross@usda.gov

Xiping Wang

Research Forest Products Technologist, USDA Forest Service Forest Products Laboratory, United States Department of Agriculture, Wisconsin State, WI 53726-2398. USA. Email: xiping.wang@usda.gov

Seyed Abolghasem Fatemi

Post-Doctoral Associate. Department of Sustainable Bioproducts, Mississippi State University, MS 39762-9820. USA. Email: sf1006@msstate.edu

* Corresponding author

Abstract

The value of timber is often reduced following storm events. The wood from windthrown trees declines in value over time. There is a need to rapidly assess wood quality from downed timber. In this research the impact of time-on-ground of felled trees on the quality of mass timber was investigated. Southern yellow pine trees were felled and remained in the forest for 0 to 6 months. Trees were then processed into dimension lumber. Lumber quality was recorded. Nondestructive characteristics of lumber were evaluated. Density, acoustic velocity (AV) and dynamic modulus of elasticity (D_{MOE}) were calculated for each piece. Cross laminated timber (CLT) panels were then prepared from the lumber. The AV and D_{MOE} of CLT panels were evaluated. Statistically significant differences were detected between lumber and CLT panels in both AV and D_{MOE} . It was concluded that nondestructive evaluation can be used to estimate D_{MOE} of these CLT panels.

Keywords: Nondestructive evaluation, cross laminated timber, downed trees, acoustic velocity, dynamic MOE, dimension lumber, and southern yellow pine.

Introduction

The severity and frequency of storms has been shown to increase with climate change (Emanuel et al. 2008; Knutson et al. 2021). Severe storms can negatively affect timber value and volume. High wind events often break trees and windthrow them to the ground, and/or tangle trees with each other. Subsequent salvage logging is difficult, dangerous, and costly (McNulty 2002; Gordon et al. 2018). In short order, decay, stain, beetles, and termites become problematic and log recovery efforts end relatively quickly. Relatively small quantities of windthrows or downed timber are salvaged for potential use in wood products (Gordon et al. 2018). Part of the difficulty in utilization decision making is the unknown quality of the downed trees over time. Thus, there is a need to be able to rapidly assess the condition of the downed timber and determine if salvage is economically justified (Shmulsky and Jones 2019). The wood quality of felled or windthrown trees, after several months, has not been previously well investigated. This wood quality affects the properties of both structural lumber and remanufactured products such as glulam and cross laminated timber (CLT). It was anticipated that time-on-ground would not greatly influence lumber recovery because the deleterious effects of time are known to be staining, beetles, and uneven drying. It was anticipated that time-on-ground may influence lumber quality because possible early or incipient decay may reduce lumber stiffness. Several invasive and noninvasive methods including traditional, radiographic, acoustic, and electrical resistivity techniques have been previously developed to assess felled wood deterioration (Soge et al. 2020). However, the above-mentioned techniques are relatively costly, cumbersome, and/or require expertise to be administered (Soge et al. 2020). Nondestructive testing has been used to test mechanical and physical properties of wood-based materials, without damaging their integrity. NDE of wood provides an appropriate determination of wood quality as well as accurate detection of defects (Zielińska and Rucka 2021). The nondestructive evaluation of felled timber has not been previously investigated. Therefore, the objective of this research was to investigate the impact of time-on-ground of pine trees on the quality of lumber and CLT.

Materials and Methods

Experimental Design and Sample Preparation

Twenty-five loblolly pine (*Pinus taeda*) trees, approximately 38 years old and 36 cm to 41 cm (14 in. to 16 in.) in diameter at breast height, were selected. The trees were located at the John W. Starr Memorial Forest, Oktibbeha County, MS. All trees were felled on the same day (time zero). Overall, four felled trees were collected during each of the five-time intervals which were 0, 3, 4, 5 and 6 months. After falling, trees were not topped or bucked until their scheduled further processing. This action was taken to simulate storm-based windthrow. No actual storm damage such as top breakage, torsion, excessive bending, or shearing occurred which is considered as the limitation of this study. Trees were removed within their respective monthly target time, plus or minus one week. At the time of removal, the trees were cut into logs with an 18 cm to 20 cm (7 in. to 8 in.) minimum top diameter, inside the bark. These long logs were then transported to the Sustainable Bioproducts Department facilities at Mississippi State University. Logs were then bucked and processed into dimension lumber. Log ends were painted to denote time classes (Table 1). Lumber was tallied, dried, planed, and the quality of each board was observed and recorded with respect to blue stain, beetle attacks, decay, and other notable characteristics related to delays in processing. Then, NDE characteristics were measured. Length and weight were recorded and density was calculated. Acoustic velocity (AV) and dynamic modulus of elasticity (D_{MOE}) were calculated for each board. In order to reach an approximated 12% moisture content prior to CLT pressing, lumber was kept at an approximate 22°C temperature with 61% relative humidity for 60-90 days. Then, 3-ply CLT panels were prepared from lumber according to time classes between 0 to 6

months. Cold-setting polyurethane was used. After CLT panels preparation, the AV and D_{MOE} were nondestructively evaluated (Figure 1).

Table 1- Log collection times (post felling)

Time ID	Months	Color
0	1	No color --
3	3	Red --
4	4	Blue --
5	5	Green --
6	6	Black --



Figure 1 – Processed lumber (left side) and cross laminated timber manufactured by lumber (right side).

Nondestructive Evaluation

After an approximately two-month long moisture equalization period, moisture content (MC) and NDE data was collected. Moisture content was measured using a Wagner capacitance type meter (model L601-3), specific for nominal 2-inch-thick pine lumber in order to ensure approximately 15% MC remained until NDE tests. Each specimen's thickness, width, and length were measured to the nearest 0.158 cm (1/16th-in.) and weighed to the nearest 0.045 kg (0.1 lb) to determine density (kg/m^3). Acoustic velocity (AV) was measured using a Hitman HM220 instrument and dynamic modulus of elasticity (D_{MOE}) were determined using a Metriguard E-computer (model 340 Transverse Vibration) and then the D_{MOE} were calculated for each board with the following formula,

$$D_{MOE} = \rho \times (AV^2) \quad (1)$$

Where D_{MOE} is dynamic module of elasticity (million psi), ρ is density (kg/m^3), and AV is acoustic velocity (m/s).

Statistical Analysis

Each individual board was considered as the experimental unit and a completely randomized design (CRD) was the experimental design of this study. All data were analyzed using the Two-Way Analysis of Variance (ANOVA) with 2×5 factorial arrangement of treatments to test for the main and interactive

effects of the two CLT panels-lumber group treatments and five time-period treatments. The individual effects of time-on-ground felled timber or CLT panels on AV and D_{MOE} were also analyzed using the One-Way ANOVA. General linear mixed models (PROC GLIMMIX) of SAS 9.4© (SAS, 2013) were used to analyze all data. P-value equal or lower than 0.05 was considered for treatment differences, and treatment means separations was applied using Fishers protected least significant difference (Steel and Torrie 1980). The following statistical model was used for all data.

$$Y_{ijk} = \mu + T_i + M_j + (TM)_{ij} + E_{ij} \quad (2)$$

Where μ was the population mean; T_i was the effect of CLT panels-lumber group treatment ($i = 1$ to 2); M_j was the effect of time classes treatment ($j = 1$ to 5); $(TM)_{ij}$ was the interaction of each CLT panels-lumber group treatment with time classes treatment; and E_{ij} was the residual error.

Results and Discussions

No statistically significant differences in AV were detected among the time classes for the lumber groups ($P_{value} = 0.1779$) (Figure 2-A). However, there was a significant difference in D_{MOE} ($P_{value} = 0.0139$) of the lumber group between the 6-month time class and the 0-, 4-, and 5-month time class (Figure 2-C). For CLT panels, AV ($P_{value} = 0.8571$) and D_{MOE} ($P_{value} = 0.7317$) did not differ at any time intervals (Figure 2-B and D).

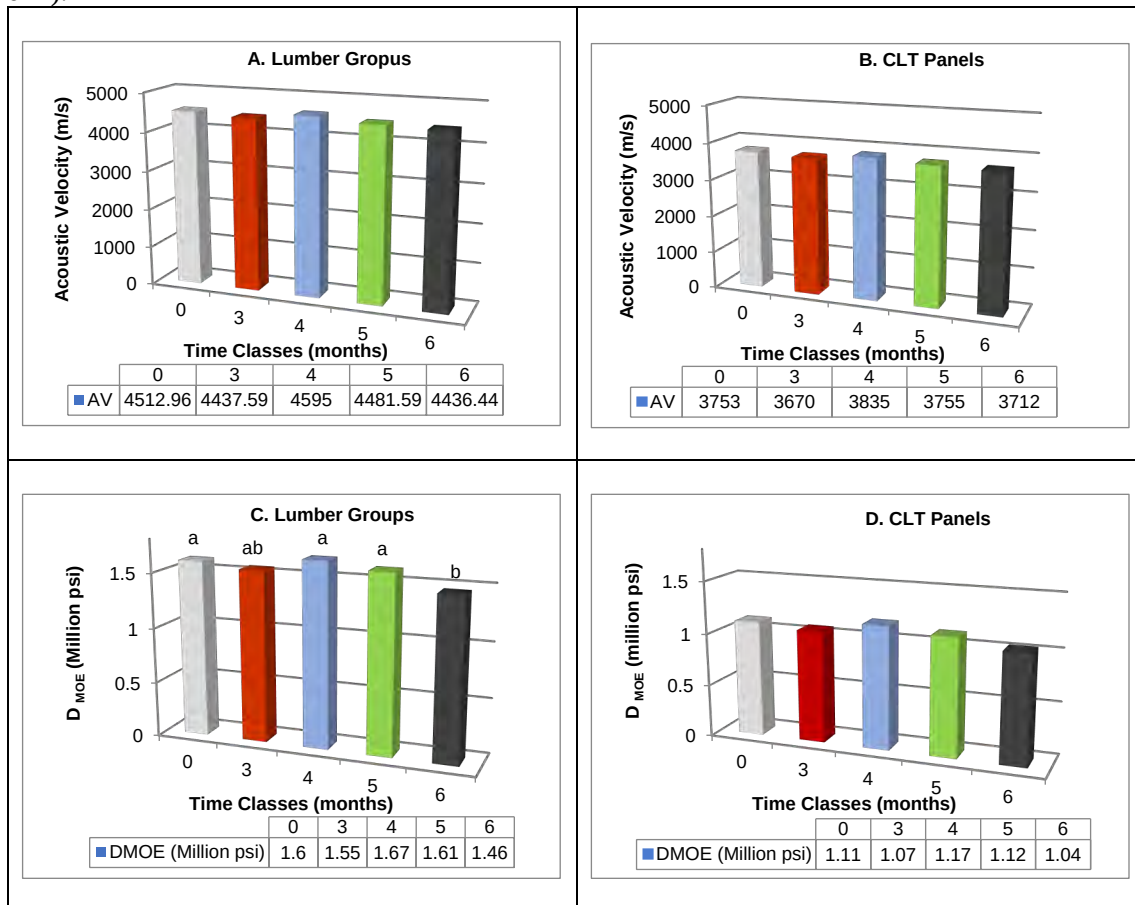


Figure 2- The effects of time-on-ground classes on AV (m/s) and D_{MOE} (million psi) for lumber groups and CLT panels. ^{a,b} Treatment means within each chart with common superscripts were not significantly different ($P \leq 0.05$).

Furthermore, no interaction effects between time classes and CLT panels-lumber group were observed for AV ($P_{value} = 0.9733$) and D_{MOE} ($P_{value} = 0.9932$). No statistically significant differences were detected among time classes for both AV ($P_{value} = 0.7626$) and D_{MOE} ($P_{value} = 0.3796$) regardless of lumber groups and CLT panels. However, AV differed between lumber groups and CLT panels, in which approximately 20% higher AV ($P_{value} = <0.0001$) was observed in lumber groups when compared to CLT panels regardless of time on ground classes (Figure 3-A). Furthermore, lumber groups had a higher D_{MOE} ($P_{value} = <0.0001$) by approximately 40% than those in CLT panels (Figure 3-B).

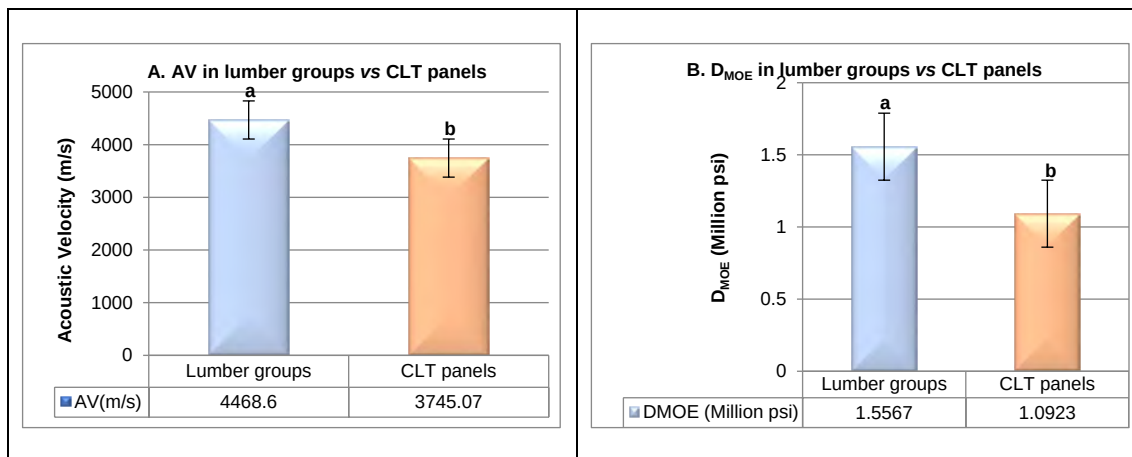


Figure 3- The effects of lumber groups and CLT panels made by the felled pine trees on AV (m/s) and D_{MOE} (million psi). ^{a,b} Treatment means within the same column within effect with no common superscripts are significantly different ($P \leq 0.05$).

The nondestructive results of this study demonstrated that the quality of lumber from the felled trees had little change within the six months on ground. No significant change was found in the performance of CLT manufactured from the lumber of different time classes. This finding is encouraging as it suggests that salvage logging could occur between 0 to 6 months without affecting lumber quality. However, the wood quality of felled trees beyond 6-month on ground is still unknown. More research is needed to assess the effect of longer on-ground time on the quality of both salvaged lumber and CLT.

Conclusion

Herein it was found that time on the ground, up to 6-months, after felling may impact lumber quality. Lumber D_{MOE} was significantly reduced for lumber that was milled from logs that had been on the ground for 6-months.

Acknowledgment

This publication is a contribution of the Forest and Wildlife Research Center, Mississippi State University (MSU). This research was conducted in cooperation with the USDA Forest Service. The authors would like to thank Tanaya Johnson, graduate student at MSU, for helping with the destructive and nondestructive data collection.

References

- Emanuel, K.; Sundararagan, R.; Williams, J. 2008. Hurricanes and global warming: results from downscaling IPCC AR4 simulations. *Bull. Am. Meteorol. Soc.* 89(3): 347-368. <https://doi.org/10.1175/BAMS-89-3-347>.
- Gordon, J.S.; Auel, J.B.; Blair-Agyeman, N.; Montague, I.B.; Shmulsky, R. 2018. Infrastructure enhancement to support value-added bioproduct recovery. *Natural Resources*. 2018,9,129-149. <https://doi.org/10.4236/nr.2018.94009>.
- Knutson, T.R.; Chung, M.V.; Vecchi, G.; Sun, J.; Hsieh, T.L.; Smith, A.J.P. 2021. Climate change is probably increasing the intensity of tropical cyclones. In: le Quere, C., Liss, P., Forster, P. (Eds.), *Critical Issues in Climate Change*. Science Brief Review.
- McNulty, S.G. 2002. Hurricane impacts on U.S. Forest Carbon Sequestration. *Environ. Pollut.* 116, S17-S24. [https://doi.org/10.1016/S0269-7491\(01\)00242-1](https://doi.org/10.1016/S0269-7491(01)00242-1)
- SAS Institute. 2013. SAS Proprietary Software Release 9.4. SAS Inst. Inc., Cary, NC.
- Shmulsky, R.; Jones, P.D. 2019. *Forest Products and wood Science: An Introduction*, 7th ed. Wiley Blackwell. Hoboken, NJ. Chapter 10.
- Shortle, W.C.; Dudzik, K.R. 2012. Wood decay in living and dead trees: A pictorial overview. Tech. Rep. NRS-97. Newtown Square, PA: U.S. Department of Agriculture, Forest Service. 26 p. <https://doi.org/10.2737/NRS-GTR-97>.
- Soge, A.O.; Popoola, I.O.; Adedeji, A. 2020. Detection of wood decay and cavities in living trees: a review. *Canadian Journal of Forest Research*. 51:937-947. <https://doi.org/10.1139/cjfr-2020-0340>.
- Steel, R.G.D.; Torrie, J.H. 1980. *Principles and procedures of statistics. A biometrical approach*. 2nd ed. McGraw-Hill, New York, NY.
- Zielińska, M.; Rucka, M. 2021. Nondestructive testing of wooden elements. *IOP Conf. Ser.: Mater. Sci. Eng.* 1203:032058. <https://doi:10.1088/1757-899X/1203/3/032058>.

Evaluation of Modulus of Elasticity and Modulus of Rupture of Cross-Laminated Timber with Longitudinal Vibration NDE Techniques

Laurice M. Spinelli Correa

Department of Sustainable Bioproducts, Mississippi State University, Starkville, MS, USA,
ls2090@msstate.edu

Frederico José Nistal França

Department of Sustainable Bioproducts, Mississippi State University, Starkville, MS, USA,
fn90@msstate.edu

Rubin Shmulsky

Department of Sustainable Bioproducts, Mississippi State University, Starkville, MS, USA,
rs26@msstate.edu

R. Daniel Seale

Department of Sustainable Bioproducts, Mississippi State University, Starkville, MS, USA,
rds9@msstate.edu

Robert J. Ross

USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, robert.j.ross@usda.gov

C. Adam Senalik

USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, christopher.a.senalik@usda.gov

Abstract

This paper presents research conducted to examine the potential of using longitudinal vibration techniques to evaluate the modulus of elasticity and strength of cross-laminated timber (CLT). Twenty-four CLT panels were manufactured from southern pine dimension lumber in accordance with accepted manufacturing standards. Nominal 2 by 8 in. southern pine lumber specimens were used for the three-ply panels. A 10-ft-long specimen, having a 4.125- by 18-in. cross-section, was obtained from each panel. Weight and dimensions were determined for each specimen, and longitudinal vibration nondestructive evaluation techniques were used to determine frequency of oscillation and energy loss characteristics of the specimens. The dynamic modulus of elasticity was then determined. Each specimen was then tested to failure in a flatwise (third point) bending mode. Flatwise bending modulus of elasticity and strength (modulus of rupture) were determined. Excellent correlative relationships were observed between dynamic and flatwise bending moduli. A strong positive relationship was observed between the dynamic modulus and flatwise bending strength. Nondestructive testing of CLT panels is recommended for quality control protocols.

Keywords: CLT, MOE, MOR, SYP, longitudinal vibration, time domain, frequency domain, strength model.

*This paper was originally published as a FPL Research Paper, FPL-RP-714 (Correa et al. 2022).

Introduction

The use and production of mass timber products in the United States and North America have grown significantly in the past three years. More than 100 structures have been built using cross-laminated timber (CLT) and other mass timber panel products, with hundreds of additional projects under development (WoodWorks 2021). Primary markets include commercial and multifamily residential buildings, but interest in single-family homes and timber bridge decks is growing. Four CLT producers are currently operating in the United States, with at least five more manufacturing facilities announced or under construction. To support production, an American National Standard, Standard for Performance-Rated Cross-Laminated Timber PRG 320 (ANSI/APA 2019), was developed and approved through a consensus process. The original was published in 2017 and updated in 2018 and 2019. Delamination tests and visual quality inspection of panels are required for industrial mass production as part of an in-plant quality control program. CLT is a multilayer wood composite material manufactured from structural lumber. Depending on how the properties of the lumber change or on which adhesive is used, its manufacture may adversely influence its performance. The abilities to detect the presence of delamination and to determine stiffness and strength of CLT are important in its production and in-service.

The wood nondestructive evaluation community has been investigating techniques to locate delamination in wood composite materials since the 1960s. One of the earliest efforts was that of Jayne (1965) and Suddarth (1965), who worked jointly on a study funded by the Department of Defense designed to investigate the possibility of using mechanical impedance to locate poorly bonded or debonded areas in the nose cones of Polaris missiles. A variety of techniques have been investigated since then, with a significant effort aimed at investigating acoustic (stress wave, ultrasound) techniques in a variety of modes (through transmission, pulse echo, contact, noncontact). Most composite manufacturing facilities (oriented strandboard, particleboard, plywood) currently use some type of noncontact acoustic sensing system to monitor their products on-line. They specifically look for delamination, commonly referred to as “blows,” caused by excess steam buildup during the pressing operation. These systems are commercially available. They are designed for use in large production facilities. Portable equipment that utilizes the same concepts is widely available and used for inspection of wood structures around the world.

Several studies (Ross and Pellerin 1988, Vogt 1986) investigated the relationship between sound transmission (sound) and bending and tension strength of wood composites. Excellent correlative models were developed relating sound transmission properties and the strength of wood composites. This research aims to develop (1) quality assurance procedures for monitoring the quality of mass timber and CLT after manufacturing and (2) techniques to assess mass timber in-service. Its objective was to investigate the use of a longitudinal vibration nondestructive technique to predict static bending properties of southern pine CLT panels. To achieve (1) the longitudinal stress wave signal was recorded and analyzed, (2) correlations between nondestructive testing (NDT) variables with CLT stiffness and strength were analyzed, and (3) regression models were developed to predict bending MOE and MOR.

Materials and Methods

Twenty-four 8- by 16-ft (2.43- by 4.88-m) three-ply commercial panels were procured. The panels were made per PRG-320 from 2 by 8 (nominal) No. 2 southern yellow pine (SYP) lumber and with core layer from No. 3 SYP. Table 1 shows the design values for lamination in longitudinal layers. Per ANSI / APA PRG 320-2019, this material is classified as V3. Twenty-eight specimens were tested. One test specimen was ripped from each of 20 panels. From the four panels remaining, two test specimens were ripped. Each

specimen was cut from the original CLT panel and was approximately 4.125 in. (105 mm) thick, 18 in. (457 mm) wide, and crosscut to 120 in. (3.05 m) long.

Table 1: Design values (MPa) for laminations in longitudinal layers, per V3.

F_b^a	Characteristic value ^b	Fb for #2 2x8 lumber ^c	MOE ^c
5.17	10.86	6.38	9,653

a: PRG-320, Table A1; b: PRG-320, Table 1. (Note: F_b = Characteristic value / 2.1); c: SPIB 2014

Final dimensions of each specimen were measured, and weight was recorded for density estimation. Specimen density was determined using the bulk weight and bulk volume. Percentage moisture content (MC) was determined using a Model MMC 220 electric moisture meter (Wagner Meters, Rogue River, Oregon). Longitudinal vibration signal (also called longitudinal stress wave signal) was obtained and recorded for every specimen using a Hitman HM 200 tool (Fibre-gen, Ltd., Christchurch, New Zealand). An impact was applied on each test specimen in the longitudinal direction per ASTM E1876 (ASTM 2015). A consistent impact was done using a hammer, trying to ensure similar level of impact energy for all specimens. Which ply was impacted had no effect because panels vibrated as a single piece. The direction of the wave motion was in the same direction as the longitudinal vibration mode. Dynamic modulus of elasticity (MOE) was calculated for the information collected by the longitudinal vibration tool by applying

$$E_L = \rho v^2 = \rho (2Lf)^2 \quad (1)$$

where E_L is dynamic MOE (MPa), ρ is density (kg m⁻³), L is length of the piece (m), f is first harmonic longitudinal vibration frequency (Hz), and v is wave velocity (m s⁻¹).

A linear regression analysis was conducted to determine the values for the unknown empirical constants, K and x , for flexural MOE and modulus of rupture (MOR), following the procedure described by Senalik and Ross (2015). The model was implemented using the dynamic MOE as the sole nondestructive variable:

$$\ln P = \ln K + x \cdot \ln E_d \quad (2)$$

where P is the property being estimated, K is a constant, and E_d is dynamic MOE.

The Hitman HM 200 software converts the time-domain into a frequency-domain signal through a fast Fourier transform. The software output permits visualization of the time-domain and frequency-domain graph. Identification of the fundamental frequency was possible for every CLT specimen. A consistent longitudinal strike (hammer hit) on the cross section excited the CLT specimen and generated the fundamental frequency. Note that the fundamental frequency is very prevalent, and the sub-sequential harmonics were not detectable for most specimens.

After the acoustic signals were recorded for all specimens, the sample was tested destructively by third point bending over a 9.5-ft (2.9-m) span. This setup provided a span-to-depth ratio of 27.6 and consistent with PRG-320 (ANSI/APA 2019) guidance “specimen width not less than 12 inches (305 mm) and the on-center span equal to approximately 30 times the specimen depth for the tests in the major strength direction...”. Flexure testing was conducted on each specimen using a four-point bending setup per ASTM D 5456 (ASTM 2017a). Evaluation of energy loss (damping) was conducted. The calculation of the frames’ hysteresis damping using the logarithmic decrement (LD) method collected from longitudinal vibration described in Senalik et al. (2020a). LD (recorded in the database for every piece) is calculated from the exponential covering curve over the time-domain sinusoidal curve, given by

$$LD = \beta \cdot t \quad (3)$$

where β is the parameter of the exponential covering curve and t is period of time (s) (the inverse of frequency in Hz).

An approach following the one described by Senalik et al. (2020b) was followed. Preliminary assessment focused on two regions of the time domain signal: the earliest arrival of the signal and late in the signal when the wave energy begins to attenuate. A CLT specimen should have disruption to the wave as it travels due to features such as knots and slope of grain; the signal will be disrupted through reflection, mode conversion, and increased attenuation.

The areas under the curve in the time-domain signal (TDA) and the frequency-domain signals (FDA) in specific segments were calculated. The region between 300 and 400 μ s was chosen for measuring the area in the time-domain signal. The natural frequency peak was the second area measured for each specimen. Statistical analyses and associated graphs were completed according to ASTM D2915 (ASTM 2017b) using SAS version 9.4 (SAS 2013). Bivariate correlations among variables were evaluated. The variables MOE and MOR were used as multiple linear functions of density and NDT properties. To predict MOE and MOR using NDT variables, a stepwise procedure was used for fitting models. For each relationship obtained, the coefficient of correlation (R) and coefficient of determination (R^2) were calculated. The following equations were used to predict MOE and MOR:

$$MOE = f(dMOE, LD, TDA, FDA) + \epsilon_1 \quad (4)$$

$$MOR = f(dMOE, LD, TDA, FDA) + \epsilon_2 \quad (5)$$

Results and Discussion

Table 2 shows result summaries for each physical and mechanical property for the CLT specimens tested. Overall means for MOE and MOR were 8,057 and 34.87 MPa, respectively. The values found in this study showed a narrow range for both properties compared with those of structural lumber. Low coefficient of variation (2.63%) was found for density among specimens. Dynamic MOE values found in this study were lower than the related static MOE values because of the low longitudinal vibration velocities found in CLT compared with those of 2 by 8 SYP lumber ($\sim 4,500$ m s⁻¹) and explained by the lower length-to-width ratio (6.6 to 1).

Table 2. Bending modulus of elasticity (MOE), modulus of rupture (MOR), density, stress wave velocity and dynamic MOE values for CLT specimens.

	MOE (MPa)	MOR (MPa)	Density (kg·m ⁻³)	Velocity (m·s ⁻¹)	dMOE (MPa)	LD	FDA	TDA
Ave	8,057	34.8	535	3,563	6,800	0.04	6,575	940
Min	5,755	23.1	503	3,110	4,865	0.04	4,444	197
Max	10,277	44.9	561	3,940	8,600	0.06	9,541	1817
COV (%)	12.5	14.7	2.63	5.22	12.1	11.3	15.9	57.1

COV = coefficient of variation (%). dMOE – Dynamic modulus of elasticity; LD – Logarithmic Decrement; FDA – Frequency-domain Area; TDA – Time-domain Area

Comparing the static MOE values found in this study with the current design value for 2 by 8 SYP No. 2 lumber (9,653 MPa), the results show that MOE values for CLT specimens were lower than the published design value (American Wood Council 2018). The overall MOR was lower than the values reported for southern pine lumber by other authors: Dahlen et al. (2014; 40.7 MPa) for different No. 2 lumber sizes; Yang et al. (2017; 38.26 MPa) for No. 2 2 by 4; França et al. (2020; 39.60 MPa) for No. 2 2 by 8.

Bivariate correlations among the variables under investigation are presented in Table 3. For MOR, the highest correlation was seen for dMOE ($R = 0.63$). Logarithmic decrement had a negative correlation with MOE ($R = -0.43$) and MOR ($R = -0.26$), where higher decrement is related to weaker pieces. Similar LD results were found by Divós and Sismándi-Kiss (2010) for spruce, larch, and pine structural lumber. França et al. (2019) found an $R = -0.22$ studying southern pine 2 by 4 and 2 by 6 lumber.

Table 3. Pearson's bivariate correlation (R) among modulus of elasticity (MOE), modulus of rupture (MOR), density, longitudinal vibration velocity, dynamic MOE, logarithmic decrement, frequency-domain area, and time-domain area for the tested CLT sample.

	MOE (MPa)	MOR (MPa)	Density (kg/m ³)	Velocity (m/s)	dMOE (MPa)*	LD	FDA	TDA
MOE (MPa)	1	0.58 (<0.01)	0.85 (<0.01)	0.90 (<0.01)	0.95 (<0.01)	-0.43 (0.02)	-0.50 (<0.01)	0.61 (<0.01)
MOR (MPa)		1	0.41 (0.03)	0.57 (<0.01)	0.63 (<0.01)	-0.26 (0.18)	-0.57 (<0.01)	0.62 (<0.01)
Density (kg/m ³)			1	0.67 (<0.01)	0.75 (<0.01)	-0.37 (0.06)	-0.38 (0.05)	0.47 (0.01)
Velocity (m/s)				1	0.98 (<0.01)	-0.50 (<0.01)	-0.48 (0.01)	0.48 (0.01)
dMOE (Mpa)					1	-0.48 (<0.01)	-0.50 (<0.01)	0.54 (<0.01)
LD						1	0.18 (0.35)	-0.27 (0.16)
Frequency-domain area							1	-0.72 (<0.01)
Time-domain area								1

*dMOE – Dynamic modulus of elasticity; LD – Logarithmic Decrement; FDA – Frequency-domain Area; TDA – Time-domain Area

Frequency-domain area had a negative correlation with MOR ($r = -0.57$). It was noticed that narrow base peak contributes to a smaller fundamental frequency area. Timedomain area exhibited a positive correlation with MOR ($r = 0.62$). Higher quality pieces had greater area under the timedomain curve segment. Figure 1 shows linear regression plots for three-ply SYP CLT showing bending MOE vs dynamic MOE and bending MOR vs dynamic MOE.

The R^2 for MOE prediction was 0.90, showing an increase when compared to lumber resulting from the homogeneity of the panels. Yang et al. (2015) studying the prediction of MOE of southern pine dimensional lumber using longitudinal vibration waves found R^2 values ranging from 0.77 to 0.86. França et al. (2020) studying SYP No. 2 lumber found a higher $R^2 = 0.76$ and 0.77 (2 by 8 and 2 by 10, respectively) using the Director HM 200. The results found in this study emphasize the potential of longitudinal vibration wave techniques to estimate MOE.

Although the results for predicting static MOE are favorable and accurate ($R^2 = 0.90$), the relationships for MOR are still limited (Fig. 1). The R^2 for MOR prediction found in this study was 0.33. Yang et al. (2017) found R^2 values for dMOE and bending MOR ranging from 0.23 to 0.28. França et al. (2020) studying SYP No. 2 lumber found $R^2 = 0.15$ and 0.20 (2 by 8 and 2 by 10, respectively) using the Director HM 200.

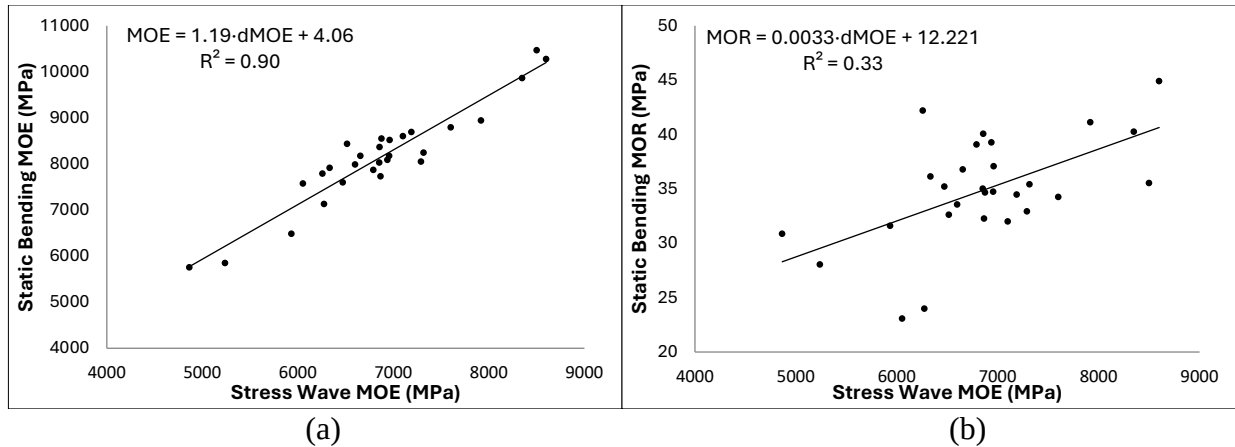


Figure 1 – Linear regression plots for 3-ply SYP cross laminated timber showing (a) bending MOE vs dynamic MOE, and (b) bending MOR vs dynamic MOE.

Two possible outliers were detected in Figure 6b. Further evaluation of the specific specimens led to the detection of knots on the tension surface of the specimen. Although the knots affected panel performance, the size of the knots are accepted in visually No. 2 graded lumber. The presence of knots on the tension face reduced the static bending strength values of the two specimens. Moreover, higher grade lumber on outer layers is recommended and would increase strength values of CLT panels.

The natural logarithmic relationship between predicted bending MOE and static bending MOE is shown in Figure 2 (left). Data from this study were compared with data of Ross and Pellerin (1988) from a wide range of composite panels. The $R^2 = 0.93$ value from the composite specimens was slightly higher than that of the CLT specimens ($R^2 = 0.90$). It can be concluded that the CLT specimens fit in the original MOE composite model from Ross and Pellerin (1988) reconstructed by Senalik and Ross (2015).

The relationship between predicted natural logarithmic MOR and bending MOR from the CLT specimen testing is shown in Figure 2 (right). Once again, the CLT specimens fit in the original MOR composite model from Ross and Pellerin (1988). However, the $R^2 = 0.33$ value from the CLT specimens was significantly lower than that of the composite specimens ($R^2 = 0.89$) from Ross and Pellerin (1988).

After evaluating the potential of dMOE on CLT stiffness and strength prediction, more nondestructive variables exhibiting potential use were added to the models to improve the prediction of MOE and MOR. Several studies showed the benefit of combining different grading variables (Diebold et al. 2000, Denzler et al. 2005, Hanhijarvi and Ranta-Maunus 2008, França et. al. 2019).

To determine the best-fit multiple regression equation, a stepwise regression approach was employed. Tables 4 and 5 show the regression model, coefficient of determination (R^2), standard error, and improvement of the linear regression for MOE and MOR on CLT sample. Time-domain area was the most significant secondary variable to predict MOE ($R^2 = 0.91$), adding an improvement of 5.33%. The combination of dMOE with TDA + FDA, and TDA + FDA + LD presented slightly higher R^2 (0.91 and 0.92, respectively) but were not significant. In addition, the combination of these variables resulted in higher standard error when compared to dMOE + FDA model (Table 4).

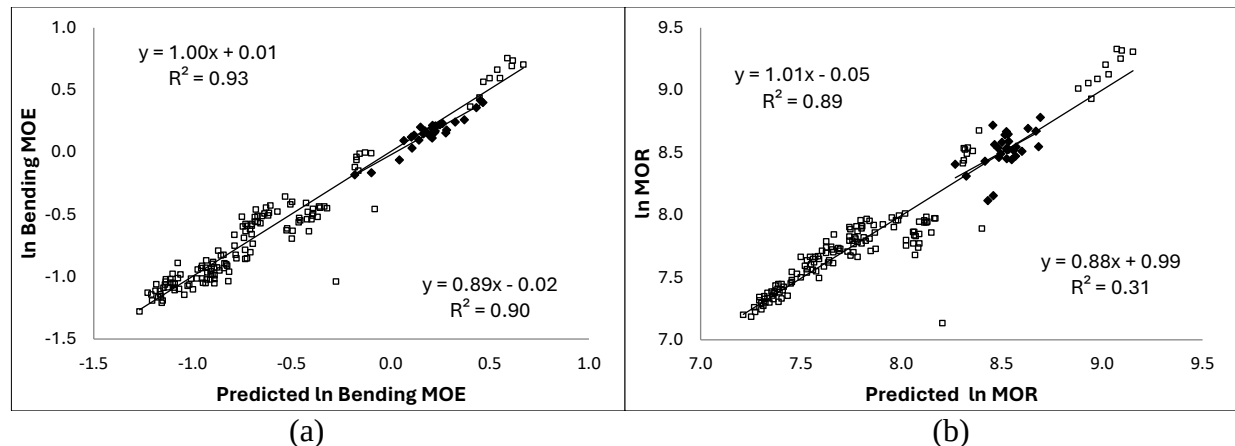


Figure 2 – Natural logarithmic of (a) predicted bending MOE vs bending MOE, and (b) predicted MOR vs bending MOR.

Table 4 — Modulus of elasticity (MOE) regression model, coefficient of determination (R^2), p-value, standard error of the estimate, and improvement of the linear regression.

Modulus of elasticity (MOE)	R^2	Standard error (MPa)	Improvement (%)*
Dynamic MOE (dMOE)	0.90	346.9	—
dMOE + LD	0.90	352.7	-1.67
dMOE + FDA	0.90	351.3	-1.27
dMOE + TDA	0.91	328.4	+5.33
dMOE + TDA + FDA	0.91	331.3	+4.50
dMOE + TDA + FDA + LD	0.92	336.4	+3.03

* Improvement (%) is in reference to the single predictor dMOE; All regressions were significant ($p < 0.01$).

Logarithmic decrement did not support the MOE and MOR prediction ($R^2 = 0.90$ and 0.33 , respectively). Time-domain area exhibited a potential increase of 8.52% when combined with dMOE ($R^2 = 0.46$). The combination of all NDT variables slightly improved the regression model ($R^2 = 0.48$). However, the model was not significant (Table 5).

The result shows that the capability of prediction can be improved when two or more variables are added to the model. The result agrees with Senalik et al. (2020b), who found an increase in R^2 from 0.52 to 0.71 testing southern pine lumber pieces. The regression equations with the best models to predict MOE and MOR are shown in Table 6. Models with independent variables whose addition did not improve the model are not shown. Figure 3 shows linear regression plots for three-ply SYP CLT using the models from Table 6. Predicted MOE using the generated model slightly improved the MOE estimation (from $R^2 = 0.90$ to $R^2 = 0.91$). In contrast, using two nondestructive variables substantially improved the prediction of the bending MOR ($R^2 = 0.33$ to $R^2 = 0.46$).

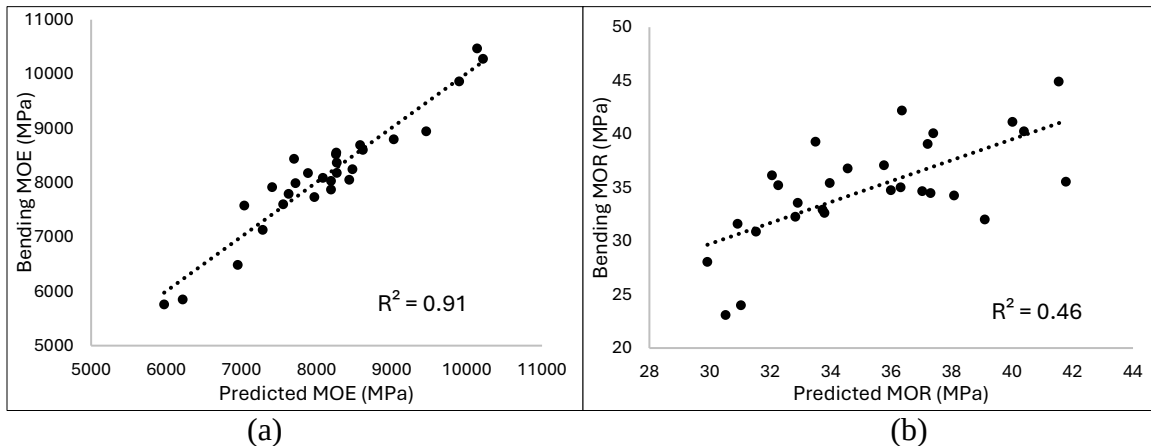
Table 5 — Modulus of rupture (MOR) regression model, coefficient of determination (R^2), p-value, standard error of the estimate, and improvement of the linear regression.

Bending strength (MOR)	R^2	Standard error (MPa)	Improvement (%)*
Dynamic MOE (dMOE)	0.33	4.11	—
dMOE + LD	0.33	4.19	-1.94
dMOE + FDA	0.44	3.84	+6.57
dMOE + TDA	0.46	3.76	+8.52
dMOE + TDA + FDA	0.48	3.77	+8.27
dMOE + TDA + FDA + LD	0.48	3.85	+6.33

* Improvement (%) is in reference to the single predictor (dMOE); All regressions were significant ($p < 0.01$).

Table 6 – Linear regression models with the largest coefficient of determination (R^2) and smallest error of estimate (μ) for dependent variables modulus of elasticity (MOE) and modulus of rupture (MOR).

	β_0	β_1	β_2	μ	R^2	Durbin-Watson
$MOE = \beta_0 + \beta_1 \cdot dMOE + TDA$	388	1.09	0.27	328	0.91	2.26
$MOR = \beta_0 + \beta_1 \cdot dMOE + TDA$	17.63	0.002	0.004	3.76	0.46	1.45

**Figure 3** – Linear regression plots for 3-ply SYP cross laminated timber showing (a) predicted MOE vs bending MOE, and (b) predicted MOR vs bending MOR.

Conclusions

- Longitudinal vibration dynamic modulus of elasticity exhibited a high correlation with bending properties of CLT.
- Longitudinal vibration can be used to evaluate bending properties of CLT panels.
- The presence of knots on the outer layers of panels affected the strength the panels. Therefore, lumber with higher quality should be recommended for external layers.
- The addition of frequency-domain area in the regression model improved the MOE prediction.
- The addition of time-domain area in the regression model improved the MOR prediction.
- NDT evaluation of CLT panels is recommended for quality control protocols.

Acknowledgments

This research was funded by a grant from USDA Forest Service. This publication is a contribution and is approved as journal article SB 1044 of the Forest and Wildlife Research Center, Mississippi State University.

References

ANSI/APA. 2019. 2018. PRG 320-2019. Standard for performance-rated cross-laminated timber. Tacoma, WA: APA–The Engineered Wood Association.

ASTM. 2015. E1876: Standard test method for dynamic Young's modulus, shear modulus, and Poisson's ratio by impulse excitation of vibration. West Conshohocken, PA: American Society for Testing and Materials.

ASTM. 2017a. D5456: Standard specification for evaluation of structural composite lumber products. West Conshohocken, PA: American Society for Testing and Materials.

ASTM. 2017b. D2915: Standard practice for sampling and data-analysis for structural wood and woodbased products. West Conshohocken, PA: American Society for Testing and Materials.

American Wood Council. 2018. National Design Specification (NDS) Supplement: Design Values for Wood Construction 2018 Edition. Leesburg, VA. May 2018.

Correa, Laurice Mara Spinelli; França, Frederico José Nistal; Shmulsky, Rubin; Seale, R. Daniel; Ross, Robert J.; Senalik, Christopher. 2022. Evaluation of modulus of elasticity and modulus of rupture of cross-laminated timber with longitudinal vibration NDE techniques. Research Paper FPL-RP-714. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 9 p.

Dahlen, J.; Jones, P.D.; Seale, R.S.; Shmulsky, R. 2014. Bending strength and stiffness of wide dimension southern pine No. 2 lumber. *European Journal of Wood and Wood Products*. 72(6): 759–768.

Denzler, J.; Diebold, R.; Glos, P. 2005. Machine strength grading—commercially used grading Machines—current developments. In: *Proc., 14th international symposium on nondestructive testing of wood*: 9–16.

Diebold, R.; Schleifer, A.; Glos, P. 2000. Machine grading of structural sawn timber from various softwood and hardwood species. In: *Proc., 12th international symposium on nondestructive testing of wood*: 139–146.

Divós, F.; Sismándi-Kiss, F. 2010. Strength grading of structural lumber by portable lumber grading—effect of knots. In: *The future of quality control for wood & wood products*. 4–7 May 2010, Edinburgh, Final Conference of COST Action E53.

França, F.J.N.; Seale, R.D.; Shmulsky, R.; França, T.S.F.A. 2019. Modelling mechanical properties of 2 × 4 and 2 × 6 southern pine lumber: longitudinal vibration and visual characteristics. *Forest Products Journal*. 68(3): 286–294.

Franca, F.J.N.; Franca, T.S.F.A.; Seale, R.D.; Shmulsky, R. 2020. Nondestructive evaluation of 2 by 8 and 2 by 10 southern pine dimensional lumber. *Forest Products Journal*. 70(1): 79–87.

Hanhijärvi, A.; Ranta-Maunus, A. 2008. Development of strength grading of timber using combined measurement techniques—report of the Combigrade-project—phase 2. Espoo, Finland: VTT Publications 686.

Jayne, B.A. 1965. The concept of mechanical impedance and its application to nondestructive testing. In: *Proceedings, second nondestructive testing of wood symposium*. Spokane, WA: Washington State University: 245–266.

Ross, R.J.; Pellerin, R.F. 1988. NDE of wood-based composites with longitudinal stress waves. *Forest Products Journal*. 38(5): 39–45.

SAS. 2013. SAS version 9.4. Cary, NC: SAS Institute Inc.

Senalik, C.; Ross, R.J. 2015. Predicting plywood properties with wood-based composite models. In: Proceedings: 19th international nondestructive testing and evaluation of wood symposium. General Technical Report FPL–GTR–239. Madison, WI: USDA Forest Service, Forest Products Laboratory.

Senalik, C.; França, F.J.N.; Seale, R.D.; Ross, R.J.; Shmulsky, R. 2020a. Estimating lumber properties with acoustic-based technologies—part 1: modeling acoustic (stress) wave behavior in clear wood and lumber. *Wood and Fiber Science*. 52(4): 380–389.

Senalik, C.; França, F.J.N.; Seale, R.D.; Ross, R.J.; Shmulsky, R. 2020b. Estimating lumber properties with acoustic-based technologies—part 2: ultimate tension stress estimation from time- and frequency-domain parameters. *Wood and Fiber Science*. 52(4):3 90–399.

SPIB. 2014. Standard grading rules for southern pine lumber, table 1-c-structural light framing, structural joists and planks, and studs—2" to 4" thick (8"-wide only). Pensacola, FL: Southern Pine Inspection Bureau. Suddarth, S.A. 1965. Detection of adhesive bond defects in the Polaris missile nose fairing through mechanical impedance measurements. In: Proceedings, second nondestructive testing of wood symposium Spokane, WA: Washington State University: 267–287.

Vogt, J.J. 1986. Longitudinal stress waves as predictors of internal bond strength. In: Proceedings, 12th international particleboard/composite materials symposium. Pullman, WA: Washington State University.

WoodWorks. 2021. Building trends: mass timber: quarterly update + map of U.S. mass timber projects. Washington, DC: Woodworks. <https://www.woodworks.org/publicationsmedia/building-trends-mass-timber/>

Yang, B.Z.; Seale, R.D.; Shmulsky, R.; Dahlen, R.J.; Wang, X. 2015. Comparison of nondestructive testing methods for evaluating No. 2 southern pine lumber: part A, modulus of elasticity. *Wood and Fiber Science*. 47(4): 375–384.

Yang, B.Z.; Seale, R.D.; Shmulsky, R.; Dahlen, R.J.; Wang, X. 2017. Comparison of nondestructive testing methods for evaluating No. 2 southern pine lumber: part B, modulus of rupture. *Wood and Fiber Science*. 49(2): 134–145.

Session 4

**Urban Tree Inspection
and Risk Analysis**

Non-Destructive Tomographic Testing on Monumental Trees in the Sila National Park – South Italy

Andrea R. Proto*

Department of AGRARIA, University of Reggio Calabria, Italy, andrea.proto@unirc.it

Federica Perri

Department of AGRARIA, University of Reggio Calabria, Italy, federicaperri93@live.it

Ilario Treccosti

Sila National Park, Via Nazionale, 87055 Lorica (CS), direttore@parcosila.it

Francesco Curcio

Sila National Park, Via Nazionale, 87055 Lorica (CS), presidente@parcosila.it

Giuseppe Zimbalatti

Department of AGRARIA, University of Reggio Calabria, Italy, gzimbalatti@unirc.it

Salvatore F. Papandrea

Department of AGRARIA, University of Reggio Calabria, Italy, salvatore.papandrea@unirc.it

* Corresponding author

Abstract

In Italy, ancient forests have an importance recognized throughout the world, they are ecosystems that have reached maturity without disturbances during their life and growth cycles. Inside them we very often find some majestic arboreal specimens of large and tall trunks defined as "Monumental Trees". This definition was adopted in Italy thanks to some legislative regulations (Law n. 10/2013; Law n. 1497/1939) which introduce the univocal legal definition of "Monumental Tree" at a national level. Several parameters are necessary for the tree to be listed as monumental: significant age and size, peculiar shape, ecological value, botanic rarity, plant architecture, landscape value and historical-cultural-religious aspects. In Italy, an important reserve of old-growth forest is located in the Sila National Park, South Italy. This is the Fallistro Biogenetic Nature Reserve, a precious forest heritage made up of centuries-old trees of *Pinus nigra* J.F. Arnold subsp. *calabrica* (Poir.) locally known as "Giants of Sila". This majestic, ancient woodland in the centre of Calabria region preserves 58 examples of corsican pine trees which are estimated to be over 350 years old. These pine trees of indescribable dimensions, reach up to 45 meters in height and have a diameter that reaches even 2 meters. Each of the trees, in fact, could endanger the safety of users and tourists who flock to visit the site every day. Therefore, the aim of this study has been to examine the health status of the monumental trees located in the Fallistro Nature Reserve and identify the most significant morphological character (height, diameter, tree architecture, slenderness) correlated to the result of the tomographic measurement. In this study, 20 ancient trees of *Pinus nigra* J.F. Arnold subsp. *calabrica* (Poir.) were examined.

Keywords: Tomography, ancient forests, Giants, Fallistro

A New Tomographic Device for the Non-Destructive Testing of Trees—25 Years On

Steffen Rust *

University of Applied Science and Art, Göttingen, Germany, steffen.rust@hawk.de

Lothar Göcke

lothar.goecke@web.de

Josefine Liebisch

University of Applied Science and Art, Göttingen, Germany, josefine.liebisch@stud.hawk.de

* Corresponding author

Abstract

Tree risk assessment has greatly benefited from technological advancements in non-destructive testing of trees. This paper presents a novel tomographic device with innovative features, such as automatic tapping with defined strength and a system for recording and analyzing the full signal spectrum, including frequency and damping characteristics. Additionally, the device has an improved method for easily recording sensor positions, which streamlines the data acquisition process.

The innovative instrument has shown promising preliminary results. The data now available opens up new possibilities for multivariate analysis of time of flight, frequency and signal attenuation and will thus lead to better detection of internal defects in trees. The automatic signal excitation and recording of sensor positions hold remarkable potential for application in previously challenging or inaccessible situations, i.e. operation from aerial platforms or by climbing arborists. This paper presents initial findings, detailing the device's operational mechanism, its application in real-world scenarios, and its potential impact on the future of tree risk assessment.

Keywords: urban forestry, tree risk assessment, tomography, stress wave, time of flight

Introduction

A wide range of methods and tools are available to aid in the process of tree risk assessment (Rust and van Wassenae 2017). Most trees can be assessed visually, but when the likelihood of failure remains uncertain after a visual inspection, several tools can be used to measure the extent of decay, loss of strength, or anchorage. ISA's Best Management Practices (Smiley, Matheny, and Lilly 2011) define different levels of tree risk assessment, (limited visual, basic and advanced) while guidance in Germany defines only two levels, which correspond to the ISA's 'basic' and 'advanced'. A basic assessment is a detailed visual inspection of the entire tree, both from a distance and close, staying on the ground, optionally using simple tools like a mallet. If the basic assessment is not sufficient to evaluate the risk of failure of a tree, advanced assessments can provide specific information about the tree, targets or the site. Only a very small fraction of all inspected trees should require advanced assessment.

Advanced assessment does not necessarily involve high-tech instruments. Often, aerial inspection, either from an aerial lift, a ladder, or by climbing the tree, will help to assess features invisible from the ground, such as cracks, included bark, codominant stems, or decay on the upper side of branches. But most advanced methods are used either to map internal decay, to assess root loss and its effects on anchorage, or to investigate pathogens. They measure physical properties of the wood, the geometry of the stem and the decay, or the reaction of the tree when a load is applied, to assess the likelihood of failure.

The most common way to assess the strength of a tree part is based on the distribution of sound wood. The size and position of decay, cracks, or included bark in the trunk or branches can be measured with a variety of tools. They vary in terms of damage to the tree, spatial resolution, and parameters measured. Commonly used tools yield results along one line or across a thin cross-section of the tree. The measuring level on the stem and, in the case of drilling devices, the point or points to assess, must be carefully identified. A visual inspection and a mallet are often used to detect areas of weakness for further assessment. Once a preliminary inspection has identified areas of potential weakness, the extent of decay versus solid wood can be mapped using drilling devices or tomographs.

The advent of sonic and electrical resistivity tomographs around the start of the millennium has significantly advanced the field of tree tomography for risk assessment (Rust 2001; Rust et al. 2007; Just and Jacobs 1998; Nicolotti and Miglietta 1998). These innovative techniques have greatly increased the precision in detecting internal defects and decay in tree trunks – issues that traditional visual assessments often miss.

While stress wave tomographs have made strides in unveiling the internal characteristics of trees, their capacity to pinpoint the exact causes of low velocity in cross-sections – which could range from cracks, decay, to cavities – remains a challenge (Burcham et al. 2019). This study tested a new variant of stress wave tomographs. This advanced model extends its data collection capabilities beyond current market offerings and integrates automated signal excitation to enhance reproducibility.

Methods

Trees

This study focused on a diverse range of tree species (see Table 1) distributed across various German cities, including Bremen, Pillnitz near Dresden, Göttingen, Jena, and Leipzig. The trees were primarily located in parks and forests, with a smaller number in urban areas as street trees. Each tree had either single or multiple measuring levels, as well as levels with one or more impactor measurements, depending on the number of sensor positions present at each level. A total of at least 12 measurement points per level were employed to ensure comprehensive data collection.

At the outset of this study, trees with sound wood and nearly round stems were selected to create a consistent data set. This homogeneous data set allowed for the exploration of potential influences of experimental factors, including tapping strength, tree dimensions, sensor distance, and tree species. In the project's second phase, which has recently commenced, trees with various defects, including cracks, holes, and decay in different stages from various fungi, have also been measured. Following the completion of the measurements, some trees have been felled in order to obtain stem discs. This sampling method enables further investigation into the relationship between sonic signals and actual wood quality, thereby strengthening our understanding of the role sonic tomography can play in the conservation and management of trees.

Table 1 - Overview over the trees measured

Species	n	Measurements	Circumference at measuring level [cm]
<i>Acer platanoides</i>	13	49	131 - 253
<i>Aesculus hippocastanum</i>	2	3	230
<i>Fagus sylvatica</i>	19	96	149 - 362
<i>Fraxinus excelsior</i>	10	32	121 - 270
<i>Gymnocladus dioicius</i>	1	4	na
<i>Picea abies</i>	18	54	153 - 311
<i>Pinus nigra</i>	9	27	142 - 343
<i>Quercus robur</i>	17	67	135 - 361
<i>Quercus rubra</i>	2	6	278
<i>Robinia pseudoacacia</i>	1	6	16 - 84

Tomography

Data were collected using the prototype of a new tomograph, called “impactor”. Reference measurements were also done with the IML Picus Sonic Tomograph Version 3 and the IML Electrical Resistance Tomograph Version 3.

The impactor represents a significant departure from traditional sonic tomographs, featuring a central unit equipped with 12 multifunctional transceivers. These transceivers serve as both sound transmitters and receivers, housing impact engines to generate mechanical impulses and sensors to detect incoming sound waves. This enables the impactor to strike the tree with consistent force and record the resulting vibrations in the wood. The device can capture one million data points per second, which are then transmitted to a PC via an USB connection for further analysis. Sample rate and impact force were varied to analyze the effect on data quality.

The impactor also incorporates an innovative sensor positioning system, leveraging pattern recognition technology to determine the location of sensors around the tree's cross-section. This process can be conveniently performed using a smartphone or tablet, with the positions of the nail tips securing the transceivers to the wood calculated automatically, thereby streamlining the measurement process.

Data analysis

The collected data was processed using Python, where parameters such as dominant frequency and signal amplitude were estimated through the application of Fast Fourier Transformation (FFT). Additional features were created using CATCH22 (Lubba et al. 2019). Subsequent analysis was conducted using R, with experimental effects modelled using mixed-effect models. For this study, we concentrated on data collected with a sample rate of 5µs and healthy trees, plus a data set of *F. sylvatica* infected by *K. deusta*, which we used to train an XGBoost model for defect prediction.

Results

Depending on the distance between sender and receiver, the frequency of signals significantly varied with impact intensity (Figure 1). This effect was, however, very small. At the highest strength, the frequency was stable over the entire range of distances. Furthermore results show a significant difference between the main frequencies depending on the tree species (Figure 2). They slightly varied with sensor distance.

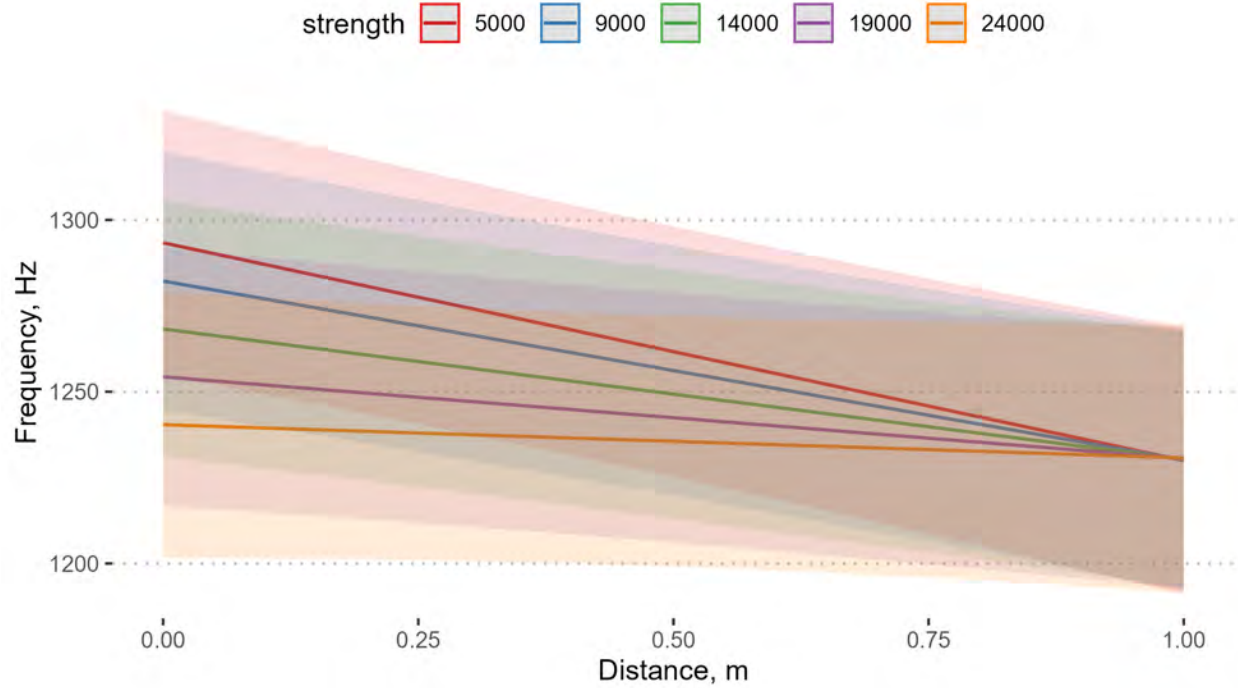


Figure 1 - At lower excitation strengths, the main frequency of the signal was slightly distance dependent.

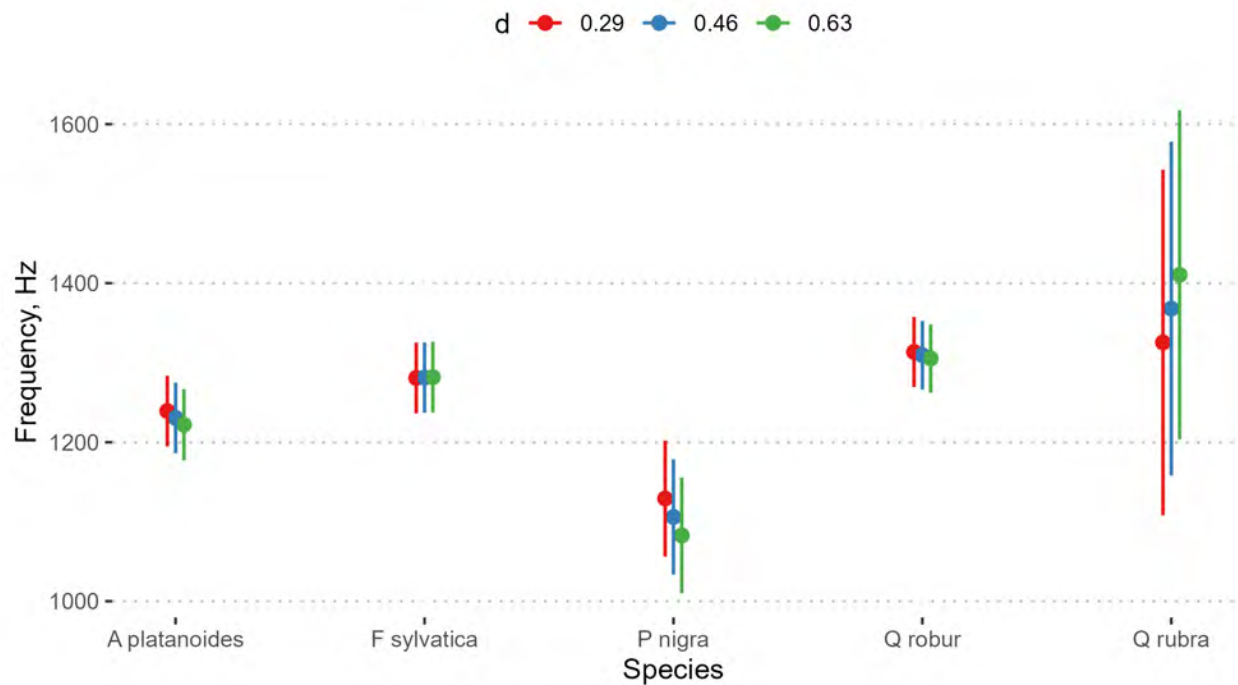


Figure 2 - The main frequency of signals differed significantly between species and varied slightly with sensor distance.

Brittle Cinder (*Kretschmaria deusta*)

The presence of defects affected the shape of signals profoundly. Figure 3 and Figure 4 present different sender-receiver combinations with one receiver situated in decayed wood (Receiver 7, blue), represented by distinct colors. Weaker signals were associated with decayed wood, even when they had the same distance from the sender. Furthermore, signals from decayed wood were more chaotic, exhibiting less order. Decayed wood did not produce signals with high frequencies (above 2500 Hz).

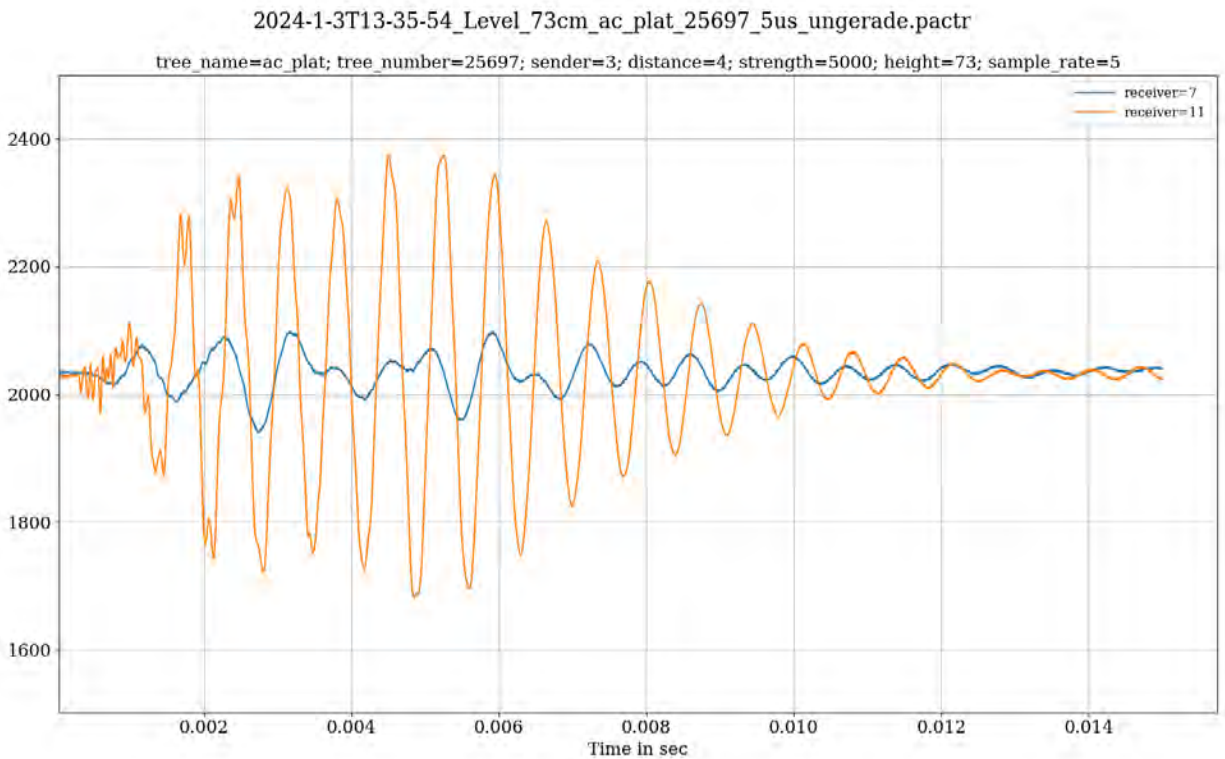


Figure 3 - The amplitude of the sonic signal differs, depending on whether the receiver is situated in sound wood (orange, Receiver 11) or decayed wood (blue, Receiver 7).

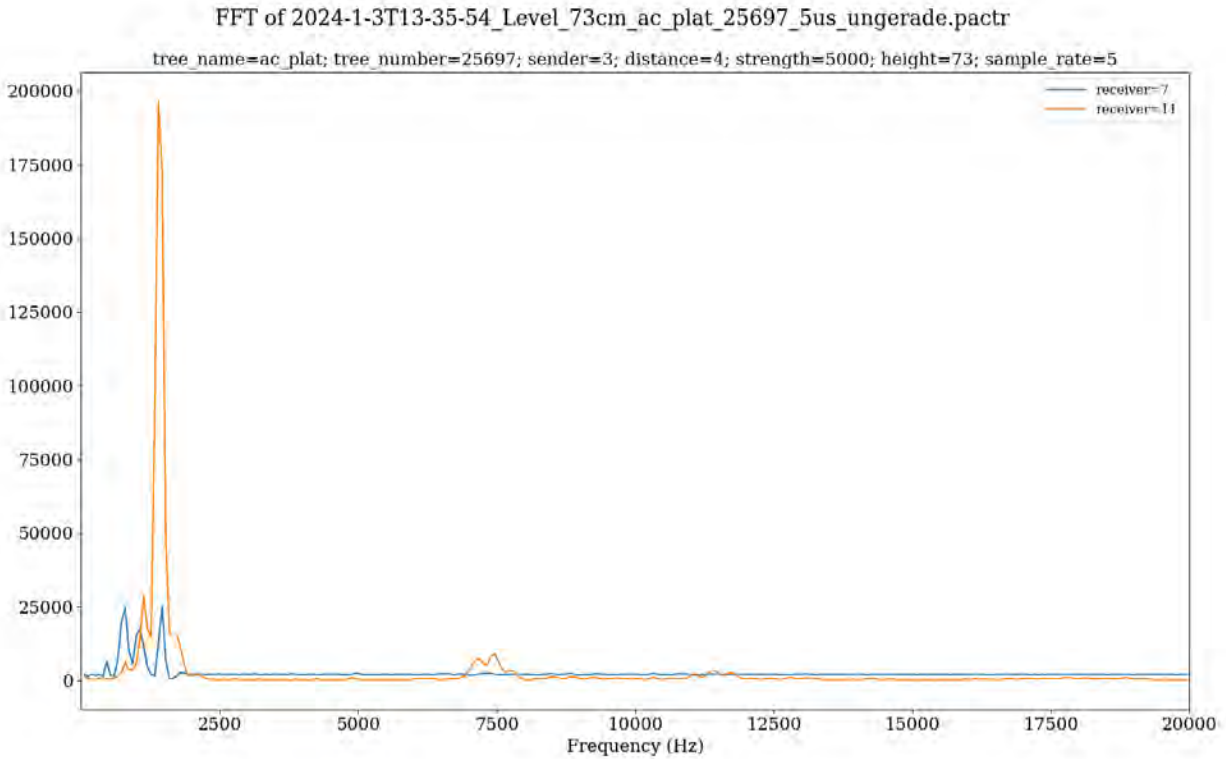


Figure 4 - Corresponding FFT to Figure 3, displaying a chaotic signal without high frequencies at Receiver 7.

Both, velocity and presence of brittle cinder had highly significant effects on the amplitude of a signal. Brittle cinder reduced the amplitude across the range of velocity (Figure 5). XGBoost predicted the presence of brittle cinder from the signal (without information on time of flight) with an accuracy of 0.98.

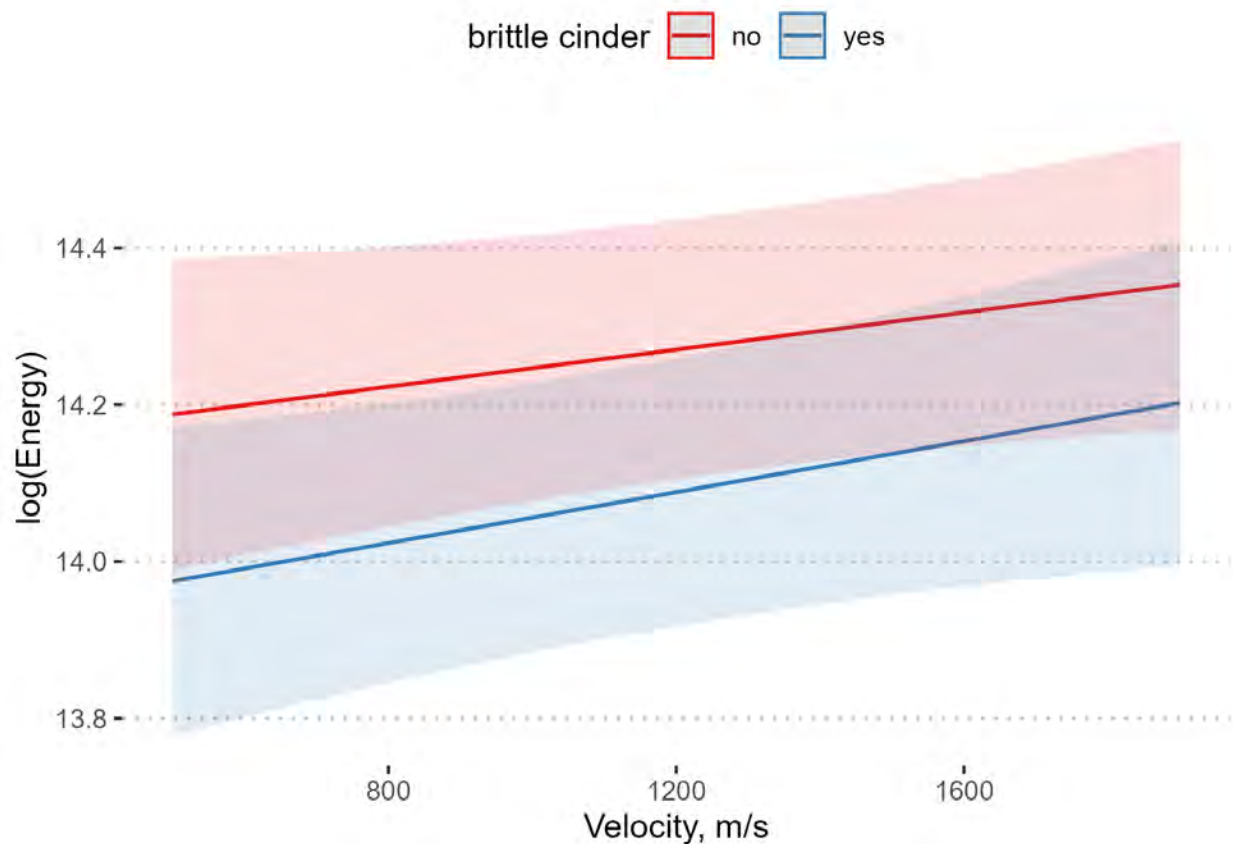


Figure 5 - The energy contained in a signal was significantly reduced in the presence of brittle cinder.

Discussion

Acoustic tomography has become an indispensable tool for assessing the health and stability of trees. However, the information they currently provide about defects in the cross section of a tree is somewhat limited, potentially impacting proper management decisions. Despite the wealth of data collected by these tomographs, our study was primarily driven by the hypothesis that even more useful information could be gleaned from the stress wave signals beyond the time of flight.

In this study, we tested a novel type of sonic tomograph under consistent conditions across different standing trees. We sought to identify new ways in which sonic signals could improve the detection and understanding of different defects within a tree, thereby enhancing the ability of assessors to make informed decisions about tree preservation.

Somewhat surprisingly, we found that the strength of the initial knock, although small, played a significant role in sonic tomography. This result confirmed previous findings by Aurich (2017), highlighting the importance of consistent tapping strength. Furthermore, we found that brittle cinder could be detected without relying solely on time-of-flight analysis, highlighting the added value of studying the sonic signal as a multi-component entity.

Our results regarding the range of dominant frequencies also correlated strongly with those of Craighead et al. (2001), adding to a growing body of research in this area. However, our current approach focuses on analyzing the frequency and energy of a sound signal, and we recommend that future considerations include the analysis of amplitudes or time of flight for a more comprehensive understanding.

The promising results of our study set the stage for future exploration and optimization of acoustic tomography. In particular, future research should focus on comparing sonic signals with actual wood quality using collected stem discs. This could provide further evidence of the ability of the sonic tomograph to detect changes in wood properties. Our first step in the detection of brittle cinder is significant, and it is hoped that these findings will stimulate future research that seeks to better exploit the potential within sonic signal analysis.

Acknowledgment

We would like to acknowledge Christian Brock for implementing the Python scripts. We would also like to thank our fellow students J. Nieland, M. Oertel, Y. Quast, P. Ulrich and J.-P. Herbers and his colleagues from the tree service company Der Baummarder for collecting the data. Another thank you goes to the city administrations of Bremen and Leipzig, to the forest administrations of Reinhausen near Göttingen and Jena and to the park administration of Pillnitz palace near Dresden that made their trees available for our measurements.

References

- Aurich, Morris. 2017. “Einfluss der Klopfstärke auf die Schalltomographie.” BSc, Göttingen: HAWK - Hochschule für angewandte Wissenschaft und Kunst, Hildesheim/Holzminde/Göttingen.
- Burcham, Daniel C., Nicholas J. Brazee, Robert E. Marra, and Brian Kane. 2019. “Can Sonic Tomography Predict Loss in Load-Bearing Capacity for Trees with Internal Defects? A Comparison of Sonic Tomograms with Destructive Measurements.” *Trees-Structure and Function* 33 (3): 681–95.
- Craighead, Ian A., S. Thackery, M. Redstall, and M. R. Thomas. 2001. “Monitoring Wood Decay in Poles by the Vibroacoustic Response Method.” *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 215 (8): 905–17.
- Just, A., and F. Jacobs. 1998. “Elektrische Widerstandstomographie zur Untersuchung des Gesundheitszustandes von Bäumen.” In VII. Arbeitsseminar “Hochauflösende Geoelektrik”, 3.-5.11.1998, edited by Erik Danckwardt. Bucha/Sachsen: Institut für Geophysik und Geologie der Universität Leipzig.
- Lubba, Carl H., Sarab S. Sethi, Philip Knaute, Simon R. Schultz, Ben D. Fulcher, and Nick S. Jones. 2019. “Catch22: CAnonical Time-Series CHaracteristics.” arXiv. <http://arxiv.org/abs/1901.10200>.
- Nicolotti, Giovanni, and Paolo Miglietta. 1998. “Using High Technology Instruments to Assess Defects in Trees.” *Journal of Arboriculture* 24 (6): 297–302.
- Rust, S. 2001. “A New Tomographic Device for the Non-Destructive Testing of Standing Trees.” *Ndt* 6.
- Rust, S., and P. van Wassenae. 2017. “Tools for Tree Risk Assessment.” In *Routledge Handbook of Urban Forestry*.
- Rust, Steffen, Lothar Göcke, U. Weihs, T. Günther, and C. Rücker. 2007. “Combining Sonic and Electric Impedance Tomography for Nondestructive Testing of Trees.” In *Proceedings of the 15th International Symposium on Nondestructive Testing of Wood*. September 10-12, 2007. Duluth, MN, USA: Forest Products Society.
- Smiley, Edgar Thomas, Nelda P. Matheny, and Sharon Lilly. 2011. *Tree Risk Assessment. Best Management Practices*. Champaign, Illinois: International Society of Arboriculture.

Urban Tree Root Stability—A Possible New Approach

Ferenc Divos

R&D Coordinator, FAKOPP enterprise, Hungary

Professor, Hungarian University of Agriculture and Life Sciences, Godollo, Hungary divos@fakopp.com

Lajos Puskas

President, "Park-Erdo Studio" company, Hegyko, Hungary, puskas.lajos@park-erdo.hu

Laszlo Bejo *

Professor, University of Sopron, Hungary, bejo.laszlo@uni-sopron.hu

* Corresponding author

Abstract

Currently, there are two methods for tree root stability evaluation: the pulling test and the dynamic root stability test. While these are the most trustworthy, proven methods for stability testing, arborists sometimes use a more subjective approach. While climbing or working on trees, they sometimes get a “bad feeling” that the tree is unsafe. This subjective impression later often turns out to be accurate and the tree fails in high wind or is condemned based on instrumental testing. This suggests a possible new approach for instrumental tree stability evaluation.

The experimental work involved measuring the inclination of several trees while arborists were climbing them, to pick up the vibrations of the tree generated by climbing and working in the tree. Inclination sensors were mounted at the root collar, and 2 m above ground level. Test results indicated significant differences between stable and weak trees. The oscillation equilibrium level, i.e. the baseline inclination value around which tree inclination oscillated, was unchanged in case of stable trees, but shifted suddenly when climbing an unstable specimen (as reported by the arborist). The “bad feeling” described by arborists is very likely the result of this sudden shift. This behavior may offer a new approach to characterizing the stability and safety of urban trees.

Keywords: urban trees, tree safety, tree stability, arborists, oscillation equilibrium

Introduction

Trees add much value to urban life: they offer stress relaxation, provide habitat for birds and insect, shade that reduces temperature in the summer, and capture carbon dioxide and dust particles. On the other hand, urban trees often grow in adverse conditions; hard pavement inhibits rainwater absorption into the soil, traffic around the trees leads to soil compaction, and air pollution impacts growth conditions adversely (Shigo 1986). As trees go older, worsening condition and a possible loss of stability poses dangerous risk to both property, and human safety and health.

It is important to balance the important benefits of trees against the possible risk arising from tree breakage or uprooting of aging or diseased trees. Tree inspectors regularly assess the condition and stability of urban trees to assess these risks, and their recommendations often include specialized, instrumented tree inspection to assess the tree’s safety against breakage and/or uprooting.

There are several methods available for assessing tree safety, including single-pass sound velocity measurement, acoustic and impedance tomography, and resistance drilling. Fewer methods are available for uprooting safety assessment. Some researchers proposed techniques for root mapping based on acoustic signal conduction through the roots, but this only works for large and shallow roots, as deeper accessing deeper roots is not possible from the surface (Buza and Divos 2016). The standard method for uprooting safety determination is the pulling test. This approach is based on simulating horizontal loads through a concentrated load introduced through a cable, and increased gradually, while measuring tree collar inclination, which allows the determination of the ultimate uprooting torque (Wessoly and Orb, 1998).

More recently, researchers examined the possibility of measuring trees under actual wind load conditions (Kent et al. 2016, Moore and Maguire 2008, etc). While the relationship between wind intensity and tree inclination is not as straightforward, as is the case of static pulling load, a statistical approach allows the evaluation of trees in a similar manner as the one used in the case of the pulling test. Earlier studies based on this approach demonstrated the principles and introduced some results and comparisons with static testing (Bejo et al. 2017, Fathi et al. 2019, 2020). Recent years has also brought several innovations that makes the evaluation of the dynamic test results more simple, and the accuracy and reliability of the evaluation also improved (Divos et al. 2022).

Due to the paramount importance of urban tree safety, researchers keep striving for new and more reliable methods of evaluating urban trees. Even though now there are various techniques available for breakage and uprooting safety evaluation, developing new inspection methods may improve the reliability of these predictions. The purpose of the research presented in this paper is pointing out a hitherto unexploited phenomenon that may provide a new approach to tree safety evaluation.

The proposed method examines the changes in baseline inclination or displacement, around which tree movement oscillates. Sudden shifts in this baseline may indicate a loss of stability arising from detrimental changes in the root system (e.g. root breakage or partial soil shear) that may ultimately lead to the tree's uprooting. Arborists often experience this phenomenon as a subjective "bad feeling" when a sudden shift occurs while climbing trees. This study is a first attempt to objectively observe and quantify this phenomenon.

Research Methods

This paper introduces three different instances where the baseline shift phenomenon was observed. The location of the measurements was in Sopron, Hungary, in all cases.

- 1) The first investigation included two Norway spruce (*Picea abies*) trees. The diameter and height of the trees was 45 cm and 19 m, respectively. The trees had recently died due to woodworm infestation, but their root system was still in a relatively good condition. The inclination of the trees was measured while an arborist was climbing them (**Figure 1**), at heights of 0.1 m and 2.0 m in two orthogonal directions, using bubble type biaxial inclinometers, with sampling frequencies of 10 Hz and a resolution of 0.001 degree. A mounting plate with 3 pins and a ball head were used to attach the inclinometer at the bottom of the tree trunk. The inclinometer's operating range is ± 2 degrees. The duration of the measurements was 6 mins and 10 mins, respectively. The measured inclination values were compared to the subjective experience of the arborist.

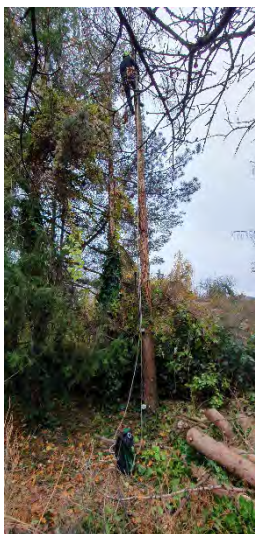


Figure 1—Measuring the movement of a dead Norway spruce while an arborist is climbing the tree.

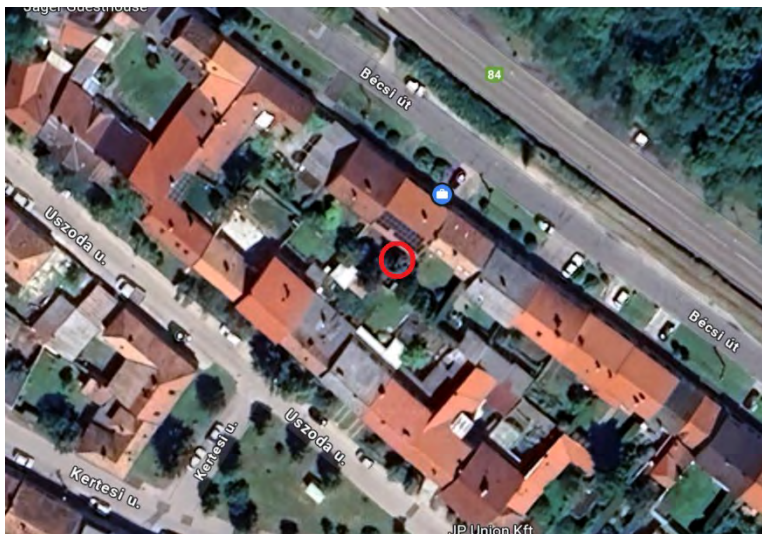


Figure 2—The location of the Scots pine tree measured in southerly winds. The tree is sheltered from prevailing northern winds, but is exposed from the south.

- 2) In the second test a 9 m tall, diseased box elder (*Acer negundo*) tree, 25 cm in diameter, was investigated. The measurement involved attaching a rope, at a height of 4.5 m, and repeatedly tugging on the tree, while measuring the inclination at a height of 0.1 m in two orthogonal directions, using the same inclinometer as in the first experiment. The first two tugs did not induce significant movement, but the third tug led to a significant loss of stability (sudden swaying), after which the tree did not return to its original equilibrium, resulting in a permanent change of inclination.
- 3) The third and final investigation involved measuring the inclination of a Scots pine (*Pinus sylvestris*) tree in Sopron, as a response to wind loading. The tree is situated very close to a house, which provides shelter from the prevailing northwest winds (see **Figure 2**). The measurement took place in windy weather with predominantly southern winds (ranging from SW to SE), and wind gust velocities reaching 75 km/h (22 m/s). The duration of the measurement was a little over three hours. Two distinct baseline shift events occurred during the measurement, where the oscillation equilibrium shifted, which indicates a loss of stability in the tree, possibly rendering it unsafe, which was also confirmed by dynamic Safety Factor analysis.

Results and Discussion

Movement of Norway spruce while climbing

Figures 3 and 4 show the movement of Norway spruce trees #1 and #2 at a height of 2 m, while climbing. Details **a** and **b** show the movement in the X and Y directions over time, while detail **c** shows the movement in both directions, in both figures. The movements were similar at a height of 0.1 m, albeit less pronounced.

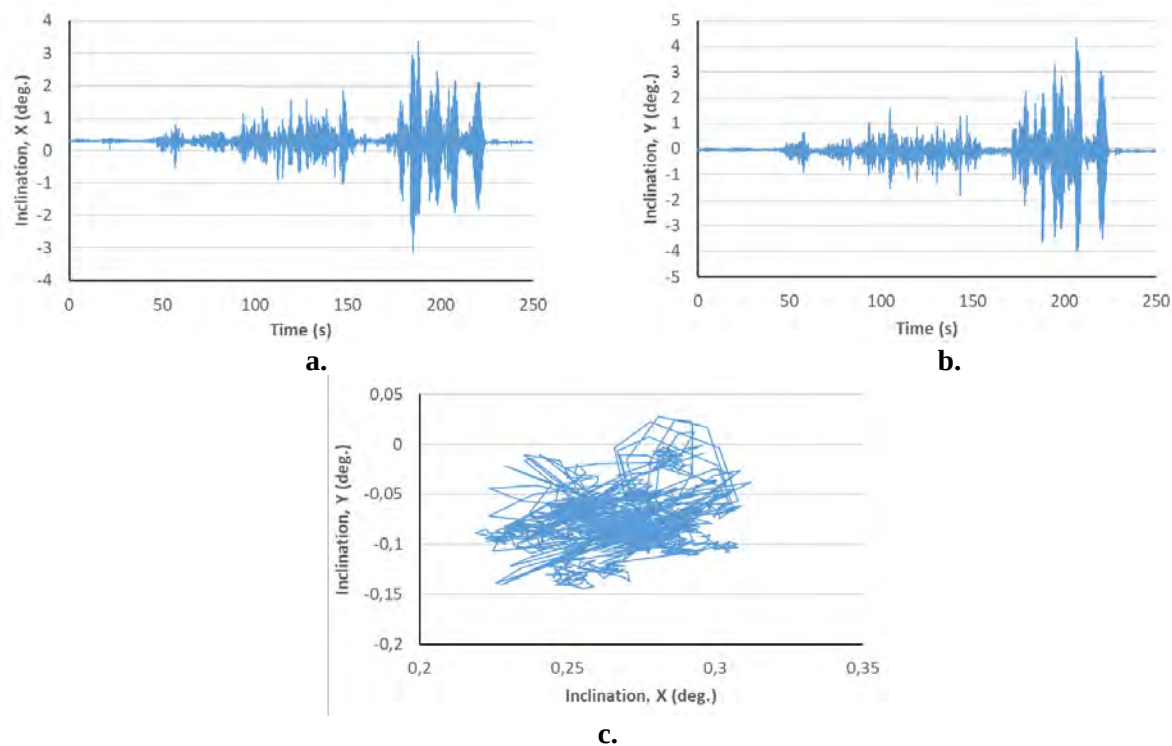


Figure 3—Inclination of Norway spruce tree #1 measured while climbing, in the X (a) and Y (b) direction, and movement in the XY plane (c, 10s moving average). No stability loss observed.

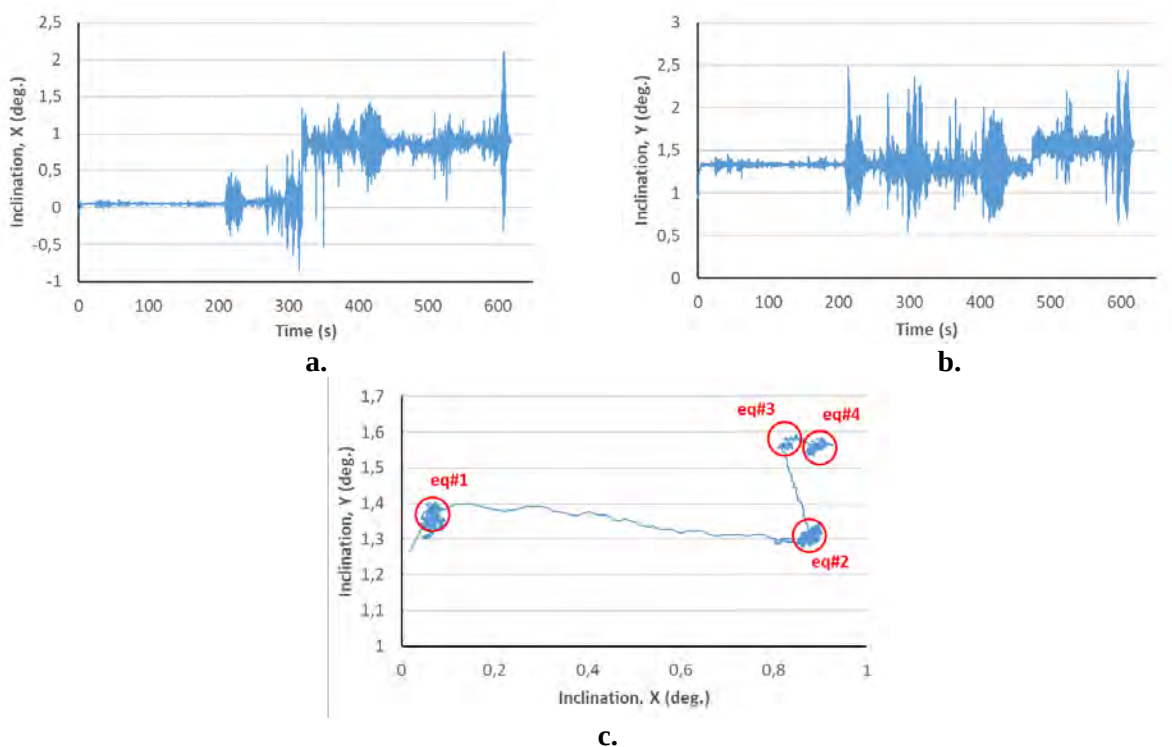


Figure 4—Inclination of Norway spruce tree #2 measured while climbing, in the X (a) and Y (b) direction, and movement in the XY plane (c, 10s moving average). Stability loss occurred in 3 stages (equilibrium states eq#1 through eq#4).

Periodically occurring oscillations in **Figures 3** and **4** indicate the movement of the tree due to the arborist climbing the tree. In **Figure 3a** and **3b**, the inclination returns to the same equilibrium after each oscillation event, there is no baseline shift. **Figure 3c** also shows random movement; there is no clustering of the inclination data. The arborist reported that the tree felt safe; he felt no sudden movement or loss of balance while climbing the tree.

In contrast, there are several sudden shifts in the oscillation equilibrium in **Figure 4**. First, there was a very significant jump at around 315 s in the X direction, from 0.05 degrees to 0.9 degrees. This was followed by another, smaller shift in the Y direction at 480 s, and another very slight shift at 525 s in the X direction again. The changes are especially striking in **Figure 4c** (note that the direction of the shift did not completely align with the two arbitrarily chosen axes.) These shifts were permanent; the tree did not return to its original equilibrium even after leaving the tree. The arborist reported the tree to be unsafe; the baseline shifts were evident by subjective observation as well.

Pulling-induced movement of a box elder

Figure 5 shows the movement of the box elder tree in response to tugging.

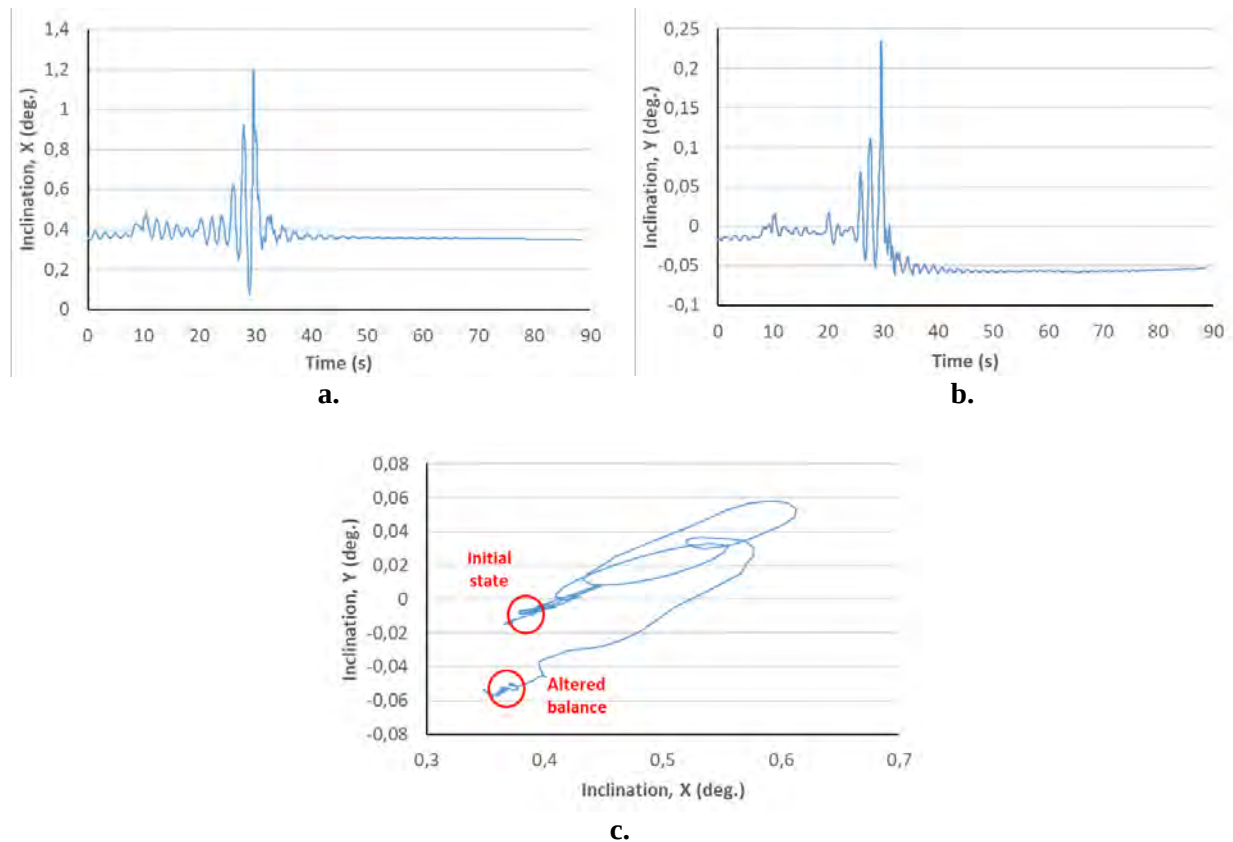


Figure 5—Inclination of the box elder tree, measured in the X (**a**) and Y (**b**) direction, while tugging with a cable, and its movement in the XY plane (**c**, 2.5s moving average). A balance loss occurred and the inclination permanently changed after the third tug.

The diagrams in **Figures 5a** and **5b** exhibit a sudden loss of balance (high amplitude oscillations), after which the tree stabilized in a different position. The oscillation baseline changed significantly, especially in the Y direction. **Figure 5c** shows the significant change that led to the altered balance of the tree. High amplitude oscillations manifest as large loops in this diagram.

Movement of a Scots pine tree in the wind

Figure 6 shows the inclination measured in windy weather on an unstable Scots pine tree in Sopron, over a three hour period. There are two sudden shifts in the oscillation equilibrium of the measured tree, similar to those in **Figures 4a** and **4b**. There are also more subtle, gradual changes in the baseline; these are due to changes in wind direction and intensity. These changes are smaller and more gradual than the two sudden shifts that most likely occur due to permanent and significant changes in the root system (i.e. breakage of or soil shear around some of the roots.)

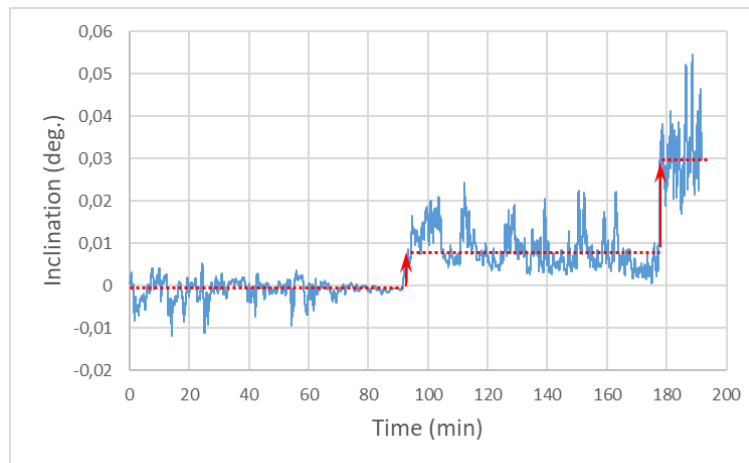


Figure 4—The inclination of an unstable Scots pine tree measured in windy weather. Changes in the oscillation equilibrium are shown in red.

This tree had been monitored for its safety, by measuring the dynamic Safety Factor (SF) repeatedly in various wind conditions. In prevailing northwest winds, the measurements usually resulted in relatively high SF values, ranging from 2.5 to 5. This is due to the tree being sheltered from northerly winds by the house next to it. However, in less frequent, southerly winds (similar to those at the time of this measurement), there is no shelter effect (see **Figure 2**). In such conditions, the SF value is much lower, typically around or below 1. This provides further confirmation that the tree may be unsafe against uprooting in southerly winds.

The same phenomenon was also observed by Dr. Ken James in Australia. He investigated a *Jacaranda mimosifolia* tree with a very weak root system in a park in Brisbane by measuring the movement of its crown in the wind for nearly 20 hours. During this time, the movement amplitude consistently increased. The increase was generally gradual, but there were also 7 or 8 sudden shifts of varying intensity. The tree was uprooted at the end of the measurement, exhibiting extensive root breakage. His results also support the assumption that this phenomenon may be a good indicator for the safety of urban trees. (Based on unpublished results provided by Dr. Ken James.)

Conclusions

Arborist regard sudden shifts in the balance of trees while climbing as warning signs of an unsafe tree. This subjective observation may provide the basis for developing a new instrumental inspection technique for tree safety evaluation

The aim of the research described in this paper was to measure and quantify the above phenomenon using tree inclination measurements. Different species, size and age trees have been investigated using different techniques, including taking measurements while climbing, while tugging at the tree, and during windy weather. In all three measurements, sudden shifts in the oscillation equilibrium could be observed. Subjective observation by the arborist climbing the tree, as well as dynamic Safety Factor analysis confirmed the unstable status of the trees that exhibit this behavior.

The presented results demonstrate the potential of instrumental tree evaluation to objectively measure and quantify the balance shift felt and used by arborist to evaluate the safety of trees subjectively. This may be the first step towards developing a new technique for urban tree safety evaluation. However, significant amount of research is needed to provide further confirmation and a reliable and quantifiable method to evaluate tree safety based on this phenomenon.

Acknowledgments

This study has been financed by Project no. TKP2021-NKTA-43, which has been implemented with the support provided by the Ministry of Innovation and Technology of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme. The authors are grateful for Mr. Imre Sumegi for his assistance in part of the experiments, as well as Dr. Kenneth James for making his results available.

References

- Bejo L., F. Divos, S. Fathi 2017. Dynamic root stability assessment – basics and practical examples. In: X. Wang; C.A. Senalik; R.J. Ross ed. Proc. 20th International Nondestructive Testing and Evaluation of Wood Symposium Madison, Wisconsin, USA, pp. 262-269.
- Bejo, L., I. Sumegi, F. Divos. 2022. Dynamic tree stability: improved testing methodology and indications of reliability. In: X. Wang; C.A. Senalik; R.J. Ross ed. Proc. 22nd International Nondestructive Testing and Evaluation of Wood Symposium. Quebec City, Canada, pp. 175-183.
- Buza, A.K., F. Divos. 2016. Root Stability Evaluation with Non-Destructive Techniques. *Acta Silvatica et Lignaria Hungarica* 12(2):125-134.
- Fathi, S., L. Bejo, F. Divos 2020. Investigating the Effect of Weather and Seasonal Factors on Root Stability Using Dynamic Measurements. *Open Journal of Forestry* 10(1):124-134.
- Fathi, S., Mag. K. Schwanda, R. Gschwandtner, N. Nemestothy, Nikolaus, L. Bejo, A. K. Buza, F. Divos 2019. Dynamic and Static Root System Evaluation. In: X. Wang, U. Sauter ed. Proc. 21st Int. Nondestructive Testing and Evaluation of Wood Symposium. USDA Forest Service pp. 394-400.
- J. Kent, N. Haritos, and P.K. Addes. 2006. Mechanical stability of trees under dynamic loads. *American Journal of Botany* 93(10):1361–1369.
- Moore, J.R., and D.A. Maguire. 2008. Simulating the dynamic behavior of Douglas-fir trees under applied loads by the finite element method. *Tree Physiology* 28:75–83
- Shigo, A. 1986 *A New Tree Biology: Facts, Photos, and Philosophies on Trees and their Problems and Proper Care*. Shigo and Trees, Snohomish, Washington
- Wessolly, L., and M. Erb 1998. *Handbuch der Baumstatik und Baumkontrolle*. Patzer Verlag, Berlin, Germany.

Dynamic Evaluation Stability of the Standing Plane Tree in Urban Area (Farahzad-Tehran)

Shadabeh Fathi*

Project cooperater in Darkoob Enterprise, Tehran, Iran- shadabeh.fathi@gmail.com

Mehran Roohnia

Full Professor Karaj branch Islamic Azad University Karaj Iran- mroohnia@gmail.com

Mehdi Ebrahimi

Tree Tomography Expert. Paydar Sanat Ayrik Co. Ltd. Tehran Iran

Negin Manoushehri

Tree Tomography manager, Darkoob Enterprise, Tehran, Iran

Abstract

The crowded points in the urban area with old trees are concerning about the safety in the wind storms. In this study, the health of trunk was investigated to predict their behavior in storms. The trees were chosen in a park which is located in Farahzad, Tehran and were examined by TOMOTREE[®] Acoustic Tomomography instrument (Darkoob NDT enterprise). The history of this trees belongs to Safavid era. (1501-1736). The aim of this research was keeping them healthy and avoid to uprooting, therefore tomography was done on the 10 oriental planes in two different heights of trunk also biological properties of each tree was recorded and compared together. The result showed, 65% of plane tree was observed less than 10% decay in both height (bottom and middle of trunk), 20% of samples have had 10-40% decay in their trunk and needed to treatment and pruning of crown. Unfortunately, 10% of them were attacked by insects and fungi. So that, one of them was evaluated too unstable (with 65% decay at bottom) and recommended to be uprooted.

Key Words: Tree trunk, Uprooting, Wind storm, Safety, Urban area, Crown

Introduction

The tree of life represents a history and oldness of cultures also illustrate how all life in Earth is related. For instance, the most aged long-lived tree is Abarkouh Cedar in Yazd province-IRAN. Scientist estimated 4000 years old while there is no any other ancient item to proof this old age (Farahmand & Karimi 2019). Urban trees, along with other precious ecosystems, allow life on earth to survive and flourish and are home to apparently limitless amounts of biodiversity. No matter how, with most of humanity now living in cities the importance of trees in urban area should not be underestimated. Farahzad is the one of the green space areas in Tehran and it located north-west of Tehran and South of the Alborz mountain range, which is belong to Safavid Era. This place had different changes during recent decades. This kind of greenspace are valuable from 2 sides, first having old stout trees and second urban rivers which are connect to each other as a chain therefore, local authorities are responsible for protecting and maintaining some urban green spaces and also for protecting and improving public health. Large amount of water is transported down, tream by urban rivers and feed ground water reservoirs along the route which have high function in the in the dynamic of the morphological process (Ostrowski & Falkowski 2020). Urban trees reduce greenhouse gases through carbon storage and mitigate the urban heat island effect thorough reduction in surface and air temperatures at a local scale (Nowak et all 2006). Nowadays decay of trunk diagnoses through acoustic

tomography. Acoustic tomography technology uses multiple sensors (usually eight to 32) to measure stress wave transmission times in multiple directions (Lin and Yang, 2015). Computer projection software then uses the acoustic wave data matrix to create an image (tomogram) of the apparent acoustic wave velocity for the cross section of the tree. Although the acoustic tomograms obtained from urban trees with central rot have shown good agreement with the true physical condition for the cross section, an acoustic tomogram is not a spatially precise map of the internal structure, instead it represents the wood's acoustic characteristics as determined by the perceived velocities (Allison and Wang, 2015). The purpose of this research is evaluating tree stability and give useful information to local authorities. Scientific information could be effective to make right decisions. For this reason, at the end of this project each tree had a barcode label which is easy to scan by smartphones and all information is available for everyone who is interested to know about mechanical properties of this trees.

Methods and Equipment

Ten Oriental plans located at Abdolrazagh restaurant-garden in Farahzad (GPS: 35°47'56.5"N 51°20'46.3"E) were inspected. (with Authorization of Tehran municipality). using a combination of visual inspection and acoustic tomography. Their information was surveyed (Table 1). The trees were conducted by person with sufficient professional level of expertise. Step by step trees were assessed for understanding and insight.

Table 1- Information of visual inspection

ID NO:	2-9-1	2-9-2	2-9-4	2-9-5	2-9-6	2-9-7	2-9-8	2-9-9	2-9-10	2-9-17
Factors:										
Diameter of Breast (m)	51	65	66	37	41	67	52	64	46	55
Height (m)	14	16	23	21	23	22	21	16	17	18
Crown Position	10% Dried	Not Dried	30% Dried	30% Dried	30% Dried	30 % Dried	30 % Dried	10% Dried	5% Dried	20% Dried
State of crown symmetry	Dense to E	Dense to W	Dense to S	Dense to W	Dense to W	Dense to N	Dense to S	Dense to W	Dense to W	Dense to S
Weight (kg)	1300	2000	3500	1200	1300	3500	2500	2400	1300	2000
Direction of Visible Cracks of the trunk	N collar pint	----	S collar point	E collar point	----	----	N collar point	W&E collar point	SW collar point	S&SW collar pint
Crack length (m)	2	----	Less than 0.5	1.5	----	----	hole	1.5	2	16
Decay position (root or trunk)	T-S	T-N	T-W	roots	----	----	T-N	T-E	T-E&S W	T_SW
Fungal reproductive organs	---	----	-----	-----	-----	In the roots	-----	-----	-----	---
Tree Orientation leaning	10° To E	straight	straight	200° To W	100° TO W	straight	300° to S	straight	10° to E	10° to SW
Insect net	---	-----	In the roots	In the roots	In the collar	In the collar	Hole in the collar	Termite net	-----	Full of net
Visible roots on the surface	Flare	Flare	Visible roots	Flare	Flare	Flare	Flare	Visible roots	Flare	---
Factors limiting root growth	Curb in N	Curb in E	----	-----	----	-----	-----	-----	Curb in E	Curb in E

The trees were given a code as an ID Number also photographic documentation and to determine the locations of tree trunks. Conduct acoustic tomography measurements at the selected elevations on each tree trunk using a TOMOTREE device, introduced by Darkoob® enterprise Tehran, Iran. (Roohnia 2018) The measurement was performed at two different points (table 2) where internal decay is most likely to occur. The trees were tested using a standard protocol with 8 sensors.

Table 2- the height of connected sensors

ID NO	2-9-1	2-9-2	2-9-4	2-9-5	2-9-6	2-9-7	2-9-8	2-9-9	2-9-10	2-9-17
The height of sensors (cm)	15	20	15	15	15	15	18	15	15	10
	165	160	180	170	170	180	175	170	175	165

All the heights were recognized according to visible decay of trunks.

Results and Discussion

The most of the trees were found healthy and was recommended to keep them with treatment and pruning. In between just one of them identified to have deep internal decay (i.e. fungal attacks, ant and termite net and etc.) (table 3)

Table 3- percentage of decay in each height

ID NO	Height of Tomography (cm)	Percentage of Decay (%)
2-9-1	15	0
	65	0
2-9-2	20	8
	160	2
2-9-4	15	1
	180	3
2-9-5	15	10
	170	44
2-9-6	15	1
	170	4
2-9-7	15	0
	180	0
2-9-8	18	1
	175	4
2-9-9	15	52
	170	17
2-9-10	15	36
	170	3
2-9-17	10	65
	165	0

As it is clear at the table 3 the tree with ID NO 2-9-17 in the height of 10 m had 65% decay (figure 1)

Figure 1-A illustrate huge fungal attack and insect net from bottom to height (approximately 8 m). biomechanical analysis shows the tree will easily uproot in windstorm, fell down to SW. (Figure 1-c). It

was recommended to uproot the tree before causing damage (TOMOTREE data were processed in Arborsonic Software, FAKOPP).

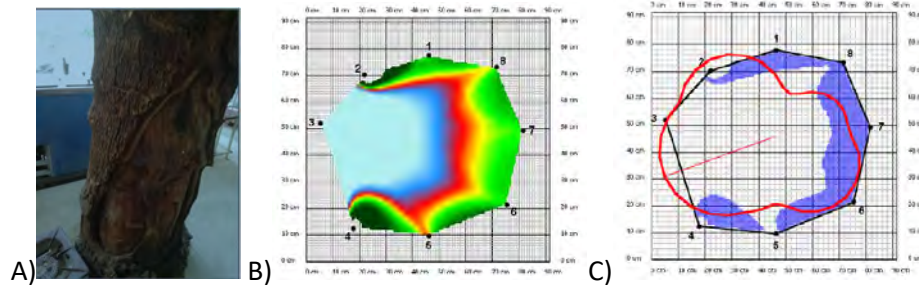


Figure 1-A) Photo of trunk tree B) Acoustic tomography image of cross section C) biomechanical analysis (ID NO: 2-9-17 in the height of 10cm)

The interesting point about tree NO 2-9-17, was not observed any decay in height 165 cm. (figure 2-A &B) However in tomography image of the trunk is clearly visible how the decay disappeared at the height of 165cm. (Figure 2-C)

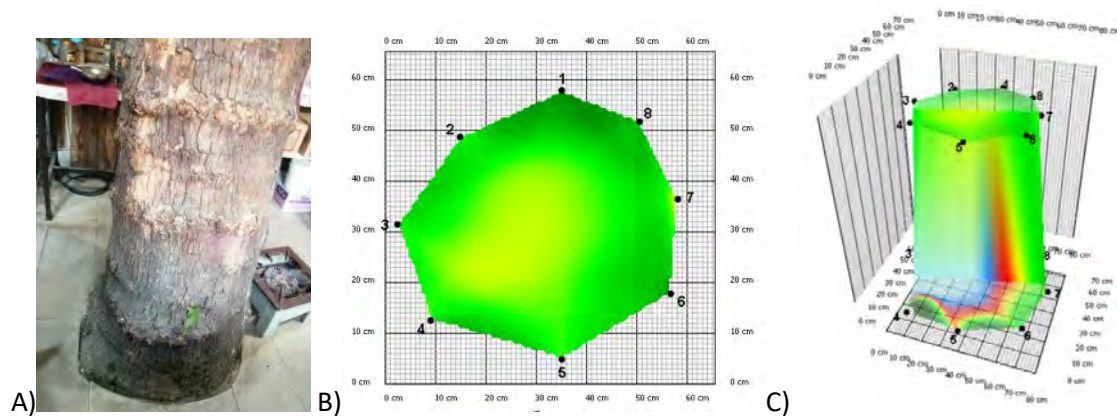


Figure 2-A) Photo of trunk tree B) Acoustic tomography image of cross section C) Tomography image of the trunk (ID NO: 2-9-17 in the height of 165cm)

Tree No 2-9-5 (figure 3) shows is bent 20° and as it mentioned in table 1&3, decay in the height of 170 cm is approximately 40% although it was not recommended to uproot instead of that was recommended to pruning of crown area.

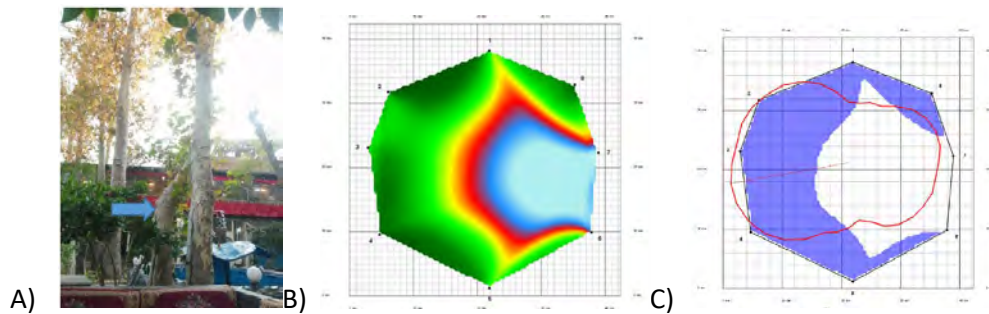


Figure 3-A) Photo of trunk tree B) Acoustic tomography image of cross section C) biomechanical analysis (ID NO: 2-9-5 in the height of 170cm)

Conclusion

The majority of the trees which were inspected have had good condition at Farahzad, Tehran-Iran. Three defective trees were identified, which were not rated at high risk, and were recommended special treatment and pruning of crown area. There was a tree very rotten and unsafe, it was recommended to uproot before damage. Using a combination of visual inspection and acoustic tomography showed there may be collar rot (or any defect at the bottom of the trunk) while the trunk is completely healthy and vice versa. Image processing procedures which could facilitate the implementation of acoustic tomography technology and improve the science-based tree risk assessment process. At the end, a QR code was stuck on the tree and after scanning through a smartphone all information of that tree will be available.

References

- Allison, R. B., and X. Wang. 2015. Nondestructive testing in the urban forest. In R. J. Ross [ed.], *Nondestructive evaluation of wood*, 2nd ed., 77–86. General Technical Report FPL-GTR-238. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA.
- Darkoob NonDestructive Testers (D-NDT) Knowledge-based Enterprise, 2018
- Farahmand H and Karimi H.R., 2019., Old Persian cypress accessions, a rich and unique genetic resource for common cypress (*Cupressus sempervirens* L.) in the world., *Role of Plant Genetic Resources in Reclaiming Lands and Environment Deteriorated by Human and Natural Actions.*, P113-118
- Fakopp Ltd. 2018 Arborsonic Software
- Lin, C.-J., and T.-H. Yang. 2015. Detection of acoustic velocity and electrical resistance tomographies for evaluation of peripheral-inner wood demarcation in urban royal palms. *Urban Forestry and Urban Greening* 14(3): 583–589.
- Nowak D.J., Crane D.E., Stevens J.C. 2006 Air pollution removal by urban trees and shrubs in the United States. *Urban For. Urban Green.*
- Ostrowski P, Falkowski T. 2020 Application of Remote Sensing Methods to Study the Relief of Lowland River Valleys with a Complex Geological Structure—A Case Study of the Bug River. *Water.*; 12(2):487.

A Method of Tree Root Detection and Parameter Estimation Based on GPR Inversion Model

Xiaowei Zhang

Joint International Research Institute of Wood Nondestructive Testing and Evaluation, School of Technology, Beijing Forestry University, Beijing 100083, China, email: zhangxw@bjfu.edu.cn

Shenghua Lv

Joint International Research Institute of Wood Nondestructive Testing and Evaluation, School of Technology, Beijing Forestry University, Beijing 100083, China, email: shenghualv@bjfu.edu.cn

Shuang Li

Joint International Research Institute of Wood Nondestructive Testing and Evaluation, School of Technology, Beijing Forestry University, Beijing 100083, China, email: beilinls@163.com

Linfei Xv

Joint International Research Institute of Wood Nondestructive Testing and Evaluation, School of Technology, Beijing Forestry University, Beijing 100083, China, email: xvlingfei123@163.com

Jian Wen *

Joint International Research Institute of Wood Nondestructive Testing and Evaluation, School of Technology, Beijing Forestry University, Beijing 100083, China, email: wenjian@bjfu.edu.cn

* Corresponding author

Abstract

The root system, as one of the important organs for tree support and material exchange, is latent, plastic and complex. Rapid, accurate, and efficient root detection and three-dimensional reconstruction in subsurface space for the research on functional roles of root systems and changes in the inter-root environment. Ground Penetrating Radar (GPR) is widely used as an efficient and portable detection technique for non-destructive testing of tree roots. Aiming at the issue of the difficult interpretation of radar wave data and the low accuracy of root parameter estimation due to the complexity and diversity of the root system and soil. In this paper, a deep learning-based radar wave inversion method is used to implement automatic root detection and multi-parameter estimation by recovering the physical information of the profile. First, a deep learning-based generative network was built to construct an inverse mapping from root radar wave data to the profile dielectric constant distribution. Then, an unsupervised clustering algorithm was employed to segment the root targets in the recovered profile dielectric model. Finally, the root contour was fitted by minimizing the ellipse and estimating the root location, size, orientation angle, water content. The results of numerical simulation and pre-embedded experiments indicate that the method in this paper achieves high accuracy in the estimation of multiple parameters of the root system and has obvious advantage over existing methods for automated root detection. Accurate root localization and multi-parameter estimation will provide important data support for three-dimensional reconstruction of tree root systems and carbon storage estimation.

Keywords: GPR inversion, Root detection, Root parameter estimation, Root contour fitting

Introduction

The root system provides an important organ for trees to absorb water and nutrients (Ma et al., 2018), and serves to support the tree and stabilize the soil. However, most of the roots are located under the soil, their wide distribution and complex structure make direct observation difficult, limiting the study of root growth and its interactions with the inter-root soil. For a long time, root systems have been studied by excavation, soil core and soil profile methods. Although these methods allowed direct measurements of the root system, they were time-consuming and prone to damage, which could lead to root infections and diseases, resulting in the death of the entire tree. Non-destructive detection techniques, such as micro-root tubes, X-ray scanning and resistive conductivity, are difficult to implement in the field due to the limited range of observations, making it difficult to monitor the root systems of spatially dispersed trees on a large scale over a long period of time.

Recently, ground-penetrating radar (GPR), as an efficient geophysical detection tool, has been widely used in the fields of subsurface structure detection, buried object localization and planetary exploration (Liu et al., 2023). As an important subsurface target, the parameters (size, location, growth direction, water content, etc.) of the root system are not only the primary target for root detection, but also important information for conducting three-dimensional root reconstruction, root biomass estimation, and tree carbon sequestration surveys. In an earlier study and analysis, the influence factors of radar signal response characteristics in root detection were revealed by extracting the characteristic parameters of radar wave signals, constructing correlations among physical parameters of the root system and estimating the relevant parameters (Stokes et al., 2002 , Hirano et al., 2009 , Tanikawa et al., 2021 , Alani and Lantini, 2020). Although the feasibility of using ground-penetrating radar for root parameter estimation has been verified by the radar signal features selected by manual design, the automatic identification, localization and parameter estimation of root targets by interpreting the radar wave images are still subject to many difficulties.

Roots are normally represented as hyperbola signal in radar wave image, and the localization detection and parameter estimation of targets could be achieved by identifying the hyperbola response characteristics of underground targets (Windsor et al., 2013). The generalized Hough transform method based on the least square method has been used to carry out the location and radius of buried targets by fitting the extracted hyperbolic response (Li et al., 2016 , Luo et al., 2022). Due to factors such as background noise, radar wave energy attenuation and interference between neighboring root responses, a clustering algorithm based on hyperbolic features was designed to extract and separate the root responses on pre-processed radar images to improve the hyperbolic curve fitting accuracy. Several emerging machine learning methods have been introduced into radar image interpretation. The use of Faster-RCNN and YOLO, popular target detection algorithms based on simulated and measured data, was used to detect hyperbolic response regions of the root system (Li et al., 2022). The integrated Mask-RCNN scheme (Hou et al., 2021) allows automatic detection and segmentation of root features in radar images.

Traditional root detection methods based on the proposed method are difficult to obtain a higher quality hyperbolic point set due to the weakened, interfered, missing and distorted hyperbolic responses caused by reflection coefficients, background noise, neighboring root response crossings and terrain undulation factors, resulting in such methods not only being prone to leakage of detections, but also having low accuracy rates. Benefiting from the development of deep learning techniques, data-driven deep learning-based methods have been used in ground-penetrating radar inversion studies. A trajectory-based GPRInvNet (Liu et al., 2021) and PINet (Ji et al., 2021), which introduces global information, have been proposed to reconstruct geologic structures. DMRF-UNet (Dai et al., 2022) recovers the dielectric constants of subsurface targets in complex backgrounds by adding a denoising network.

In this paper, a novel radar wave inversion-based root detection and parameter estimation scheme is proposed to address root detection and parameter estimation in inhomogeneous soil scene. Firstly, a radar wave inversion model for U-shaped root systems based on spatial and temporal fusion is proposed to invert the dielectric constant distribution of reconstructed scanning profiles using both time and space domain information contained in the radar wave data. Then, the targets contained in the reconstructed profiles were clustered using the density method and screened for root systems based on the estimated dielectric constants. Finally, a minimum enclosing ellipse is fitted to the filtered targets to realize the estimation of the physical parameters of the root system. And a dataset of multilayered soil environments and multiparameter root targets, including profile dielectric constant models and corresponding radar wave images, was generated using the gprMax (Warren et al., 2016) simulation software and used to train and test the STF-UNet network. Meanwhile, a variety of pre-embedded and field experiments were designed to verify the accuracy of root detection and parameter estimation.

Methods

The process of ground-penetrating radar scanning for underground root scenes to obtain radar wave BScan images is shown in Figure 1. The inversion process is carried to restore the dielectric constant distribution of the scanned profiles from BScan images. Compared to traditional detection methods based on root response characteristics, the inversion process could transform the hyperbola curve fitting problem to be converted into a detection problem of an ellipse of root-like shape within the recovered profile model, furthermore providing an important parameter of the root system's relative dielectric constant value. Thus, in this paper, we propose a root radar wave inversion network based on spatio-temporal information fusion and root detection and parameter estimation on its recovered medium distribution. The details are described below.

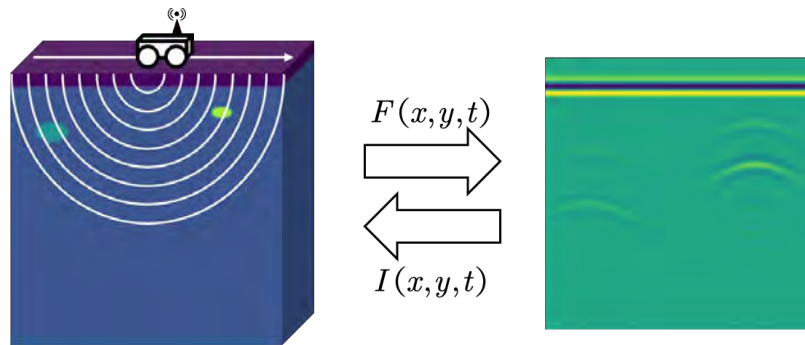


Figure.1. Root detection imaging process with GPR.

Permittivity Distribution Inversion

Root measurement by ground-penetrating radar could be decomposed into two processes: in the first step, electromagnetic waves are transmitted downward through the transmitting antenna at a certain location on the ground surface, and the receiving antenna receives the reflected electromagnetic waves within a certain window of time; in the second step, the process is repeated by moving a certain distance along the direction of the measurement to reach the next detection location. The collected images contain spatial information about the subsurface structure and temporal information about the propagation of the radar wave signal. Thus, a U-shaped network based on a spatio-temporal feature fusion module is designed to take the input radar wave B-Scan image and recover its corresponding profile dielectric constant distribution.

The structure of STF-UNet, as illustrated in Fig. 2, contains a symmetric structure of encoder and decoder. There are four levels of encoding structure for the encoder, each level contains one STFM module and one down-sampling convolutional layer, and the corresponding level for the decoder also employs one STFM module and one up-sampling convolutional layer. In order to compensate for the loss of information during the down-sampling process, skip-connections are added to combine the coding features and decoding features of the same hierarchy.

In order to extract the spatio-temporal information in the input radar wave B-Scan image, a spatio-temporal feature fusion module based on CNN and LSTM was designed on the basis of ResNetBlock module. To extract the longitudinal and lateral features of the radar wave image, a BiLSTM structure containing two LSTMs is employed to form a tandem structure with the CNN.

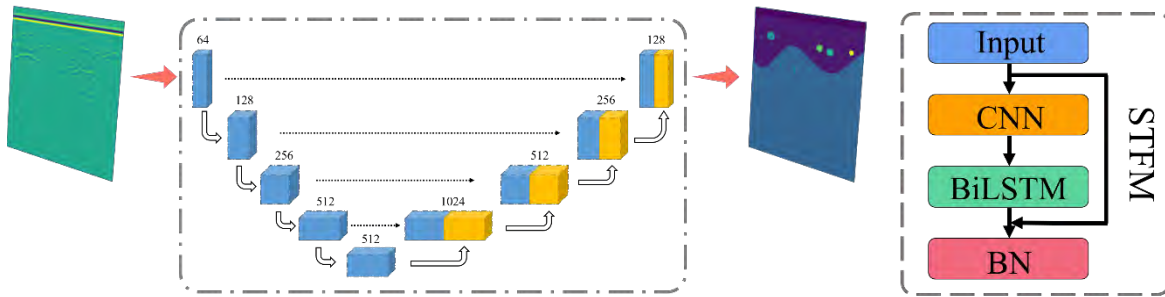


Figure.2. Architecture of STF-UNet.

In order to make the dielectric constant distribution, which has been inverted by the network model, closer to the true value of the profile model, a hybrid loss function based on L1 regularization and SSIM structural similarity is used to optimize the parameters of the STF-UNet model as shown in Eq. 1. Hybrid loss functions have been proven to be more advantageous in the fields of image denoising, super-resolution reconstruction and image transformation compared to the commonly used L2 regularization for image detail recovery and image structure reconstruction (Zhao et al., 2016).

$$loss(P_{gt}, P_{pre}) = \alpha \cdot L_1(P_{gt}, P_{pre}) + (1 - \alpha) \cdot L_{MS\_SSIM}(P_{gt}, P_{pre}) \quad (1)$$

where P_{gt} and P_{pre} are denoted as the target profile model and radar wave inversion results, respectively, and the value of α was set to 0.8 to balance the contributions of the two losses. The Adam optimizer was employed in the training phase and the learning rate was set to 0.0001, which allowed the inversion network to obtain lower mixing losses while the inversion results were closer to the target profile model.

Root Detection

Roots normally appear as ellipsoid-like morphology in measured profiles, and could be converted to ellipsoid morphology for detection based on the accurate profile media distribution that can be obtained through inverse modeling. Compared with the traditional hyperbolic pattern of root radar waves, it not only reduces the effects of environmental disturbances and hyperbolic intersection, but also overcomes the inaccuracy of parameter estimation caused by the distribution of soil dielectric constants. Therefore, a new root localization and parameter estimation scheme based on the inversion of the subsurface dielectric constant distribution model was constructed, including root target segmentation and root ellipse fitting.

Due to the random character of the root distribution, the measurement profile usually contains several root targets with random locations and numbers. a density-based unsupervised clustering method, BSCAN, was employed to extract root target areas from the recovered profile media distribution. And a minimum elliptic area fitting method was designed to match different root systems and thus estimate the parameters such as root position, size and dielectric constant, as shown in Eq. 2.

$$\begin{aligned} \min f(a, b) &= \pi ab \\ \text{s.t.} \quad &\begin{cases} \left(\frac{x - x_{f_1}}{a}\right)^2 + \left(\frac{y - y_{f_1}}{b}\right)^2 - 1 \leq 0 \\ \sqrt{(x - x_{f_1})^2 + (y - y_{f_1})^2} + \sqrt{(x - x_{f_2})^2 + (y - y_{f_2})^2} \leq 2a \end{cases} \end{aligned} \quad (2)$$

where a and b denote the long and short axes of the ellipse, (x_{f_1}, y_{f_1}) and (x_{f_2}, y_{f_2}) are the two foci of the ellipse respectively.

Results

Data preparation

In order to provide sufficient training data for the inversion model STF-UNet, an open-source ground-penetrating radar simulation software based on finite-time-domain differencing, gprMax, was used to perform numerical orthorectification simulations to generate simulation data simulating the root system and inter-root soils in a naturalistic scenario, specifically, soil stratification, non-uniformity, and the diversity of root attitudes. Each data set consists of the profile dielectric constant model and its paired radar wave scan data. A random spline curve is generated in the soil domain as a soil stratification, with different layers set to varying dielectric constants. For subsurface root targets with different spatial attitudes, circular models with scaling, rotation and translation transformations were used to simulate root morphology in the scanned profiles. Combining these three features, a dataset containing several scenarios with different root morphologies and complex root domain environments was constructed, which contains a total of 6000 sets of paired profile models and radar wave scanned images.

A sample of the root complex environment dataset in this paper is shown in Figure 1. In this case, the size of the soil two-dimensional measurement area is 2×0.6 m, and the discretization factor in both x and y directions is 0.0001 m. A Ricker wave antenna with a frequency of 900 MHz was used and in a co-offset spacing mode, with a measurement time window of 15 ns. And soil parameters ranged from $[3-20]$ in terms of the relative permittivity according to the stratification and non-uniformity. For each root system, the radius ranges from $[0.01-0.05]$, the scaling factor ranges from $[1-1.5]$, and is placed at a random location within the measurement soil domain after translation transformation, the dielectric constant ranges from $[3-60]$, and the number of roots included in a single simulation ranges from $[0-15]$.

Inversion result

In order to validate the performance of the proposed inversion model based on spatio-temporal feature fusion for reconstructing the dielectric constant distribution of measured profiles in root complex environments, we conducted a comparative study on the ground-penetrating radar simulation dataset. There are three inversion models included in the comparison experiments: 1) EncDec, which contains the classical encoding and decoding structure, 2) UNet, which adds skip connections, and 3) PINet, which is currently the best model for radar wave inversion.

The study compares the results of root radar wave inversion under different scenarios, as shown in Figure. 3, including multiple root targets in a homogeneous medium and multiple root targets in different media. The comparative inversion results indicated that the STF-UNet model worked best for root target recovery in multiple scenarios. At the same time, compared with the other three models, the model in this paper provides a more accurate reconstruction of the boundary positions of different media, and a more uniform dielectric constant inside the same media.

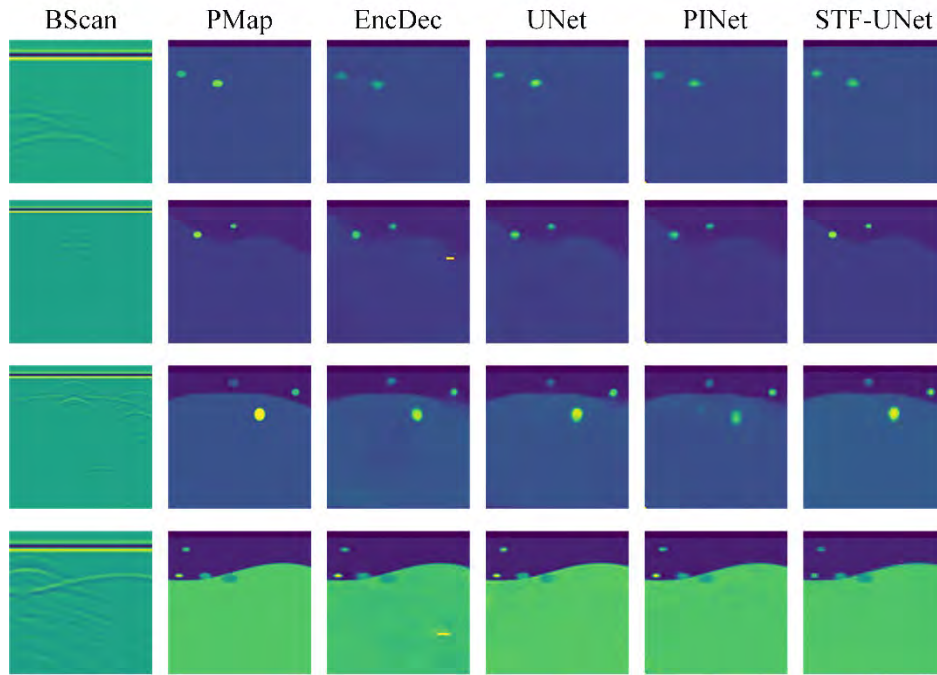


Figure.3. Restoration results of different subsurface scenes from multiple inversion models.

Detection result

In order to verify the accuracy of this paper's profile inversion-based ellipse-fitting root detection scheme for root detection, the results of different scenarios in the test set are shown in Figure 4. In an underground scene with several targets in different backgrounds, the inversion model is able to recover the location and morphology of most of the targets. Root targets that are less different from the background and smaller in size are easily overlooked. The test results indicated that the method based on ellipse fitting was able to accurately localize the root target and closer to the ground truth. However, there are also some misidentifications and morphological transformations that are affected by the predictions of the inversion network.

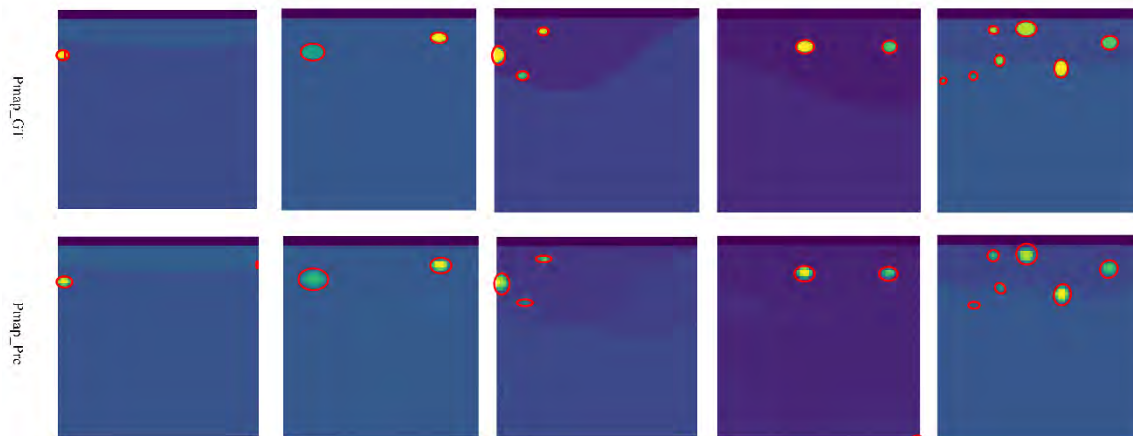


Figure.4. Restoration results of different subsurface scenes from multiple inversion models.

Conclusion

In this paper, we propose a root detection and parameter estimation scheme based on radar wave inversion. Firstly, a radar wave inversion model STF-UNet was designed to extract the spatio-temporal features of the fused radar wave data and reconstruct the dielectric constant distribution of the scanned profile. Then an unsupervised clustering algorithm was used to segment the root system of the scanned profile. Finally, the root position, size and dielectric constant estimation were realized based on the ellipsoid fitting method of root morphology with minimum area. The test results and comparative experiments exhibit that the root detection scheme in this paper achieves satisfactory accuracy in complex soil environments and multi-root target scenarios.

The data-driven supervised learning-based technique can achieve the conversion from radar wave image to profile dielectric constant by learning the inversion process. Meanwhile, the root detection within the profile model can not only effectively avoid the interference of hyperbolic noise, crossover and aberration compared to the original detection target, but also adapt to the root morphology changes in the detection profile brought about by the root orientation.

Due to the complexity of the field environment, efficient and accurate radar wave inversion can not only provide information on the distribution of dielectric constant in the root environment, but also contribute to high-precision root position, size and dielectric constant estimation, which facilitates the reconstruction of three-dimensional structure of the root system, the estimation of root biomass, and the study of the root environment. The inference method of radar wave inversion in real scenarios will be an important part of our future work.

Acknowledgments

This research was funded by the the National Natural Science Foundation of China (Grant No. 32071679) and Beijing Municipal Natural Science Foundation (Grant No. 6202023). We thank all authors for their cooperation.

References

- ALANI A M, LANTINI L 2020. Recent advances in tree root mapping and assessment using non-destructive testing methods: a focus on ground penetrating radar. *Surveys in Geophysics* [J], 41: 605-646.
- DAI Q, LEE Y H, SUN H H, OW G, YUSOF M, YUCEL A C 2022. DMRF-UNet: A Two-Stage Deep Learning Scheme for GPR Data Inversion under Heterogeneous Soil Conditions. *arXiv e-prints* [J].
- HIRANO Y, DANNOURA M, AONO K, IGARASHI T, ISHII M, YAMASE K, MAKITA N, KANAZAWA Y 2009. Limiting factors in the detection of tree roots using ground-penetrating radar. *Plant and Soil* [J], 319: 15-24.10.1007/s11104-008-9845-4.
- HOU F, LEI W, LI S, XI J, XU M, LUO J 2021. Improved Mask R-CNN with distance guided intersection over union for GPR signature detection and segmentation. *Automation in Construction* [J], 121: 103414.
- JI Y, ZHANG F, WANG J, WANG Z, JIANG P, LIU H, SUI Q 2021. Deep neural network-based permittivity inversions for ground penetrating radar data. *IEEE Sensors Journal* [J], 21: 8172-8183.
- LI S, CUI X, GUO L, ZHANG L, CHEN X, CAO X 2022. Enhanced Automatic Root Recognition and Localization in GPR Images Through a YOLOv4-based Deep Learning Approach. *IEEE Transactions on Geoscience and Remote Sensing* [J], 60: 1-14.
- LI W, CUI X, GUO L, CHEN J, CHEN X, CAO X 2016. Tree Root Automatic Recognition in Ground Penetrating Radar Profiles Based on Randomized Hough Transform. *Remote Sensing* [J], 810.3390/rs8050430.

- LIU B, REN Y, LIU H, XU H, WANG Z, COHN A G, JIANG P 2021. GPRInvNet: Deep learning-based ground-penetrating radar data inversion for tunnel linings. *IEEE Transactions on Geoscience and Remote Sensing* [J], 59: 8305-8325.
- LIU R, XU Y, CHEN R, ZHAO J, XU X 2023. An improved hyperbolic method and its application to property inversion in Martian Tianwen-1 GPR data. *IEEE Transactions on Geoscience and Remote Sensing* [J].
- LUO W, LEE Y H, SUN H H, OW G, YUSOF M, YUCEL A C 2022. Tree Roots Reconstruction Framework for Accurate Positioning in Heterogeneous Soil. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* [J], 15.
- MA Z Q, GUO D L, XU X L, LU M Z, BARDGETT R D, EISSENSTAT D M, MCCORMACK M L, HEDIN L O 2018. Evolutionary history resolves global organization of root functional traits. *Nature* [J], 555: 94-+.10.1038/nature25783.
- STOKES A, FOURCAUD T, HRUSKA J, CERMAK J, PRAUS L 2002. An evaluation of different methods to investigate root system architecture of urban trees in situ. I. Ground-penetrating radar. *Journal of Arboriculture* [J], 28: 2-10.
- TANIKAWA T, IKENO H, YAMASE K, DANNOURA M, AONO K, HIRANO Y 2021. Can ground-penetrating radar detect adjacent roots and rock fragments in forest soil? *Plant and Soil* [J], 468: 239-257.
- WARREN C, GIANNOPOULOS A, GIANNAKIS I 2016. gprMax: Open source software to simulate electromagnetic wave propagation for Ground Penetrating Radar. *Computer Physics Communications* [J], 209: 163-170.
- WINDSOR C G, CAPINERI L, FALORNI P 2013. A data pair-labeled generalized Hough transform for radar location of buried objects. *IEEE Geoscience and Remote Sensing Letters* [J], 11: 124-127.
- ZHAO H, GALLO O, FROSIO I, KAUTZ J 2016. Loss functions for image restoration with neural networks. *IEEE Transactions on computational imaging* [J], 3: 47-57.

Session 5

**Wood Material
Characterization**

State-of-Art NIR Technology for Wood Products

Satoru Tsuchikawa

Graduate School of Bioagricultural Sciences, Nagoya University, Japan, st3842@agr.nagoya-u.ac.jp

Te Ma

Graduate School of Bioagricultural Sciences, Nagoya University, Japan, mate@agr.nagoya-u.ac.jp

Tetsuya Inagaki

Graduate School of Bioagricultural Sciences, Nagoya University, Japan, inatetsu@agr.nagoya-u.ac.jp

Abstract

Wood products are strongly required to be a uniformity of quality attributes, which necessitates the development of NDT. Near-infrared spectroscopy (NIRS) represents a highly suitable approach for the characterization of organic compounds, and is generally combined with several multivariate analysis methods. Several kinds of state-of-art technology is useful for this. Especially, spectroscopic and imaging method is a great method for examining organic compounds, often used with advanced data analysis techniques. We show how spectroscopic and imaging method can contribute to sustained wood supply. Thanks to improvements in spectral imaging and data analysis, some devices can do more than ever before.

Keywords: NIR, Data science, Imaging

Introduction

The non-destructive quality evaluation of organic materials, including agricultural and forest products, has been extensively studied using near-infrared spectroscopy (NIRS) [1]. This technology analyzes the reflected and transmitted light spectra within the wavelength range of approximately 800 to 2500 nm. NIRS is capable of measuring high-density organic materials non-destructively due to its weaker absorption energy compared to that in the infrared (IR) region. Furthermore, NIRS is particularly useful for analyzing samples with high moisture content (MC), such as trees or green wood, because it has lower molar absorptivity [2].

Chemometric methods for NIR spectral analysis include mathematical pretreatments (e.g., standard normal variate (SNV) transformation), classification methods (e.g., soft independent modeling of class analogy (SIMCA)), and regression methods (e.g., principal component regression (PCR), partial least squares regression (PLSR), and neural network regression (NNR)) [3].

Hyperspectral imaging (HSI), which combines traditional spectroscopic methods with imaging, has become a popular technique since its origins in the remote sensing community in the 1980s. With advancements in spectral imaging cameras, computers, and data analysis tools, we can reasonably conclude this technology to mature and eventually be used for quality monitoring and control of variated forest and wood products [4].

Stiffness and Moisture Content Prediction Model of Wooden Veneer using Fast Online Near-Infrared (NIR) Spectroscopic System [5]

This research highlights significant advancements in the field of wood quality assessment through the implementation of an online NIR spectroscopic system. This system is notable for its remarkable operational speed of 120 meters per minute and was specifically used to predict key quality parameters of wooden veneer: namely, stiffness, measured by the modulus of elasticity (MOE), and moisture content (MC). The study focused on veneers derived from two distinct species, Japanese cedar (*Cryptomeria japonica*) and Douglas-fir (*Pseudotsuga menziesii*), which are critically important in the plywood production industry.

The methodology for assessing MOE involved conducting a three-point bending test on veneer samples with an air-dry moisture content ranging between 12% and 13%. Simultaneously, moisture content measurements were taken from a high of 30% down to 12%, capturing a broad range of moisture levels that the veneer might exhibit during processing. The accuracy of the NIR spectroscopic system's predictions was evaluated using the root mean square error of cross-validation (RMSECV). The results indicated MOE prediction errors of 0.9 GPa for Japanese cedar and 1.8 GPa for Douglas-fir veneers, respectively. Meanwhile, the prediction errors for MC were 1.0% for Japanese cedar and 0.6% for Douglas-fir veneers, demonstrating the system's robust accuracy in assessing these critical properties.

This research underscores the significant potential of using a fast, online NIR spectroscopic measurement technique in the industrial plywood production line, pointing towards a marked improvement in prediction accuracy for both MOE and MC. The efficiency and speed of this technology could lead to significant advancements in quality control processes, thereby enhancing overall production efficiency within the plywood industry.

Experimental Study and Three-Dimensional Modeling of Moisture Transport in Wood by Means of Near-Infrared Hyperspectral Imaging Coupled with a Heat and Mass Transfer Simulation Method [6]

The NIR-HSI (Near-Infrared Hyperspectral Imaging) methodological approach enabled, for the first time, the visualization of water movement within wood samples in three dimensions by meticulously slicing thick samples into thinner sections. This visual portrayal not only highlights the potential of NIR-HSI-based moisture content (MC) mapping to validate and refine the parameters used in complex

simulations of wood drying processes, but also establishes a foundational understanding of how water distributes itself within the wood across different drying environments.

A key limitation noted in the study is the inherent penetration depth of NIR technology, which is limited to just a few millimeters beneath the wood's surface. This limitation means that the accuracy of the MC information is confined to the superficial layers of the wood sample. However, the study presents a promising solution to this challenge by proposing the integration of NIR-HSI with other analytical techniques that can penetrate deeper into the wood, or by leveraging computer simulation methods. This integrative approach holds the promise of extending the range of new applications far beyond the current scope.

In conclusion, this pioneering study effectively demonstrates the usefulness of the NIR-HSI technique in supporting and validating the construction of MC simulation models for wood. Through detailed visualization and simulation of moisture distribution, the research sets the stage for substantial enhancements in the wood drying process, indicating a pathway forward for producing superior wood products.

Cognitive Spectroscopy for Wood Species Identification: Near Infrared Hyperspectral Imaging Combined with Convolutional Neural Networks [7][8]

This research introduces cognitive spectroscopy, which combines near-infrared hyperspectral imaging (NIR-HSI) and deep convolutional neural network (CNN) technologies, to enhance wood species identification. This advancement is crucial for combating illegal logging and analyzing wood properties. Despite the development of several nondestructive identification systems, their limited reliability and accuracy highlight the need for further advancements. Cognitive spectroscopy autonomously extracts features from complex data, offering a sophisticated, automated solution without human intervention. In this study, 120 samples from 38 hardwood species were scanned using an NIR-HSI camera. A deep learning model was constructed based on the first six principal components (PC1-PC6) of the hyperspectral images, achieving a 90.5% identification accuracy, which significantly outperforms traditional visible imaging techniques. This approach not only proves highly effective in species differentiation but also underscores the potential for advancements in wood analysis and identification technologies. It suggests that continuous sample collection could further refine and validate the model.

Conclusion

This article highlights advancements in Near-Infrared Spectroscopy (NIRS) technology for both qualitative and quantitative analysis of forest and wood products. It covers a wide range of applications including the analysis of chemical composition, moisture content (MC), density, anatomical features, mechanical properties, wood modification and degradation, as well as pulp, paper, and species classification.

NIRS is renowned for its simplicity, speed, and precision, establishing it as a leading analytical tool, particularly for quality control in the forest and wood industries. The development of spectral imaging techniques has enhanced both the performance and accessibility of NIRS, pointing to its expanding role in real-time quality monitoring across various sectors. Despite its limitations in conventional online grading, primarily due to the time required for data collection and processing, NIRS remains highly effective for batch testing of small sample quantities and in laboratory settings for studies on moisture dynamics, wood modification, degradation, and species classification.

Reference

1. Tsuchikawa S, Inagaki T, Ma T. Application of Near-Infrared Spectroscopy to Forest and Wood Products. *Curr For Reports*. 2023;9:401-412.
2. Kobori H, Gorretta N, Rabatel G, Bellon-Maurel V, Chaix G, Roger J-M, et al. Applicability of Vis-NIR hyperspectral imaging for monitoring wood moisture content (MC). *Holzforschung*. De Gruyter; 2013;67:307–14.
3. Roggo Y, Chalus P, Maurer L, Lema-Martinez C, Edmond A, Jent N. A review of near infrared spectroscopy and chemometrics in pharmaceutical technologies. *J Pharm Biomed Anal*. 2007;44:683–700.
4. Schimleck L, Ma T, Inagaki T, Tsuchikawa S. Review of near infrared hyperspectral imaging applications related to wood and wood products. *Appl Spectrosc Rev [Internet]*. Taylor & Francis; 2022;0:1–25. Available from: <https://doi.org/10.1080/05704928.2022.2098759>
5. Sofianto IA, Inagaki T, Itoh M, Tsuchikawa S. Stiffness and moisture content prediction model of wooden veneer using fast online near-infrared (NIR) spectroscopic system. *For Res Eng Int J*. 2017;1:40–3.
6. Ma T, Morita G, Inagaki T, Tsuchikawa S. Experimental study and three-dimensional modeling of moisture transport in wood by means of near-infrared hyperspectral imaging coupled with a heat and mass transfer simulation method. *Holzforschung*. 2022;76:699–710.
7. Kanayama H, Ma T, Tsuchikawa S, Inagaki T. Cognitive spectroscopy for wood species identification: Near infrared hyperspectral imaging combined with convolutional neural networks. *Analyst*. Royal Society of Chemistry; 2019;144:6438–46.
8. Zeng W, Fujimoto T, Inagaki T, Tsuchikawa S, Ma T. Three-dimensional modeling of moisture transport in wood using near-infrared hyperspectral imaging and X-ray computed tomography in conjunction with finite element analysis. *J Wood Sci*. 2024;70.

Determination of Stiffness and Strength Variability of Structural Timber by Acoustic Methods

Aleš Straže

Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, Ljubljana, Slovenia, ales.straze@bf.uni-lj.si

Bogdan Šega

Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, Ljubljana, Slovenia, bogdan.sega@bf.uni-lj.si

Jure Žigon

Department of Wood Science and Technology, Biotechnical Faculty, University of Ljubljana, Ljubljana, Slovenia, jure.zigon@bf.uni-lj.si

Abstract

Structural timber made of spruce (*Picea abies* Karst.) with the dimensions $3000 \times 100 \times 35$ mm was visually classified according to the European standards DIN 4074-1 and EN 338 into the grading/strength classes S7 (C18), S10 (C24) and S13 (C30). In addition, the mechanical strength grading of each specimen was supplemented by the determination the mean dynamic modulus of elasticity (MOE_d) using the longitudinal vibration resonance method. Based on the visual structural characteristics and the anomalies present, the weakest and strongest cross-section of each specimen were identified and sampled, where the MOE_d was determined, and finally a static four-point bending test was performed, to determine static MOE and bending strength. The study confirmed that visual grading of sawn timber for construction purposes is more conservative compared to dynamic mechanical testing. The stiffness and bending strength of the structural timber varied considerably, from low values in the weakest cross-sections to high values in the strongest cross-sections, which were above the mean values of the test specimens. The variability of bending strength, stiffness, density and wood structure decreased with increasing strength class of the timber. The bending strength of the specimens at locations with and without structural anomalies correlated equally with the dynamic and static modulus of elasticity.

Keywords: wood, structural timber, visual grading, non-destructive testing, dynamic mechanical properties, sound velocity.

Introduction

Strength grading of structural timber is a process for increasing the value of sawn timber products. In Europe, the process for grading structural timber is defined in the EN 14081-1 standard. There are two systems for grading timber: visual and machine grading. Both systems define classes to which characteristic values for strength, stiffness and density can be assigned in accordance with EN 338, whereby the characteristic values are defined and measured in accordance with EN 384. The two classification systems differ in the properties that are measured to determine the classification criteria and the normative requirements. The test methods for determining the mechanical properties of sawn timber are defined in EN 408 (Ridley-Ellis et al., 2016; Steiger and Arnold, 2009).

Visual strength grading requires a non-destructive evaluation of each piece of wood to establish grading rules based on visual characteristics such as knots, ring width, grain direction, warping, etc. For visual strength grading, the common strength class system is defined in EN 338, while the EN 1912 standard

regulates the assignment of wood species from national standards to strength classes. In general, each European country has developed its own grading rules to define the methods for measuring properties and their limits. For coniferous sawn timber, for example, the German standard DIN 4074-1 defines three grades (S7, S10 and S13) (Oscarsson, 2012; Ridley-Ellis et al., 2016; Trulli et al., 2017).

The machine grading of structural timber is carried out in accordance with European regulations on the basis of statistical correlations between the so-called indicating properties and the bending strength. The most commonly used indicating property (IP) is stiffness in the form of the average modulus of elasticity (MOE) of a timber piece, although MOE is a material property that varies within timber (Steiger and Arnold, 2009). The oldest grading machines measured MOE of wood by non-destructive bending tests. Nowadays, new technologies and a variety of IPs are used that correlate well with wood properties. For example, ultrasonic pulse velocity and longitudinal or bending vibration frequency are measured to determine the dynamic modulus of elasticity (MOE_d), and X-ray analysis is performed to determine density and detect knots, etc. (Ridley-Ellis et al., 2016; Trulli et al., 2017).

In the approval tests for a grading machine, the wood quality influences the (non-adjustable) initial settings. However, the settings of the machine are not only based on the weakest sample, but on the average of all subsamples used in the approval process. Consequently, the origin of the timber in the subsamples has an important influence on the assigned mechanical properties of the graded timber and on the settings (Stapel et al., 2009). The strength of structural timber depends to a large extent on the occurrence of knots, whereby not only the size and position of the knots, but also the fibre deviations in the surrounding clear wood are of great importance for the local stiffness and the development of fractures under load. Despite the great development of machine grading of structural timber based on acoustic wave propagation in recent years, the correlations described are relatively poor and not completely reliable due to several influencing factors (Oscarsson, 2012).

This study deals with strength grading in Europe and focuses on the effects of visual and acoustic (machine) grading methods on the properties of structural timber. In addition, the results are compared to evaluate the efficiency of the different methods. Various parameters that influence the results of the grading are considered.

Material and Methods

Sampling

The 21 boards included in the analysis were spruce structural sawn timber (*Picea abies* Karst.) measuring 3000×100×30 mm (L×W×H), unsorted by quality and randomly sourced from the local manufacturer's warehouse (Fig. 1). The boards were conditioned in the laboratory for one month in a normal climate ($T = 20\text{ }^{\circ}\text{C}$, $RH = 65\%$) before testing.

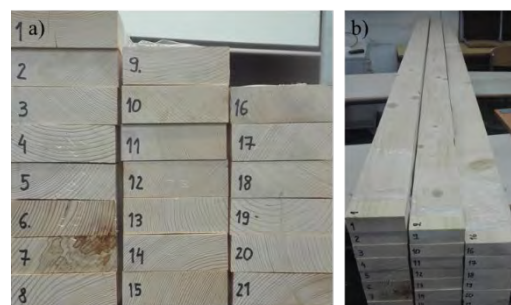


Figure 1— Random sampling of structural sawn timber with face markings (a) and appearance (b).

Strength grading

Visual grading of sawn timber

Structural sawn timber was divided into strength classes according to DIN 4074-1. The boards were visually inspected and classified into one of the grading classes (S7 – grade 1, S10 – grade 2 or S13 – grade 3), then the strength classes (C18, C24 and C30; EN 338:2016) were assigned according to EN 1912.

Machine grading of sawn timber

For the machine strength grading, the boards were placed on elastic, thin rubber pads and excited from one end face with an impact hammer (mass 100 g). The sound vibrations were recorded on a second end face with a unidirectional condenser microphone (PCB-130D20) and recorded with an NI-9234 DAQ module in 24-bit resolution at 51.2 kHz sampling frequency (Fig. 2). The measured natural frequency of the board in the first longitudinal vibration mode (f_L) was used to determine the velocity of sound (v_L) and the modulus of elasticity (MOE_d) in the longitudinal direction of the board (Eq. 1).

$$MOE_d = \rho \cdot (2 \cdot L \cdot f_L)^2 = \rho \cdot v_L^2 \quad (1)$$

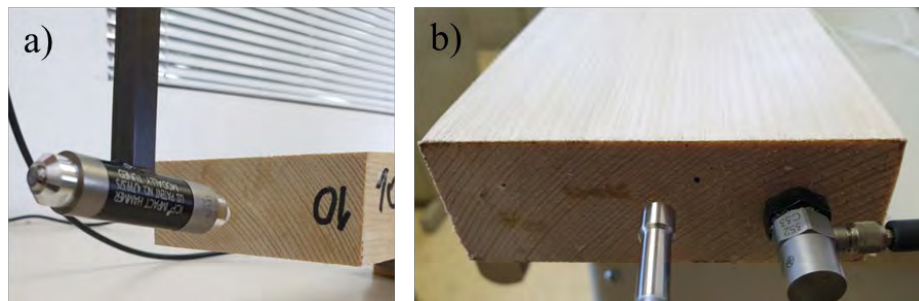


Figure 2— Impulse excitation with an impact hammer at the front (a) and measurement of the sound vibration at the rear end of the board (b).

Based on the calculated dynamic modulus of elasticity (MOE_d) and the density of the boards (ρ), the individual test samples were divided into strength classes in accordance with the EN 338 standard. Both criteria, i.e. the measured dynamic modulus (MOE_d) of elasticity and the wood density (ρ), were used for the classification into the strength classes, whereby the lower of the two values was decisive.

Locating the weakest and strongest cross-section of sawn timber for load-bearing purposes

After sorting the sawn timber, the weakest, i.e. critical (W) and the strongest (S) cross-section of each board were selected and marked (Fig. 3). The positioning of the W and S cross-section of the boards was carried out according to the rules of the DIN 4074-1 standard. All relevant growth anomalies were analysed on the boards, such as the presence of knots, wane, grain deviations, cracks, rotting, reaction wood, insect attack and warping. These cross-sections were then selected as the location of the maximum bending moment in the static-mechanical testing of the characteristic, small test specimens ($L = 700$ mm), which were then cut off and marked.



Figure 3— Visual identification of the weakest (W) and strongest (S) cross-section in a sawn timber board from which the characteristic weak (W) and strong (S) small test specimens ($L = 700$ mm) were cut out.

Mechanical testing of small specimens

The dynamic-mechanical testing of small test specimens was carried out in the same way as for structural sawn timber. The fundamental frequency of the longitudinal vibration (f_L) of the small specimens was used to determine the velocity of sound (v_L) and the dynamic modulus of elasticity (MOE_d) (Fig. 4a, Eq. 1).

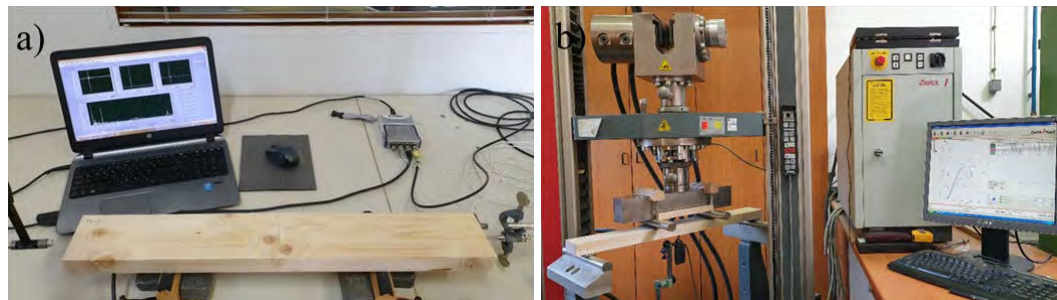


Figure 4— Dynamic mechanical testing (a) and static 4-point bending testing of characteristic (W, S) small specimens (b).

The static bending mechanical properties of the small specimens were determined on a Z100 universal testing machine (Zwick/Roell, Ulm, Germany) and the data evaluated using TestXpert III software. The static 4-point flat-wise bending test was carried out in accordance with EN 408 standard with a span of 630 mm, and a distance of 210 mm between the loading points. The static global modulus of elasticity (MOE_s) was determined by measuring the deflection with an LVDT (Eq. 2, Fig. 4b).

Results and Discussion

Visual and machine strength grading of structural sawn timber

Based on the visual assessment, the boards were classified into 3 strength classes. 28.6 % ("Reject") of the boards could not be classified as they had anomalies that exceeded the classification criteria. The largest proportion of boards were assigned to class C18 (38.1 %), 19.0 % to class C24 and 14.3 % to class C30. The most common decision criteria for the visual classification of the boards into strength classes were knot size and presence of knot cluster (Fig. 8b). In several cases, the knot size reduced the load-bearing cross-section of the boards significantly beyond the permissible limit ($> 3/5$) or within the limits of the standard ($\leq 1/5$; $\leq 2/5$; $\leq 3/5$; Fig. 7b).

In the dynamic mechanical test, we found that all boards met the criteria for classification into the strength classes according to EN 338 (without the subsequent visual override inspection prescribed in EN 14081-1, while in the visual classification we were unable to assign almost 30 % of the test specimens to any strength class. The highest proportion of boards (28.6 %) were classified in strength class C50 using dynamic

mechanical testing, which corresponds to the proportion of unclassified boards in the visual classification (28.6 %) (Fig. 5a). The lowest proportions of boards were classified in strength classes C24 and C27 (4.8%). The proportion of boards classified in strength classes C14 (9.5 %) and C16 (9.5 %) was also quite low. In the machine grading the same proportion of boards were classified in strength class C35 as in class C30 (14.3 %), determined visually. However more boards were classified in class C30 in the dynamic test (19.0 %) (Fig. 5b).

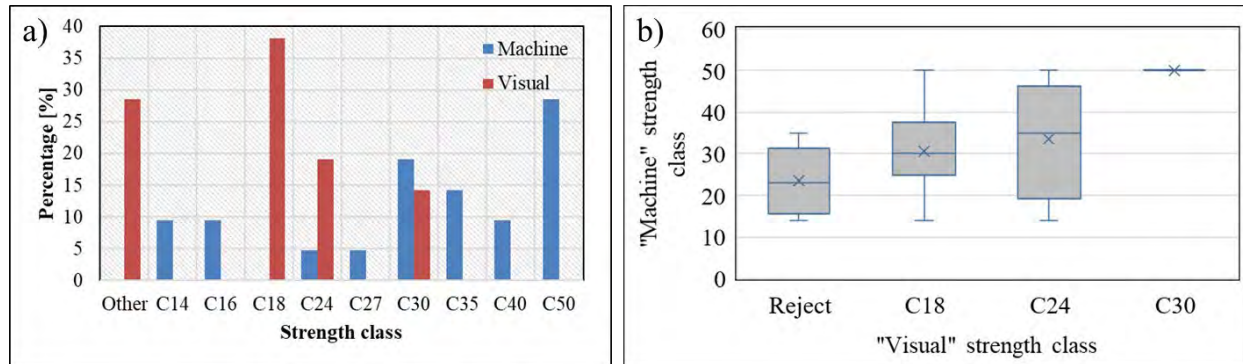


Figure 5— Proportion of boards in each strength class, determined by visual and machine strength grading (a) and comparison of the classification of boards into strength classes (horizontal and vertical axes) by visual and machine strength grading (b).

However, in order to directly compare the two classification methods, it is necessary to use equal starting point. Since the visual classification of the wood is based on the weakest points and considers that only a maximum of 5 % of the boards do not meet the criteria, the same statistical principle was tested for the dynamic measurements. It was found that the average wood density was 445 kg/m³ (Coef. of variation, CV = 10.0 %). However, examination of the density distribution of the wood revealed a normal distribution with a density at the 5th percentile of the distribution of 384 kg/m³.

The frequency distribution of the dynamic modulus of elasticity of the boards was also confirmed to be normally distributed. The value of the MOE_d at the 5th percentile of the distribution was 7.75 GPa and the mean value was 13.26 GPa (CV = 25.9 %).

A comparison of the characteristic values for the wood density and the MOE_d with the information on the strength classes in the EN 338 standard shows that the tested boards could be classified in strength class C27. However, due to the small number of boards, the indicative properties would have to be further corrected and lowered, as defined in EN 384. The distribution of the test specimens in the strength classes of the dynamic and static methods would therefore be very close to each other. For the same reason, the complete sorting procedure required by EN 14081-2, which also includes a cost matrix, was not carried out. For this reason, the measured dynamic moduli of the boards were compared directly with the criteria of EN 338.

Variability of the physical and dynamic mechanical properties of sawn timber

The measured density range of the boards, from 350 kg/m³ to 550 kg/m³, is consistent with the literature data for the density of spruce wood (Mäkinen et al., 2002; Wagenführ, 2007). The density of the boards generally increased with increasing strength class (Fig. 6a). Within the strength classes, we found that the variability in wood density was lower in the higher strength classes, i.e. C30 to C50. This is related to the more homogeneous wood structure of the boards in these classes, where there are no growth anomalies (Figure 7a).

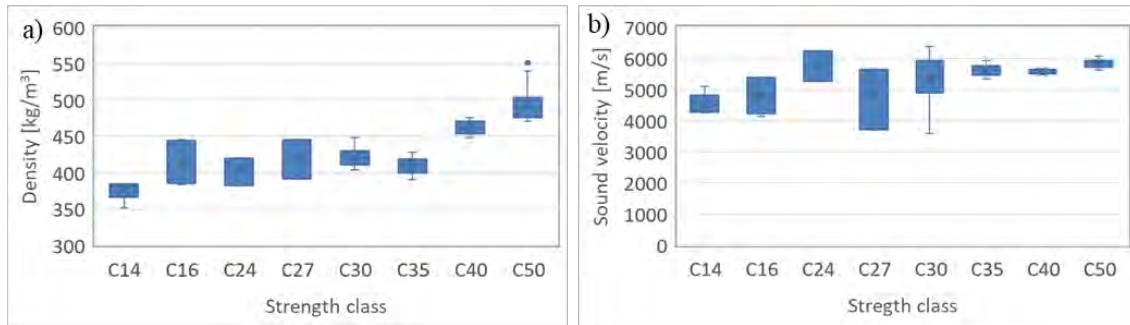


Figure 6— Variation of wood density (a) and sound velocity (b) in boards of each strength class, determined by the mean value for the entire test piece and by the density at the weakest and strongest cross-section.

With increasing strength class, the sound velocity and the natural frequency of the boards generally increased, while the variability was lower (Fig. 6b). Similar sound velocities were determined by other authors in spruce wood (Halachan et al., 2016), although lower values were also observed in samples from lower strength classes (C14, C16, C20, C27, with wood densities of less than 450 kg/m³).

Using the longitudinal vibration resonance method, we found a higher number of frequencies near the fundamental vibration at the weakest cross-section of the boards. We attribute this to the presence of anomalies, especially knots, and the resulting deviation of the wood grain (Fig. 7b). However, at the strongest cross-section of the same boards, without visible structural anomalies, only the fundamental resonance frequency was detected in the spectra in combination with higher harmonic frequencies (Fig. 7a).

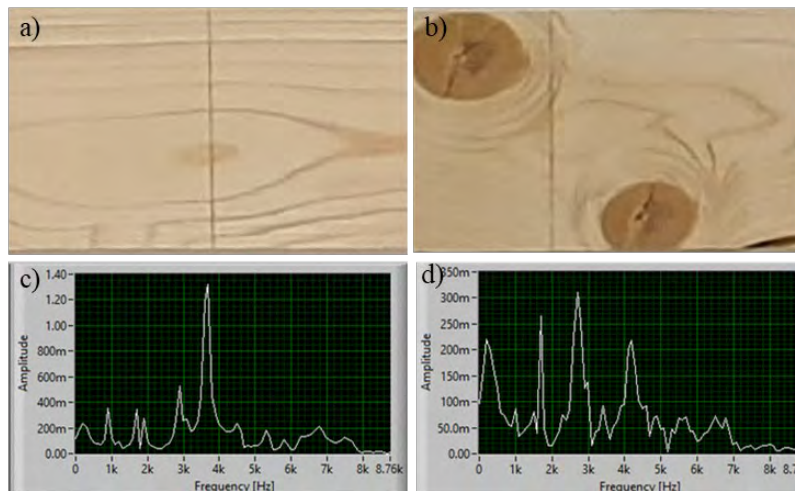


Figure 7— Visual appearance and measured frequency spectrum in weak (W) crosssection of small test specimens from the boards in the highest (C30; a, c) and in the lowest strength class (C14; b, d).

Related studies on the dynamic and static mechanical properties of sawn timber have also confirmed the high variability of wood density. Previous studies also show, similar to this one, that the average wood density is positively correlated with the modulus of elasticity and bending strength of spruce wood (Fig. 7; Sonderegger et al., 2008). We have found that the static modulus (MOE_s) and the dynamic modulus of elasticity (MOE_d) can predict the bending strength of the small test specimens. A better linear regression model ($R^2 = 0.88$ to 0.95) was obtained when using MOE_s than when using MOE_d ($R^2 = 0.66$ to 0.73).

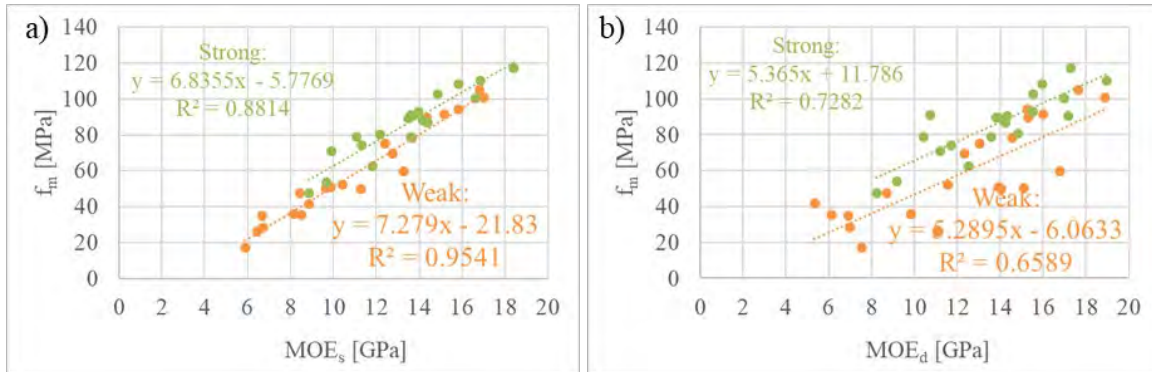


Figure 8— Dependence of the bending strength (f_m) of small test specimens from the weakest and the strongest cross-section of the boards on the static modulus of elasticity (MOE_s) (Fig. 9a) and on the dynamic modulus of elasticity (MOE_d) (Fig. 9b).

As can be seen (Fig. 8), a high bending strength was determined at the test specimens. For the weak cross-section, more than twice the bending strength specified in the strength class was measured. However, bending strength values up to 3 times the strength class were measured at the strongest cross-sections of the boards. We also found that the variability in bending strength decreases with increasing strength class.

Conclusions

The visual grading of sawn timber for load-bearing purposes according to DIN 4074-1 is conservative compared to non-destructive (machine) acoustic grading, which is based on the determination of density and dynamic modulus of elasticity according to the longitudinal vibration resonance method. The variations in wood density, structure and mechanical properties are greater for boards in the lowest strength classes. The stiffness of structural timber can already be determined non-destructively by determining the mean dynamic modulus of elasticity and the mean density of the wood, which, however, typically varies in samples with more structural anomalies, such as the presence of knots. Stiffness is low for weak cross-sections when the bending strength of the wood is also low. The bending strength of structural timber can be predicted equally well by the dynamic and static modulus of elasticity.

Acknowledgments

The work was created within the research project J2-50063 (“Sustainable long-term use of timber structures - fire and post-fire deterministic and probabilistic solutions) and the research programs P4-0430 (“Forest-wood value chain and climate change: transition to circular bioeconomy”) and P4-0015 (“Wood and lignocellulosic composites”), founded by the Slovenian Research and Innovation Agency (ARIS).

References

- Bates, J. 1998. Small mammal and bird inventories. In: Leavengood, S.; Swan, L., eds. Proceedings, western juniper forum '97. Gen. Tech. Rep. PNW-GTR-432. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 29-30.
- DIN 4074-1. 2008. Strength grading of wood - Part 1: Sawn softwood. Berlin, Deutsches Institut für Normung e.V (DIN), Berlin, 21 p.
- EN 338. 2016. Structural Timber - Strength classes. CEN, Brussels, 16 p.

EN 384. 2016. Structural timber. Determination of characteristic values of mechanical properties and density. CEN, Brussels, 24 p.

EN 408. 2010. Timber structures - Structural timber and glued laminated timber: Determination of some physical and mechanical properties. CEN, Brussels, 38 p.

EN 1912. 2024. Structural Timber - Strength classes: Assignment of visual grades and species. CEN, Brussels, 16 p.

EN 14081-1. 2016. Timber structures - Strength graded structural timber with rectangular cross section - Part 1: General requirements. CEN, Brussels, 44 p.

EN 14081-2. 2018. Timber structures - Strength graded structural timber with rectangular cross section - Part 2: Machine grading; additional requirements for type testing. CEN, Brussels, 38 p.

Halachan P. 2016. Physico-acoustic characteristics of spruce and larch wood. Zvolen, Technical University in Zvolen, Faculty of Wood Science and Technology, 238 p.

Mäkinen, H., Saranpää, P. & Linder, S. 2002. Wood-density variation of Norway spruce in relation to nutrient optimisation and fibre dimensions. Canadian Journal of Forest Research, 32(2), 185-194.

Oscarsson, J. 2012. Strength grading of structural timber and EWP laminations of Norway spruce – Development potentials (Licentiate thesis). Växjö, Linnaeus University, School of Engineering, 156 p.

Ridley-Ellis, D., Stapel, P. & Baño, V. 2016. Strength grading of sawn timber in Europe: an explanation for engineers and researchers. Eur. J. Wood Prod., 74, 291–306.

Sonderegger, W., Mandallaz, D. & Niemz, P. 2008. An investigation of the influence of selected factors on the properties of spruce wood. Wood Sci Technol 42, 281-298.

Stapel, P., van de Kuilen, J. V. G. 2013. Effects of grading procedures on the scatter of characteristic values of European grown sawn timber. Materials and Structures, 46, 1587-1598.

Steiger, R., Arnold, M. 2009. Strength grading of Norway spruce structural timber: revisiting property relationships used in EN 338 classification system. Wood Science and Technology, 43, 259-278.

Trulli, N., Valdés, M., De Nicolo, B. & Fragiaco, M. 2017. Grading of Low-Quality Wood for Use in Structural Elements. In. Wood in Civil Engineering (Concu, G., editor), IntechOpen Limited, London, 24 p.

Wagenführ, R. 2007. Holzatlas. Hanser, Munich, 924 p.

Nordmann and Noble Fir Lamellas for Structural Purposes—Grading and Determination of Elastomechanical Properties by Non-Destructive and Destructive Testing

Katja Fruehwald-Koenig

Department of Production Engineering and Wood Technology, OWL University of Applied Sciences and Arts, Lemgo, Germany, katja.fruehwald@th-owl.de

Martin Hackel

Department of Production Engineering and Wood Technology, OWL University of Applied Sciences and Arts, Lemgo, Germany, martin.hackel@th-owl.de

Dennis Kipp

Department of Production Engineering and Wood Technology, OWL University of Applied Sciences and Arts, Lemgo, Germany, dennis.kipp@stud.th-owl.de

Karin Lueke

Department of Production Engineering and Wood Technology, OWL University of Applied Sciences and Arts, Lemgo, Germany, karin.lueke@stud.th-owl.de

Felix Leonard Stracke

Department of Production Engineering and Wood Technology, OWL University of Applied Sciences and Arts, Lemgo, Germany, felix.stracke@stud.th-owl.de

Noah Burghaus

Department of Production Engineering and Wood Technology, OWL University of Applied Sciences and Arts, Lemgo, Germany, noah.burghaus@stud.th-owl.de

Stefanie Wieland

Forest and Wood NRW, Center for Forestry and the Timber Industry (FB V), Timber Industry Team, Olsberg, Germany, stefanie.wieland@wald-und-holz.nrw.de

Abstract

Since the early 2000s, forest owners in Central Europe have increasingly planted Nordmann fir (*Abies nordmanniana* (STEVENSON) SPACH) and Noble fir (*Abies procera* REHD.) for Christmas trees, intending to convert them into high forests. Climate-related damage, especially since 2018, has significantly reduced spruce populations, requiring a shift towards climate-adaptable tree species in future forests. Additionally, to reduce CO₂ emissions from construction, there's a push for expanding timber construction, requiring non-spruce species for load-bearing products and applications. Although Nordmann and Noble fir are potential alternatives to spruce, they are not yet integrated into European standardization for load-bearing construction. Therefore, an assessment of German-origin Nordmann and Noble fir for use in glued laminated building products (GLT and CLT) is underway. Kiln-dried lamellas are graded visually and by machine using longitudinal vibration, with selected lamellas tested for tensile strength. Various mechanical properties are determined using non-destructive and destructive methods to establish input parameters for Finite Element Analysis (FEA).

Keywords: Nordmann fir, Noble fir, grading, elastomechanical properties, ultrasonic testing, vibration measurement

Introduction

Background

Following storm and calamity events in Europe since the early 2000s, many forest owners decided to establish Christmas tree plantations featuring Nordmann fir (*Abies nordmanniana* (STEVEN.) SPACH) and Noble fir (*Abies procera* REHD.), which are currently and further will be transformed into high forests. Moreover, climate-related forest damages and associated large-scale calamities resulted in significant depletion of spruce since 2018. Therefore, future forests should be characterized by a climate-adaptable variety of tree species. To further reduce the construction sector's contribution to CO₂ emissions, there is an emphasis on expanding timber construction. Therefore, in the medium term, wood species other than spruce have to be used in load-bearing timber construction products. But EN 14080 (2013 (D)) and EN 16351 (2021 (D)), which specify the requirements for glued laminated and cross laminated timber, do not list Nordmann and Noble fir. Both species of European origin are also not listed in pr EN 1912 (2022 (D)) – only Nordmann fir (*Abies nordmanniana* (STEVEN.) SPACH and *Abies nordmanniana subsp. Bornmuelleriana* (= *Abies bornmuelleriana* (MATTF.)) from Turkish origin and visual grading according to the Turkish standard (C18, C24, C27) and Noble fir (*Abies procera* REHD.) from the United States and Canada and visual grading according to the standards from Canada (NLGA), Ireland and Great Britain in the “Hem-fir” species group (C14, C16, C20, C24). But these cannot be directly compared with Nordmann and Noble fir from Central European origin, as the morphological and therefore the elastomechanical properties can vary greatly depending on the growth region. But it shows that Nordmann and Noble fir are already being used as construction timber. As there is still no Approved Grading Report (AGR) on the adjustment of grading machines for the grading of Nordmann and Noble fir from Central European origin that has been evaluated and recognized by the European Committee for Standardization/Technical Committee 124 (CEN/TC 124), no sawn timber of Nordmann and Noble fir that is mechanically graded with machine-controlled systems may be placed on the European market (EN 14081-1 (2019), section 5.1.3).

The application of simulations using analytical and numerical methods is increasing in R&D and the wood processing industry, especially concerning the optimized composition of engineered wood products based on solid wood lamellas or veneers (e.g. GLT, CLT, LVL), as well as combinations of wood with other materials. Therefore, small-size, defect-free test specimen are considered idealized as an orthotropic material using a right-angled coordinate system with clearly different properties along the three main axes longitudinal, radial and tangential and three planes of symmetry formed by the axes.

For numerical modelling, twelve elastic material parameters (3 E, 3 G and 6 ν) must be known. Güray et al. (2019) describe the bending MOE for Nordmann fir. For *Abies nordmanniana* (STEVEN.) SPACH *subsp. Bornmuelleriana* (= *Abies bornmuelleriana* (MATTF.)) from Turkey, the bending MOE is described by Vurdu et al. (2013) and Özkan et al. (2017). For Noble fir from the United States, the Young's modulus in compression parallel to grain is described by Paul et al. (1959), the bending MOE by Betts (1929) and Ross (2021). Gil-Moreno (2018) describes the bending MOE for Noble fir from Great Britain. Bodig and Jayne (1982) mention the three Young's moduli and the three shear moduli for Noble fir. All other elastic constants are not determined for Nordmann and Noble fir till now.

For plastic modelling, the plastic material parameters compressive yield strengths (= strength of a material at the transition from elastic to plastic material behaviour), the hardening moduli (= slope between the compressive yield strength and the compressive strength) and the tensile yield strengths (assumed to be equal to the tensile strengths) must be known for the three anatomical main directions as well as the shear yield strengths (assumed to be equal to shear strengths) for the three planes. Güray et al. (2019) describe the bending MOR for Nordmann fir. For *Abies bornmuelleriana* (MATTF.) from Turkey, the compression strength parallel to grain is described by Berkel (1963) and Özkan et al. (2017), the tensile strength perpendicular to grain by Berkel (1963) and the bending MOR by Vurdu et al. (2013), Berkel (1963) and Özkan et al. (2017). For Noble fir from the United States, the compression strength parallel to grain is described by Betts (1929), Paul et al. (1959) and Ross (2021), the compression strength perpendicular to grain by Betts (1929) and Ross (2021), the tensile strength perpendicular to grain by

Ross (2021), the shear strength parallel to grain by Betts (1929), Ross (2021) and the bending MOR by Betts (1929), and Ross (2021). Gil-Moreno (2018) describes the bending MOR for Noble fir from Great Britain.

Gil-Moreno and Ridley-Ellis (2015) determined for construction timber of Noble fir grown in Scotland the static MOE and Gil-Moreno (2018) performed strength grading tests on Noble fir grown in Great Britain and determined its MOE and MOR.

Research Question, Assumptions and Approach

Nordmann and Noble fir represent possible alternatives to spruce, however from European origin they are not yet integrated into European standardization and therefore cannot actually be used for load bearing construction products. Consequently, an assessment of the potential of Nordmann and Noble fir of German origin for the load-bearing use as construction timber as well as in Glued Laminated Timber (GLT) and Cross Laminated Timber (CLT) is conducted. Kiln-dried lamellas are visually graded according to the German Standard DIN 4074-1 (2012) and machine graded using longitudinal vibration. Selected glulam lamellas are subjected to a tensile test, establishing an initial correlation between visual grading classes according to DIN 4074-1 (2012) and strength classes according to EN 338 (2016 (D)). This allows for a preliminary classification of both wood species in pr EN 1912 (2022 (D)) and confirming the suitability of longitudinal vibration for machine strength grading. Subsequently, graded lamellas are finger-jointed and used to produce combined and homogeneous glulam, which is tested for bending and longitudinal compression. The elastomechanical properties of these glulam beams will be presented in a separate paper and are not within the scope of this paper. To establish input parameters for Finite Element Analysis (FEA), the tensile, compression, shear, and bending properties in various anatomical directions are determined on small, defect-free samples with destructive and non-destructive methods. The comprehensive set of input parameters for finite element method (FEM) modeling will be compiled in a separate paper in the near future.

Material

The Nordmann fir wood originates from the Südsauerländes Bergland, 450 to 540 m above sea level, classified as a mid-slope with a north-west facing slope. The slope inclination is very steep. The Noble fir originates from Reiste (Sauerländisches Bergland). The logs are cut on a mobile horizontal band saw, the boards are kiln dried to 10 ± 2 % mc. The Nordmann fir boards appear to be of comparatively low wood quality with many internal tension (which leads to warping of the lamellas), furthermore knots and cracks are visible. The boards are cut into lamellas using a circular table saw and planed on four sides (dimensions see Table 1). From the material, the test specimens compiled in Table 1 are produced in accordance with the specifications in the corresponding standards. Before testing, all test specimens are stored to constant weight in standard climate 20°C, 65 % relative humidity (DIN 50014-20/65-1 according to DIN 50014 (2018)).

Methods

Visual grading of the lamellas is carried out in accordance with DIN 4074-1 (2012), but the annual ring width is not taken into account for visual grading. The **annual ring width** (rw) is determined on a representative sample of the small-sized specimens. For each specimen, the **density** is determined from mass and volume of the entire specimen. The density of the small-size tensile specimen is determined on the rectangular bars prior to curve milling of the specimens, since the determination of the density on a contour-milled, two-dimensional specimen would have led to inaccuracies. The **natural frequency** of longitudinal vibration (f_l) is determined on the full size test specimen and of longitudinal (f_l) and flexural (f_f) vibration on the small-size, defect-free tensile and bending specimens using the GrindoSonic MK5, J.W. Lemmens N.V. The small-size tensile specimens are measured as rectangular bars prior to the curve milling of the specimens. During vibration measurements, the test specimens are supported on rectangular foam stripes in the nodal points. Impulse is initiated using a small impact hammer. Dynamic Young's modulus from longitudinal ($E_{L,long}$) and flexural vibration ($E_{L,flex}$) are calculated following the equations

presented by Görlacher (1984). On the small-size compression test specimens, **ultrasonic time-of-flight** is measured using the Epoch 650 flaw detector with a through-transmission technique and Olympus C103 transducer with a diameter of 13 mm and a frequency of 1 MHz for longitudinal waves and Olympus V153 transducer with a diameter of 13 mm and a frequency of 1 MHz for transverse waves. The transducers are pressed manually onto the specimen with a contact pressure of around 30 N without coupling agent. The time of flight (TOF) of three longitudinal and six shear waves is measured along the principal axes resp. planes (on specimen type I according to figure 2 in Bachtiar et al. (2015)). Because no Poisson's ratios are available for Nordmann and Noble fir so far, the simplified uncorrected (SU) data evaluation technique is used (Bachtiar et al. 2015). All compression test specimens are tested in the longitudinal direction; a representative random sample is tested in radial direction.

Table 1—Overview of test specimens

DT testing	NDT method	dimension (T x R x L)	wood species	number of speci- mens tested NDT/ DT
full size test specimen				
tension II (f _{t,0} , E _{t,0}), EN 408+A1 (2012 (D))	longitudinal vibration	NDT: 95 x 25 x 1880 resp. 940 mm ³ , DT: 80 x 25 x 880 mm ³ , free test length 9 x width = 720 mm	Nordmann fir	341/36 ¹⁾
		88 x 37 x 1930 mm ³ , free test length 880 mm	Noble fir	152/12 ²⁾
small, defect-free test specimen				
compression II (f _{c,0}), DIN 52185 (1976)	ultrasonic TOF → 3 E, 3 G	20 x 20 x 60 mm ³	Nordmann fir	60/60
			Noble fir	59/59
compression radial (f _{c,90}), DIN 52192 (1979)	ultrasonic TOF → 3 E, 3 G	20 x 60 x 20 mm ³	Nordmann fir	37/37
			Noble fir	49/49
tension II (f _{t,0} , E _{t,0}), DIN 52188 (1979)	longitudinal and flexural vibration	12 ³⁾ resp. 6 ⁴⁾ x 20 x 470 mm ³	Nordmann fir	49/49 ⁵⁾
			Noble fir	47/47 ⁶⁾
bending (f _m , E _m), DIN 52186 (1978)	longitudinal and flexural vibration	20 x 20 x 360 mm ³	Nordmann fir	57/57
			Noble fir	54/54

¹⁾ 341 lamellas are tested regarding density and longitudinal vibration, 36 of these regarding tensile test (305 used for GLT production and finger-jointing tests), the tensile strength value is removed from the evaluation for 6 lamellas due to failure next to the clamping

²⁾ 3 S10 lamellas without measuring the elongation, 1 S13 lamella is taken out because of a crack

³⁾ tested cross section in NDT, thickness of 12 mm instead of 15 mm due to the limited spacing between the clamping jaws of the wedge specimen holders.

⁴⁾ tested cross section in DT

⁵⁾ 7 specimens not tested due to pre-damage (microcracks), 6 specimens excluded from the evaluation because the fracture did not occur in the tapered area

⁶⁾ 11 specimens excluded from the evaluation because the fracture did not occur in the tapered area

The **tensile test parallel of the full size test specimen** is carried out according to EN 408+A1 (2012 (D)) on the FORM + TEST universal testing machine K250-KE-SCH-SY with a clamping length of 80 mm for the Nordmann fir and on the Zum Wald GEZU 600 tensile testing machine with a clamping length of 600 mm at the University of Goettingen for the Noble fir. In deviation to EN 408+A1 (2012 (D)), the displacement is measured with a long-travel extensometer not exactly five times the width, but over a measuring distance of 300 mm. For Nordmann fir the displacement cannot be determined, as the measurement holder cannot be fixed due to the lamella thickness. The calculation of the characteristic values is carried out according EN 384 (2019 (D)) without correction of the specimen size and EN 14358 (2016 (D)) using the parametric calculation approach. Due to the very small sample size, the tensile strength is assumed to be normally distributed and the assignment to the strength classes of EN 338 (2016

(D)) is not based on the characteristic strength ($f_{t,0,k}$), but on the basis of the 5th percentile ($f_{t,0,05}$). The small-size, defect-free test specimen are tested on a ZwickRoell Z020 universal testing machine with a 20 kN load cell. The **compression test in longitudinal direction** is carried out according to DIN 52185 (1976) and the **compression test in radial direction** according to DIN 52192 (1979) with loading over the entire specimen surface (which differs from ISO 3132 (1975) in the specimen geometry) and the proportional limit is determined according to ISO 3132 (1975). As in the present investigations no external displacement measurement (e.g. video extensometer) is available to determine the strain during the compression test, only some of the compression test specimens are tested destructively in order to determine also the Young's modulus in compression of the deferred specimens at a later date. The **tensile test in longitudinal direction** is carried out according to DIN 52188 (1979), the measurement of the elongation is done by means of a manually mounted incremental piecing receiver (digiClip) from ZwickRoell. The **three-point bending test** is performed according to DIN 52186 (1978) in tangential direction. All failure types are classified according to Bodig and Jayne (1982). Due to the storage in the standard climate up to constant mass of the test specimen, the **moisture content** is determined only on randomly selected specimens after the destructive test using oven dry test.

Results and Discussion of Small-Size Specimen

A compilation of the elastomechanical properties is presented in Table 2. Noble fir has significantly lower density and elastomechanical properties than Nordmann fir due to its greater annual ring width. Dynamic Young's moduli determined with vibration and ultrasonic testing show higher values compared to static Young's modulus ($E_{L,stat}$). Furthermore, Young's moduli determined by ultrasonic testing are above that of vibration measurement, e.g. $E_{L,US}$ is 18 % higher than $E_{L,long}$ (and 66 % higher than $E_{L,stat}$ from tensile test), probably because of the simplified uncorrected (SU) data evaluation technique of the ultrasonic measurements. Table 3 shows a very close correlation between Young's moduli from longitudinal and flexural vibration, that from longitudinal vibration ($E_{L,long}$) are 4...10 % above those from flexural vibration ($E_{L,flex}$) (cf. Table 2).

For Nordmann fir the bending MOR is in the range of that described by Güray et al. (2019) (MOR = 80.44 MPa), whereas the bending MOE is above that of Güray et al. (2019) (MOE = 5,993 MPa). Comparing the Nordmann fir samples with *Abies bornmuelleriana* (MATTF.) from Turkey, the MOE and MOR is above that described by Vurdu et al. (2013) (MOE = 7,223 MPa, MOR = 64.58 MPa), Özkan et al. (2017) (MOE = 7,382 MPa, MOR = 60.14 MPa) and Berkel (1963) (MOR = 69.43 MPa), as well as above the compression strength described by Berkel (1963) (35.11 MPa) and Özkan et al. (2017) (39.1 MPa). Comparing the Noble fir samples with samples from the United States, the dynamic and static Young's modulus parallel to grain is lower than that described by Betts (1929) (MOE = 8,832 MPa), Ross (2021) (MOE = 11,900 MPa), Paul et al. (1959) (E_c = 12,252 MPa) and Bodig and Jayne (1982) (13,059 MPa), whereas the Young's moduli from ultrasonic testing perpendicular to grain with SU data evaluation technique is above that described by Bodig and Jayne (1982) (E_R = 809 MPa, E_T = 461 MPa). The shear moduli are in the range or above that described by Bodig and Jayne (1982) (G_{LR} = 685 MPa, G_{LT} = 651 MPa, G_{RT} = 63 MPa). The compression strength parallel to grain is in the range of the stress at proportional limit of 29.03 MPa respectively the maximum crushing strength of 37.92 MPa described by Paul et al. (1959), above that described by Betts (1929) (maximum crushing strength of 18.62 MPa), but lower than that described by Ross (2021) (42.1 MPa). The compression strength perpendicular to grain is between that described by Betts (1929) (2.13 MPa fiber stress at elastic limit) and Ross (2021) (3.6 MPa). The bending strength is between that described by Betts (1929) (39.23 MPa) and Ross (2021) (74 MPa). Compared to Noble fir from Great Britain described by Gil-Moreno (2018), the bending MOE (5,900 MPa), MOR (53.0 MPa) and density (0.38 g/cm³) are in the same range.

Table 3 shows the coefficients of determination (R^2) between the properties from vibration measurement and destructive testing. The modulus of elasticity from tensile and bending test ($E_{L,stat}$) can be estimated via the frequency (f_l and f_b) and the dynamic MOE from vibration measurement ($E_{L,long}$ and $E_{L,long}$). The

density has only a minor influence on Young's modulus resp. MOE and strength from static test, only the bending properties of Noble fir are moderately influenced by the density ($R^2 = 0.39$ with $E_{L,stat}$ and 0.52 with σ_L). This influence is greater than Gil-Moreno (2018) reported for Noble fir from Great Britain (density – MOE $R^2 = 0.04$, density – MOR $R^2 = 0.32$). Also only for Noble fir, the correlation between static MOE and strength is high both in this study ($R^2 = 0.68$) and according to Gil-Moreno (2018) ($R^2 = 0.71$).

Table 2—Elastomechanical properties of small-size specimens, mean values with standard deviation in brackets

	Nordmann fir				Noble fir			
	tension II	bending	compression II	compression radial	tension II	bending	compression II	compression radial
n (NDT / DT)	36 / 36	57 / 57	60 ¹⁾ resp. 11 ²⁾ / 45	37 / 28	36 / 36	54 / 54	59 ¹⁾ resp. 21 ²⁾ / 45	49 ¹⁾ resp. 23 ²⁾ / 39 ³⁾
cw [% of specimen]	25	19	22	54	0	9	0	0
rw [mm]	2.93 (1.61)	2.43 (1.20)	3.45 (1.74)	2.05 (0.62)	5.18 (2.20)	6.11 (1.69)	7.35 (3.71)	5.42 (1.00)
ρ [g/cm ³]	0.46 (0.05)	0.49 (0.06)	0.47 (0.05)	0.47 (0.06)	0.38 (0.03)	0.37 (0.04)	0.36 (0.04)	0.36 (0.02)
$E_{L,long}$ [MPa]	13,503 (1,621)	12,354 (2,029)			10,704 (1,282)	9,352 (1,931)		
$E_{L,flex}$ [MPa]	12,975 (1,424)	11,447 (1,833)			10,231 (1,257)	8,516 (1,697)		
$E_{L,US}$ [MPa]			14,829 (1,821)	15,695 (2,039)			11,220 (2,810)	10,645 (1,095)
$E_{L,stat}$ [MPa]	9,168 (1,149)	8,826 (1,225)			7,357 (1,163)	6,384 (1,101)		
$E_{R,US}$ [MPa]			2,097 (437)	2,029 (205)			1,723 (242)	1,771 (81)
$E_{T,US}$ [MPa]			1,479 (539)	1,441 (198)			552 (145)	793 (137)
G_{RT} [MPa]			510 (242)	466 (102)			338 (65)	221 (23)
G_{LT} [MPa]			951 (345)	905 (156)			676 (155)	650 (72)
G_{LR} [MPa]			1,045 (285)	1,081 (124)			863 (140)	941 (69)
σ_L resp. $\sigma_{02,R}$ [MPa]	69.48 (21.29)	76.75 (8.02)	44.38 (4.07)	3.99 (0.63)	61.55 (16.19)	51.87 (8.72)	29.99 (5.09)	2.33 (0.63)

cw: compression wood, rw: ring width, ρ : density, $E_{L,long}$: Young's modulus in longitudinal direction determined with longitudinal vibration, $E_{L,flex}$: Young's modulus in longitudinal direction determined with flexural vibration, $E_{L,US}/E_{R,US}/E_{T,US}$: Young's modulus in longitudinal/radial/tangential direction determined with ultrasonic testing, $G_{RT}/G_{LT}/G_{LR}$: Shear modulus in the respective planes determined with ultrasonic testing, $E_{L,stat}$: Young's modulus in longitudinal direction from tensile test, σ_L : tensile resp. bending strength in longitudinal direction, $\sigma_{02,R}$: compression strength in radial direction

¹⁾ measurement in longitudinal direction

²⁾ measurement in radial and tangential direction

³⁾ 16 with exactly radial growth ring orientation, the rest with more or less diagonal growth ring orientation.

Table 3—Coefficients of determination (R^2) between properties from vibration measurement and destructive testing for Nordmann fir / Noble fir (small-size tensile and bending test specimens)

	coefficient of determination (R^2)							
	rw	ρ	f_l	f_f	$E_{L, \text{long}}$	$E_{L, \text{flex}}$	$E_{L, \text{stat}}$	σ_L
tension II								
rw		0.00/0.45	0.22/0.40	0.20/0.39	0.33/ 0.67	0.29/ 0.68	0.14/ 0.60	0.00/0.09
ρ	0.00/0.27		0.40/0.02	0.44/0.03	0.02/0.42	0.05/0.44	0.02/0.23	0.01/0.04
f_l	0.30/0.40	0.64/0.01		0.97/0.89	0.44/ 0.69	0.36/ 0.61	0.32/ 0.57	0.05/0.36
f_f	0.29/0.43	0.63/0.00	0.99/0.96		0.38/ 0.65	0.34/ 0.71	0.30/ 0.60	0.12/0.42
$E_{L, \text{long}}$	0.61/0.55	0.24/0.27	0.83/0.79	0.83/0.72		0.96/0.94	0.74/0.70	0.12/0.35
$E_{L, \text{flex}}$	0.62/0.57	0.20/0.26	0.77/0.76	0.80/0.76	0.98/0.96		0.78/0.72	0.15/0.40
$E_{L, \text{stat}}$	0.60/0.54	0.15/0.39	0.70/0.63	0.72/0.62	0.93/0.93	0.95/0.95		0.26/0.42
σ_L	0.06/0.45	0.10/0.52	0.02/0.21	0.02/0.23	0.17/0.52	0.21/ 0.57	0.28/ 0.68	
bending								

rw: ring width, ρ : density, f_l : frequency of longitudinal vibration, f_f : frequency of flexural vibration, $E_{L, \text{long}}$: Young's modulus in longitudinal direction determined with longitudinal vibration, $E_{L, \text{flex}}$: Young's modulus in longitudinal direction determined with flexural vibration, $E_{L, \text{stat}}$: Young's modulus in longitudinal direction from tensile test, σ_L : tensile resp. bending strength in longitudinal direction

Table 4 shows coefficients of determination (R^2) between the properties from ultrasonic and destructive testing.

Table 4—Coefficients of determination (R^2) between properties from ultrasonic and destructive testing (small-size compression test specimens)

	Nordmann fir		Noble fir	
	II	compression test specimen radial	II	radial
$\sigma_D - E_{L, \text{US}}$ resp. $\sigma_{02, \text{R}} - E_{R, \text{US}}$	0.50	0.68	0.76	0.02
$\sigma_D - c_L$ resp. $\sigma_{02, \text{R}} - c_R$	0.02	0.03	0.49	0.13
$\sigma_D - \rho$ resp. $\sigma_{02, \text{R}} - \rho$	0.35	0.53	0.65	0.42
$E_{L, \text{US}} - c_L$ resp. $E_{R, \text{US}} - c_R$	0.55	0.10	0.83	0.01
$E_{L, \text{US}} - \rho$ resp. $E_{R, \text{US}} - \rho$	0.03	0.84	0.59	0.79

ρ : density, c_L/c_R : ultrasonic velocity in longitudinal/radial direction, $E_{L, \text{US}}/E_{R, \text{US}}$: Young's modulus in longitudinal/radial direction determined with ultrasonic testing, σ_D : compression strength in longitudinal direction, $\sigma_{02, \text{R}}$: compression strength in radial direction

Results and Discussion Full-Size Specimen

A compilation of the elastomechanical properties in the grading classes according to DIN 4074-1 (2012) is presented in Table 5. As the annual ring width is not taken into account as a grading criterion, particularly in the case of Noble fir, knots are usually the decisive grading criterion for both wood species, some lamellas are excluded due to their curvature. The **density** does not increase with the grading class (ring width and knot area are decreasing with increasing grading class; reject boards could be cut mainly from the center of the trunk, containing juvenile wood, but many knots). For the grading classes according to DIN 4074-1 (2012) the density leads to comparatively high strength classes according to EN 338 (2016 (D)), even with Noble fir the density is not the decisive criterion.

The **dynamic Young's modulus** from longitudinal vibration increases with the grading class with mean values e.g. for Noble fir from $E_{L, \text{long, reject}} = 7,654 \text{ MPa}$ to $E_{L, \text{long, S13}} = 8,758 \text{ MPa}$. They are in the range of that described by Gil-Moreno (2018) (7,200 MPa for structural pieces from 30 year old stands, 8,500 MPa for 38 and 10,500 MPa for 58 year old material). The dynamic Young's modulus is much lower for the 940 mm Nordmann fir-lamellas compared to the 1,880 mm ones, although the requirement length / width of cross section = $940 \text{ mm} / 95 \text{ mm} = 9.9$ and therefore ≥ 6 according to Iñiguez-González et al. (2015) is met. The reason cannot be explained at present, the standard deviations for the 940 mm lamellas are twice as high compared to the 1,880 mm ones. For the small-size Nordmann fir specimens tested in tension, the correlation between the dynamic Young's modulus from longitudinal vibration and the Young's modulus from tensile test is very strong ($R^2 = 0.74$, cf. Table 3), the dynamic Young's modulus from longitudinal vibration is on average 47.7 % higher than the Young's modulus from tensile test. For this reason, a correction of 47.7 % is made when assigning the dynamic Young's modulus values of the 1,880 mm lamellas to the strength classes in Table 5. For both wood species, the Young's modulus leads to an assignment of the grading class according to DIN 4074-1 (2012) to a relatively low strength class according to EN 338 (2016 (D)) (S13 $\triangleq$ T10 (C16), S10 $\triangleq$ T9 resp. T8 (C14)). The low modulus of elasticity values for Noble fir are in agreement with the mean MOE of 6,967 MPa determined for 100 x 50 mm² construction timber of Noble fir grown in Scotland (Gil-Moreno and Ridley-Ellis 2015). Gil-Moreno (2018) performed strength grading tests on Noble fir grown in Great Britain and determined as basic grade C14 with a mean local MOE of 7,700 MPa, mean global MOE of 7,600 MPa, an mean MOR of 31 MPa (5th percentile 15 MPa) at a mean density of 379 kg/m³ (5th percentile 324 kg/m³).

Table 6 shows coefficients of determination (R^2) between properties from vibration measurement and destructive testing. The tensile strength of Noble fir ($f_{t,0}$) can be estimated from the frequency of the longitudinal vibration (f_l) respectively the dynamic Young's modulus from longitudinal vibration ($E_{L, \text{long}}$) (both $R^2 = 0.53$), which is in accordance with Gil-Moreno (2018) (dynamic MOE from MTG – MOR $R^2 = 0.46$). In contrast, for Noble fir the correlation between the dynamic Young's modulus from longitudinal vibration ($E_{L, \text{long}}$) and the static Young's modulus ($E_{t,0}$) is low ($R^2 = 0.08$), which might be due to the very low number of test specimen in a very narrow Young's modulus range. In contrast to this Gil-Moreno (2018) reports a strong correlation between dynamic MOE from MTG and MOE from bending test ($R^2 = 0.9$). On average, the dynamic Young's modulus is 18 % higher than the static Young's modulus for the full-size Noble fir specimens in this investigation. Gil-Moreno (2018) reports for Noble fir structural timber a medium-strong correlation between the density and the bending MOR ($R^2 = 0.29$), which cannot be confirmed in this study.

Table 5—Elastomechanical properties of full-size specimens for the grading classes acc. to DIN 4074-1 (2012)

	S13	S10	S7	reject
<u>Nordmann fir</u> all 341 lamellas				
n lamellas with 1,880/940 mm length	35 / 13	105 / 13	108 / 8	56 / 3
share in grading glass [%]	11.5 % / 35.1 %	34.5 % / 35.1 %	35.5 % / 21.6 %	18.4 % / 8.1 %
$\rho_{\text{mean}} (s_d)$ [kg/m ³]	505.5 (45.9)	383.5 (54.2)	478.6 (44.6)	489.2 (44.5)
ρ_k [kg/m ³]	421.8 ± T28 (C45)	386.9 ± T18 (C30)	399.2 ± T22 (C35)	408.7 ± T24 (C40)
$E_{L,\text{long}}$ [MPa]	12,275 (1,220) / 9,005 (2,488)	11,790 (1,477) / 8,273 (2,983)	11,111 (1,400) / 7,993 (2,712)	10,494 (1,740) / na
Calculated $E_{t,0,\text{mean}} = E_{L,\text{long}} / 1.477$ for 1,880 mm lamellas [MPa]	8,311 ± T10 (C16)	7,982 ± T9 (C14)	7,679 ± T9 (C14)	7,105 ± T8 (C14)
36 lamellas for tensile test				
n	17 (12)	8 (7)	11	
$\rho_{\text{mean}} (s_d)$ [kg/m ³]	499.5 (48.7)	477.7 (43.7)	462.5 (52.1)	
$f_{t,0,\text{mean}} (s_d)$ [MPa]	28.18 (6.20)	25.24 (4.68)	18.75 (7.28)	
$f_{t,0,05}$ [MPa]	18.29 ± T18 (C27)	18.53 ± T18 (C27)	10.25 ± T10 (C18)	
$f_{t,0,k}$ [MPa]	15.59	14.71	3.77	
T-class acc. to EN 338 (2016 (D)) due to	T10 (C16), stiffness	T9 (C14), stiffness	T9 (C14), stiffness	
<u>Noble fir</u> all 152 lamellas				
n	15	13	53	71
Percentage in grading glass	9.9 %	8.6 %	34.9 %	46.7 %
$\rho_{\text{mean}} (s_d)$ [kg/m ³]	384.6 (15.8)	385.1 (20.1)	386.8 (19.3)	388.6 (18.1)
ρ_k [kg/m ³]	353.3 ± T14.5 (C24)	344.7 ± T13 (C22)	351.8 ± T14.5 (C24)	355.9 ± T14.5 (C24)
$E_{L,\text{long}}$ [MPa]	8,758 (1,023)	8,306 (1,420)	8,325 (1,214)	7,654 (1,413)
11 lamellas for tensile test				
n	5	6 ¹⁾		
ρ_{mean} [kg/m ³]	397.5	383.0		
$E_{L,\text{long}}$ [MPa]	9,444	8,733		
$E_{t,0,\text{mean}} (s_d)$ [MPa]	8,397 (1,300) ± T10 (C16)	7,418 (1,102) ± T8 (C14)		
$f_{t,0,\text{mean}} (s_d)$ [MPa]	35.5 (4.9)	22.6 (5.8)		
$f_{t,0,05}$ [MPa]	28.1 ± T28 (C40)	17.3 ± T16 (C27)		
$f_{t,0,k}$ [MPa]	23.3	8.96		
T-class acc. to EN 338 (2016 (D)) due to	T10 (C16), stiffness	T8 (C14), stiffness		
s _d : standard deviation				
¹⁾ 3 lamellas without measuring the elongation and therefore without determination of the Young's modulus				

Table 6—Coefficients of determination (R^2) between properties from vibration measurement and destructive testing for Nordmann fir / Noble fir (full-size specimens)

	coefficient of determination (R^2)				
	ρ	f_l	$E_{L, \text{long}}$	$E_{t,0}$	$f_{t,0}$
ρ		0.15/0.00	0.07/0.29	na/0.08	0.16/0.05
f_l			0.58/0.67	na/0.00	0.01/0.53
$E_{L, \text{long}}$				na/0.08	0.06/0.53
$E_{t,0}$					na/0.35

ρ : density, f_l : frequency of longitudinal vibration, $E_{L, \text{long}}$: Young's modulus in longitudinal direction determined with longitudinal vibration, $E_{t,0}$: Young's modulus in longitudinal direction from tensile test, $f_{t,0}$: tensile strength in longitudinal direction

Conclusions

The performance indices for minimum weight design by Ashby et al. (1995) are shown in Table 7. Most Ashby constants are slightly higher for Noble fir than for Nordmann fir. The small-size specimen are comparable to that for Norway spruce and white fir and the full-size specimen to that for softwood lamellas according to EN 338 (2016 (D)).

Table 7—Performance indices for minimum weight design according to Ashby et al. (1995)

material	modulus-density performance indices			strength-density performance indices			modulus-strength performance index	source of original / basic data
	$M_1 = E/\rho$ [GPa (Mg m ⁻³) ⁻¹]	$M_2 = E^{1/2}/\rho$ [GPa ^{1/2} (Mg m ⁻³) ⁻¹]	$M_3 = E^{1/3}/\rho$ [GPa ^{1/3} (Mg m ⁻³) ⁻¹]*	$M_4 = \sigma_f/\rho$ [MPa (Mg m ⁻³) ⁻¹]	$M_5 = \sigma_f^{2/3}/\rho$ [MPa ^{2/3} (Mg m ⁻³) ⁻¹]	$M_6 = \sigma_f^{1/2}/\rho$ [MPa ^{1/2} (Mg m ⁻³) ⁻¹]*	$M_8 = \sigma_f/E$ [-]	
	tie under uniaxial load	beam in flexure; column buckling	plate in flexure	tie under uniaxial load	beam in flexure	plate in flexure	allow large, recoverable deformations	
small-size specimen								
Nordmann fir	20.0 ^a 18.3 ^c	6.6 ^a 6.1 ^c	4.6 ^a 4.3 ^c	151.1 ^a 94.9 ^b	36.5 ^a 26.8 ^b	18.0 ^a 14.3 ^b	0.0076 ^a	own results
Noble fir	19.5 ^a 17.1 ^c	7.2 ^a 6.8 ^c	5.2 ^a 5.0 ^c	163.7 ^a 81.7 ^b	41.2 ^a 26.3 ^b	20.7 ^a 15.0 ^b	0.0084 ^a	own results
Norway spruce ¹⁾ White fir ²⁾	23.9 ^c	7.2 ^c	4.8 ^c	206.5 ^a 97.8 ^b	45.3 ^a 27.5 ^b	21.2 ^a 14.6 ^b	0.0086 ^a 0.0041 ^b	DIN 68364 (2003)
full-size specimen								
Nordmann fir	14.5... 20.8 ^{ae}	5.4...7.4 ^{ae}	3.9...5.2 ^{ae}	49.6 ^a	17.1 ^a	10.0 ^a	0.0024...0.0034 ^{ae}	own results
Noble fir	20.6 ^a	7.2 ^a	5.1 ^a	73.0 ^a	23.7 ^a	13.5 ^a	0.0039 ^a	own results
softwood lamellas T8...T30 (structural size)	20.0...30.6 ^a	7.5...7.9 ^a	5.5...4.8 ^a	27.6...69.8 ^{ad} 55.2...70.7 ^{bd}	13.8...22.5 ^{ad} 21.9...23.0 ^{bd}	9.8...12.7 ^{ad} 13.8...13.1 ^{bd}	0.0017...0.0028 ^{acd} 0.0034...0.0028 ^{bcd}	EN 338 (2016 (D))

^a based on tensile tests

^b based on compression tests

^c E based on bending tests

^d calculation based on the 5th quantile

^e calculation based on grading class characteristic values

* values are calculated based on the longitudinal strength, therefore they are not representative of the efficiency of a strong plate in bending which requires isotropic strength

¹⁾ *Picea abies* (L.) H.KAST

²⁾ *Abies alba* MILL.

The Ashby constants, comparable to those of Norway spruce and white fir, demonstrate the suitability of Nordmann fir and Noble fir for load-bearing applications. The initial tensile tests conducted on lamellas originating from Germany allow for a preliminary classification of both wood species in accordance with pr EN 1912 (2022 (D)). The Young's modulus facilitates the allocation of grading classes specified in DIN 4074-1 (2012) to relatively low strength classes per EN 338 (2016 (D)). Specifically, S13 corresponds to T10 (C16), and S10 corresponds to T9 or T8 (C14). The efficacy of longitudinal vibration for machine strength grading is reaffirmed. Further tensile tests on visually and mechanically graded lamellas, alongside bending tests on solid structural timber, are imperative. Subsequently, graded lamellas are elongated through finger-jointing and used to produce combined and homogeneous GLT, which is tested for bending and longitudinal compression. The elastomechanical characteristics of this GLT will be detailed in a separate publication. Subsequent investigations on cross laminated timber (CLT) should follow.

Initial input parameters for Finite Element Analysis (FEA) are established. The three Young's moduli are determined through ultrasonic testing and vibration measurement, with some validated via static tests. Similarly, the three shear moduli are assessed using ultrasonic testing, awaiting validation through static tests. Poisson constants remain undetermined at present. Tensile yield strength parallel to grain, assumed to be equivalent to tensile strength, is determined, while determination in radial and tangential directions remains outstanding. Compressive yield strengths, defining the material's transition from elastic to plastic behavior, alongside hardening moduli (= slope between the compressive yield strength and the compressive strength) and shear yield strengths (assumed to be equal to shear strengths), are yet to be ascertained. A more extensive array of input parameters for Finite Element Analysis (FEA) modeling will be consolidated in a forthcoming publication.

Author Contributions

In the laboratory, MSc. Dennis Kipp did measurements on the full-size test specimens on Noble fir and BSc. Karin Lueke on Nordmann fir, BSc. Felix Leonard Stracke did the bending and shear tests and BSc. Noah Burghaus the compression and tensile tests on small-size specimen. MSc. Martin Hackel supervised their laboratory work. Dr. Stefanie Wieland was responsible for the material extraction up to the dried sawn timber. Dr. Stefanie Wieland and Prof. Katja Fruehwald-Koenig had the project idea together. Prof. Katja Fruehwald-Koenig developed the scientific concept, did the non-destructive testing with the help of MSc. Martin Hackel, worked on the theoretical background and literature, supervised the laboratory work, made the analyses and wrote solely the paper.

References

- Ashby, M.F.; Gibson, L.; Wegst, U.; Olive, R. 1995. The mechanical properties of natural materials. I. Material property charts. *Proc R Soc Lond A* 450:123-140 doi:<https://doi.org/10.1098/rspa.1995.0075>.
- Bachtar, E.V.; Sanabria, S.J.; Niemz, P. 2015. Elastic characteristics of wood by means of ultrasonic waves and mechanical test. In: 5th International Scientific Conference on Hardwood Processing 2015 (ISCHP 2015), Québec City, Canada, Sept. 15-17, 2015, pp 12-19.
- Berkel, A. 1963. Untersuchungen über physikalische und mechanische Eigenschaften der Bornmüllerstanne (*Abies Bornmülleriana* MATTFELD). *Holz als Roh- und Werkstoff*. 21:165-172.
- Betts, H.S. 1929. The strength of North American woods. Vol No. 46. US Department of Agriculture, Washington D.C.

Bodig, J., Jayne, B.A. 1982. Mechanics of wood and wood composites. Van Nostrand Reinhold Company, New York.

DIN 4074-1 2012. Sortierung von Holz nach der Tragfähigkeit – Teil 1: Nadel schnittholz. Beuth Verlag, Berlin.

DIN 50014 2018. Normalklimate für Vorbehandlung und/oder Prüfung – Festlegungen. Beuth Verlag, Berlin.

DIN 52185 1976. Prüfung von Holz – Bestimmung der Druckfestigkeit parallel zur Faser. Beuth Verlag, Berlin.

DIN 52186 1978. Prüfung von Holz – Biegeversuch. Beuth Verlag, Berlin.

DIN 52188 1979. Prüfung von Holz – Bestimmung der Zugfestigkeit parallel zur Faser. Beuth Verlag, Berlin.

DIN 52192 1979. Prüfung von Holz – Druckversuch quer zur Faserrichtung. Beuth Verlag, Berlin.

DIN 68364 2003. Kennwerte von Holzarten. Beuth Verlag, Berlin.

EN 338 2016 (D). Structural timber – Strength classes. Beuth Verlag, Berlin.

EN 384 2019 (D). Structural timber – Determination of characteristic values of mechanical properties and density. Beuth Verlag, Berlin.

EN 408+A1 2012 (D). Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties. Beuth Verlag, Berlin.

EN 14080 2013 (D). Timber structures – Glued laminated timber and glued solid timber – Requirements. Brussels, Beuth Verlag, Berlin.

EN 14081-1 2019. Timber structures – Strength graded structural timber with rectangular cross section – Part 1: General requirements. Beuth Verlag, Berlin.

EN 14358 2016 (D). Timber structures – Calculation and verification of characteristic values. Beuth Verlag, Berlin.

EN 16351 2021 (D). Timber structures – Cross laminated timber – Requirements. Beuth Verlag, Berlin.

Gil-Moreno, D. 2018. Potential of noble fir, Norway spruce, western red cedar and western hemlock grown for timber production in Great Britain. PhD at the Edinburgh Napier University.

Gil-Moreno, D.; Ridley-Ellis, D. 2015. Comparing usefulness of acoustic measurements on standing trees for segregation by timber stiffness. In: Ross, R.J.; Gonçalves, R.; Wang, X. (ed). 19th International Nondestructive Testing and Evaluation of Wood Symposium, Rio de Janeiro, Brazil, September 22–25, 2015. USDA Forest Service, Forest Products Laboratory, 688 p.

Görlacher, R. 1984. Ein neues Meßverfahren zur Bestimmung des Elastizitätsmoduls von Holz. Holz als Roh- und Werkstoff. 42:219-222.

Güray, E.; Kasal, A.; Demirci, S.; Ceylan, E.; Kuşkun, T. 2019. Effects of cross-sectional geometry and force direction on bending strength and modulus of elasticity of some softwood beams. *BioResources*. 14:9258-9270.

Íñiguez-González, G.; Arriaga, F.; Esteban, M.; Llana, D.F. 2015. Reference conditions and modification factors for the standardization of nondestructive variables used in the evaluation of existing timber structures. *Construction and Building Materials*. 101:1166-1171.

ISO 3132 1975. Wood – Testing in compression perpendicular to grain. International Organization for Standardization.

Özkan, O.E.; Temiz, A.; Vurdu, H. 2017. Effects of heat treatment on Turkish fir wood properties. *Wood Research*. 62:783-794.

Paul, B.H.; Dohr, A.W.; Drow, J.T. 1959. Some physical and mechanical properties of noble fir. Report No. 2168. United States Department of Agriculture, Forest Service, Forest Products Laboratory.

pr EN 1912 2022 (D). Structural Timber – Strength classes – Assignment of visual grades and species. Beuth Verlag, Berlin.

Ross, R.J. 2021. Wood Handbook: Wood as an Engineering Material. General Technical Report FPL–GTR–282. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

Vurdu, H.; Kesik, H.İ.; Kurtuluş, O.Ç.; Özkan, O.E. 2013. Some physical and mechanical properties of antique and fresh cut *Pinus sylvestris* and *Abies nordmanniana* subsp. *bornmulleriana* woods. *Pro Ligno* 9(4):562-567.

Elasticity Modules of *Pinus taeda* Wood by Destructive and Non-Destructive Tests

Rodrigo Figueiredo Terezo

Department of Forest Engineering, State University of Santa Catarina, Lages, Santa Catarina, Brazil, Brazil, rodrigo.terezo@udesc.br

Matheus Zanghelini Teixeira

Pos-Graduate Program in Forest Engineering, State University of Santa Catarina, Lages, Santa Catarina, Brazil, Matheus_zt@hotmail.com

Talitha Oliveira Rosa

Pos-Graduate Program in Forest Engineering, Federal University of Paraná, Curitiba, Paraná, Brazil, rosa.talitha@gmail.com

Abstract

It's necessary to follow regulations and carry out tests to guarantee the safety and quality of wood as a structural element. Therefore, the objective of this work was to estimate and compare the longitudinal modulus of elasticity to static bending (MOE) of *Pinus taeda* wood by destructive and non-destructive tests, in addition to evaluating the influence of visual classification on the mechanical performance of the pieces. For this purpose, 22 boards from a plantation located in Campo Belo do Sul region, Santa Catarina State, Brazil were tested. The visual classification followed the specifications of ASTM D245, the non-destructive tests performed were based on ASTM D4761 and the destructive tests on EN 408. The high Pearson Correlation Coefficient and the result of the "t Test" showed that there is no significant difference between MOE values by destructive and non-destructive methods. The visual classification showed no significant difference in the mechanical performance of the parts.

Keywords: Lumber; Structural Visual Class; Bending Tests.

Introduction

Brazil is a country that stands out worldwide in the productivity of forest plantations, and in 2020 it had a total area of 9.55 million hectares of planted trees, 18% of which was composed only of pine cultivation (IBÁ 2021). In civil construction, wood combined with technology emerges as a more conscious and sustainable way of building.

For the design of structures, it is necessary to follow regulations and carry out tests to ensure the safety and quality of wood as a structural element. One of the ways to assess the quality of wood is through structural visual classification. The ASTM D245 standard defines basic criteria and principles for the visual classification of any piece of wood with respect to bending strength. Good results were achieved by (Carreira and Dias 2005) when using the ASTM D245 rules to make the visual classification of *Pinus* sp planted in Brazil and recommend the method because it is cheap and effective.

Another way to evaluate wood is through mechanical classification, which is done taking into account factors such as the Modulus of Elasticity (MOE), which is determined through destructive and/or non-

destructive bending testing. ASTM D4761 determines the MOE in structural parts without breakage, making it possible to reuse the tested material, in addition to allowing the test to be performed in a non-laboratorial environment. Another standard that also establishes guidelines for determining the MOE is EN 408, however, this one by destructive testing on samples free of visual defects.

The objective of this work was to determine and compare the longitudinal modulus of elasticity to static bending (MOE) of *Pinus taeda* wood by destructive and non-destructive tests, as well as to evaluate the influence of visual classification on the mechanical performance.

Material and Methods

Sampling

A total of 22 boards from *Pinus taeda* logs were tested from a plantation located in Campo Belo do Sul region in Santa Catarina State, Brazil, and supplied by a sawmill located in Capão Alto region. The sawing system procedure was carried out with dimensions of 2.5 x 15.0 x 306.0 cm and 2.5 x 10.0 x 306.0 mm (thickness, width and length) and kiln-drying, with a total program of 70 hours, aiming at a final moisture content of 12%. Subsequently, the wood was transported to the UDESC Timber Structures Laboratory, at the Center for Agricultural Sciences, located in Lages city.

Structural Visual Classification

The structural visual classification followed the specifications of ASTM D245, measuring the nodes in the radial and tangential planes and identifying the visual class of the wood from the proportion of area that the nodes occupy in the cross-section of the board. The visual classes are: Special Structural Class (SE) – which has fewer defects; Structural Class No. 1 (S1); Structural Class No. 2 (S2); Structural Class No. 3 (S3) – which has more defects, but is still considered structural. NS, on the other hand, are those that are not considered structural.

Non-Destructive Testing

The non-destructive testing performed was based on ASTM D4761. The maximum load was set at 90 N and the span between supports was 220 cm, as shown in Figure 1. The displacement was determined using an inductive transducer (WA® 50 mm) coupled to a data acquisition system (Quantum-X®) and a software (Catman Easy®) from HBM® instruments.

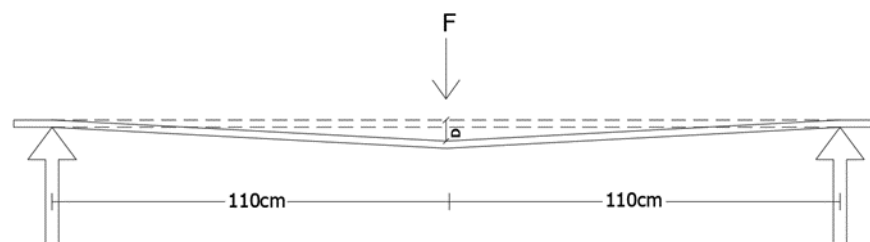


Figure 1— Scheme of the 90 N load (F) application and displacement measurement (D).

At the end of the first measurement, the procedure was repeated for the back side of the same wooden sample, in order to obtain two measurement of each sample. And then, the sample MOE was calculated with the average displacement.

Destructive Testing

The four-point destructive static bending test was performed in accordance with the recommendations of EN 408. For the test, defect-free specimens were made, with dimensions of 3.0 cm wide x 2.5 cm thick and 60.5 cm long. A universal EMIC machine (DL 300kN) was used for the test, the span between supports was 52.5 cm and the load application distance between supports was 15.0 cm. The test speed was 4.5 mm/min. In addition, the moisture content of the specimens was measured with a hygrometer, as recommended by EN 384. An average moisture content of $12.6 \pm 1.1\%$ was obtained and the MOE values were corrected to 12% moisture based on dry mass.

Results and Discussion

By the data showed in Table 1, obtained by the RStudio software, it can be observed that the magnitude of the position and dispersion measurements are similar. Its occurred because the MOE's are determined by different methods, even both refers to the MOE in the longitudinal direction. It is also worth noting that the high coefficients of variation (CV) demonstrate that the two tests analyzed have variability.

Table 1— Descriptive statistics of the MOE by destructive and non-destructive tests.

	Non-Destructive MOE (MPa)	Destructive MOE (MPa)
Average	7413.68	7886.65
Median	7260.0	7761.0
Standard deviation	1551.86	1311.60
Coefficient of Variation (%)	20.93	16.63
Standard Error	330.86	279.63

The Kolmogorov-Smirnov normality test showed normal distribution in both methods (Figure 2 - A). On the other hand, Pearson's correlation coefficient between the MOEs of the two trials resulted in 0.74, which means that the correlation is strong. The hypothesis test "t" showed that the t-tabulated (2.018) was greater than the t-calculated (1.092). Then, there is no significant difference between the values of the MOE by the destructive and non-destructive methods. Ideally, these assays should be correlated, in order to ensure a good result regardless of the method chosen. Have not been found studies comparing destructive methods, that using the displacement transducer, with non-destructive methods. In other way, the transducer method is indicated to determine mechanical properties with good accuracy (Rosa et al. 2019).

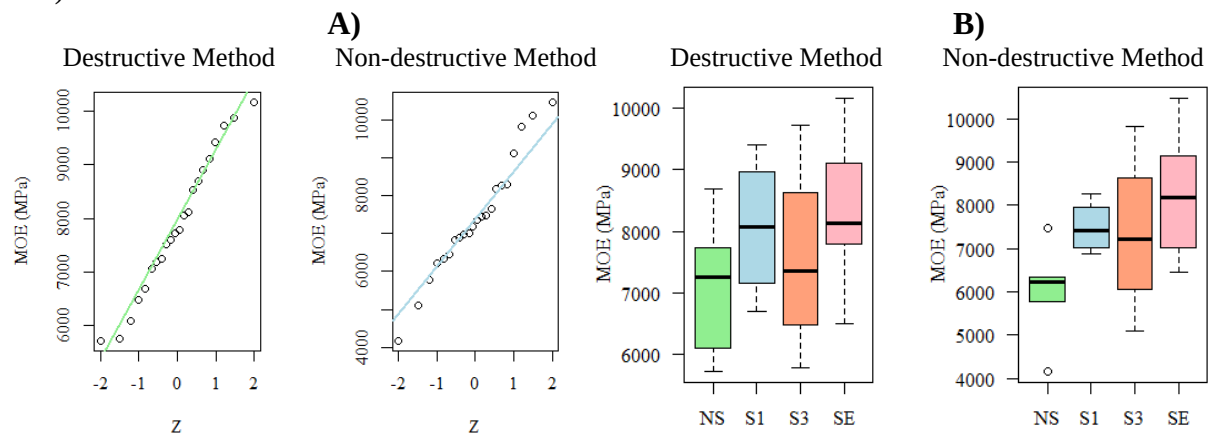


Figure 2— A) Normal Quantile Graphs of the tests; B) Boxplots of the MOEs separated by Visual Class.

Boxplots were performed to study the influence of Visual Classes on MOEs, (Figure 2 - B). Apparently, the presence of defects in the wood influences the MOE, since the variability across the interquartile range is noticeable, and the median values are higher for SE and S1, and lower for NS and S3. However, it was found that the difference is not statistically significant, since Welch's Analysis of Variance (ANOVA), at a significance level of 5%, resulted in p-values of 0.402 and 0.107 for the destructive and non-destructive methods, respectively.

Rosa et al (2020) evaluated the influence of the visual classification of *Cryptomeria japonica* lamellae on the mechanical performance, for use in glulam structural elements, and concluded that the presence of defects in the lamellae did not decrease the strength of the glulam. In the present study, the equality between the classes in the non-destructive method may have occurred due to the low sampling and high coefficient of variation.

On the other hand, by the destructive method, the CV was not so high. This result is explained because the test was performed with non visual defects samples. However, the small variation, even if not statistically significant, may be due to other characteristics of the wood, such as density, number of growth rings per inch and even the radial variation itself - juvenile wood and adult wood (Vidaurre 2011).

Conclusions

There is a high correlation coefficient between the modulus of elasticity of the destructive and non-destructive methods, which suggests that the two techniques can be used as a reliable alternative for the evaluation of flexural stiffness. On the other hand, the visual classification did not show a significant difference in the mechanical performance of the parts.

References

- American Society for Testing and Materials (ASTM). 2013. ASTM D4761: Mechanical properties of lumber and wood-Base structural material. Philadelphia.
- American Society of Testing and Materials. 2006. ASTM D245: Standard Practice for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber. West Conshohocken, 16 p.
- Brazilian Tree Industry (IBÁ). 2021. Annual Report 2021. São Paulo, 178p.
- Carreira, M. R.; Dias, A. A. 2005. Visual classification of conifers: analysis of the application of the North American method to *Pinus* sp species planted in Brazil. *Scientia Forestalis*, n. 67, p.78-87.
- European Standard (EN). 2012. EN 408: Timber structures. Structural timber and glued laminated timber: determination of some physical and mechanical properties. Brussels, 38 p.
- European Standard (EN). 2004. EN 384: Structural timber – determination of characteristic values of mechanical properties and density. Brussels, 15 p.
- Rosa, T. O.; Terezo, R. F.; Rios, P. D.; Sampietro, J. A.; Rosa, G. O. 2019. *Schizolobium Parahyba* var. *Amazonicum* Glulam classified by non-destructive tests. *Floresta e Ambiente*, 26(2): e20171202.
- Rosa, T. O.; Vieira, H. C.; Terezo, R. F.; Cunha, A. B; Sampaio, C. A. de P., Waltrick, D. B.; Zangalli, C.; Rosa, G. O. 2020. Visual and mechanical classification of the species *Cryptomeria japonica* D. Don for use in glulam wood. *Ciência Florestal*, p.451–462.
- Vidaurre, G. G.; Lombardi, L. R.; Oliveira, J. T. S.; Arantes, M. D. C. 2011. Juvenile and adult wood and the properties of wood. *FLORAM – Magazine. Forest and Environment*, 18(4): 469-480.

Detection of Moisture Content in Logs Using Multi-Parameter GPR Signal Analysis and Neural Network Models

Huadong Xu *

College of Mechanical and Electrical Engineering, Northeast Forestry University, Harbin, Heilongjiang Province, China, huadongxu@nefu.edu.cn

Jiaxing Guo

College of Mechanical and Electrical Engineering, Northeast Forestry University, Harbin, Heilongjiang Province, China, 1161897056@nefu.edu.cn

Lihai Wang

College of Engineering & Technology, Northeast Forestry University, Harbin, Heilongjiang Province, China, wanglihai2012@126.com

Dawei Qi

College of Science, Northeast Forestry University, Harbin, Heilongjiang Province, China, qidw9806@126.com

* Corresponding author

Abstract

To improve the accuracy of non-destructive moisture content (MC) detection in small-diameter logs using ground penetrating radar (GPR), a back-propagation neural network (BPNN) model was developed. B-scan signals were collected from spruce, Manchurian ash, and white birch logs (10-15 cm diameter). Using Lasso and PCA, 31 time-frequency parameters from the signals were optimized. The MC prediction accuracy of the Lasso-BP model surpassed that of PCA-BP and BPNN models. Both single-species and hybrid models showed strong predictive capabilities, with residual errors under 6% and 10% when MC was below 20%. These models enhance the efficiency of wood processing by significantly improving MC detection accuracy.

Keywords: GPR signals, Log moisture content, Time-frequency feature, Lasso, Back-propagation neural network

Introduction

TRU is a radar detection device based on ground penetrating radar (GPR) technology. Because different media layers (bark, heartwood, and sapwood) in the trunk have different dielectric properties, the high-frequency electromagnetic waves emitted by the tree radar through the transmitting antenna produce reflection and refraction in different media layers (Rodriguez-Abad et al. 2010). The receiving antenna receives the reflected wave and processes the signal data based on its waveform, amplitude, and travel time to form a radar wave reflection image, which can be used to detect changes in the different structures of the trunk. Similarly, tree radar is suitable for MC detection of wood because of the significant

differences in the dielectric properties of wood with different MC. It has been shown that a decrease in MC at different wood fibre orientations leads to an increase in the propagation velocity of electromagnetic waves (Rodriguez-Abad et al. 2010). Subsequently, MC models (R^2 0.56-0.83, RMSE 0.07-0.14) based on partial least squares (PLS) regression were obtained for three unfrozen tree species using GPR signals through log bark (Hans et al. 2015), but the detection accuracy needed to be improved. Numerical simulations of previous studies show that there are significant errors in the early time signal amplitude and travel time for small-diameter logs (10-15 cm in diameter), which would affect the prediction of the log MC. Therefore, solving the problems of low accuracy of MC in small-diameter logs using GPR signals is the main objective of this study.

The present study aimed to accurately and non-destructively measure log MC (especially for small diameters) using ground-penetrating radar (GPR) signals. The MCs of spruce, Manchurian ash, and white birch logs were predicted using the time-frequency parameters of GPR signals combined with BPNN.

Materials and Methods

GPR data acquisition

Four discs (approximately 20 cm thick and 10-15 cm in diameter) of spruce (*Picea abies*), Manchurian ash (*Fraxinus mandshurica*), and white birch (*Betula pubescens*) were selected from 12 fresh green logs of three different species chosen for their economic importance in northeast China. Changes in disc MC were used to represent changes in log MC. The discs were divided into five equal parts on the side, marked with numbers 1-5, immersed in water for more than 15 days, and weighed. Then, B-scan signals were obtained using tree radar (TRU-900) for each disc in five different directions (frequency 900 MHz, radar gain 0, and dielectric constant 10) (Figure 1).

The samples were then dried at 105 °C. When the weight dropped by 100-200 g, the discs were removed, weighed, and measured using B-scan signals until the discs were completely dry. The log MC was calculated using Equation 1.

$$MC = \frac{M_1 - M_2}{M_1} \times 100\% \quad (1)$$

M_1 is the wet weight and M_2 is the dry weight of the discs.



Figure 1—Illustration diagram for detecting moisture contents of wood discs using tree radar.

Raw signal statistical characteristics

The feature parameters were extracted from the middle trace of the B-scan signals using a MATLAB program whose design was based on the MATGPR software. Previous studies have only considered the early time signal amplitude or travel time, completely ignoring the other major parts of the GPR signals. If only 1-2 time-frequency feature parameters are used in the radar MC detection, it will lead to problems of non-robustness to noise. This is because the amplitude and distribution may change in the time-domain signal when log MC changes. Meanwhile, new frequency components may emerge and the convergence of the frequency spectrum may change (Zhang et al. 2020). To improve the detection accuracy, more feature parameters (31 feature parameters) were used in the present study: 19 parameters (P_1 - P_{19}) were in the time domain and 12 parameters (P_{20} - P_{31}) were in the frequency domain (Table 1). Parameters P_1 - P_5 and P_9 - P_{12} indicate the amplitude and energy in the time domain. Parameters P_6 - P_8 and P_{13} - P_{19} reflect the time-series distribution of the signal in the time domain. Parameter P_{20} represents the vibration energy in the frequency domain. Parameters P_{21} - P_{23} , P_{25} and P_{29} - P_{31} describe the convergence of the spectrum power. Parameters P_{24} and P_{26} - P_{28} show the position changes in the main frequency.

Lasso regression screening variables

If all the feature parameters are directly fed into the neural network, too many variables may easily lead to overfitting, which will slow down the training process and reduce the prediction accuracy. Therefore, it is necessary to select some parameters from the entire feature set that obviously characterise the log MC condition. The least absolute shrinkage and selection operator (Lasso) regression model is a biased estimation method proposed by Tibshirani (Tibshirani 1996). It penalises the coefficients of the regression variables, shrinking some of them to zero, and eliminating non-zero coefficients after the shrinking process to deal with multicollinearity in the data (Shafiee et al. 2021).

Construction of the BPNN

The neural network prediction model used has a 3-layer feed-forward network structure, including an input layer, a hidden layer, and an output layer. The input layer receives the input data and feeds it to the next layer. The number of neurons in the input layer is equal to the number of features in the input data. The hidden layer is an intermediate layer that processes the input data using mathematical operations called activation functions. Depending on the complexity of the model, it can contain one or more layers. A single hidden layer can be chosen to increase the processing speed when the network accuracy fulfils the requirements. Therefore, a single hidden layer was selected based on the research requirements. The number of hidden neurons also has an evident impact on the network. A trial-and-error method was used to determine the optimal number of neurons (Li et al. 2021). The output layer produces the final output of the model based on processed input data from the hidden layers. The present study used 320, 460, and 360 MC samples of spruce, Manchurian ash, and white birch, respectively, of which 75% were used for training and 25% were used for testing. Meanwhile, the feature parameters were normalised to eliminate any dimensional influence between them (2).

$$p = \frac{p_1 - p_{\min}}{p_{\max} - p_{\min}} \quad (2)$$

P is the P_1 normalisation value, $P_{\max}$ and $P_{\min}$ are the maximum and minimum values of P_1 , respectively. The network training error effectively converged when the number of nodes in the hidden layer was six and the initial learning rate was 0.01.

Table 1—Time-domain and frequency-domain feature parameters of log moisture content.

Name	Explanation	Name	Explanation
Maximum	$P_1 = \max(X_i)$	Total energy	$P_{11} = \sum_{i=1}^n X_i^2$
Minimum	$P_2 = \min(X_i)$	Average energy	$P_{12} = \frac{1}{n} \sum_{i=1}^n X_i^2$
Mean	$P_3 = \frac{1}{n} \sum_{i=1}^n X_i$	Standard deviation	$P_{13} = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (X_i - P_3)^2}$
Average absolute value	$P_4 = \frac{1}{n} \sum_{i=1}^n X_i $	Skewness coefficient	$P_{14} = \frac{P_7}{(n-1)P_{13}^3}$
Peak-to-peak value	$P_5 = \max(X) - \min(X)$	Kurtosis coefficient	$P_{15} = \frac{P_8}{(n-1)P_{13}^4}$
Variance	$P_6 = \frac{1}{n} \sum_{i=1}^n (X_i - P_3)^2$	Peak factor	$P_{16} = \frac{P_1}{P_9}$
Skewness	$P_7 = \frac{1}{n} \sum_{i=1}^n (X_i - P_3)^3$	Peak-to-mean ratio	$P_{17} = \frac{P_1}{P_{10}}$
Kurtosis	$P_8 = \frac{1}{n} \sum_{i=1}^n (X_i - P_3)^4$	Form factor	$P_{18} = \frac{P_9}{P_4}$
Root mean square	$P_9 = \sqrt{\frac{1}{n} \sum_{i=1}^n X_i^2}$	Amplitude factor	$P_{19} = \frac{P_1}{P_4}$
Mean square amplitude	$P_{10} = \left(\frac{1}{n} \sum_{i=1}^n \sqrt{ X_i } \right)^2$	Amplitude average	$P_{20} = \frac{1}{m} \sum_{k=1}^m s(k)$
Amplitude standard deviation	$P_{21} = \sqrt{\frac{1}{m-1} \sum_{k=1}^m (s(k) - P_{20})^2}$	Frequency Bandwidth Index	$P_{29} = \frac{P_{25}}{P_{24}}$
Sample Skewness	$P_{22} = \frac{\sum_{k=1}^m (s(k) - P_{20})^3}{(m-1)P_{21}^3}$	Frequency mean	$P_{24} = \frac{\sum_{k=1}^m f_k s(k)}{\sum_{k=1}^m s(k)}$
Sample Kurtosis	$P_{23} = \frac{\sum_{k=1}^m (s(k) - P_{20})^4}{(m-1)P_{21}^4}$	Frequency standard deviation	$P_{25} = \sqrt{\frac{\sum_{k=1}^m (f_k - P_{24})^2 s(k)}{K}}$
Frequency Root Mean Square	$P_{26} = \sqrt{\frac{\sum_{k=1}^m f_k^2 s(k)}{\sum_{k=1}^m s(k)}}$	Frequency skewness	$P_{30} = \frac{\sum_{k=1}^m (f_k - P_{24})^3 s(k)}{m \times P_{25}^3}$
Frequency Fourth Root Mean Square	$P_{27} = \sqrt{\frac{\sum_{k=1}^m f_k^4 s(k)}{\sum_{k=1}^m f_k^2 s(k)}}$	Frequency kurtosis	$P_{31} = \frac{\sum_{k=1}^m (f_k - P_{24})^4 s(k)}{m \times P_{25}^4}$
Frequency Band Index	$P_{28} = \frac{\sum_{k=1}^m f_k^2 s(k)}{\sqrt{\sum_{k=1}^m s(k) \sum_{k=1}^m f_k^4 s(k)}}$		

Where x_i is the i^{th} sample point of a GPR trace and $i = 1, 2, \dots, n$, n is the sample point per trace. $s(k)$ is the frequency amplitude transformed from the GPR trace by the Fast Fourier Transform method, $k = 1, 2, \dots, m$, m is the number of frequency components, and f_k is the k^{th} frequency component.

Materials and Methods

Extraction of Lasso feature parameters and BPNN construction for tree species

The Lasso feature parameters (13 parameters for spruce, 16 parameters for Manchurian ash, and 19 parameters for white birch) were used as input nodes for the respective BPNN of the three tree species, with one node in the output layer for log MC (Figure 2).

The least absolute shrinkage and selection operator and back-propagation neural network (Lasso-BP) for the MCs of spruce, Manchurian ash, and white birch logs are shown in Figure 3a. The prediction models for the three species had $R^2 \geq 0.9758$ and $RMSE \leq 0.0425$, with the prediction model for birch giving the best testing result, with R^2 and RMSE values of 0.9846 and 0.0361, respectively. This indicates that all the prediction models have highly satisfactory results. Figure 3b compares the residual error of the BPNN for predicting the log MCs in spruce, Manchurian ash, and white birch. Their maximum residual error was almost within 12%, and their mean absolute errors (MAE) were 3.48%, 3.20%, and 2.80%, respectively. This demonstrates the good practicability of log MC detection. In particular, the maximum residual error was almost within 6% when the log MC was less than 20%. This shows that the prediction models at low MC are more accurate, which is useful for the actual wood-drying process.

Comparison of the three prediction models for Lasso-BP, PCA-BP and BPNN

Principal component analysis (PCA) is the most commonly applied multi-parameter extraction algorithm because it can effectively extract typical features and reduce their dimensions (Dong and Luo 2013). Therefore, PCA-BP prediction models were developed, and the prediction abilities of PCA-BP, Lasso-BP, and BPNN were compared. Feature parameters with a cumulative contribution rate greater than 95% were selected. To better compare the prediction abilities of the three models, the same training and test sets were used.

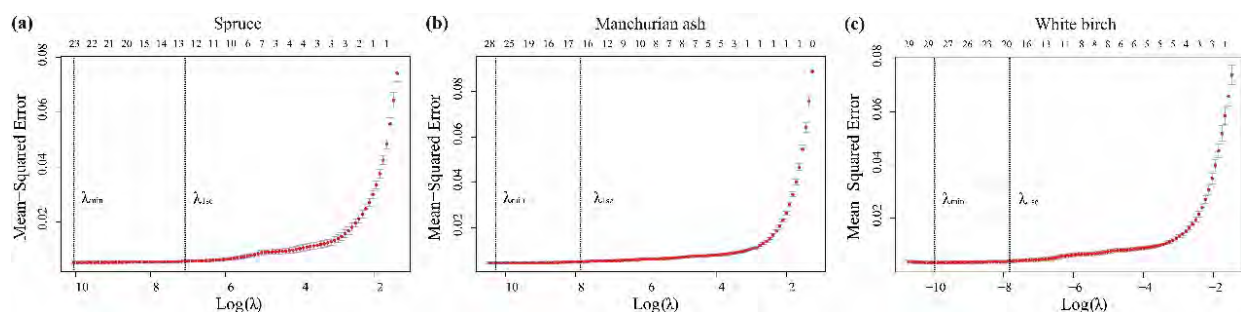


Figure 2—Extraction of Lasso feature parameters for (a) spruce, (b) Manchurian ash, and (c) white birch

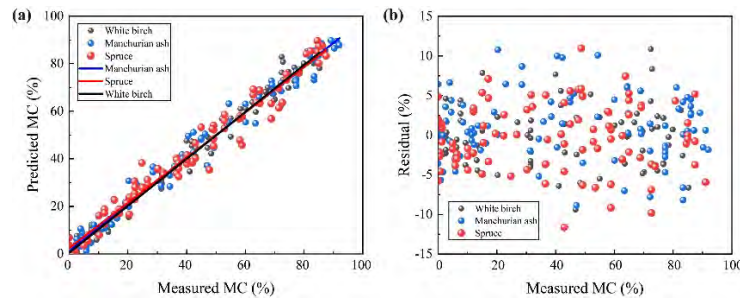


Figure 3—(a) Lasso-BP prediction models and (b) residuals of moisture content for spruce, Manchurian ash, and white birch logs.

Table 2—Predictive performance for Lasso-BP, PCA-BP, and BPNN methods.

Model	Tree Species	Number	R^2	RMSE	MAE
Lasso-BP	Spruce	13	0.9758	0.0425	0.0348
Lasso-BP	Manchurian ash	16	0.9833	0.0417	0.0320
Lasso-BP	White birch	19	0.9846	0.0361	0.0280
PCA-BP	Spruce	4	0.8740	0.0956	0.0695
PCA-BP	Manchurian ash	4	0.9748	0.0509	0.0395
PCA-BP	White birch	4	0.9753	0.0456	0.0352
BPNN	Spruce	31	0.9638	0.0512	0.0388
BPNN	Manchurian ash	31	0.9828	0.0420	0.0328
BPNN	White birch	31	0.9832	0.0376	0.0274

As shown in Table 2, although the prediction accuracy of Lasso-BP was only slightly better than that of BPNN for Manchurian ash and white birch, it required fewer variables and less computation and training was faster. PCA-BP had lower accuracy than Lasso-BP and BPNN, especially for spruce, mainly because of the significant reduction in the number of related variables. This shows that PCA-BP lacks some fitting ability, although it had fewer parameters and faster training. However, Lasso-BP could bridge this gap and was more suitable for the multiparameter extraction used in the prediction models. Similar results have been reported by several researchers (Shafiee et al. 2021). In addition, the prediction accuracy of Lasso-BP, PCA-BP, and BPNN for log MC was much better than that of previous research using partial least squares (Hans et al. 2015), probably because more relevant variables were extracted and the BPNN had a better fitting ability. This indicates that it is more appropriate to use the multiparameter Lasso-BP method for log MC detection.

Construction of a hybrid model for the log MC of three species

To make it easier to detect log MC, a hybrid model was constructed for three species (spruce, Manchurian ash, and white birch). Seventeen feature parameters were extracted using the Lasso method (Figure 4a). The R^2 , RMSE, and MAE of the Lasso-BP were 0.9532, 0.0609, and 0.0465, respectively (Figure 4b). The maximum residual error was almost within 15% and did not exceed 10% when the log MC was less than 20% (Figure 4c), indicating that because of its good prediction ability, especially when the MC is low, the hybrid model can play a role in the actual wood drying process.

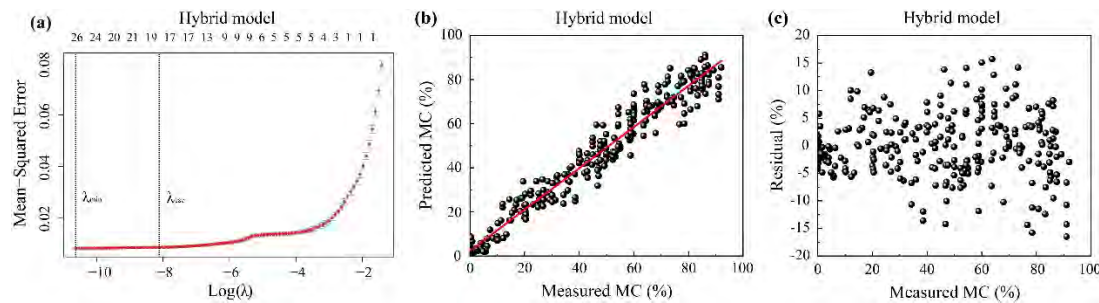


Figure 4—(a) Lasso feature extraction, (b) hybrid model, and (c) residuals for the moisture content of spruce, Manchurian ash, and white birch logs.

The main reason that the hybrid model is lower than the individual species models is that the density and internal structure (thickness of the bark, heartwood, and sapwood) vary depending on the tree species. In addition, the MC prediction models for logs were inaccurate for MC detection in living trees. This may be because the moisture in wet logs is reduced from the outside to the inside during the drying process, whereas the MCs in heartwood and sapwood are almost all reduced to some extent when the living tree in the field is threatened by drought. The two patterns of moisture variation are obviously different. Therefore, the prediction models in the present study are only suitable for detecting MC changes in logs. However, time-frequency multi-parameter Lasso feature extraction combined with BPNN by GPR signals provides a potential method for the MC detection of living trees. Future studies will further examine the non-destructive and accurate MC detection of living trees using GPR signals.

Conclusions

In the present study, it was found that the predictive performance for log MCs given by the Lasso-BP models ($R^2 \geq 0.9758$, $RMSE \leq 0.0425$) was better than that of PCA-BP and BPNN. It indicates that these prediction models can meet the practical needs of actual wood processing and provide a potential research method for the MC detection of living trees.

Acknowledgments

We thank all authors for their cooperation and the work was supported by the Fundamental Research Funds for the Central Universities (grant no. 2572022AW46).

References

- Dong, S.; Luo, T. 2013. Bearing degradation process prediction based on the PCA and optimized LS-SVM model. *Measurement*. 46: 3143-3152.
- Hans, G.; et al. 2015. Determination of log moisture content using ground penetrating radar (GPR). Part 1. Partial least squares (PLS) method. *Holzforschung*. 69: 1117-1123.
- Li, J.; et al. 2021. High-throughput simulation combined machine learning search for optimum elemental composition in medium entropy alloy. *Journal of Materials Science and Technology*. 68: 70-75.
- Rodriguez-Abad, I.; et al. 2010. Non-destructive methodologies for the evaluation of moisture content in sawn timber structures: Ground-penetrating radar and ultrasound techniques. *Near Surface Geophysics*. 8.
- Shafiee, S.; et al. 2021. Sequential forward selection and support vector regression in comparison to LASSO regression for spring wheat yield prediction based on UAV imagery. *Computers and Electronics in Agriculture*. 183: 106036.
- Tibshirani, R.; 1996. Regression Shrinkage and Selection Via the Lasso. *Journal of the Royal Statistical Society: Series B (Methodological)*. 58: 267-288.
- Zhang, J.; et al. 2020. In-situ recognition of moisture damage in bridge deck asphalt pavement with time-frequency features of GPR signal. *Construction and Building Materials*. 244: 118295.

Dynamic Indentation Test with HardScan®: An Effective Tool for Monitoring Railway Sleepers Quality and Performance on Track

M. Salomao

Senior Railway Consultant, Rumo Logística, Araraquara, Sao Paulo, Brazil,
mauricio.salomão@rumolog.com

H Eufrade-Junior

Assistant Professor, University of Sao Paulo – USP, Piracicaba, Sao Paulo, Brazil, h.eufrade@usp.br

A Assis

Maintenance Coordinator, Eucatex Particleboard and Laminate Flooring, Botucatu, Sao Paulo, Brazil,
albert.a.assis@gmail.com

A Ballarin *

Director, A2 Engenharia e Tecnologia Ltda, Botucatu, Sao Paulo, Brazil, adriano.ballarin@unesp.br

* Corresponding author

Abstract

Railway companies face substantial challenges in inspecting sleepers, both during the receiving phase and after their installation on the permanent track. Inspection protocols typically depend on visual analysis and qualitative assessments. This paper introduces the dynamic indentation test, performed with a portable hardness tester - HardScan®, as a tool for the quick and easy assessment of the quality and performance of sleepers installed on the permanent track. Beyond dynamic hardness, which is directly presented on the equipment display, more than 100 dynamic indentation parameters are extracted - using specific software - to correlate with the physical and mechanical properties of the tested material. Results, already validated with wooden sleepers, showcase the tool's effectiveness in selecting samples with superior performance. This is achieved using the Cluster Analysis technique and considering variables such as wood density and dynamic hardness for each sleeper. The combination of specific parameters extracted in the dynamic indentation test accurately estimates physical and mechanical properties (strength and stiffness) non-destructively through regression analysis. HardScan® demonstrated the ability to estimate wood density with a mean absolute error of 45 kg m⁻³. Furthermore, field tests on wooden sleepers with 11 months of use reveal variations in dynamic hardness over time, suggesting the potential for monitoring its temporal decay. This could lead to establishing reference performance degradation curves to guide sleeper replacements on the track. Preliminary results for prestressed concrete sleepers indicate statistically significant differences in dynamic hardness between sleepers of distinct ages.

Keywords: dynamic indentation, hardness, HardScan, sleepers

Cambium Detection in CT Scans of Green Sawlogs for Bark and Volume Quantification—Analytical Approaches and Methodological Difficulties

Martin Huber*

Forest Research Institute of Baden-Württemberg, Department of Forest Utilisation, Freiburg, Germany,
martin.huber@forst.bwl.de

Franka Brüchert

Forest Research Institute of Baden-Württemberg, Department of Forest Utilisation, Freiburg, Germany,
franka.bruechert@forst.bwl.de

Jörg Staudenmaier

Forest Research Institute of Baden-Württemberg, Department of Forest Utilisation, Freiburg, Germany,
joerg.staudenmaier@forst.bwl.de

Udo H. Sauter

Forest Research Institute of Baden-Württemberg, Department of Forest Utilisation, Freiburg, Germany,
udo.sauter@forst.bwl.de

* Corresponding author

Abstract

Wood volume and bark thickness are fundamental information for sawlog marketing and biomass prediction. Difficulties arise when log volume is measured in bark, but is paid for as under-bark volume. Bark thickness tables provide a rough approximation for the necessary reduction of the measured diameter, but are not available for all commercial softwood and hardwood species grown in Europe.

In most European tree species wood and bark development are initiated by cell division and maturation from the cambium. Intrinsic genetic patterns of growth and bark development over time are superimposed by site conditions and silvicultural management. This leads to a specific transition zone between wood and bark for the different hardwood and softwood species. The objective of our investigations is to identify these transition zones in high-resolution CT scans of softwood and hardwood species in order to further develop applications for roundwood mensuration and classification / grading.

We will report on experimental and analytical approaches for an automated detection of the border between wood and bark, i.e. the cambial circumference, in CT scans of green sawlogs. The test material consists of discs of several softwood and hardwood species grown in Central Europe. The discs are scanned with a CT scanner directly after felling to keep them at green conditions. Afterwards the discs are immediately debarked and scanned again in order to get a reference and to create a ground truth data set for machine learning by using image registration. Several analytical approaches are applied to determine the cambial line in cross sections of the scanned discs: Density profiles from pith to bark analysed on discrete single scanning planes and density patterns on 2D-CT reconstructions analysed with traditional image processing methods as well as with KI-based approaches.

Keywords: CT scanning, cambium, bark, wood, softwoods, hardwoods

Small Diameter Oak Logs for Construction— Considerations for Strength Pre-Grading of Green Logs

Martin Huber*

Forest Research Institute of Baden-Württemberg, Department of Forest Utilisation, Freiburg, Germany, martin.huber@forst.bwl.de

Franka Brüchert

Forest Research Institute of Baden-Württemberg, Department of Forest Utilisation, Freiburg, Germany, franka.bruechert@forst.bwl.de

Nicolas Hofmann

Forest Research Institute of Baden-Württemberg, Department of Forest Utilisation, Freiburg, Germany, nicolas.hofmann@forst.bwl.de

Kay-Uwe Schober

Hochschule Mainz, Mainz University of Applied Sciences, Mainz, Germany, kay-uwe.schober@hs-mainz.de

Beate Hörnel-Metzger

Hochschule Mainz, Mainz University of Applied Sciences, Mainz, Germany, beate.hoernel-metzger@hs-mainz.de

Maximilian Müller

Hochschule Mainz, Mainz University of Applied Sciences, Mainz, Germany, maximilian.mueller@hs-mainz.de

Udo H. Sauter

Forest Research Institute of Baden-Württemberg, Department of Forest Utilisation, Freiburg, Germany, udo.sauter@forst.bwl.de

* Corresponding author

Abstract

The project aimed to make small-diameter oak logs available as structural timber members, e.g., for columns, frameworks, and agricultural buildings. In this context, we report on the results of stiffness and strength prediction for small-diameter oak logs' strength classification applying similar approaches as known for sawn timber machine strength grading. Machine strength grading is based on statistical prediction models to relate internal and physical wood characteristics to mechanical properties from which strength grades are determined.

R^2_{corr} of the models for MOE_{stat} varied between 0.32 and 0.34, and for MOR between 0.41 and 0.52. For MOR , *green density*, MOE_{dyn} , *knot volume* and *weighted knot position* added to the simplest, meaningful model. In different combinations *number of growth rings* and *stem taper* showed an acceptable relevance as predictors, too. However, due to the very small dataset the number of predictors in the models needed to be restricted to avoid overfitting.

Keywords: Oak, small-diameter logs, internal wood structure, strength prediction

Introduction

In oak stands in Germany the volumetric annual increment is far larger than the harvested volume. Especially small-diameter oaks are currently either not used or only used as firewood. However, long term carbon storage in wood products should be preferred to direct emission of CO₂ by combustion wherever possible. A finished research project aimed to make small-diameter oak logs available as structural timber members to achieve long-term carbon dioxide storage and higher added value. The idea is to use such members for columns, frameworks, and agricultural buildings, such as barns. For sawn timber, strength grading classification is a pre-requisite for structural uses of wood. Machine strength grading in this context is based on statistical prediction models to relate internal and physical wood characteristics such as density and knot structure to mechanical properties. From these relations strength grades are determined. We report on the results of stiffness and strength prediction for small-diameter oak logs applying similar approaches as known for sawn timber strength grading.

Materials and Methods

Based on a broad experimental characterisation program more than 60 variables were determined for comprehensive characterisation of 66 oak logs (*Quercus petraea* (Matt.) Liebl.) from two sub-samples. The logs had a length of about 5 m and an average mid-diameter of about 23 cm. The characteristics include static MOE and MOR, which were measured by a static bending test, and dynamic MOE, which was derived from a Microtec[®] Viscan measurement. Internal characteristics like wood density, knots and other internal defects were extracted from CT-scans using conventional algorithms, which were developed for softwood, as well as a new machine learning approach. Log geometry characteristics like curvature and taper were gained from 3D-scans of the logs using algorithms of the “Rahmenvereinbarung für die Werksvermessung von Stammholz” (RVWV) (DeSH and DFWR 2021). Additionally, an external inspection according to the “Rahmenvereinbarung für den Rohholzhandel in Deutschland” (RVR) (DFWR and DHWR 2020) was applied in particular for assessing branch positions. These branch positions were used to consider the position of the knots in the static bending test. For this, the position of each knot was assigned to the corresponding position on a dial of a clock and then weighted according to Figure 1, i.e. the value 0 was assigned to knots at 12:00 o’clock while the value 2, for example, was assigned to knots at 2:00 and 10:00 o’clock. The sum of the weights of all the knots in the test area was defined as parameter *sum of weighted knot positions*.

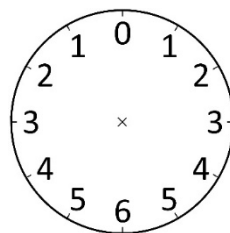


Figure 1—Weights of the knot positions for the definition of the parameter *sum of weighted knot positions*.

The over 60 variables collected and calculated from the measurements were used for the statistical modelling of the static MOE and MOR based on GLM modelling approaches.

Results and Discussion

The mean value and its standard deviation for some of the main characteristics of the logs can be found in Table 1. The results are listed for the complete sample as well as for the two sub-samples separately.

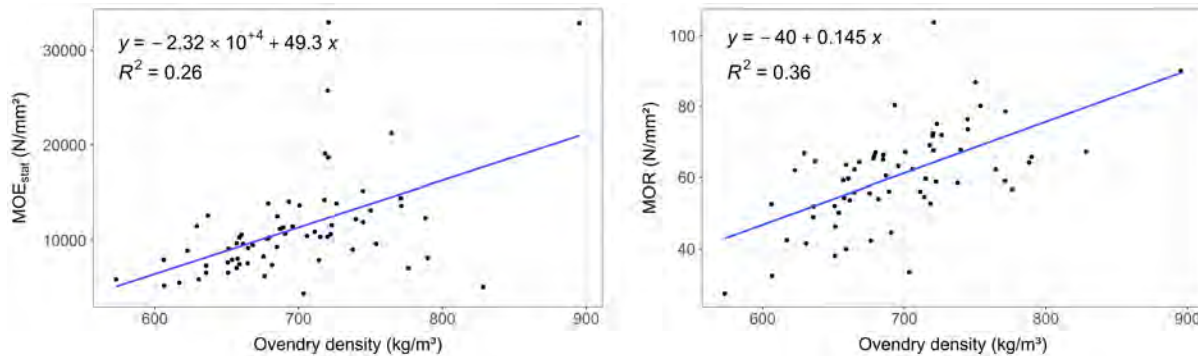
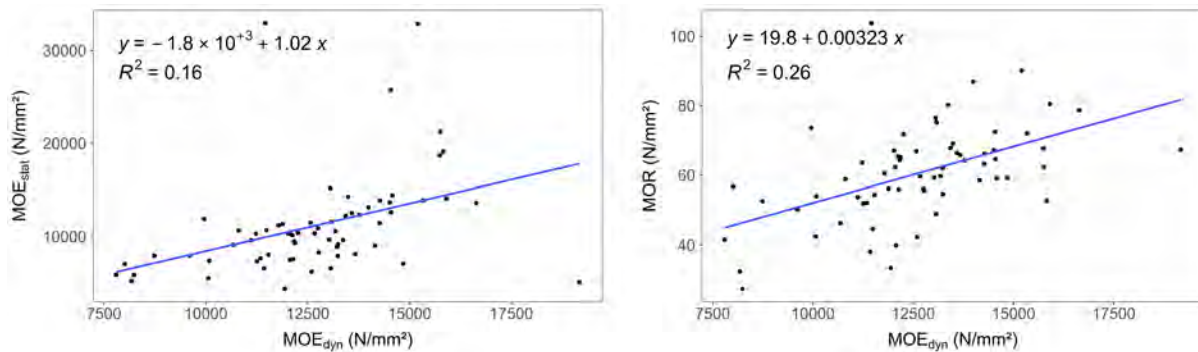
Table 1—Characteristics of the test material. Mean plus-minus standard deviation.

	All	sub-sample 1	sub-sample 2
Number of logs	66	44	22
Average diameter [cm]	23.4±3.4	22.6±3.3	25.0±2.9
Ovendry density [kg/m ³]	696±56	678±47	730±58
Wood density CT [kg/m ³]	869±40	858±37	892±36
Number of knot features RVR	25.6±19.0	23.2±16.7	30.5±22.6
Knot volume CT [%]	2.75±1.34	2.80±1.42	2.65±1.19
Curvature [cm/m]	1.81±0.76	1.60±0.65	2.22±0.82
Taper [cm/m]	0.66±0.24	0.66±0.23	0.66±0.26
Average width of growth rings [mm]	1.32±0.26	1.28±0.26	1.40±0.25
MOE _{dyn} [N/mm ²]	12648.9±2155.6	11974.3±1866.5	13998.0±2095.0
MOE _{stat} [N/mm ²]	11138.0±5455.9	9373.3±2527.7	14667.5±7712.2
MOR [N/mm ²]	60.6±13.6	58.0±12.5	66.0±14.3

The mechanical characteristics are similar to oak logs tested in other studies (Nocetti et al. 2021, Sauter et al. 2018).

When comparing the sub-samples especially a considerable difference between the MOE_{stat} of both sub-samples can be recognised. The average MOE_{stat} of sub-sample 2 as well as its variation were much higher (Table 1). Accordingly, there is a moderate correlation of the sub-samples with the MOE_{stat} , although the logs originate from the same stand. Nonetheless, the variable “sub-sample” was excluded as a predictor, since the final pre-grading model should be independent of any sub-sample groupings.

Of all measured characteristics *ovendry density*, MOE_{dyn} and *moisture content* were three of the four characteristics with the highest correlation to both target variables MOE_{stat} and MOR . The relation of the *ovendry density* to MOE_{stat} and MOR as well as the relation of MOE_{dyn} to MOE_{stat} and MOR are presented (Figure 2, Figure 3).

**Figure 2**—Variation of the MOE_{stat} and MOR over the *ovendry density*.**Figure 3**—Variation of the MOE_{stat} and MOR over the MOE_{dyn} .

Despite their correlation with MOE_{stat} and MOR , *ovendry density* and *moisture content* were not considered as predictors for the final model, since there is no easy online method so far to implement such measurements in a non-destructive strength pre-grading of green logs.

Instead of these two characteristics *green wood density* from the CT-scans was used as a predictor. Its correlation with MOE_{stat} and MOR is considerably lower than the one of *ovendry density*, but *green wood density* is still among the characteristics with the highest correlation to the two target variables.

However, combining MOE_{dyn} , *green wood density* and for example some knot variable to a model for the prediction of the MOE_{stat} did not lead to a prediction model of reasonable accuracy.

One of the main reasons for this are outliers regarding the variation of the MOE_{stat} over *ovendry density* and MOE_{dyn} (Figure 2 and Figure 3) in combination with the small sample size. By the time of writing no explanation for these extreme values has been found.

The best model for the prediction of the MOE_{stat} reaches an R^2_{corr} of 0.34 based on a combination of *green density* and log geometry variables as predictors.

The R^2_{corr} of the models for the MOR varied between 0.41 and 0.52. Using the variables with the highest correlation to MOR , i.e. MOE_{dyn} and *green density*, in combination with knot variables as predictors results in the simplest models with an R^2_{corr} of more than 0.4 and p-values for the predictors that are lower than 0.01. Especially the combination of *knot volume in the test area* and the *sum of weighted knot positions* proved to be a good predictor to account for the knot features in the logs. With a p-value lower than 0.05 or sometimes 0.01, *Number of growth rings* and *stem taper* showed an acceptable relevance as predictors in some models, too, but due to the small sample size overfitting became an issue when testing more complex models. The model combining *green density*, MOE_{dyn} , the previously mentioned knot variables and the *number of growth rings* is presented in Table 2 and Table 3.

Table 2—Linear model for the MOR .

Predictors	Estimate	Std. Error	t-value	p-value
Intercept	-18.52	37.53	-0.49	0.62
Green density CT	0.098	0.037	2.67	0.0097
$(MOE_{dyn})^{1/2}$	0.041	0.14	2.82	0.0064
Number of growth rings	-0.49	0.17	-2.97	0.0043
Knot volume CT test area × Sum of weighted knot positions	-0.00016	5.95x10 ⁻⁵	-2.85	0.0060

Table 3—Evaluation of the linear model for the MOR .

Number of parameters	Degrees of freedom	Residual standard error	R-squared	Adjusted R-squared	F-statistic	p-value
4	61	9.93	0.5	0.46	15.05	1.3x10 ⁻⁸

Nearly all models for the prediction of MOR with an R^2_{corr} of more than 0.35 and p-values lower than 0.01 for the predictors depend on the predictors *green density* and MOE_{dyn} . This is in agreement with other studies which describe a positive correlation between density as well as the dynamic MOE and the strength of the logs. The negative impact of knots on the strength of logs is also well known and therefore the importance of knot variables as predictors is expected, too.

The quality of the knot variables has, however, potential for improvement as they were derived either using a conventional detection algorithm, which was developed for softwood, or a machine learning approach, which is still in the early stages of its development. Both algorithms yield good results, but an improvement in accuracy might lead to improved prediction models for MOE_{stat} and MOR . A differentiation between different types of knot features might improve the models, too. The knot variables, which were determined by the algorithms, did only take into account the knot volume and not the type of knot feature, although the different types might differ in their influence on the log strength.

With the detection algorithms used the definition of a predictor, which combines the weighted knot position and volume of each individual knot, was not possible. However, as the combination of *knot volume* and the *sum of weighted knot positions* was a good predictor in several models, developing such a predictor might be promising.

Conclusions

While the overall results indicate, that a pre-classification of oak logs for strength might be promising, the small sample size in this study always needs to be considered. On the one hand, the small sample size very likely leads to a limited variation of the wood features of the oak logs, especially since all logs originated from the same stand. On the other hand, the number of predictors for each model had to be restricted because of the small sample size, since the models quickly showed tendencies of overfitting. Therefore the expansion of the data set is a necessity to validate and adjust the existing models and develop improved ones. The correlation of some additional predictors with the two target variables suggests, for example, that including them in some of the models could lead to further improvements.

Acknowledgments

This project (support code 2218WK18C3) was funded by the Federal Ministry of Food and Agriculture (BMEL) and the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) through the Agency for Renewable Resources (FNR) from the Forest Climate Fund (WKF).

References

- Deutsche Säge- und Holzindustrie Bundesverband e.V. (DeSH); Deutscher Forstwirtschaftsrat (DFWR). 2005. Rahmenvereinbarung für die Werksvermessung von Stammholz des Deutschen Forstwirtschaftsrates e.V. und des Verbandes der Deutschen Säge- und Holzindustrie e.V. (RVWV) [Version 2005-01-14]. Available online: <http://www.werkeingangsvermessung.info/> (accessed on 25 June 2021).
- Deutscher Forstwirtschaftsrat e.V. (DFWR); Deutscher Holzwirtschaftsrat e.V. (DHWR). 2020. Rahmenvereinbarung für den Rohholzhandel in Deutschland des Deutschen Forstwirtschaftsrates e.V. und des Deutschen Holzwirtschaftsrates e.V. (RVR). Berlin, Germany, Volume 3.
- Hofmann, N.; Brüchert, F.; Sauter, U.H.; Schober, K.-U.; Hörnel-Metzger, B. 2023. Green oak building with high-tech methods, Part 1: Characterisation of the raw material. WCTE World Conference on Timber Engineering 2023; Timber for a Livable Future. Oslo, Norwegen, / [ed] Nyrud, A. Q. Malo, K. A.; Nore, K., World Conference on Timber Engineering 2023 (WCTE 2023), 2023, p. 711-716.
- Nocetti, M.; Aminti, G.; Wessels, C. B.; Brunetti, M. 2021. Applying Machine Strength Grading System to Round Timber Used in Hydraulic Engineering Works. *Forests* 2021, 12, 281. <https://doi.org/10.3390/f12030281>
- Sauter, U. H.; Breinig, L.; Brüchert, F. 2018. European hardwoods for the building sector (EU Hardwoods), Schlussbericht zum Vorhaben FKZ 22004114, 92 S., Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg, Abteilung Waldnutzung.
- Schober, K.-U.; Hörnel-Metzger, B.; Hofmann, N.; Brüchert, F.; Sauter, U. H. 2023. Green oak building with high-tech methods, Part 2: Log bending tests for determination of strength and stiffness. WCTE World Conference on Timber Engineering 2023; Timber for a Livable Future. Oslo, Norwegen, / [ed] Nyrud, A. Q. Malo, K. A.; Nore, K., World Conference on Timber Engineering 2023 (WCTE 2023), 2023, p. 119-125.

Preliminary Investigation of Pineapple Crowns for Paper Production

1. Mojibayo, Ikusedun. Chemical, Fibre and Environmental Technology Department, Federal Institute of Industrial Research Oshodi, Lagos, Nigeria. Email: omoikusedun03@gmail.com

2. Owolabi, F.A.T. Chemical, Fibre and Environmental Technology Department, Federal Institute of Industrial Research Oshodi, Lagos, Nigeria.

3. Olajumoke Fagbemi Deborah. Chemical, Fibre and Environmental Technology Department, Federal Institute of Industrial Research Oshodi, Lagos, Nigeria. Email: ayoniwealth@yahoo.com

4. Aderinlewo A. A. Bioresources and Agricultural Engineering Department, Federal University of Agriculture Abeokuta, Nigeria. Email: aderinlewoaa@funaab.edu.ng

5. Adeosun O.J. Bioresources and Agricultural Engineering Department, Federal University of Agriculture Abeokuta, Nigeria. Email: adeosunoj@funaab.edu.ng

6. Bada, B.S. Environmental Management and Toxicology Department, Federal University of Agriculture Abeokuta, Nigeria. Email: badabs@funaab.edu.ng

Corresponding Author: Ikusedun Mojibayo. Email: omoikusedun03@gmail.com

Abstract

The study investigated the potentials of pineapple crowns (wastes) for paper production. The pineapple crowns were defiberized and the fibre dimensions were examined. Fibre length, fibre diameter, lumen width and cell wall thickness were found to be 2.54 mm, 35.19 μm , 36.67 μm and 5.75 μm respectively. Pulping was done through soda pulping method, papers were produced with the resulting pulps, the papers exhibited different tensile strength values ranging from 188.667 N/m² to 248.667 N/m², elongation @ break and force @ Peak(N) of papers were found to have different values. The chemical components, fibre dimensions, and tensile properties exhibited, all show that pineapple crowns have great potentials for paper production.

Key words: pineapple, fibres, dimensions, paper, environment

Introduction

The world population is increasing with increase in demand for papers. As the paper industry is expanding globally on a daily basis; paper applications are steadily increasing, and has exceeded 400 million tons per year according to The Environmental Paper Network (TEPN 2018). The expansion of the paper industry has been a thing of great concern from an environmental perspective due to the over reliance of the pulp and paper industry on wood fibres as raw materials. The paper industry raises environmental concerns on multiple fronts from deforestation to climate change, loss of biodiversity and soil erosion to various degrees of health issues (Ayoade 2023). Paper production absorbs a substantial and increasing portion of the global wood harvest. In 1983, roughly 35 percent of the commercial wood harvest worldwide was used in the production of paper products, and this is projected to grow to 70 percent by the year 2030. The global production of paper and cardboard stood at approximately 419.7 million metric tons in 2017. More than

half of that production was attributable to packaging papers, while almost one third was attributable to graphic and writing papers. Currently, pulp and paper products consume 50 % of harvested timbers in the United States. The paper industry is facing environmental pressure on multiple dimensions, especially in light of global concerns over CO₂ emissions, deforestation and climate change. Paper is one of the most obvious culprits of deforestation—after all, paper is made from trees. In 2019, the US paper industry produced 78 million tons of paper and cardboard. Making one ton of paper requires 24 trees. The paper industry routinely destroys forests to make way for papers (Fagbemi 2014), hence the need to look for non-wood fibre sources that can give quality pulp for paper production.

Materials and Methods

Materials

The materials used for this research are as follows: sodium hydroxide, hydrogen peroxide, acetic acid, sulfuric acid (H₂SO₄) distilled water, acetone, laboratory slides, slide covers , potassium permanganate (KMNO₄), sulfuric acid, starch solution, sodium thiosulphate, iodine solution, ethanol, benzene, toluene fushsin stain (violet colour) , cotton wool, knitting papers, porcelain crucible, aluminium foil ,filter paper, plastic trays, 50-litre bowl (2), 25-litre buckets, filter papers, disposable hand gloves, disposable nose mas, 1000 ml conical flasks, 500 ml beakers, 50 ml test tubes, 500ml beakers, petri dishes, crucibles, digital weighing balance, vertical rotary digester, hammer mill, moisture analyser, scissors and knives, magnetic stirrer, handmade sheet formers(a 4 size deckles), microscope, testometric tensile testing machine (instron 5500), laboratory oven ,desiccators , water bath, microscope.

Methods:

Determination of fibre dimensions of pineapple crowns.

It is with increasing interest that agricultural by-products such as pineapple crowns are now being considered as raw materials having potentials in pulp and paper production. It is important to examine their potentials in terms of their fibre characteristics so as to be able to know how they can be best utilized in pulp and paper production. The experiment was carried out following the approach employed by Jorge (2000) to keep error below 5 % for a 95 % confidence level. Pineapple crowns were collected, dried and cut into strands of 1 cm x 2mm x 2mm each of the pineapple crowns. The strands were put in a test tube. The test tube containing the strands of pineapple crown leaves was filled with the solution of acetic acid and hydrogen peroxide ratio 1:2 (v/v). i. e. 75 ml of acetic acid and 150 ml of hydrogen peroxide. The test tube was put in a water bath. The water bath was heated to boiling point for 2hrs. The bombardment of the water molecules in the water bath and the action of the solution of acetic acid–hydrogen peroxide caused the fibres to bleach to become white and disintegrated into slivers of fibres (loose, slender fragments), the process which is termed maceration. The test tube was agitated to aid further disintegration of the fibres into slivers.

After hot maceration, the slivers were washed by decanting the acetic acid–hydrogen peroxide solution in the test tube and replaced it with water in the test tube, it was done three times to ensure thorough washing of the slivers. The washed slivers were poured into petri dishes, stained with fushsin stain (violet blue) and then examined under a micrometer mounted on an Olympus light microscope (Standard 25) and as a result, smooth and easy microscopic examination of the slivers was achieved. The microscopic examination of examined ten slivers showed the fibre dimensions such as fibre length (FL), fibre diameter (FD), lumen width (LW) and cell wall thickness (CW) of the slivers.

Table 1: Fibre Dimensions of Pineapple Crowns

Parameter	Test Samples										
	1	2	3	4	5	6	7	8	9	10	Mean
F L (mm)	3.02	2.91	3.02	2.26	2.64	2.26	2.01	2.39	2.64	2.25	2.54
F D (µm)	26.30	16.42	57.96	75.60	64.26	15.04	11.34	37.56	10.08	37.30	35.19
LW (µm)	42.52	12.52	43.78	52.52	43.90	22.64	22.52	13.78	42.52	13.78	31.05
CWT (µm)	1.53	1.58	21.93	29.58	24.42	0.96	3.57	1.53	3.06	1.42	8.96

Pulp Refining and Sheet Forming

A mass of 25g of unbleached pineapple crown pulp was mixed with 500ml of water to form a mixture. The mixture of pulp and water was gently blended with a laboratory blender (Model No. ES - 1008) for about 10 min to form slurry. The resulting slurry from the blended mixture was poured into a handmade sheet former (A4 size deckle and mold) with netted sieve (400 - mesh). The sheet former was partially immersed below the water level, the slurry consisting of separated and loose cellulose fibres in water was agitated to disperse completely, the sheet former was raised up for water to drain through the screens of the sieve and consequently, a mat of randomly interwoven fibres was formed on the mold. The mold and the formed mat of randomly interwoven fibres were air dried; the mat was removed as paper after drying.

Tensile Test of Papers Produced

Tensile tests were carried out on all the paper samples produced according to testometric testing method with a testometric material testing machine (Model No: BS903, M500-25KN, OL11 INR, Roshdale) at test a speed of 100.000 mm/min. The papers were cut into stripes and loaded through the clamps of the machine. Test specimens geometry was sample width: 25.000 mm, sample length: 100.000 mm and sample grammage: 60.000 g/m².

Table 2: Pulping Conditions for Pineapple Crown (Batch 1 Experiments 1-5)

Conc	Temp	Time	Pressure	Yield	Kappa
NaOH (%)	(°C)	(Min)	(Bar)	(%)	Number
1. 10	160	60	0.60	65	30
2. 15	160	60	0.65	62	25
3. 20	160	60	0.60	55	20
4. 25	160	60	0.60	51	18
5. 30	160	60	0.60	49	15

Table 3: Pulping Conditions for Pineapple Crown. Batch 2 Experiments 1-5

	Conc	Temp	Time	Pressure	Yield	Kappa
	NaOH (%)	(°C)	(Min)	(Bar)	(%)	Number
1.	10	120	60	0.20	75	32
2.	10	130	60	0.25	73	26
3.	10	140	60	0.30	70	18
4.	10	150	60	0.35	66	16
5.	10	160	60	0.40	62	15

Table 4: Tensile Properties of Pineapple Crown Papers (Pulping Conditions: Batch 1 Experiments 1-5) NaOH (10-30 %) Temp.160 (°C) Time (60min)

Experiment	Elongation@	Force@	Final	Tensile
	Break (mm)	Peak (N)	Strain (mm)	Strength (N/m ²)
1.	18.148	57.200	18.148	223.333
2.	14.406	61.800	14.406	235.333
3.	12.592	64.500	12.592	241.333
4.	7.783	64.600	7.783	253.667
5.	6.187	74.900	6.187	278.667

Experiment 1-5: NaOH concentration varied from 10 % - 30 %, temperature 160 °C and time 60 min remained constant

Table 5: Tensile Properties of Corn Sheath Papers (Pulping Conditions: Batch 2 Experiments 1-5) NaOH (10%) Temp.120 - 160 (°C) Time (60min)

Experiment	Elongation@	Force@	Final	Tensile
	Break (mm)	Peak (N)	Strain (mm)	Strength (N/m ²)
1.	21.116	3.600	21.116	188.667
2.	14.510	4.300	14.510	195.667
3.	9.761	4.400	9.761	216.667
4.	7.183	6.100	7.183	235.667
5.	5.040	7.600	5.040	248.667

Experiment 1-5: Temperature varied from 120 - 160 °C, NaOH concentration and time were kept constant at 10 % and 60 min respectively

Results and Discussion

The results obtained as shown in Table 1 reveal that pineapple crown fibres exhibited good potentials and are suitable for pulp and paper production. Table 1 shows pineapple crown fibres exhibited fibre length, fibre diameter, lumen width and cell wall thickness of 2.54 mm, 35.19 μm , 36.67 μm and 5.75 μm respectively, the values which conform with TAPPI standard values and are desirable for quality pulp for quality paper production. Pulping of pineapple crowns was done with as low as 10 – 30% (NaOH) concentration at 120 - 160 $^{\circ}\text{C}$ for 40 – 60 min. Tables 2 to 5 show the effects of pulping conditions (concentration, temperature and time) on pulp yield, kappa number of pulps and tensile properties of papers produced from pineapple crowns. The results in Tables 2 - 5 indicated that pulping conditions: NaOH concentration, temperature and time also play a significant role in the quality of pulps and papers in terms of pulp yield, pulp kappa number and tensile strength of papers.

Conclusions

The following conclusions are drawn from the study:

Pineapple crown fibres showed good potentials and are suitable for pulp and paper production as they exhibited fibre characteristics desirable for pulp and paper production. Pineapple crowns exhibited fibre length of 2.54 mm, fibre diameter 35.19 μm , lumen width 31.05 μm and cell wall thickness of 8.96 μm . Pineapple crowns are good sources of long fibre (2.54 mm) as found in soft woods. Processing conditions have effects on pulp yield, pulp kappa number and the strength of papers produced. Concentration of the pulping chemical (NaOH) as low as 10 % gave high pulp yield and high kappa number at 160 $^{\circ}\text{C}$ for 60 min. Concentration of the pulping chemical (NaOH) as high as 30 % gave low pulp and low kappa number at 160 $^{\circ}\text{C}$ for 60 min. The higher the concentration of the pulping chemical (NaOH) , the lower the pulp yield and the lower the pulp kappa number at 160 $^{\circ}\text{C}$ and 60 min.

The higher the pulping temperature and time, the lower the pulp yield and pulp kappa number, the lower the pulping temperature and time, the higher the pulp yield and pulp kappa number. The optimum pulping conditions for pineapple crowns were found to be chemical concentration of 10%, 120 $^{\circ}\text{C}$ and 60 min with the highest pulp yield of 75% and 32 as the pulp kappa number.

Acknowledgement

I give glory, honour and adoration to God Almighty who has made the program possible for me.

My profound gratitude goes to my major supervisor Prof Aderinlewo A. A and my co-supervisors, Prof. Bada B. S and Prof. Adeosun O. J for their patience, encouragement and love towards me, they are wonderful supervisor. To the Deputy Director, Pulp and Paper Division, Federal Institute of Industrial Research Oshodi, Dr. F. A. T. Owolabi, I say a very big thank you for his support and contribution. Also to Dr. Fagbemi O.D, I say a very big thank you for her contribution. I thank Dr. Adeniyi and Dr. Odozie, both of the Forestry Research Institute of Nigeria (FRIN), Ibadan, for their contributions.

References

- Ayoade, J.O. 2003. Climate Change: Synopsis of Its Nature, Causes, Effects and Management. Vantage Publishers, Ibadan.
- Alcaide, L. J.; Baldovin F. L.; Parra, I. S. 1991, Characterization of cellulose pulp from agricultural residues. TAPPI Journal 74(1): 217-221.
- Alcaide, L. J.; Baldovin, F. L.; Herranz F. 1993. Evaluation of agricultural residues for paper manufacture, TAPPI 76(3): 169-173
- Ekhuemelo, D.O.; Tor. K. 2013. Assessment of fibre characteristics and suitability of maize husk and stalk for pulp and paper production. Journal of Research in Forestry, Wildlife and Environment. 5(1)

Fagbemi, O. D.; Fagbemigun, T.K.; Mgbachiuzor, E. 2014. Investigation of strength properties of paper samples from pulp blends of hibiscus cannabinus and pineapple leave fibres.

Fagbemi, O. D.; Mgbachiuzor, .E.; Otitoju .O.; Igwe C. 2014. Pulp and paper making potentials of corn husk. International Journal of AgricScience. 6 (3)

The Environmental Paper Network (TEPN 2018)

Non-Destructive Evaluation of Felled Burned Logs Used as the Anti-Erosion Barriers

Salvatore Francesco Papandrea *

Department of AGRARIA, University of Reggio Calabria, Feo di Vito snc, 89122, Reggio Calabria, Italy, salvatore.papandrea@unirc.it

Maria Francesca Cataldo

Department of AGRARIA, University of Reggio Calabria, Feo di Vito snc, 89122, Reggio Calabria, Italy, maria.cataldo@unirc.it

Giuseppe Bombino

Department of AGRARIA, University of Reggio Calabria, Feo di Vito snc, 89122, Reggio Calabria, Italy, gzimbalatti@unirc.it

Giuseppe Zimbalatti

Department of AGRARIA, University of Reggio Calabria, Feo di Vito snc, 89122, Reggio Calabria, Italy, gzimbalatti@unirc.it

Andrea Rosario Proto

Department of AGRARIA, University of Reggio Calabria, Feo di Vito snc, 89122, Reggio Calabria, Italy, andrea.proto@unirc.it

* Corresponding author

Abstract

The countries of the Mediterranean basin are often the scene of forest fires with great environmental and economic damage and a serious risk to human life. The rapid and extensive change in land use caused by extreme fires plays a crucial role especially where large areas are subject to instability phenomena such as the Mediterranean area. A study conducted in South Italy on the Aspromonte Massif (Calabria region) has investigated the control of soil erosion by the manual redirection along contour lines of burned felled logs as a contribution to forest self-regeneration.

Non-destructive techniques have been adopted to evaluate the durability of the woody barriers testing how long the structural function of the measure can be prolonged to facilitate the forest establishment and to perform the anti-erosion barrier function mechanically before the wood degradation of the logs happens. Drilling resistance and acoustic stress wave approaches were applied and repeated every six months to monitor the wood status. The obtained durability results showed that the nature-based solution is compatible with the time required for seedlings to regenerate the forest ecosystem and it could be considered for their implementation in the field of bioengineering.

Keywords: Nature-based solution, log durability, drilling resistance, stress wave.

Potential of Seven Brazilian Amazon Hardwood Species for Xylophone

Luciano Roitman* Forest Products' Laboratory, Brazilian Forest Service, Brasília, Distrito Federal, Brazil, luciano.roitman@florestal.gov.br

Eduardo da Silva Santos

University of Brasília, Brasília, Distrito Federal, Brazil, duardo.eduu1@gmail.com

Fernando Nunes Gouveia

Forest Products' Laboratory, Brazilian Forest Service, Brasília, Distrito Federal, Brazil, fernando.gouveia@florestal.gov.br

Abstract

Increasing demand has led to the search for new wood species suitable for musical instruments to substitute overexploited ones. In this study, we evaluated the properties (density, dynamic modulus of elasticity, speed of sound and damping coefficient) of seven Brazilian Amazon hardwoods (*Allantoma decandra*, *Dipteryx magnifica*, *Dipteryx odorata*, *Erisma uncinatum*, *Handroanthus incanus*, *Martiodendron elatum* and *Peltogyne lecointei*) and their potential for manufacturing xylophones. We determined wood acoustic properties using the non-destructive method with the impulse excitation technique and using the Stress Wave Timer. *A. decandra* and *E. uncinatum* were considered inadequate for educational standard xylophones. The other five species were well qualified for xylophone bars. However, *P. lecointei* was not well qualified for all analyzed properties. The study of the acoustic properties of Brazilian native woods, authorized for exploitation, can add new economic values, and contribute to supply the market with new species for musical instruments' production.

Keywords: musical instrument, acoustic properties, nondestructive test.

Introduction

General information

Wood is a unique and prestigious material for musical instruments worldwide. Traditional timber species are widely used in the art of manufacturing musical instruments (Brémaud 2012a). Despite the advent of synthetic and technological materials, wood is still highly appreciated for musical instruments (Bucur 2016). The high diversity of wooden-made musical instruments is directly related to the variety of woody species and their characteristics (physical, mechanical and anatomical) that provide specific acoustic properties (Aramaki et al. 2007). Selecting the ideal wood depends on the specific resonance properties required for each type of instrument and its parts. These properties are related to the wood's intrinsic properties, such as density, modulus of elasticity and damping coefficient (Bucur 2006; Traoré et al. 2010).

Some tropical wood species from Brazil are known worldwide for their excellent acoustic qualities (Slooten and Souza 1993; Angyalossy et al. 2005; Haag et al. 2018). However, predatory exploitation has increased their extinction risk, making it very difficult to obtain them in the formal market (Martinelli and

Moraes 2013). For instance, species of the genus *Dalbergia*, which are highly appreciated by musical instrument makers, are listed as endangered or as having some trade restrictions in the Convention on International Trade in Endangered Species of Wild Fauna and Flora (Zauer and Pfriem 2018).

The Amazon rainforest has the greatest biodiversity on the planet, with more than 11,000 cataloged tree species (Ter Steege et al. 2016). However, there are few studies on wood acoustic properties of Amazon species (Teles et al. 2018). Finding alternative species to replace traditional ones used for musical instruments could be an ecologically sound and viable economic solution to this problem. Therefore, we assessed wood properties of seven Brazilian Amazon species to identify their potential for manufacturing xylophones.

Materials and Methods

Sampling

Trees were collected in the Jacundá National Forest (coordinates 8°29'0"S and 62°50'0"W), located in the state of Rondônia, Brazil, in July 2017. The area is within a forest concession granted by the Brazilian Forest Service to the company *Madeplona Industrial Madeireira Ltda*. All species used in this study are authorized commercial species that can be exploited under approved sustainable forest management plans (Table 1).

Table 1. Seven wood species from the Brazilian Amazon used in this study, collected in the Jacundá National Forest, Rondônia, Brazil, in 2017.

Scientific name	Family
<i>Allantoma decandra</i> (Ducke) S.A.Mori, Y.-Y.Huang and Prance	Lecythidaceae
<i>Dipteryx magnifica</i> (Ducke) Ducke	Fabaceae
<i>Dipteryx odorata</i> (Aubl.) Willd	Fabaceae
<i>Erismia uncinatum</i> Warm.	Vochysiaceae
<i>Handroanthus incanus</i> (Ducke) Gleason	Bignoniaceae
<i>Martiodendron elatum</i> (Ducke) Gleason	Fabaceae
<i>Peltogyne lecointei</i> Ducke	Fabaceae

Specimens' preparation and analysis

We evaluated the following wood properties: apparent density; dynamic mode of elasticity (MOEd); fundamental resonance frequency, speed of sound and damping coefficient ($\tan \delta$). All tests and preparation of specimens were performed in the Forestry Products' Laboratory from the Brazilian Forest Service, in Brasilia, Federal District.

We used 12 specimens per species. Test specimens consisted of defect-free specimens from the heartwood with dimensions 22 cm x 2 cm x 1.5 cm.

Apparent density

Apparent density is the density based on the mass of a specimen including moisture and its volume at the same moisture content (ASTM 2014). For this analysis, test specimens were previously placed under controlled temperature ($21 \pm 3^\circ\text{C}$) and humidity ($65 \pm 3\%$), until the stabilization of their mass, with a

moisture content around 12% humidity. Dimensions on width and thickness were determined by the average of three measurements performed on each face, with a digital indicator (Mitutoyo) with a resolution of 0.01 mm. The length in the longitudinal direction was measured using a millimeter ruler. The mass at the time of the test was registered using a digital electronic scale with a capacity of 2,100 g and a resolution of 0.01 g.

Dynamic analysis

After mass stabilization, we performed the dynamic analysis. Dynamic analysis was performed using the impulse excitation technique (IET), according to the ASTM E1876 standard (ASTM 2005). IET is a non-destructive method that determines the elasticity and damping of materials based on the acoustic response emitted by a sample after receiving a slight impulse excitation.

We analyzed the flexural vibration mode using the Sonelastic equipment manufactured by *ATCP Engenharia Ltda.* from São Carlos, state of São Paulo, in which the samples are supported by steel cables at the end of the specimen, at a distance of 0.224 times its length, which corresponds to the nodal points. The impulse was generated by an automatic pulse at one end of the specimen and the signal was captured by a microphone at the opposite end (Figure 1).

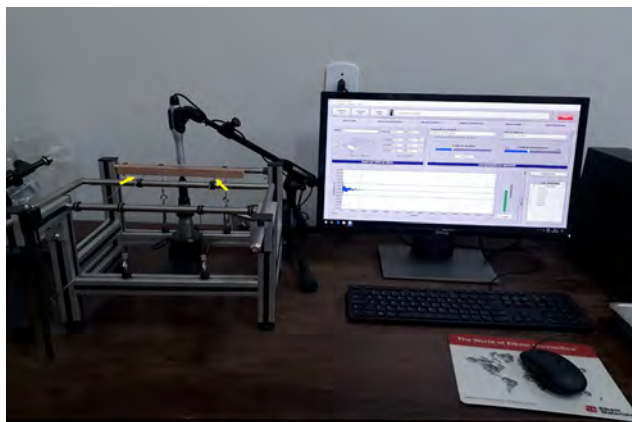


Figure 1. Sonelastic equipment used to determine wood acoustic properties with the impulse excitation technique in the flexional vibration mode for seven wood species from the Brazilian Amazon. Yellow arrows indicate the nodal points where the specimen is supported.

The software of the Sonelastic equipment calculates based on the fundamental frequency the speed of sound propagation, the dynamic mode of elasticity (MOEd) and the damping coefficient ($\tan \delta$).

We also used another nondestructive equipment, the Stress Wave Timer (SWT), model 239A. (Metriguard Inc.), which measures the propagation time of a stress wave along the test piece, using two transducers with an accelerometer (Figure 2). It calculates the propagation time of a signal emitted by the impact of a pendulum with a metal sphere, from one end of the sample to the other, in its longitudinal direction.

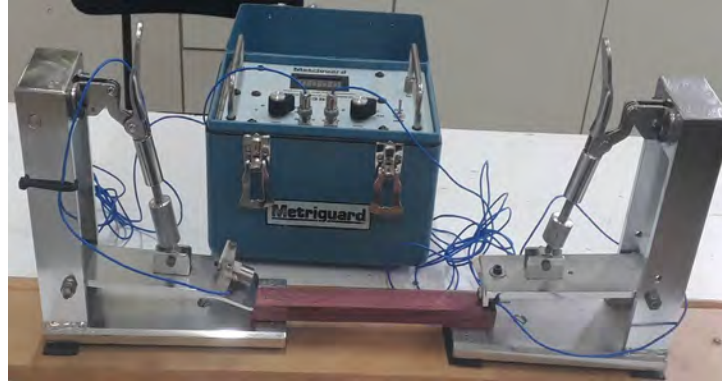


Figure 1. Stress Wave Timer equipment used to obtain speed of sound propagation and dynamic mode of elasticity (MOEd) for seven wood species from the Brazilian Amazon.

The speed of sound propagation and the MOEd can be calculated using Equation 1 and Equation 2, respectively.

$$c = \frac{L}{t} \quad (1)$$

Where c is the speed of sound (m.s^{-1}), L is the length of specimens (m), and t is the stress wave propagation time obtained by the Stress Wave Timer (s).

$$\text{MOEd} = c^2 \times \frac{\rho(\text{ap})}{100} \times 9.80665 \times 10^{-5} \quad (2)$$

Where, MOEd is the dynamic mode of elasticity (GPa), c is the speed of sound (m.s^{-1}), and ρ (ap) is the apparent density (g.cm^{-3}).

For both equipment (IET and SWT), three consecutive measurements were taken, and the results were averaged.

Statistical analysis

The verification of outliers was carried out using the Excel program. The analysis of variance ANOVA and the Tukey test at 5% significance was performed using the IBM SPSS program, to find out which species had a significant difference for the analyzed parameters.

Results and Discussion

Outliers were detected (two or less individuals per species) and not removed from the analysis. Species had significant differences in apparent density, fundamental resonance frequency, and damping coefficient and separated into five, three and three distinct groups for the three properties, respectively ($p < 0.05$) (Table 3).

Wood density is a major factor in species selection for musical instruments and their parts (Bucur 2016; Liu et al. 2020). The average apparent density of the analyzed species varied between 0.70 g.cm^{-3} for *E. uncinatum* and 1.08 g.cm^{-3} for *D. odorata*.

Table 2. Apparent density, fundamental frequency and damping coefficient obtained by the impulse excitation technique (IET) in the flexural vibration mode for seven Amazon wood species. Different letters in the same column indicate differences between species or species groups ($p < 0.05$), values in parentheses correspond to the coefficient of variation (%), $\tan \delta$ = damping coefficient.

Species	Apparent Density (g.cm ⁻³)	Fundamental Resonance Frequency (Hz)	($\tan \delta$)
<i>Erismia uncinatum</i>	0.70 (2.62) a	1399 (2.76) ab	0.0082 (17.03) cd
<i>Allantoma decandra</i>	0.74 (3.56) b	1546 (5.50) c	0.0081 (18.13) cd
<i>Dipteryx magnifica</i>	0.96 (3.90) c	1386 (4.14) a	0.0063 (21.98) abc
<i>Peltogyne lecointei</i>	0.99 (3.87) cd	1346 (5.41) a	0.0085 (18.72) d
<i>Martiodendron elatum</i>	0.97 (4.17) c	1494 (4.72) bc	0.0058 (11.91) ab
<i>Handroanthus incanus</i>	1.01 (3.15) d	1505 (4.33) a	0.0051 (18.72) a
<i>Dipteryx odorata</i>	1.08 (1.31) e	1396 (10.16) b	0.0074 (29.42) bc

Species with high wood densities are suitable for xylophones (Slooten and Souza 1993; Wegst 2006). *E. uncinatum* and *A. decandra* were not suitable for manufacturing xylophone keys due to their low density, according to the values proposed by HOLZ (1996) and WEGST (2008), which should be within the range of 0.8 g.cm⁻³ to 1.14 g.cm⁻³.

Wood species for musical instruments with low damping coefficients are desirable (Bucur 2016). For instance, woods for xylophones and violin bows have very low damping coefficients (Wegst 2006). Most tropical hardwood species, even with a wide geographical distribution, have low $\tan \delta$ values, and extremely low values (0.006) are common to these types of woods (Brémaud 2012b).

The $\tan \delta$ values ranged from 0.0051 (*H. incanus*) to 0.0085 (*P. lecointei*) in the flexural vibration mode (Table 3). Except for *P. lecointei*, high-density species had the lowest $\tan \delta$ values.

Brémaud et al. (2012) studied the vibrational properties of 79 species, including softwood and hardwood species with different geographic distribution and densities. In their study, $\tan \delta$ values varied between 0.0033 and 0.0206, with a mean value of 0.007. They found that tropical hardwood species had predominantly low values for $\tan \delta$, while temperate hardwood species had high values.

Baar et al. (2016) studied four tropical species from different regions of the world, used for different musical instruments, mainly xylophones. They found damping coefficients between 0.006 and 0.008.

There was a difference between the results obtained by IET and SWT. The values in IET were higher than SWT values. Nonetheless, the behavioral trend regarding MOEd for the studied species was the same for both equipment, with separation into five distinct groups ($p < 0.05$) (Figure 3).

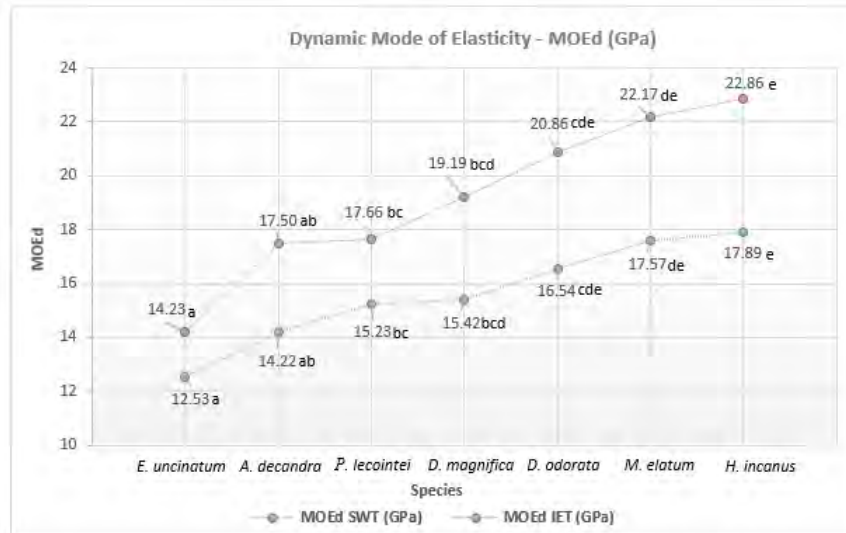


Figure 3. Average values for Dynamic Mode Elasticity (MOEd) obtained in Impulse Excitation Technique (IET) and Stress Wave Timer (SWT) for seven Amazon wood species. Different letters in the same line indicate differences between species or species groups ($p < 0.05$).

The species with low apparent density showed the lowest values for MOEd followed by *P. lecoitei*. Wood species traditionally used in xylophones have high density, MOE values between 15 and 20 GPa, high degree of hardness and durability and low tendency to crack and break (Holz 1996 *apud* Wegst 2008)

For speed of sound the species were grouped into three different groups ($p < 0.05$) in both equipment, but a small variation in distribution between different groups was observed mainly for *E. uncinatum* (Figure 4). Nevertheless, all species presented speed of sound values recommended for manufacturing xylophone keys, according to the average values proposed by WEGST (2008), between 3650 m.s^{-1} and 4500 m.s^{-1} .

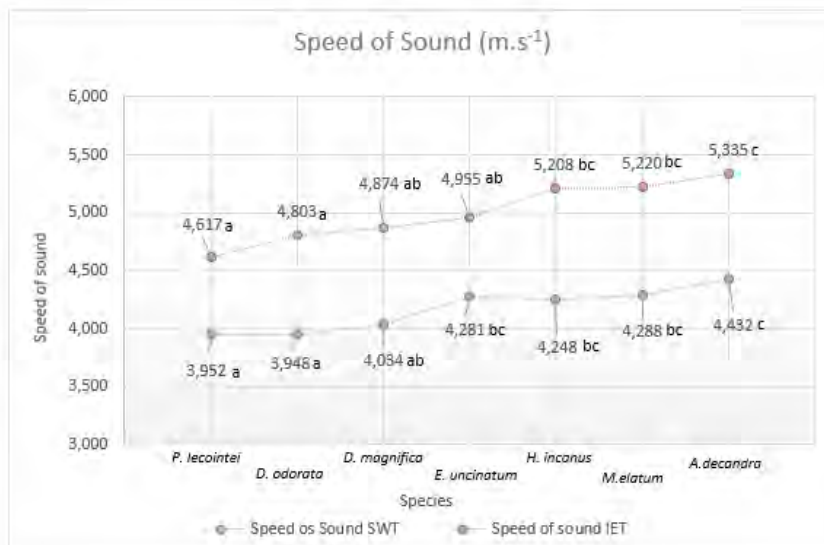


Figure 4. Average values for speed of sound obtained in Impulse Excitation Technique (IET) and Stress Wave Timer (SWT) for seven Amazon wood species. Different letters in the same line indicate differences between species or species groups ($p < 0.05$).

The speed of sound is one of the most important acoustic properties for selecting of materials for musical instruments (Wegst 2006). *A. decandra* presented the highest values for speed of sound, followed by *M. elatum* and *P. lecointei*.

Of the seven species studied, five were considered suitable for making educational standard xylophones. The species *A. decandra* and *E. uncinatum*, due to their lower density and low values for MOEd, were not considered suitable for xylophones bars.

Even though it was considered suitable for use on xylophone bars, *P. lecointei*, despite its high density, presented the third lowest MOEd value, and the lowest speed of sound, in addition to the highest damping coefficient (0.0085). An explanation for the values found in the properties studied here for this species could be its high extractive content as well as its anatomical characteristics with lack of stratification (Roitman 2021).

Conclusion

Studies aimed at evaluating the potential of alternative tropical wood species for musical instruments are essential for biodiversity conservation and the market of new musical instruments. *A. decandra* and *E. uncinatum* were considered inadequate for educational standard xylophones. The other five species were well qualified for manufacturing xylophone bars. However, *P. lecointei* was not well qualified. The study of the acoustic properties of Brazilian native woods, authorized for exploration, can add new economic values, and contribute to supply the market with new species for musical instruments production.

Acknowledgments

We thank Brazilian National Council for Scientific and Technological Development (CNPQ-Brazil) for the grant to the second author and the Forest Products' Laboratory (LPF) of Brazilian Forest Service (SFB).

References

- American Society for Testing Materials. 2005. ASTM E1876: Standard Test Method for Dynamic Young's Modulus, Shear Modulus, and Poisson's Ratio by Impulse Excitation of Vibration. ASTM International.
- American Society for Testing Materials (2014) ASTM D2395:14. Standard Test Method for Density and Specific Gravity (Relative Density) of Wood and Wood-Based Materials.
- Angyalossy, V.; Amano, E.; Alves, E.S. 2005. Madeiras utilizadas na fabricação de arcos para instrumentos de corda: aspectos anatômicos. *Acta Bot Bras* 19(4):819-834.
- Aramaki, M.; Baillères, H.; Brancheriau, L. 2007. Sound quality assessment of wood for xylophone bars. *J. Acoust. Soc. Am.* 121(4):2407–2420.
- Brémaud, I. 2012a. Acoustical properties of wood in string instruments soundboards and tuned idiophones: biological and cultural diversity. *J Acoust Soc Am* 131(1):807-818.
- Brémaud, I.; El Kaïm, Y.; Guibal, [and others]. 2012b. Characterization and categorization of the diversity in viscoelastic vibrational properties between 98 wood types. *Ann For Sci* 69(3), 373-386.
- Bucur, V. 2006. Acoustics of Wood. The Thirteen International Congress in Sound Vibration. ICICSV13. July 2-6, Vienna-Austria.

Bucur, V. 2016. Handbook of Materials for String Musical Instruments. Springer, Melbourne.

Haag, V.; Kirsch, S.; Koch, G. [and others]. 2018. Non-Destructive Investigation of Historical Instruments Based on 3D-Reflected-Light Microscopy and High-Resolution μ -X-ray CT. In: Pérez E, Marconi E (eds). Wooden musical instruments: different forms of knowledge: book of end of wood MusICK COST Action FP1302, pp 143-156.

Holz, D. Acoustically important properties of xylophone-bar materials: can tropical woods be replaced by European species? ACUSTICA. acta acustica vol. 82 (1996) p.878-884.

Martinelli, G.; Moraes, M.A. 2013. Livro vermelho da flora do Brasil. Instituto de Pesquisas Jardim Botânico do Rio de Janeiro, Rio de Janeiro.

Liu, M.; Peng, L.; Lyu, S.; Lyu, J. 2020. Properties of common tropical hardwoods for fretboard of string instruments. J Wood Sci 66(1):1-11.

Roitman, L. 2021. Avaliação das propriedades de sete espécies de madeiras da Amazônia brasileira para fabricação de instrumentos musicais. Brasília - DF. Dissertação de Mestrado em Engenharia Florestal, Publicação PPGEFL.DM- Jun/2021. Departamento de Engenharia Florestal. Universidade de Brasília, DF. 112p.

Slooten, H.J.V.D.; Souza, M.R. 1993. Avaliação das espécies madeireiras da Amazônia selecionadas para a manufatura de instrumentos musicais. Instituto Nacional de Pesquisas da Amazônia, Manaus.

Teles, R.F; Souza, M.R.; Wimmer, P. 2018. Acoustical Properties of 10 Amazonian Hardwoods. 25th International Congress on Sound and Vibration. ICSV25. Hiroshima. 8-12 July, 2018.

Ter Steege, H.T; Vaessen, R.W.; Cárdenas-López, D.; [and others]. 2016. The discovery of the Amazonian tree flora with an updated checklist of all known tree taxa. Sci Rep 6:1-15.

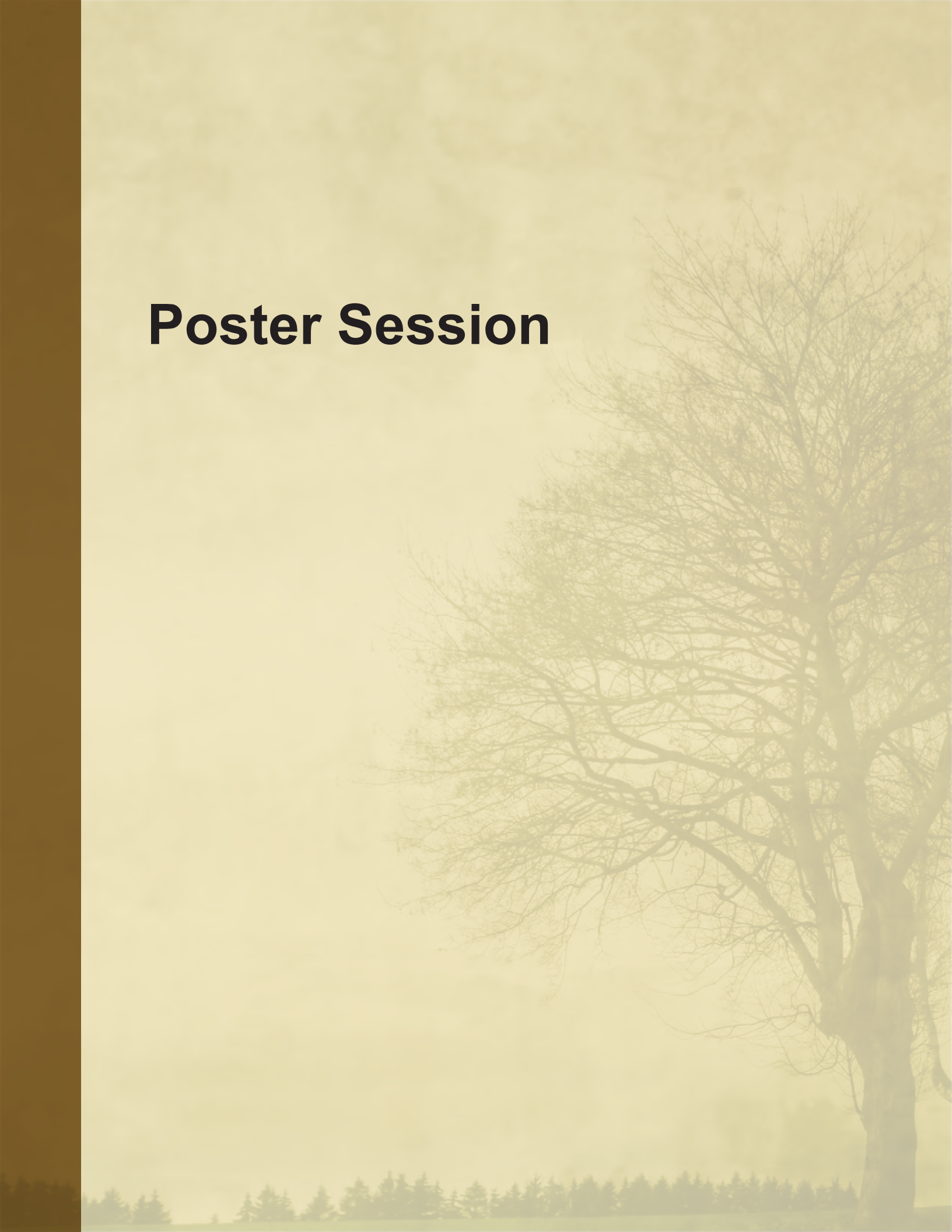
Traoré, B.; Brancheriau, L.; Perré, P.; Stevanovic, T.; Diouf, P. 2010. Acoustic quality of vene wood (*Pterocarpus erinaceus* Poir.) for xylophone instrument manufacture in Mali. Ann For Sci 67(8), 815-815.

Wegst, U.G.K. 2006. Wood for sound. Am J Bot 93(10):1439-1448.

Wegst, U.G.K. 2008. Bamboo and wood in musical instruments. Ann Rev Mater Res 38:323-349.

Zauer, M.; Pfriem, A. 2018. Tropical and traditional wood species in musical instruments and case studies of their substitution with modified wood. In: Pérez E, Marconi E (eds) Wooden musical instruments: different forms of knowledge: book of end of wood MusICK COST Action FP1302, pp 82-96.

Poster Session



Three Underlying Principles in Tree Risk Evaluation

Camila Linhares*

University of Coimbra, Isise, Arise, Department of Civil Engineering, Coimbra, Portugal; University of Trás-os-Montes and Alto Douro, Citab - Centre for the Research and Technology of Agro-Environmental and Biological Sciences, Vila Real, Portugal; Serq - Innovation and Competence Forest Centre, Sertã, Portugal, clinhares@serq.pt

Raquel Gonçalves

Feagri, Unicamp - School of Agricultural Engineering, University of Campinas, Campinas, São Paulo, Brazil, raquelg@unicamp.br

Alfredo Dias

University of Coimbra, Isise, Arise, Department of Civil Engineering, Coimbra, Portugal; SERQ - Innovation and Competence Forest Centre, Sertã, Portugal, alfgdias@dec.uc.pt

Luís Martins

University of Trás-os-Montes and Alto Douro, Citab - Centre for the Research and Technology of Agro-Environmental and Biological Sciences, Vila Real, Portugal, lmartins@utad.pt

Sofia Knapic

University of Coimbra, Isise, Arise, Department of Civil Engineering, Coimbra, Portugal; Serq - Innovation and Competence Forest Centre, Sertã, Portugal, sknapic@serq.pt

* Corresponding author

Abstract

Three fundamental principles should form the basis of urban forest decision-making and space management: the Safety Principle, Conservation Principle, and Legal Principle. The application of these principles informs decisions regarding the maintenance or removal of trees, ensuring a balance between community safety and the preservation of vital ecological contributions. This study investigates these three principles, within the context of practical management, using tools (Visual Tree Assessment (VTA) and drilling resistance) to assess the risks associated with tree alignments of *Populus alba* (Site 1 – Aveiro) and *Platanus × hispanica* (Site 2 – Ponte de Lima) species. Based on the concept of a green strip, it has been proposed to undertake the requalification of the space gradually, replacing with an arboreal and shrub layer better suited to the site's climatic conditions. The intervention has successfully improved the structural condition and vitality, reducing the likelihood of fracture, the prevalence of pathologies and the site's susceptibility to external factors. It is concluded that, collectively, the initial diagnosis and subsequent interventions allowed for the reduction of the risk condition.

Keywords: urban forest management, tree inventory, nondestructive testing

Introduction

An essential component of tree risk analysis involves evaluating their phytosanitary condition. Technological advancements have facilitated tree inspections and serve as a quality control measure for managing urban forests (Linhares, 2021).

Three fundamental principles should form the foundation of decision-making and space management strategies: the Principle of Safety, the Principle of Conservation, and the Legal Principle. These principles utilize technological analysis tools to uphold the advantages of effective space management, thus directing decisions on urban forests. These tools aid in collecting key data for evaluating tree failure risks and shaping management strategies, justifying their use and the strategic investment in urban forest maintenance by the significant social and cultural benefits they provide to communities. Urban trees in streets and parks enhance community belonging and resilience, contributing to stronger, more stable communities in the face of climate change (Dandy, 2010). Urban forests can alter wind patterns through obstruction, deflection, and channeling, thereby improving local climate conditions and making landscapes more accessible. (Rivero, 1986). The incorporation of vegetation in urban areas enhances both psychological well-being and the landscape. Various plant types improve city aesthetics and support mental health by promoting happiness and socializing in recreational parks and squares (Givoni, 1991).

The extensive health and environmental advantages provided by urban forests, such as biodiversity conservation and the mitigation of climate change impacts, are of paramount importance and should always be considered (Molla, 2015).

This study investigates these three principles within the context of practical management, using tools to assess the risks associated with tree alignments of *Populus alba* (Site 1 – Aveiro) and *Platanus × hispanica* (Site 2 – Ponte de Lima) species.

Utilizing these tools, the study seeks to assess the ecological, architectural, and socioeconomic facets of managing these tree alignments. This includes evaluating the health and condition of the trees, identifying potential risks or diseases, and making informed decisions about their maintenance or removal. By specifically focusing on two species, the study enables a more detailed analysis of their growth patterns, genetic variability, and responses to various environmental factors within the scope of urban forestry management.

Through this study, valuable insights can be gained regarding the practical implementation of these principles and the use of technological tools in assessing and managing urban tree populations.

The principle of safety is closely associated with the protection of property and people. Understanding the phytosanitary condition of trees is crucial in preventing accidents. This principle is particularly important in large urban centers, where the risk of trees falling and causing human casualties and significant economic losses is higher (Linhares et. al., 2019).

Guided by the principle of conservation, this study employs nondestructive techniques for phytosanitary assessments to preserve the internal structure of the wood. These nondestructive assessment methodologies are crucial for providing insights into the health and safety conditions of trees (Gilbert, 2004; Linhares et al., 2019; Gonçalves, 2020; Linhares et al., 2021; Linhares et al., 2023). These tools are capable of reproducing, with a high degree of confidence, the real condition of the tree, without the use of invasive tests that harm the evaluated structures (Socco et. al., 2004; Linhares et. al., 2013; Balázs and Divós, 2015).

The study involves monitoring the health of trees to assess the internal condition of the wood and guide suitable treatment when feasible. It adheres to the conservation principle by aiming to preserve the environmental services and benefits offered by the urban forest, while also addressing the safety principle through effective risk management of potential tree falls.

The evaluation process begins by assessing intervention capabilities and the availability of tools necessary for informed decision-making. One of the most significant challenges in research on trees and natural biological processes is the acquisition of materials. Trees are preserved organisms and cannot be used for testing purposes without prior authorization. At this stage, the legal principle becomes relevant, as this management and decision-making model pertains to public spaces (Galenieks, 2017; Badura et. al. 2021).

The main objective was to integrate a practical approach to phytosanitary assessment, based on the three underlying principles in tree risk evaluation, and to propose a reconfiguration of the space when necessary. Within this framework, the phytosanitary study was developed with a focus on understanding the best interventions and evaluating the risk. The decline condition was evidenced through the presence of cavities in the base, stem, and branches, identification of biotic agents, and analysis of wood condition using the Visual Tree Assessment (VTA) and resistance drilling.

Material and Methods

The first task of the assessment consists of determining the geographic area. The trees used for this study were obtained through the Aveiro Municipal Council and Ponte de Lima Municipal Council, under public legal framework. Initially, a visual analysis of the trees was conducted to identify visible deteriorations and defects. After this analysis, resistance drilling equipment was used to infer the degree of deterioration and associate the results with wood strength and stiffness.

During the data collection, the IDTREE application was used, created from the AppSheet platform for use in the fieldwork. This application enables real-time entry and updates of tree assessment data into an alphanumeric database. The application minimizes errors related to transcribing data from paper to digital formats, accelerates updates, modifications, and the entry of new records, supports simultaneous use by multiple technicians, maintains a historical record for each tree, and streamlines the management of planned interventions (Martins et al., 2017).

The methodology incorporates previous studies (Mattheck and Breloer, 1994; Martins, 2015), where a set of attributes are considered for the characterization of the phytosanitary condition and safety of the trees.

The dendrometric parameters can be aggregated to provide a comprehensive overview of the population. Diameter at Breast Height (DBH) class and Basal Area (BA) are two critical parameters aiding in this evaluation. DBH class categorizes measured diameters into intervals typically centered around 5 cm increments. For instance, tree diameters may be grouped into classes such as 5-10 cm, 10-15 cm, 15-20 cm, and so forth, based on the diameter ranges observed in the population. This classification method enables a thorough analysis and enhances comprehension of the distribution of trees within specific size ranges.

Conversely, Basal Area (BA) measures the total cross-sectional area of tree stems within a designated area. These parameters are fundamental for understanding the structure of the tree population, assisting in growth and forest management studies, and evaluating the health status.

In VTA analysis, attributes related to lesions are detailed when a more in-depth diagnosis of a specific tree lesion is required. In these cases, the use of diagnostic auxiliary equipment, namely resistance drilling, is necessary. This allows for a better foundation for intervention proposals. The assessment of the dimensions of deteriorations and cavities enables a proper understanding of their severity. The severity of the lesion (L) is a function of the stem perimeter (PL) at a given height of L (hL), where L represents the center of the lesion, i.e., the location of the highest risk of fracture due to cavity, canker, or codominant stem. The measurements consider the three Cartesian axes, X, Y, Z, as depicted in Figure 1.

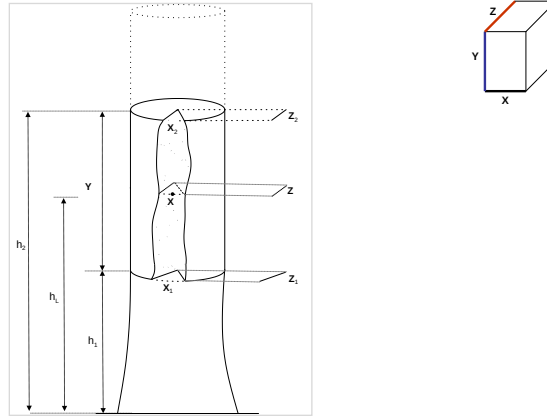


Figure 1— Schematic representation of the lesion dimensions: X = perimeter of the lesion (L) at a given height h; Z = radius of the lesion (L) at a given height h; Y = vertical dimension of the lesion ($Y = h_2 - h_1$)

Data Analysis and Results

The Site 1 is an important access route to the city of Aveiro, with a high volume of automobile traffic. It is also significant for pedestrian circulation, mainly due to the presence of two Secondary Schools, both located on the northeast side of the avenue. Additionally, the surrounding residential neighborhoods contribute to pedestrian movement. The effect of sun exposure has a significant impact on the condition of the trees in this alignment, where their decline is more noticeable.

The Site 2 is situated along one bank of the Lima River and serves as a vital recreational area in the city, frequently used for cultural events. This area is made up of 70 trees of the *Platanus x hispanica* species, installed in a park with good soil, constantly used.

In the predisposing factors (Manion, 1991), a significant number of *Populus alba* trees (Site 1) exhibited a weakened condition due to limited space for root development, compaction and impermeable pavement, improper pruning (induction factors), and poor adaptation to the site. Inadequate pruning practices, such as large cross-sectional removal, have contributed to the development of cankers and cavities of varying severity. These lesions, when combined with the presence of biotic agents, represent a serious risk to many of the trees evaluated. The species' inherent defense typology and the nature of interventions result in weak compartmentalization of wounds. Consequently, various opportunistic fungi have developed, leading to brown, white and wet rot of varying degrees of severity.

Regarding the DBH class, the tree population is relatively uniform and predominantly consists of mature trees. This uniformity underscores a lack of regeneration, indicating that trees removed due to weakened conditions have not been adequately replaced.

The BA measurements indicate that the *Populus alba* trees have reached considerable sizes based on the cross-sectional areas of their stems. However, there is a disproportion concerning their height (H), which averages 18.3 meters. This indicates that their growth has been restricted due to inadequate interventions, which oppose their natural growth and development.

At Site 1, out of 70 trees, 19 fall into the high-risk category. Felling operations are prioritized for 9 of these trees due to their extremely fragile state and the associated risks. The intervention plan also includes the replacement of one dead tree and another that is decrepit. Furthermore, 10 trees are classified as moderate priorities for replacement owing to risks of stem and branch fractures. However, these trees can be maintained for a longer period through measures such as crown volume reduction, cleaning, cavity treatment, and branch anchoring.

At Site 2, out of 70 trees, 4 fall into the high-risk category because of their height and phytosanitary condition. Adequate pruning is emphasized as critical, especially for those specimens with a significant number of heavy branches, with particular attention to the taller ones. Additionally, phytosanitary treatments are necessary, including cleaning and drainage of cavities, to prevent the degeneration of woody tissues and curb the progression of biotic agents.

Despite their condition, it is considered that *Populus alba* and *Platanus x hispanica* trees play a relevant ecological and environmental role. Mature trees, with their larger canopies, offer several ecological advantages such as enhanced carbon sequestration, improved air quality, increased shade and temperature regulation, and better habitat for wildlife (Gao, 2020). Moreover, the urban forest contributes to the overall aesthetics and sense of well-being in urban environments, providing a more pleasant and livable space for the community. Considering the importance of these ecological and aesthetic benefits, it becomes necessary to carefully manage the pruning practices to maintain a balance between their health, natural growth, and their role in enhancing the urban environment. In this context, a recovery strategy is an important tool to lead to a less inequitable distribution (Kaur et. al. 2022).

For this reason, at Site 1, the risk assessment indicates that requalification should be implemented gradually, involving the replacement of tree and shrub species better adapted to local climate conditions. It is crucial to emphasize the need to reassess the trees during the next vegetative rest period to determine the most appropriate actions. Given the combination of evident pathologies, advanced age, and frequent target location, effective monitoring of the risk condition is necessary. The decline in tree health was clearly demonstrated in the study through dendrometric measurements, lesion assessments, identification of biotic agents, and evaluation of wood condition using drilling resistance equipment.

To ensure the continued health and resilience of the urban tree population, it is essential to implement proper tree management practices, including tree planting and maintenance programs, to promote the establishment and growth of young trees and maintain the overall balance of the tree population in the area.

The study highlights several constraints affecting the reconversion of the study area. At Site 1, the selection of tree specimens was not ideal, considering their riparian nature and susceptibility to dry summer conditions. Despite their rapid growth, these trees reach maturity relatively quickly (within 40-50 years) and subsequently lose resilience, rendering them more vulnerable to biotic and abiotic stressors. The limited space available for the trees, confined to narrow wells surrounded by impermeable pavement, severely restricts gas exchange, water infiltration, and nutrient uptake (Botes and Zanni, 2021). This leads to the development of shallow roots that not only deform sidewalks but also encroach on neighboring green spaces where some soil is available.

In addition to the unfavorable soil and climate conditions, the trees were subjected to interventions involving the removal of large branches at the base. The development of wood decay, cankers, and cavities serves as just one example of how improper pruning practices can contribute to the deterioration of urban green infrastructure.

In this study, it is proposed that the trees be aligned in a green strip, utilizing shrubs adapted to the summer dryness. This model better meets the needs of the trees and companion plants compared to the traditional 1 m³ planting pit (Jim, 1998), which hinders the proper development of the trees and their optimal environmental contributions.

The planning process should consider the necessary volume and quality of soil, as these premises are vital for achieving all the expected environmental benefits of the green infrastructure of the avenue. The distribution of green infrastructure within cities today is unequal (Schneider et. al. 2024). The proposed model is based on the simple concept of a green strip and aims to minimize this inequality (Figure 2). In order to improve the conditions for trees and enhance the urban greenery, it will be crucial to consider more suitable tree species for the area, provide larger and more conducive planting spaces, and implement proper tree maintenance practices.

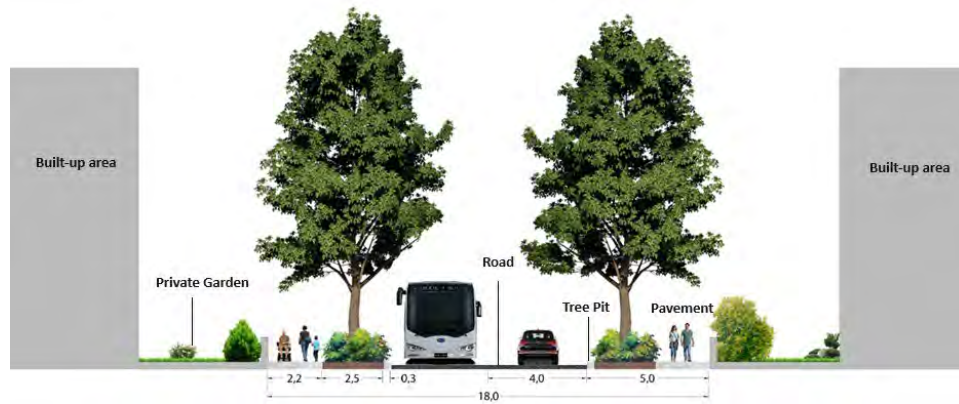


Figure 2— Green Strip Model for Site 1.

The green strip improves visual, physical, and psychological comfort for pedestrians. It also allows for the maintenance of a high-quality green infrastructure in alignment, with consequent environmental advantages and contributions to greater biodiversity (Phillips and Atchison, 2020).

The model can easily incorporate shrubs that assist in retaining pollutant particles, reducing noise, renewing nutrients, and retaining water in the soil. In this regard, Mediterranean flora includes many plants that require little water and provide diverse flowering throughout the seasons of the year. (*Lavandula* spp., *Rosmarinus officinalis*, *Erica* spp., *Juniperus horizontalis*, *Crataegus monogyna*, *Ruscus aculeatus*). For the tree layer at Site 1, selecting plants that are both drought-resistant and visually striking in alignment is crucial. The sweetgum tree (*Liquidambar styraciflua*) appears well-suited for the location and is a favorable choice for gradually replacing the white poplar (*Populus Alba*).

It has a relatively columnar, almost pyramidal shape and presents intriguing color variations in the fall. While it grows slower and is more tolerant to pruning, in locations where enhanced visibility is necessary, such as near pedestrian crossings, smaller-sized species like the Judas tree (*Cercis siliquastrum*) or cherry plum (*Prunus cerasifera*) could be considered.

Providing about 4 m³ of permeable soil per tree represents a compromise solution to contribute to a high-quality environmental avenue. Thus, effective investment in soil preparation is essential, focusing on its fertility to apply suitable organic and mineral amendments. On the other hand, correcting the soil to ensure a good structure can promote the development of more vertical roots, thereby addressing the most limiting factor, which is naturally the available area.

The installation of riprap systems with soil interstices is a viable solution. The placement of modular structures has the advantage of being able to accommodate technical infrastructures, incorporate irrigation systems, aeration, nutrient renewal, and allow for adjusting the soil volume needs to the requirements of the species (Figure 3).



Figure 3— Installation of trees in alignment on impermeable pavement

After implementing appropriate interventions, the percentage of weak specimens decreased from 74.3% to 8.3%. The proportion of trees in an overall reasonable condition increased from 21.4% to 40.0%, while those in good condition improved significantly from 1.4% to 51.7%.

Conclusions

Innovative and sustainable concepts should be embraced to create a thriving and resilient urban forest environment along Site 1 and Site 2. Thus, two different types of greening measures were analyzed, and risk assessment attributes were examined, providing preliminary information on complementarity and substitution. The study suggests a third alternative for the trees, beyond just removal or unsafe maintenance, namely, an attempt at recovery. The proposed model (Site 1) adheres to the philosophy of gradually transforming the environment, incorporating plants of varying ages and developmental patterns. The Three Underlying Principles in Tree Risk Evaluation encompass the following points:

Sustainable Urban Planning: Developing plans that balance vehicular traffic and pedestrian needs, enhancing pedestrian and cycling infrastructure, and integrating public transportation more effectively.

Replanting Suitable Trees: Choosing species that are well-adapted to local conditions, prioritizing native species to ensure better survival and integration into the ecosystem.

Arbor Care Maintenance: Establishing a maintenance program that includes proper pruning, irrigation, and fertilization, and employing professional arborists to maintain tree health.

Increasing Tree Wells: Expanding the space around trees to facilitate better root development, which helps trees access necessary nutrients and water, thereby enhancing their stability and health.

Community Awareness: Raising community involvement and awareness about the significance of urban trees and the need for their preservation.

Traffic Control Measures: Implementing traffic management strategies to reduce vehicle speeds and emissions, creating a healthier environment for both pedestrians and urban greenery.

Continuous Monitoring: Setting up a system to monitor the health of the trees and the effectiveness of implemented strategies, allowing for ongoing adjustments and improvements.

References

- Badura, T.; Lorencová, E. K.; Ferrini, S.; Vačkářová, D. 2021. Public support for urban climate adaptation policy through nature-based solutions in Prague. *Landscape and Urban Planning*, 215, 104215.
- Balázs, M.; Divos, F. 2015. Glue laminated timber structure evaluation by acoustic tomography. General Technical Report FPL-GTR-239. In *Proceedings of the 19th International Nondestructive Testing and Evaluation of Wood Symposium*, Rio de Janeiro, Brazil; pp. 462–466.
- Botes, C. M.; Zanni, A. M. 2021. Trees, ground vegetation, sidewalks, cycleways: users' preferences and economic values for different elements of an urban street—a case study in Taipei. *Environmental Economics and Policy Studies*, 23, 145–171.
- Dandy, N. 2010. The Social and Cultural Values, and Governance, of Street Trees. *Climate Change & Street Trees Project: Social Research Report*; Forestry Commission: Surrey, UK; Volume 39.
- Galenieks, A. 2017. Importance of urban street tree policies: A Comparison of neighbouring Southern California cities. *Urban Forestry & Urban Greening*, 22, 105–110.
- Gao, T.; Liu, F.; Wang, Y.; Mu, S.; Qiu, L. 2020. Reduction of atmospheric suspended particulate matter concentration and influencing factors of green space in urban forest park. *Forests*, 11(9), 950.
- Gilbert, E.A.; Smiley, T. 2004. Picus Sonic tomography for the quantification of decay in white oak (*Quercus alba*) and hickory (*Carya sp.*). *J. Arboric.*, 30, 277–281.

- Givoni, B. 1991. Performance and applicability of passive and low-energy cooling systems. *Energy Build*, 17, 177–199.
- Gonçalves, R.; Linhares, C.; Yojo, T. 2020. Drag coefficient in urban trees. *Trees*, 1-13. DOI :10.1007/s00468-019-01951-1.
- Jim, C. Y. 1998. Urban soil characteristics and limitations for landscape planting in Hong Kong. *Landscape and urban planning*, 40(4), 235-249.
- Kaur, N.; Kaur, M.; Padhi, S. S.; Singh, K. K. 2022. Geospatial analysis of the distribution of urban green spaces: a study of four Indian cities. *Cities & Health*, 6(3), 443-459.
- Linhares, C.; Trinca, A.; Gonçalves, R. 2013. Ultrasonic Tomography in Knots Detection. In *Proceedings of the 18th International Nondestructive Testing and Evaluation of Wood*, Madison, WI, USA; Forest Products Society, p. 664.
- Linhares, C.; Gonçalves, R.; Yojo, T. 2019. Simplified Methodology for the Inference of Drag Coefficient Applied in Species of Tropical Zone. In *Proceedings of the 21st International Nondestructive Testing and Evaluation of Wood*, Freiburg, Germany; Forest Products Society, Forest Research Institute Baden-Württemberg, p. 657.
- Linhares, C.; Gonçalves R., Martins, L. M.; Knapic, S. 2021. Structural stability of urban trees using visual and instrumental techniques: A review. *Forests*, 12(12), 1752.
- Linhares, C.; Gonçalves, R., Dias, A.; Knapic, S.; Martins, L. M. 2023. Assessment of Summer Branch Drop: A Case Study in Four Portuguese Cities. *Forests*, 14(7), 1398.
- Manion, P. D. 1991. Tree Disease Concepts. In *Mycologia* (Vol. 83, Issue 5). Prentice-Hall, Inc. <https://doi.org/10.2307/3760234>
- Martins, L. M. 2015. New challenges in urban forest. Università degli Studi di Firenze; Conference in ERASMUS Program.
- Martins, L.M.; Macedo, F.; Saraiva, S. 2017 .Avaliação da condição das árvores dos parques do porto com apoio da aplicação idtree em appsheet®. In: 2º Simpósio SCAP de Proteção das Plantas. Santarém, 26 e 27 de outubro. (In Portuguese)
- Mattheck, C.; Breloer, H. 1994. Field guide for visual tree assessment (VTA). *Arboricultural Journal* 18(1):1–23.
- Molla, M. 2015. The value of urban green infrastructure and its environmental response in urban ecosystem: A literature review. *Int. J. Environ. Sci.*, 4, 89–101.
- Phillips, C.; Atchison, J. 2020. Seeing the trees for the (urban) forest: more-than-human geographies and urban greening. *Australian geographer*, 51(2), 155-168.
- Rivero, R. 1986. *Arquitetura e Clima: Acondicionamento Térmico Natural*; D. C. Luzzatto Editores: Porto Alegre, Brazil, 1986.
- Schneider, A.; Neuhuber, T.; Zawadzki, W. 2024. Understanding citizens' willingness to contribute to urban greening programs. *Urban Forestry & Urban Greening*, 128293.
- Socco, L.V.; Sambuelli, L.; Martinis, R.; Comino, E.; Nicolotti, G. 2004. Feasibility of ultrasonic tomography for nondestructive testing of decay on living trees. *Res. Nondestruct. Eval.*, 15, 31–54.

Impulse Tomography as a Non-Destructive Methodology for Assessing the Health of Trees of the Species *Populus nigra* L. on the Banks of an Urban River

Alexsandro Bayestorff da Cunha

Department of Forestry Engineering, Santa Catarina State University, Lages, Santa Catarina, Brazil,
alexsandro.cunha@udesc.br

Amanda Krüger

Department of Forestry Engineering, Santa Catarina State University, Lages, Santa Catarina, Brazil,
amandakruger26@gmail.com

Tarcisio Francisco de Camargo

Department of Forestry Engineering, Santa Catarina State University, Lages, Santa Catarina, Brazil,
tarcisiofcamargo@gmail.com

Camila Alves Corrêa

Department of Forestry Engineering, Santa Catarina State University, Lages, Santa Catarina, Brazil,
tarcisiofcamargo@gmail.com

Abstract

The present study aimed to evaluate the health of trees of the species *Populus nigra* L, along an urban river in the city of Lages, Santa Catarina. 219 trees were evaluated, from which dendrometric data and frequency distribution were obtained. With the application of tomography, tomographic images were generated that helped to assess the risk of falling. Correlation analysis and scatter plots were also prepared between the percentage of the injured area of the trees and the dendrometric data. As results, averages were identified for diameter at breast height, total height, height of the first branch and slope of 52.8 cm, 8.0 m, 3.0 m and 24.5%, respectively. Of the trees evaluated, 9.13% presented a low risk of falling, 24.2% medium, 19.2% high and 47.5% severe. An inverse correlation was observed between the percentage of the injured area and diameter, while the correlation was positive with height and slope.

Keywords: Risk of falling trees, Tomographic image, Dendrometric variables.

Introduction

The increase in urban populations is a notable fact, especially in recent decades, caused by several factors, such as improved quality of life, professional opportunities and facilities in general. A consequence of this fact is the abandonment of natural landscapes, generating a need to introduce factors into the urban environment that reflect the benefits generated by rural areas.

Therefore, the introduction of arboreal individuals into urban environments is a widely used practice. Afforestation is a determining factor in environmental health, as it has a direct influence on human well-being, due to the multiple benefits it provides to the environment, in addition to contributing to climate stabilization, it beautifies the varied colors it displays, provides shelter and food for fauna and provides shade and leisure in squares, parks and gardens, streets and avenues (Dantas and Souza, 2004).

The species chosen to fulfill the role of afforestation in the urban environment must have characteristics appropriate for this function. According to Ribeiro (2009), the planting of trees unsuitable for the urban structure generates conflicts with urban equipment, electrical wiring, plumbing, gutters, sidewalks, walls and lighting posts. Therefore, the behavior of the species targeted for use must be evaluated from the beginning of implementation, as they develop, as well as when they reach an advanced stage of development. Several species are used for afforestation purposes, such as *Populus nigra* L., which is recommended for planting in riparian forests, as it is tolerant to saturated soils (Lorenzi et al., 2003). It is an arboreal and pioneer species, geographically widespread, as in large parts of Europe and Asia (Arens et al., 2002).

P. nigra has a high number of individuals on the banks of the main river in the city of Lages, Santa Catarina. The health of the trees located on the banks of the aforementioned river must be assessed based on the fact that there is a large flow of cars and pedestrians nearby, as well as buildings and commercial points. Furthermore, although the species is considered tolerant to riparian environments, there are frequent floods and floods in the watercourse in which the trees are located, which can compromise their health over time.

One of the widely used analysis methods is the forest inventory, where quantitative and qualitative characteristics are collected to define the best form of management. Such a survey is fundamental for planning and managing afforestation, providing information on the need for pruning, phytosanitary treatments, removal and planting, as well as for defining intervention priorities (Melo et al., 2007). The impulse tomograph is a widespread non-destructive method for analyzing the trees that make up urban afforestation. Tomography allows the reconstruction of entire cross-sections of the tree, using information provided by the passage of energy through the wood (Pereira et al., 2007). Impulse tomography, in turn, is based on the principle of timing mechanical waves to reconstruct tree sections (Rinntech, 2005).

In this sense, the objective of the present study was to evaluate the health of trees of the species *P. nigra*, located on the banks of the Carahá river in the city of Lages, Santa Catarina, using the impulse tomograph as an evaluation tool.

Material and Methods

The analysis of *P. nigra* trees was carried out on the banks of the Carahá River, in the city of Lages, Santa Catarina, which is located on the southern plateau of Santa Catarina. The characterization of the trees was carried out on Avenida Belizário Ramos, between the intersections with Rua Frei Gabriel and Rua Papa João XXIII. In total, 219 individuals were evaluated by collecting information on circumference at chest height, total height, height of the first bifurcation and slope.

To assess the health of the trees, the Rinntech Arbotom impulse tomograph was used. With the aid of a measuring tape, 0.30 m was measured from the ground. At this point, magnetic north was obtained with a

compass; At this point, the first CT scanner sensor was placed. Along the circumference of the tree, the other sensors were placed clockwise and equidistant.

Subsequently, information regarding the number of sensors, test height, total circumference and position of each sensor in the tree was filled in in the ARBOTOM software. Then, testing of the software began. With the help of a hammer, a mechanical wave was generated, which traveled through the wood, being captured by the other sensors. Five hammer blows were made on each sensor, always ensuring the same intensity. Finally, in the 2D tab, the wave propagation velocity graph was presented, that is, the tomographic image for analysis.

When interpreting the tomographic images, separation was carried out into three classes: bad (red color), intermediate (yellow color) and good (green color). The class segmentation was carried out using the TNT mips software, in which the percentage of each class in relation to the total wood of the tree was determined. To classify trees in relation to the risk of falling, an adaptation of the methodology proposed by Bond and Tucker (2006) was used, which was reformulated by Rollo (2009), represented in Table 1

Table 1 — Criteria for classifying the determination of fall risk.

Fall risk	Percentage of injured area identified by supervised automatic classification
Low	Internal injuries covering up to 10% of the section area
Medium	Internal injuries covering 10 to 30% of the section area
high	Internal injuries covering 30 to 50% of the section area
Severe	Internal injuries covering up to 50% of the section area

For data analysis, frequency tables and graphs were created referring to the dendrometric variables. Regarding the risk of falling, tables were created containing the percentages corresponding to each class; With this, it was possible to carry out the classification according to the referenced values. The correlation between the dendrometric variables and the percentage considered bad of the injured area was carried out using the Statgraphics Plus 5.1 software. Finally, the Spearman correlation was determined to characterize the data.

Results

Dendrometric characteristics of trees

The dendrometric characteristics of the trees analyzed along the river are presented in Table 2, where average values of diameter at breast height, total height, height of the first branch and slope of 52.8 cm, 8.0 m, 3.0 m and 24.5% respectively. High coefficient of variation values are also evident, which demonstrates a high variability of the data, especially with regard to the height of the first branch and slope. In the study by Amico et al. (2010) for the species *P. nigra* in a linear plantation, an average DBH of 56.7 cm was found, a value similar to that found in the present study, which was 52.8 cm. As for Reis et al. (2009), in which the study was carried out in the same location, for the species *P. nigra*, the average for DBH was 44.9 cm, a value lower than the average found.

Table 2 — Dendrometric characteristics of *Populus nigra* L trees

Dendrometric variable	Average	CV (%)	Minimum	Maximum
DBH (cm)	52,8	23,27	21,3	102,2
Total height (m)	8,0	28,13	4,7	19,1
Height of first branch (m)	3,0	99,97	1,0	13,3
Slope (%)	24,5	64,24	5,0	77,6

The dendrometric characteristics of the trees analyzed along the river are presented in Table 2, where average values of diameter at breast height, total height, height of the first branch and slope of 52.8 cm, 8.0 m, 3.0 m and 24.5% respectively. High coefficient of variation values are also evident, which demonstrates a high variability of the data, especially with regard to the height of the first branch and slope. In the study by Amico et al. (2010) for the species *P. nigra* in a linear plantation, an average DBH of 56.7 cm was found, a value similar to that found in the present study, which was 52.8 cm. As for Reis et al. (2009), in which the study was carried out in the same location, for the species *P. nigra*, the average for DBH was 44.9 cm, a value lower than the average found.

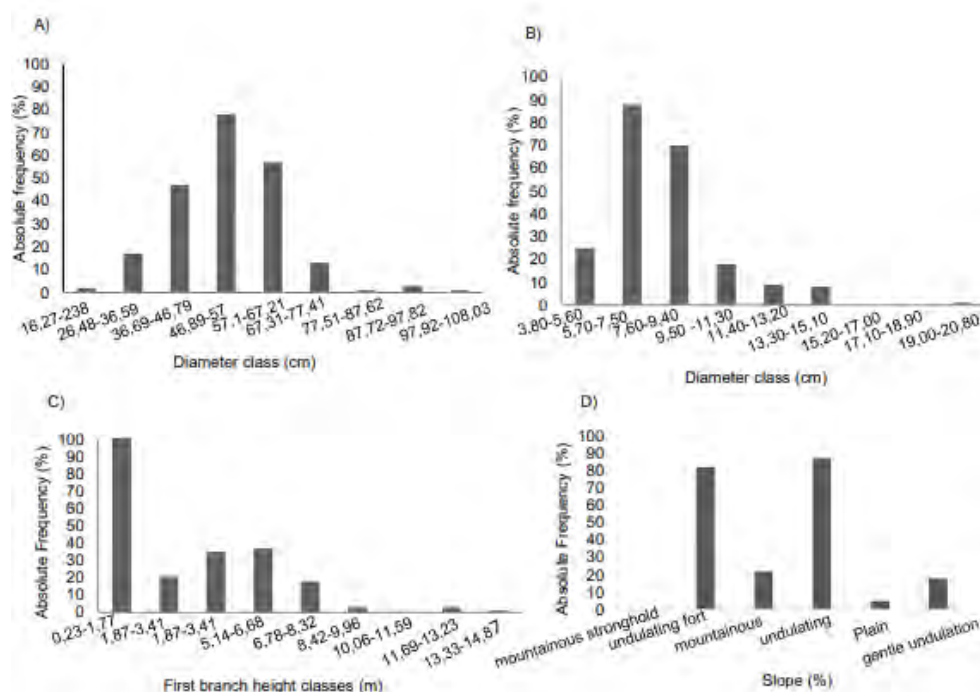


Figure 1 — Frequency distribution of dendrometric variables: A) Diameter at breast height (cm); B) Total height (m); C) Height of the first branch (m); D) Slope (%).

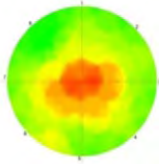
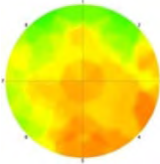
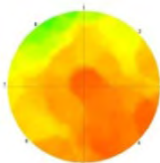
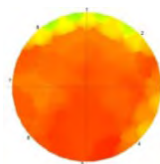
In relation to the height of the first branch, there is a significantly large number of individuals in the smallest class, emphasizing that there is no disparity between the trees, that is, the characteristics evaluated do not vary considerably between individuals. In the study by Reis et al. (2009), already mentioned previously, an average height of the first branch was found to be 1.7 m, a value much lower than that found, which was 3 m. This fact can be explained by the large time interval in which the data were collected. According to Santos et al. (2013) the height of the first branch indicates the interference of trees with pedestrian and/or vehicle traffic, the authors emphasize that, to avoid interference, it is recommended that this height be above 2.0 m. Therefore, the average found (3m) is in accordance with the height of the first branch indicated for urban afforestation. With regard to slope, according to the

Embrapa classification (1999), the highest frequency was concentrated in the strong-mountainous and undulating relief classes, indicating that the majority of trees were located on greater slopes.

Tomographic Assessment

From the analysis with the impulse tomograph, results were obtained regarding the damaged areas of the tree wood (Table 3).

Table 3 — Classification in relation to the risk of falling

Tomographic Imaging	Number of Trees	Injured Area	Injured Area Percentage	Fall Risk
	20	Bad Intermediary Good	0- 9,61 6,12 - 85,68 8,45 - 93,88	Low (up to 10%)
	53	Bad Intermediary Good	10,03 - 29,93 28,87 - 78,47 4,95 - 59,72	Medium (10%- 30%)
	42	Bad Intermediary Good	30,14 - 48,47 29,88 - 62,78 4,47 - 32,35	High (30%- 50%)
	104	Bad Intermediary Good	50,83 - 92,05 6,46 - 43,08 1,16 - 13,74	Severe (greater than 50%)

Among the 219 trees evaluated, according to the fall risk classification, 104 trees correspond to the severe fall risk class, reaching almost 50% of the total number of individuals. On the other hand, in the low fall risk class, the smallest number of trees fall, just 20 trees, which corresponds to around 10% of the total. In the medium and high fall risk classes, 53 and 42 trees were identified respectively.

The most representative tomographic images of each class were selected (Table 3). From them it is possible to visualize how much the 3 classes of the injured area represent in the total wood. In the study by Amodei et al. (2010), in which the quality of *Tectona grandis* wood was evaluated by impulse tomography, most of the images showed coloring in the central part of the wood, indicating low values of wave speed, a fact also seen in the images in Table 3. In the center region of the trees, the colors represent an area with lower density and more susceptible to deterioration.

Characteristics X Tomographic Assessment

In the Spearman correlation analysis between the injured percentage of tree wood and the dendrometric variables (Table 4), it is observed that there is a correlation between the injured area and the DBH, height and slope, that is, not only with the height from the first branch, in which the P value was greater than 0.05. Despite there being a correlation between the variables mentioned, the R^2 values found were low, in which the highest R^2 value is the correlation between the injured area and the DBH, in which the negative sign indicates an inverse correlation, that is, the As DBH increases, the % of injured area decreases.

Table 4 — Correlation between the % injured and the dendrometric variables

		DBH (cm)	h (m)	h1(m)	Slope (%)
% Injured Area	R^2	-0,2275	0,1492	-0,0181	0,1762
	P-Value	0,0008	0,0276	0,7889	0,0093

Where: DBH: diameter at breast height, h: total height (m); h1: height of the first branch

Figure 2 shows the dispersion of individuals in relation to the dendrometric variables and the bad percentage of the injured area. In Figure 2A an inverse correlation is identified, in which the higher the DBH, the lower the percentage of area classified as poor. According to Rollo (2009), the mechanical wave has more route options as the diameter increases, as there is a greater possibility of the wave taking “shortcuts”, reaching other sensors faster. With this, the injured areas are minimized as the diameter increases.

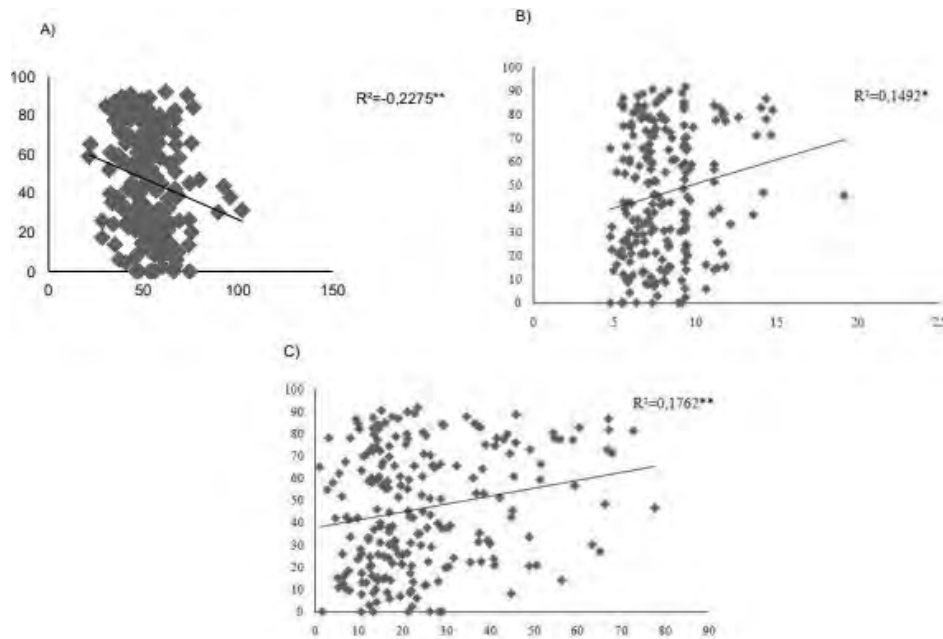


Figure 2 — Scatter plot between the % of damaged wood area and the dendrometric variables: A) DBH (cm); B) Height (m) and C) Slope (%). Where: * significant at 5% and ** significant at 1%.

The correlation in relation to height, represented in Figure 2B, shows a positive correlation, that is, the greater the height, the greater the percentage of the injured area. As with height, the correlation between the injured area and the slope is also directly proportional, indicating that the greater the slope, the larger

the injured area. Given this correlation (Figure 2C), it can be said that trees with greater slopes have a higher percentage of injured area, due to growth in adverse situations, causing lower wood quality.

Conclusion

Using impulse tomography, it was possible to determine the risk of falling trees, with 47.5% of the trees assessed presenting a severe risk of falling. For a better diagnosis of trees, along with impulse tomography, visual analysis is recommended, so that the two analyzes complement each other and present more reliable results. It was found that there is a correlation between the percentage of injured area and DBH (cm), height (m) and slope (%). In which the correlation with DBH (cm) is inverse, for two other variables the correlation is positive.

Acknowledgments

The authors would like to thank the State University of Santa Catarina (UDESC) and the Santa Catarina Research and Innovation Support Foundation (FAPESC).

References

- Amodei, J. B.; oliveira, B. R. U.; Gurgel. [and others] 2010. Avaliação preliminar da qualidade da madeira de *Tectona grandis* L. através da tomografia de impulso. *Floresta e Ambiente*, 17(2): 124-128.
- Amico, I; Bava, J; calderón, A, D. 2010. Índices de calidad de sitio de *Populus nigra* 'Italica' em plantaciones lineales em el noroeste de Chubut. *FcaUncuyo*, 42(1): 147-158.
- Arens, P.; Coops, H.; Jansen, J [and other].. 2002. Molecular genetic analysis of black poplar (*Populus nigra* L.) along Dutch rivers. *Molecular Ecology*. Dutch, fev. 2002.
- Dantas, I.C.; Souza, C. M. C. 2004. Arborização urbana na cidade de Campina Grande – PB: inventário e suas espécies. *Revista de Biologia e Ciências da Terra*, Campina Grande, 4 (1):1-18.
- EMBRAPA. 1999. Sistema brasileiro de classificação de solos. Rio de Janeiro: Embrapa Solos, 412p.
- IBGE – Instituto Brasileiro de Geografia e Estatística. Censo Demográfico 2010: Características urbanísticas do entorno dos domicílios. Rio de Janeiro, 2010.
- JUNTA DO SERVIÇO MILITAR DE LAGES. Condições climáticas e solos. Disponível em:><https://juntadoservicomilitardelages.webnode.com.br/lages><. Acesso em: 16 mai 2019.
- Lorenzi, H.; Souza, H. M.; Torres, M. A. V. [and other]. 2003. Árvores exóticas no Brasil: madeireiras, ornamentais e aromáticas. Nova Odessa: Instituto Plantarum, 368p.
- Melo, R.R.; Filho, J.A.; Rodolfo Júnior, F. 2007. Diagnóstico qualitativo e quantitativo da arborização urbana no bairro Bivar Olinto, Patos, Paraíba. *Revista da Sociedade Brasileira de Arborização Urbana*, 2 (1): .64-78.
- Moser, P.; Silva, A. C.; Higuchi, P. [and other]. 2017. Inventário da arborização e distribuição de praças-jardim em bairros centrais e periféricos de um município no sul do Brasil. *Espacios*, 38 (1):1-21.

RIBEIRO, F.A.B.S. 2009. Arborização urbana em Uberlândia: percepção da população. *Revista da Católica*, 1: 224-237.

RINNTECH. 2005. User Manual – Arbotom 3-D Tree Impulse Tomograph, version 1.59 for Microsoft Windows 98, 2000, XP. 42p.

Pereira, L. C.; Silva Filho, D. F. Tomazello Filho, M. [and others]. 2007. Tomografia de impulso para avaliação do interior do lenho de árvores. *Revista da Sociedade Brasileira de Arborização Urbana*, 2(2): 65-75.

Reis, C. A. M.; Silva, A. C.; Higuch, P. [and others]. 2009. Diagnóstico da vegetação arbórea e proposta de arborização do rio Carahá na cidade de Lages, SC. *Revsbau*, 3(4):130-142.

ROLLO, F.M.A. Identificação de padrão de resposta à tomografia de impulso em tipuanas (*Tipuanatipu* (Benth). O. Kuntze. 2009. 123p. Dissertação (Mestrado em ciências) – Escola Superior de Agricultura “Luiz de Queiroz”, Universidade São Paulo, Piracicaba.

ROLLO, L.C.P. Tomografia de impulso para estimativa da densidade da madeira. 2009.48p. Dissertação (Mestrado em ciências) – Escola Superior de Agricultura “Luiz de Queiroz”, Universidade São Paulo, Piracicaba.

SANTOS, E. M.; Silveira, B. D.; Souza, A. C. 2013. Análise quali-quantitativa da arborização urbana em Lages, SC. *Revista de Ciências Agroveterinárias*, Lages, 12 (1): 59-67.

Enhancing Urban Tree Risk Assessment through LiDAR and Machine Learning

Steffen Rust *

University of Applied Science and Art, Göttingen, Germany, steffen.rust@hawк.de

Bernhard Stoinski

Private Institute for General Dynamic Logic, Cologne, Germany, bernhard.stoinski@pifdl.eu

Abstract

Municipalities worldwide are recognizing the necessity of regular tree risk assessments to maintain safety. The lowest level of these assessments is often organized as drive-by or walk-by inspections of all trees in public spaces. They require substantial resources, often involving arborists in the inspection of numerous trees, many of which are in good condition, or too small or young to be of concern. Many cities have adopted Light Detection and Ranging (LiDAR) technology to scan trees for inventories. Our study builds on previous research that mathematically describes the structure of tree bark and explores the potential of machine learning algorithms to automatically detect cavities within LiDAR generated point clouds. The study demonstrates that this innovative approach can accurately detect even small cavities, measuring just a few centimeters. This technology has significant potential to transform urban tree risk assessment by automatically identifying trees at higher risk of failure. Arborists and tree assessors can allocate their resources more efficiently by accurately targeting trees that require in-person assessments. Focusing on trees that present complex assessment challenges or possess higher ecological value enables them to make the most of their time and expertise.

Keywords: urban forestry, tree risk assessment, invasive species monitoring, artificial intelligence, laser scanning

Introduction

Municipalities worldwide recognize the necessity of conducting regular tree risk assessments to ensure public safety (Klein et al. 2019). The most basic form of these assessments typically involves drive-by or walk-by inspections of all trees in public spaces (Dunster et al. 2013). These require substantial resources and often involve arborists inspecting numerous trees, many of which may be in good condition or too small or young to warrant concern.

Invasive species pose an increasing threat to urban forests, necessitating additional resources to monitor their potentially significant economic and ecological impacts (Fernandez et al. 2023; Gougherty 2023). Early detection is crucial for rapid response and local eradication efforts, which may include removing infested trees, implementing physical controls, or applying pesticide treatments, to prevent the establishment and spread of invasive insect populations in urban forests. Ground surveys, conducted by urban forestry professionals and pest management agencies, represent a common monitoring method. These surveys involve visual inspections, trapping, and sampling to detect the presence and assess the population levels of invasive insects.

Many cities have adopted Light Detection and Ranging (LiDAR) technology to scan trees for inventories. Our study expands on previous research that mathematically describes tree bark structure (Rust and Stoinski 2024) and explores the potential of machine learning algorithms to automatically detect cavities and exit holes made by invasive insects within LiDAR generated point clouds.

2 Material and Methods

Two experiments served to test whether cavities and exit holes can be detected in LiDAR point clouds:

- Cavity detection in a tree risk assessment project in Cologne, Germany
- Exit hole detection in an experimental forest near Braunschweig, Germany

2.1 Trees

2.1.1 Cologne

In one of the largest outdoor swimming pools in the city of Cologne, the Stadion Bad, operated by KölnBäder GmbH, a tree assessment was carried out by a certified inspector in January 2024. During this inspection, 171 trees were examined for tree defects in addition to a general tree inspection. Prior to this, LiDAR data was generated from all trees on 03.12.2023 by the company ProGea 4D from Krakow. The inspector identified 15 defects on 10 trees. The smallest cavities were 6 cm wide and 5 cm high, respectively. The dimensions were determined using a folding rule.

2.1.2 Braunschweig

In an experimental forest close to Braunschweig, Germany, 100 holes were drilled 3cm deep into six trees with bark structure varying from smooth (*Fagus sylvatica* L.) to rough (*Quercus robur* L.). Holes were prepared in groups of five at stem heights of 0m, 2m, and 4-5m. The hole diameters were 10, 12, 15, 17, and 20mm.

2.2 Laser Scanning

A Faro Focus Premium on a tripod was used to scan trees in booth experiments. Data were further processed with Faro Scene and evaluated with Dylogos. The scanner was positioned roughly at eye level, the minimal distance to the trees was 5 m.

2.3 Cavity and Exit Hole Detection

In the following, the term “defect” will be used to describe cavities and cracks. This term is more comprehensive and is intended to represent disorders of the trunk surface structure. In the defect model presented by us, the surface is mapped using a grid that can react flexibly to changes. Each node corresponds to a point of the point cloud M and is represented as a vector. The concept of this method is based on the assumption that, in a non-distorted grid, all points have an equal distance to each other. The vector space, formed from the point cloud that encapsulates an image of all distortions, serves as a comparison basis for the defect model. This surface is henceforth referred to as the reference surface. The comparison surface can be envisaged as an idealized version or, mathematically speaking, the mean value of the surface - in this case, the bark surface. The multiparametric mean value is derived from various parameters that enable characterization of the structure, such as the bark ribs, with their orientation in space and size, and considers the ratio of the smooth to the rough surface (Rust and Stoinski 2024). In this model, defects are identified by their deviations from this reference surface. This methodology is suitable not only for larger defects, but also for determining the entry or exit holes of pests such as the Asian longhorn beetle *Anoplophora glabripennis* (ALB). To better comprehend this methodology, it is important to understand how a defect, for instance, a hole, is visualized by LiDAR in a point cloud. Holes, which do not have any value pairs in the area of the hole, are not existent in the data cloud and hence produce a singularity at this location. Mathematically speaking, they form an empty set. Every defect within the comparison surface is considered a subset D of the superset M , derived from the comparison surface.

Axiom 1: The point cloud M is well-ordered with $\gamma_x := p_{x_i} - p_x$ and $\gamma_x = \gamma_n = \text{const}$ or $\gamma_y := p_{y_i} - p_y$ and $\gamma_y = \gamma_n = \text{const}$ and the separation axiom T_2 (Von Querenburg 2001) applies to the point cloud M .

Axiom 2: If a Δy_p exists as the difference between the current data point p and the approximated point $p(y)$ of the reference surface and if it also applies to p that the deviation $\Delta y_p > \delta p(y)$ at the point is greater than the standard deviation at the approximated point, then a $p(y) \in D_i$ with $D \subset M$ exists.

Since all points of the set M are well-ordered and all points on the x-axis and y-axis have the same distance, gaps in the well-ordering in the x and y directions form defects. The set of all missing points that are substituted by the approximated points of the reference surface form a subset D of M . Any number of D can exist in M . The cardinality of D corresponds to the size of the perturbation or defect. This results in the following definition for a defect (Brieskorn 2019; Zeidler 2013).

Definition 1. A defect is understood to be all points $p \in D$ from axiom 2.

According to definition 1, a defect is independent of its size but dependent on a structural change $\frac{\partial}{\partial p}$ to the reference surface. The methodology presented by us can therefore be applied not only to defects such as drill holes or defects resulting from collision damage, but also to any changes in relation to a reference surface. Using a reference surface formed by a crown mantle, branch breakouts and crown defects can also be deduced. For this application, the surface characterization model (Rust and Stoinski 2024) must be extended from R^2 to R^3 (Elstrodt 2018).

3 Results

3.1 Cavity Detection, Cologne

The tree assessor mapped 15 cavities, which were also automatically identified within the point cloud data. The dimensions of the cavities ranged significantly, with the smallest being merely 5 cm in height and the largest extending up to 127 cm, as detailed in Table 1. These dimensions were initially obtained through manual measurements conducted by the inspector. Comparatively, the LiDAR-based measurements exhibited a fair degree of correlation with the manual measurements ($r = 0.56$, $p = 0.03$), as depicted in Figure 1. This suggests a moderate agreement between the two methods of measurement.

Table 1—Dimensions of cavities.

Species	Folding rule, cm		LiDAR, cm	
	Height	Width	Height	Width
Tilia cordata	16	28	15,8	26
Betula pendula	10	6	10,6	6,8
Tilia cordata	160	20	164,5	19,8
Tilia cordata	23	16	24,6	20
Tilia cordata	180	20	181	26,3
Salix alba	5	33	4,7	34,2
Salix alba	18	16	23,2	20,8
Salix alba	127	20	167	31,8
Fraxinus excelsior	17	3	16,8	28
Aesculus hippocastanum	48	32	46,6	32
Aesculus hippocastanum	26	16	21,2	17
Aesculus hippocastanum	60	5	58,2	4,7
Aesculus hippocastanum	24	18	83	31
Aesculus hippocastanum	44	44	41,7	42,7
Aesculus hippocastanum	10	1,5	12	4,5

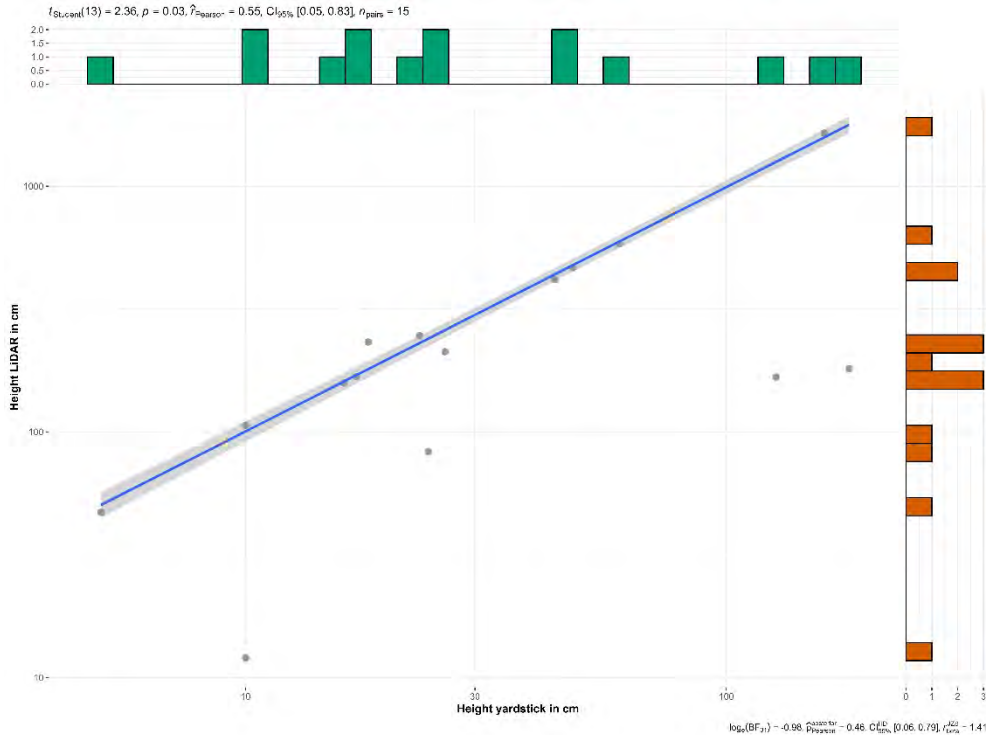


Figure 1— Cavity heights measured by either LiDAR or yardstick correlate significantly.

3.2 Exit Hole Detection, Braunschweig

All artificially created exit holes were automatically detected at the three different heights. The automatic detection was carried out from one scan for all heights per tree. The scanners were not modified for the different heights. For some holes, shadows were detected in the borehole. This phenomenon depends on the position of the scanner in relation to the borehole.

4 Discussion

Currently, tree inspections for risk assessment and invasive species monitoring rely heavily on human labor, involving time-consuming and labor-intensive surveys of the area of interest. This study explored the potential of leveraging automated LiDAR point cloud analysis via artificial intelligence to augment this process. By doing so, tree assessors could focus on complex, high-value trees and accelerate the detection of invasive species. Our research involved scanning urban trees with varying cavity sizes and forest trees with artificially created exit holes of different dimensions. The results demonstrated reliable and accurate detection of both cavities and exit holes.

The discrepancies observed between the traditional survey and LiDAR survey can be attributed to how extreme height and width values are determined. In a LiDAR measurement, these extremes are derived globally, while in manual measurements, they might only represent local extremes. This discrepancy stems from the challenge of accurately assessing maximum values on complex surfaces, such as defects.

For instance, in our experiment conducted in Cologne, if global and local extremes differ, they represent mathematically and topologically distinct surfaces. Consequently, not all points of the LiDAR area have a

corresponding representation in the manually measured area. As a result, statistical evaluations, in this context, should be viewed as comparisons rather than definitive equivalences.

Certain types of defects, such as woodpecker holes, are comparable in this sense. For these instances, the traditional tape rule measurement may need to be supplanted with more precise tools like a caliper gauge. Unfortunately, due to the specific distribution of tree species at our test site, direct comparisons of defect measurements were not feasible on trees with both smooth and rough bark. Future studies should take these considerations into account to further improve the accuracy and applicability of the measurements.

The challenge encountered in Braunschweig presented a unique problem. Unlike the issue of measuring a defect, the focus here was on identifying the number of boreholes, intended to replicate the exit holes of the Asian Longhorned Beetle (ALB), at varying heights. The diameter of these boreholes was pre-determined by the drill bit used, ranging from 10 to 20 mm. Our recent field test demonstrated the capability to detect boreholes across all specified diameters, with a 100% detection rate within the test parameters. However, this measurement served as a preliminary test, highlighting the necessity for subsequent tests to evaluate the impact of various weather and environmental conditions, including changes in weather, the boreholes' exposure to weathering, and potential fraying of the boreholes' edges.

To the best of our knowledge, this is the first instance of utilizing this technology in urban forestry for this purpose. Future studies are necessary to evaluate the accuracy of cavity depth measurement and natural insect exit hole detection.

References

- Brieskorn, Egbert. 2019. *Lineare Algebra Und Analytische Geometrie III*. Vol. III. Wiesbaden: Springer Spektrum.
- Dunster, J. A., E. T. Smiley, N. Matheny, and S. Lilly. 2013. *Tree Risk Assessment Manual*. Champaign, Illinois: International Society of Arboriculture.
- Elstrodt, Jürgen. 2018. *Maß- und Integrationstheorie*. Achte, Erweiterte und aktualisierte Auflage. Lehrbuch. Berlin [Heidelberg]: Springer Spektrum.
- Fernandez, Romina D., Phillip J. Haubrock, Ross N. Cuthbert, Gustavo Heringer, Melina Kourantidou, Emma J. Hudgins, Elena Angulo, Christophe A. Diagne, Franck Courchamp, and Martin A. Nuñez. 2023. "Underexplored and Growing Economic Costs of Invasive Alien Trees." *Scientific Reports* 13 (1): 8945.
- Gougherty, Andrew V. 2023. "Emerging Tree Diseases Are Accumulating Rapidly in the Native and Non-Native Ranges of Holarctic Trees." *NeoBiota* 87:143–60.
- Klein, Ryan, Andrew Koeser, Richard Hauer, Gail Hansen, and Francisco Escobedo. 2019. "Risk Assessment and Risk Perception of Trees: A Review of Literature Relating to Arboriculture and Urban Forestry." *Arboriculture & Urban Forestry* 45 (1): 26–38.
- Rust, Steffen, and Bernhard Stoinski. 2024. "Enhancing Tree Species Identification in Forestry and Urban Forests through Light Detection and Ranging Point Cloud Structural Features and Machine Learning." *Forests* 15 (1): 188.
- Von Querenburg, Boto. 2001. *Mengentheoretische Topologie*. Springer-Lehrbuch. Berlin, Heidelberg: Springer Berlin Heidelberg.
- Zeidler, Eberhard. 2013. *Springer-Handbuch Der Mathematik I-IV*. Wiesbaden: Springer Fachmedien.

Selection of Teak Logs Using Ultrasound Wave Propagation

Rafael Gustavo Mansini Lorensani

Valora Madeira, Campinas, Brazil, rafael@valoramadeira.com

Stella Stopa Assis Palma

Valora Madeira, Paulínia, Brazil. stella@valoramadeira.com

Raquel Gonçalves

Laboratory of Nondestructive Testing – LabEND, College of Agricultural Engineering – FEAGRI – UNICAMP, Campinas, São Paulo, Brazil, raquelg@unicamp.br

* Corresponding author

Abstract

The management of forest assets is not solely tied to volumetric gain or increased tree density. In companies producing timber for structural elements and furniture pieces, phytosanitary issues are also critical. Teak trees (*Tectona grandis*) are susceptible to attack by biodeteriorating agents, leading to economic losses for producers. This susceptibility results in wood being prone to rot, cavities, and color alterations. Beyond direct losses linked to wood quality, there's an additional loss associated with transporting material whose commercial value is compromised, as this biodeterioration isn't always visually detectable in the trunk. Consequently, logs lacking commercial value are transported, incurring additional transportation costs. Therefore, this research aimed to evaluate whether ultrasonic wave propagation testing could serve as a tool to pre-select logs in the forest, preventing the transportation of those unsuitable for commercial purposes to the sawmill and thus reducing transportation costs. For the study, 137 logs from 41 trees were assessed using ultrasonic wave propagation tests. These logs exhibited varying phytosanitary conditions, ranging from healthy to biodeteriorated due to fungal (*Ceratocystis fimbriata*) attacks. Post-ultrasonic testing, the logs were transported to the sawmill and processed into structural elements. These structural elements were visually evaluated according to the factory's standard criteria. Using this standardized visual classification alongside ultrasonic wave propagation velocity values, it was possible to associate velocity ranges with different phytosanitary conditions of the pieces. The velocity ranges of ultrasonic wave propagation proved suitable for pre-selecting teak logs before transportation, thereby qualifying the load and preventing costs associated with transporting logs unsuitable for commercial purposes.

Keywords: ultrasound, wood quality, knots.

Wood Density Estimation Independent of Moisture by NIR Spectroscopy

Fernanda Maria Guedes Ramalho *

Klabin S. A., Telêmaco Borba, Paraná, Brazil, fernanda.ramalho@klabin.com.br

Thifani Vitoria Hilario Francisco

Klabin S. A., Telêmaco Borba, Paraná, Brazil, thifani.francisco@klabin.com.br

Flaviana Reis Milagres

Klabin S. A., Telêmaco Borba, Paraná, Brazil, fmilagres@klabin.com.br

Silvana Meister Sommer

Klabin S. A., Telêmaco Borba, Paraná, Brazil, ssommer@klabin.com.br

Regiane Abjaud Estopa

Klabin S. A., Telêmaco Borba, Paraná, Brazil, restopa@klabin.com.br

Fabricio Antonio Biernaski

Klabin S. A., Telêmaco Borba, Paraná, Brazil, fbiernaski@klabin.com.br

* Corresponding author

Abstract

The assessment of wood quality with a focus on industrial processes and breeding programs is fundamental. For this, it is important to have fast and non-destructive techniques. Near infrared spectroscopy (NIRS) is a technique that has been studied in wood. The development of NIRS models promotes the ability to evaluate a greater number of individuals and an economical way when compared to traditional methods. The goal of this work was to develop multivariate models to estimate wood density based on the NIR spectral signature independent of moisture. The basic density model for the clones presented a maximum associated error in cross-validation (RMSEcv) of 32 kg/m³ and a minimum coefficient of determination (R²cv) of 0.81. The global model containing all clones presented a coefficient of determination of 0.80 and an error of 33 kg/m³. We can conclude that the NIRS models developed were robust and have potential for operational use.

Keywords: NIRS, wood quality, wood moisture, non-destructive methods

Introduction

The pulp industry seeks solutions for the rapid estimation of technological properties of the raw material to be processed, including wood density. Such information will serve as a basis for more rational and sustainable decision-making, promoting cost reduction and greater competitiveness for the company. This can lead to cost and waste reduction, as knowing the average wood density to be loaded into the digester can optimize the pulping process. Various solutions have been tested to continuously monitor the quality of wood arriving at the mill throughout the day. Additionally, knowledge of the basic density of wood allows for more precise selection in breeding programs. Furthermore, precise determination of basic density assists in strategic harvest planning and sustainable forest resource management, avoiding unnecessary depletion of forest areas. However, the analytical methods employed in the timber industry to

assess material quality are typically expensive, requiring sample preparation and wood drying. For these reasons, reliable, repeatable, and rapid methods can replace routine analyses, becoming an attractive and useful solution for quality control. Near-infrared spectroscopy (NIR), with the aid of chemometrics, shows potential for evaluating various organic materials, such as wood, pharmaceuticals, and petrochemicals (Tsuchikawa and Schwanninger, 2013).

The NIRS technique presents characteristics such as speed in analysis (one minute or less per sample), requires minimal sample preparation, is non-destructive, non-invasive, with high penetration of the emitted radiation, suitable for online use, and universally applicable to materials containing molecules with C-H, N-H, S-H, or O-H bonds (Pasquini, 2003). Due to all these advantages and the need for non-destructive sampling in breeding programs, this technique has been used for the characterization of future materials. In wood, many studies have shown that NIR spectroscopy can be applied to evaluate chemical, physical, mechanical, and anatomical properties (Tsuchikawa and Kobori, 2015).

There are reports in the literature of pioneering studies in the application of NIR spectroscopy for the prediction of properties important to the pulp and paper industry. Studies show that NIRS technology has been successfully used to estimate pulp kappa number (Birkett and Gambino, 1989); determine pulping yield in *Eucalyptus* and *Pinus* species (Wright et al., 1990; Michell, 1995) and for accurate estimation of some pulp properties, such as cellulose and , hemicellulose content, viscosity, brightness, and degree of polymerization (Schultz and Burns, 1990; Wright et al., 1990; Axrup et al., 2000; Fardim et al., 2002). There are reports in the literature of NIRS-based models with promising statistics in estimating wood quality related to chemical and physical properties, such as extractives and lignin content, and basic density (Hein, 2009; Milagres, 2009; Milagres, 2009; Estopa et al., 2017).

However, there are spectral interferences that require attention to ensure robust results. Sample moisture causes interference in wood NIR spectra. This interference can generate models with low predictive capacity for properties of unknown samples. Currently, it is necessary to control and correct the effects of moisture on samples using techniques such as drying. Therefore, the goal of this study was to develop multivariate models with a new approach capable of estimating wood basic density based on NIR spectral signature independent of moisture.

Material and Methods

Sampling material

A total of 2550 samples from 2 different clones of *Eucalyptus* species, aged 6 to 15 years, were used. The samples were collected along the entire commercial height of the tree in the form of logs in plantations located in the Paraná state. Then, specimens were extracted from the logs, exposing the transverse face. For sample extraction, regions from the pith to the bark without the presence of knots or any other defects were chosen.

Determination of basic density and moisture by conventional method

After preparation of the specimens, they underwent analysis for basic density and moisture content. The wood basic density was obtained using the hydrostatic balance method (ABNT, 2003), which is based on the displacement of water when the sample is immersed in it. Basic density is obtained by the relationship between the absolutely dry mass and the saturated volume of the sample. The moisture content of the samples was monitored from the initial determination until reaching the equilibrium moisture condition. For this, the mass loss was monitored daily until reaching a constant mass.

NIR spectra acquisition

The spectra of each specimen were acquired in the near-infrared using a Fourier-transform spectrometer and calibrated with the equipment's internal reference standards. Spectra collection occurred at each stage of moisture loss monitoring. For spectrum collection, the transverse face of each sample was positioned in the spectrophotometer's integrating sphere. Spectra acquisition was performed in the range of $4,000\text{ cm}^{-1}$ to $10,000\text{ cm}^{-1}$, with a spectral resolution of 16 cm^{-1} in diffuse reflection mode. Each spectrum represents the average of 32 scans.

Development of NIR-based models

The matrix containing the spectra at different drying stages and the reference values (basic density and moisture) of each specimen was developed. The matrix, composed of 2550 rows and 735 columns, underwent multivariate statistical analysis for the development of NIRS models capable of predicting wood basic density independent of moisture. Partial Least Squares Regression (PLS-R) was applied. PLS-R was used to establish the relationship between the information contained in the spectra and the wood characteristics for fitting predictive models.

For model adjustments, the absorbance values of the samples across the NIR spectral range were associated with values related to reference analyses for basic density (kg/m^3). Spectra without mathematical pre-treatment and treated by first derivative were used. The number of factors or latent variables used in each model was chosen by minimizing the root mean square error of validation and increasing the coefficient of determination. Global models were validated through random cross-validation using 20 segments.

The samples were also selected according to each clone (2) for the development of individual models. The models were evaluated using the coefficient of determination of cross-validation (R^2_{cv}) and the root mean square error for cross-validation (RMSE_{cv}). The closer the coefficient of determination is to 1 and the smaller the error, the more robust the model will be. Anomalous samples, when identified, were excluded from the matrix.

Results

NIR Spectra

An overview of the NIRS spectra collected from all specimens at different drying stages is presented in Figure 1. The NIRS technique is based on vibrational spectroscopy, which measures the interaction of light with the material under study (PASQUINI, 2003). The technique measures the interaction of radiation with the chemical bonds of the material used. The interaction will occur if there is resonance between the electric field generated by the oscillation of the chemical bond and the electromagnetic wave. The spectrometer emits radiation onto the sample, and the sensors capture variations in the molecular vibrations of the chemical constituents present in it. Such components will absorb, reflect, and transmit radiation that is incident upon them in a particular manner. In each wavelength range, some frequencies will be absorbed, others will not, while some will be partially absorbed. This complex figure of absorption intensity versus wavelength/wavenumber constitutes the absorption spectrum of a substance or sample (Pasquini, 2003). According to Pasquini (2003), the bonds that interact with radiation can be C-H, N-H, S-H, or O-H. The most prominent absorption bands in the spectra of the readings are between 7000 to 4200 cm^{-1} (Figure 1).

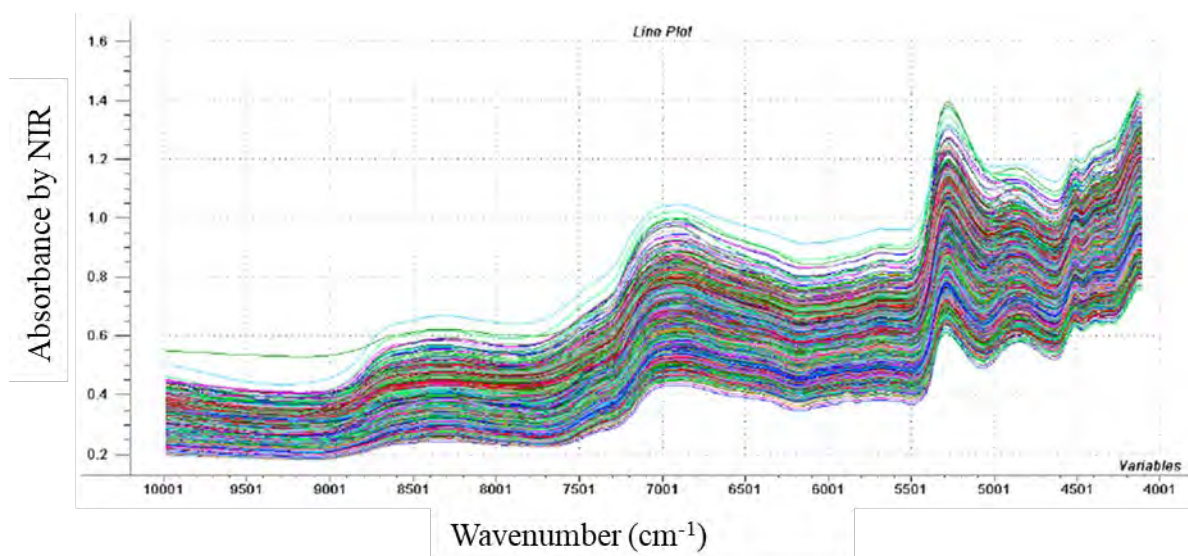


Figure 1— Untreated spectra recorded in *Eucalyptus* spp. specimens at different moisture contents.

NIR models for wood density

Models were developed through partial least squares regressions to estimate wood basic density. Spectra were treated by first derivative (second order, 13 points) with and without exclusion of anomalous samples, if identified. Random cross-validation using 20 segments was employed. All regressions were adjusted with 12 factors or latent variables (LV), but the number of eigenvectors for each model was determined by minimizing residual variance, as indicated in the table of statistics associated with the selected models (Table 1).

Table 1— Statistics associated with predictive models based on NIR spectra for basic density.

Validation	Model	N	LV	RMSEc	R ² c	RMSEcv	R ² cv
Cross-validation (random, 20 segments)	Clone 1	1544	12	31,23	0,82	32	0,81
	Clone 2	1006	12	27,57	0,85	28	0,83
	Global	2550	12	32,94	0,80	33	0,80

N: Number of samples; LV: Number of latent variables; RMSEc: Root mean square error of the calibration; R²c: Coefficient of determination of the calibration; RMSEcv: Root mean square error of the cross-validation standard error; R²cv: Coefficient of determination of the cross validation.

The matrix was divided into group based on the 2 clones, and models were developed for each one. Figures 2 and 3 present the dispersion of measured and estimated data for wood basic density from models developed for individual clones. The model for clone 1 showed a coefficient of determination for cross-validation (R²cv) of 0.81 and root mean square error (RMSEcv) of 32 kg/m³. For clone 2, it was possible to obtain models with R²cv of 0.83 and RMSEcv of 28. These models demonstrated robustness in relation to the associated statistics, especially for clone 2.

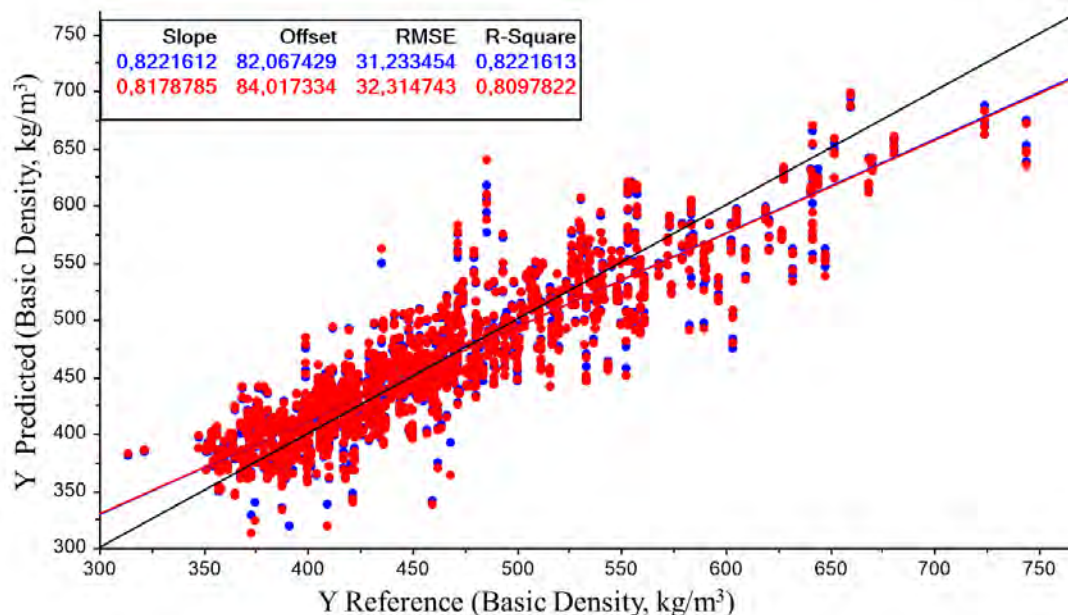


Figure 2— Statistics associated with the model for estimating wood density based on samples from clone 1.

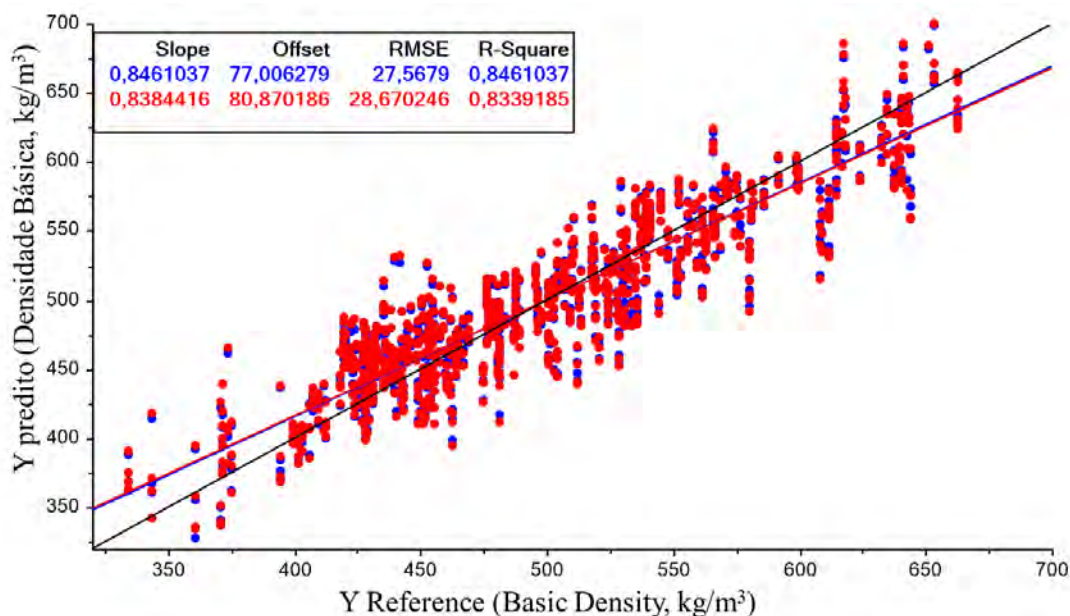


Figure 3— Statistics associated with the model for estimating wood density based on samples from clone 2.

For the adjustment of the global model using the entire database with the 2 clones, at different ages and moisture levels, cross-validation through random method, 12 principal components, and 20 segments were employed. In Figure 4, the relationship between reference values (X-axis) and values estimated by the model (Y-axis) for the global model was plotted. The coefficient of determination (R^2_{cv}) of the model using all samples was 0.80, and the root mean square error ($RMSE_{cv}$) was 33 kg/m^3 in cross-validation. The models developed by clone showed greater robustness than the global model developed with all

samples together. However, the global model has a greater ability to estimate the density of unknown samples. It can be used for characterizing wood of different ages, moisture levels, and genetic materials. The developed models present an innovative approach in which they can be applied to moist wood samples. It is not necessary to dry the specimens as commonly done.

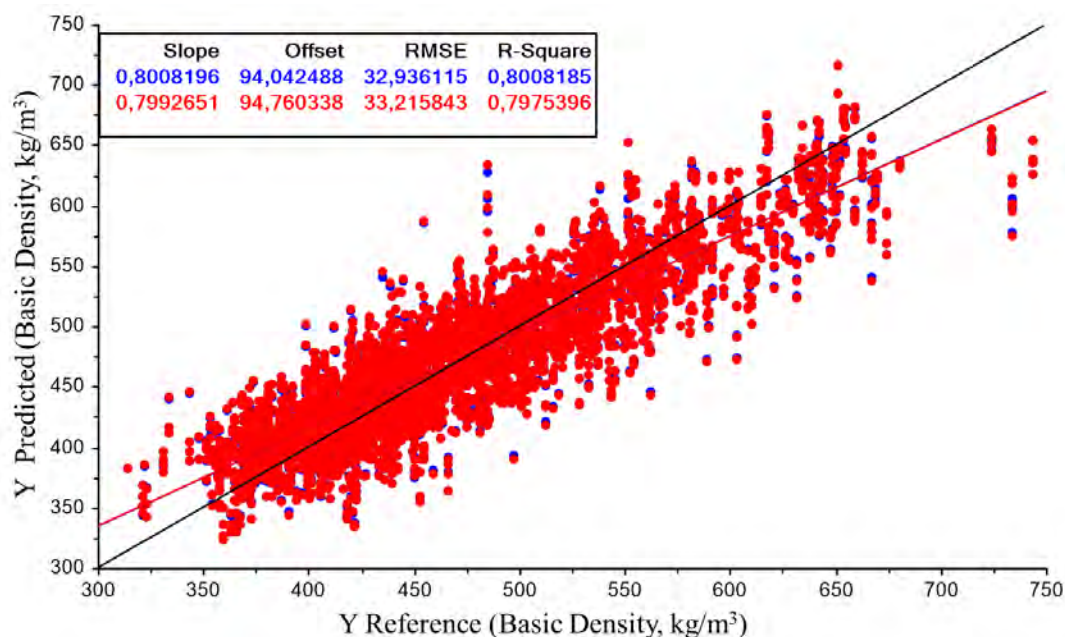


Figure 4— Statistics associated with the model for estimating wood density based on samples from all clones (global model).

Loureiro et al. (2022) developed NIRS models for estimating the density of *Eucalyptus urophylla* clones and found a maximum R^2_{cv} of 0.754 and minimum $RMSE_{cv}$ of 23 kg/m³ using dry samples. Amaral et al. (2021), when developing multivariate models for predicting the basic density of *Eucalyptus urophylla* x *Eucalyptus grandis* based on NIR spectra also measured on the transverse surface, obtained $R^2_{cv} = 0.85$ and $RMSE_{cv} = 25$ kg/m³. Arriel et al. (2019) developed multivariate models to predict the basic density of *Eucalyptus* spp. using the average density values of trees and NIR spectra measured at breast height as reference. The best result was observed in solid wood using the clone mean, which showed a coefficient of determination of cross-validation (R^2_{cv}) of 0.77 and RMSE of 15 kg/m³. When comparing the results found in this article with those in the literature, the models showed similar or superior robustness in terms of the coefficient of determination. Regarding the RMSE, the article showed a tendency toward higher values. It is important to highlight that this study has the differential of working with spectra collected from moist samples, whereas the cited articles were conducted with dry samples.

Predictive models have many industrial applications, as wood density provides valuable information about raw material characteristics. Wood density is related to various other important properties. The presented models are capable of estimating values that can be used to rank unknown materials and classify them in terms of quality based on spectra of wet woods. The ability to use NIR models on wet samples is especially important from an operational standpoint.

Conclusions

The multivariate models fitted to NIR spectra proved to be efficient in estimating the basic density of *Eucalyptus* spp. wood independent of moisture content. The developed global model, irrespective of

species and moisture content, demonstrated robustness in estimating the basic density of unknown wood samples. It can be used for characterizing wood of different ages, moisture levels, and genetic materials. Similarly, the models developed for individual species showed even better predictive capabilities independently and have potential for operational use. All models presented innovative approaches regarding the ability to estimate wood density without the need for sample drying for spectrum collection. This significantly contributes from an operational perspective.

Acknowledgments

Klabin S.A.

References

Amaral, E. A.; dos Santos, L. M.; Hein, P. R.; Costa, E. V.; Rosado, S. C. S.; Trugilho, P. F. 2021.

Evaluating basic density calibrations based on NIR spectra recorded on the three wood faces and subject to different mathematical treatments. *New Zealand Journal of Forestry Science*, 51.

Arriel, T. G.; Ramalho, F. M. G.; Lima, R. A. B.; Sousa, K. I. R. D.; Hein, P. R. G.; Trugilho, P. F. 2019. Developing near infrared spectroscopic models for predicting density of Eucalyptus wood based on indirect measurement. *Cerne*, 25: 294-300.

Associação Brasileira de Normas Técnicas. 2003. NBR 11941: Madeira – Determinação da Densidade Básica. Rio de Janeiro.

Axrup, L.; Markides, K.; Nilsson, T. 2000. Using mini-ture diode array NIR spectrometers for analyzing wood chips and bark samples in motion. *J. Chemom.* 14(5-6): 561-572.

Birkett, M.D.; Gambino, M.J.T. 1989. Estimation of pulp kappa number with near-infrared spectroscopy. *TAPPI Journal*, 72: 193– 197.

Estopa, R.A.; Milagres, F.R.; Oliveira, R.A.; Hein, P.R.G. 2017. NIR spectroscopic models for phenotyping wood traits in breeding programs of Eucalyptus benthamii. *Cerne*, 23: 367-375.

Fardim, P.; Ferreira, M. M.; Duran, N. (2002). Multivariate calibration for quantitative analysis of eucalypt kraft pulp by NIR spectrometry. *Journal of wood chemistry and technology*, 22(1): 67-81.

Hein P.R.G.; Lima J.T.; Chaix G. 2009. Robustness of models based on near infrared spectra to predict the basic density in Eucalyptus urophylla wood. *J Near Infrared Spec* 17: 141–150.

Loureiro, B. A.; Arriel, T. G.; Ramalho, F. M. G.; Hein, P. R. G.; Trugilho, P. F. 2022. NIR-based models for estimating selected physical and chemical wood properties from fast-growing plantations. *iForest-Biogeosciences and Forestry*, 15(5): 372.

Michell, A.J. 1995. Pulpwood quality estimation by near-infrared spectroscopic measurements on eucalypt woods. *Appita J.* 48(6):425-428.

Milagres, F.R. 2009. Avaliação da madeira de híbridos de Eucalyptus globulus com E. grandis e E. urophylla, para produção de celulose, utilizando espectroscopia NIR. Dissertação (Mestrado em Ciência Florestal) - Universidade Federal de Viçosa, MG.

- Pasquini, C. 2003. Near infrared spectroscopy: fundamentals, practical aspects and analytical applications. *Journal of the Brazilian Chemical Society*, v.14, n.2: 198-219.
- Schultz, T.P.; Burns, D.A. 1990. Rapid secondary analysis of lignocellulose: comparison of near infrared (NIR) and fourier transform infrared (FTIR). *Tappi J.* 73(5): 209-212.
- Tsuchikawa and Kobori. 2015. A review of recent application of near infrared spectroscopy to wood science and technology.
- Tsuchikawa and Schwanninger. 2013. A Review of Recent Near-Infrared Research for Wood and Paper (Part 2).
- Wright, J.A.; Birkett, M.D.; Gambino M.J.T. 1990. Prediction of pulp yield and cellulose content from wood samples using near infrared reflectance spectroscopy. *Tappi J.* 73(8):164- 166.

Early Detection of Compression Wood in *Pinus taeda* for the Selection of Standing Tree

Silvia Böthig *

Latitud Fundación LATU, Montevideo, Uruguay, sbothig@latitud.org.uy

Stephany Arrejuría

Latitud Fundación LATU, Montevideo, Uruguay, sarrejuria@latitud.org.uy

Andrés Baietto

Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay, abaietto@fagro.edu.uy

Fernando Bonfiglio

Latitud Fundación LATU, Montevideo, Uruguay, fbonfig@latitud.org.uy

Verónica Casaravilla

CENUR Noreste, Universidad de la República, Montevideo, Uruguay, casaravillav@gmail.com

Ana Paula Coelho-Duarte

Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay, paula.coelho@fagro.edu.uy

Noelia Franco

Latitud Fundación LATU, Montevideo, Uruguay, nfranco@latitud.org.uy

Raquel Gonçalves

FEAGRI, Campinas, SP, Brasil, raquelg@g.unicamp.br

Luciana Ingaramo

LUMIN, Rivera, Uruguay, luciana.ingaramo@lumin.com

Daniela Malates

FYMNSA, Rivera, Uruguay, dmalates@fymnsa.com.uy

Carlos Mantero

Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay, cmantero@fagro.edu.uy

Miguel Oñate

Agroempresa Forestal, Montevideo, Uruguay, monate@af.com.uy

Carla Padilla

FYMNSA, Rivera, Uruguay, cpadilla@fymnsa.com.uy

Diego Passarella

CENUR Noreste, Universidad de la República, Montevideo, Uruguay, diego.passarella@cut.edu.uy

Juan Pedro Posse

INIA, Tacuarembó, Uruguay, jposse@inia.org.uy

Ludmila Profumo

CENUR Noreste, Universidad de la República, Montevideo, Uruguay, lprofumo@cur.edu.uy

Luis Reina

CENUR Noreste, Universidad de la República, Montevideo, Uruguay, luis.reina@cut.edu.uy

Fernando Resquin

INIA, Tacuarembó, Uruguay, fresquin@inia.org.uy

Michael Rodriguez

Arboreal SA, Tacuarembó, Uruguay, michael.rodriguez@arboreal.com

Julia Sáenz

Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay, jsaenz@fagro.edu.uy

Esther Merlo

Madera Plus, San Cibrao das Viñas, Ourense, España, maderaplus@maderaplus.es

* Corresponding author

Abstract

To address the problem related to the presence of compression wood (CW) in *Pinus taeda* (loblolly pine) it is important to develop methods to classify standing trees according to this defect. CW is composed of cells with different anatomy, stiffness, density, and chemical composition. This distinction would allow its early identification in the supply chain by applying different nondestructive testing (NDT). This work demonstrates the viability of some NDT such as ultrasound wave propagation, drilling resistance and near infrared spectroscopy to infer the presence of CW in *Pinus taeda*, which is problematic for the industry. Values of ultrasonic wave propagation velocity and drilling resistance of the outer wood are provided, which are proposed to discriminate the high presence of CW as preliminary results, and must be corroborated and validated in subsequent samples. Portable NIR instruments show also interesting potential as CW characterization tools at different stages of the supply chain.

Keywords: reaction wood, pine trees, loblolly pine, acoustic tomography, ultrasound tomography, portable NIR, Resistograph

1. Introduction

Plants detect their relative position in the gravitropic field through very sensitive gravitropic sensing mechanisms and reorient their growth direction rapidly (Mouliat et al., 2019). In woody plants, a slower reaction of asymmetric radial secondary growth takes place, with the formation of reaction wood, which generates asymmetric stresses between opposite sides of the stem, causing a change in its curvature (gravitropic response) and, in turn, a opposite curvature (autotropic response) (Sierra-de-Grado et al., 2008, Gardiner et al., 2014). Therefore, the straightness of a tree trunk depends not only on external factors that induce curvatures, but also on intrinsic —probably genetically controlled— factors that govern resource allocation and tree architecture and are linked to the tree's ability to resist mechanical stresses and eventually recover its stability and straight position (Sierra-de-Grado et al 2022).

Although the production of compression wood (CW) is a vital function for the tree, it can be problematic in wood processing and utilization. CW is made up of cells with different anatomy, stiffness, density and different chemical composition content (Sierra-de-Grado et al 2022). This differentiation will allow its early identification in the supply chain, applying different technologies as it will be explained below.

The intrinsic variability of wood is reflected in wave propagation: radial velocities are higher than tangential velocities, higher velocities in knot zones than normal wood, and different velocities in reaction wood and opposite wood zones (Palma et al. 2018). These variations can be captured by variations in the propagation velocity of an acoustic wave. The anatomical structure of reaction wood is different from that of normal

wood, and this makes it possible to use the wave propagation method for its detection (Bucur 2003; Saadat-Nia et al. 2011).

Near infrared spectroscopy (NIR) is being increasingly applied to predict the chemical composition and physical properties of wood through chemometric analysis (Meder et al. 2010b; Meder and Schimleck 2011). Portable equipment is now available that allows the direct capture of spectra on a solid wood sample (Meder et al. 2010a; Thumm et al. 2010). Recent studies show that it is possible to discriminate compression wood using infrared spectroscopy applied directly on sawn wood, both in the mid-infrared and near-infrared regions and without the need to vary the humidity of such wood (McLean et al 2014).

On the other hand, the resistograph is a very reliable and efficient technique for assessing the relative density of wood from living trees that could be calibrated to detect the presence and different degrees of reaction wood.

Addressing the impact of the problem linked to the presence of reaction wood in *Pinus taeda*, it is important to develop procedures to leave the most affected logs in stands or label them as unsuitable for the production could help considerably to reduce the impact of the problem. The aim of this work was to apply different nondestructive testing (NDT) looking for a methodology or a combination of different equipment with better fit and feasible application.

2. Methodology

The work was carried out in stands of FYMNSA company and in the sawmill of DANK company, both located in the department of Rivera, Uruguay.

2.1 Log selection and samples

The selection start from a collection of 30 *Pinus taeda* logs, classified for their different levels of presence and severity of CW and 10 control logs without CW. The logs were selected ad-hoc by the industry by visual methods of color on the log head, based on previous experience regarding the presence or absence of CW. Those with a greater amount of CW would be classified in three different patterns of CW distribution: with the cross section totally covered with CW (Figure 1), asymmetric pattern with a determined zone with more CW (common CW) or CW distributed along the peripheral circumference.



Figure 1—Patterns of CW found during the research. From left to right: totally covered; common asymmetric CW; CW in periphery circumference.

The logs were measured to determine their diameters at the thick and thin ends and their length, which also made it possible to calculate their taper. In addition, they were evaluated with different NDTs prior to sawing in order to contrast with visual classification of CW, sawing results and the quality of the obtained boards. After, the log was cut, the first 90 cm were excluded and then 3 discs were taken: 4-5 cm for

chemical analysis, 4-5 cm for anatomy and 15 cm for testing. A log of 4,0 m length was sent to the sawmill. After sawing, the samples were reclassified, according to the real problems generated in the process, in the same three categories (without CW, moderate and severe CW) and six discs of each category was selected.

2.2 NDT characterization

The aim was to have a quantitative characterization that could be associated with the presence and severity of CW. For this purpose, different measurements were taken:

- 1- Longitudinal wave velocity on the logs by inserting two transducers in the wood, inclined 45° and at a distance between them of 1 m with 2 sonic equipment —acoustic sound microsecond timer (Fakopp) and ultrasonic pulse (Sylvatest). Velocity was measured in three orientations on the log with the highest CW, the opposite orientation (at 180°) and another in the perpendicular orientation (at 90°). Three measurements were taken per orientation.
- 2- Longitudinal vibration signal of the log obtained by means of the resonance equipment (Hitman HM200). In this case, three measurements were also taken.
- 3- Basic density of the external part of the CW. For this purpose, a sample of wood of 10 cm length was extracted with an increment borer, along the orientation identified as having the highest amount of CW.
- 4- NIR spectra: As an exploratory measure, spectra were taken on the cambium at about 60 cm from the log head, with a portable near infrared spectroscopy equipment, after removing the bark, in the orientation identified as having the highest amount of CW and its perpendicular orientation. The portable NIR used (MicroNIR, Viavi) collects the absorbance of the materials, along the near infrared spectrum of the light spectrum, in the wavelength range between 908 nm and 1676 nm with a high resolution of 6 nm (it captures absorbance values every 6 nm within that range).

2.3 Data process and statistical analysis

Once the database has been generated with all the NDT measurements on the logs and discs, it was related to the visual classification assigned when the trees were cut down in logs and before the discs were extracted, looking for relationships between them in order to generate descriptive information of the sample. To carry out the statistical analysis, the visual classification of compression wood was considered as treatment and all NDT or morphological measurements as variables. General linear model analysis has been carried out (GLM) to study the differences between batches of logs with different levels of compression wood and to identify which was the non-destructive methodology that allowed better differentiation between the three populations of logs related to the variables measured.

The Person correlation between all the variables measured on the logs and discs, has been analyzed in order to know the relationships between them and determine complementary methodologies as well as possible associations with the morphological variables.

For the analysis of the spectral data collected with NIR, discriminant analysis was performed using and estimating the effectiveness of the model from confusion matrices.

3. Results and Discussion

3.1 Analysis of data obtained on visual classification of logs

The logs obtained from the same stand had an average basal diameter of 42 cm (Table 1). The logs were very variable in terms of taper. The highest coefficient of variation in the morphometric variables was obtained for taper. Regarding the wave velocity, the greatest variability was obtained with the ultrasound equipment. The basic density had a low coefficient of variation (7.3%).

Table 1—Summary statistics of the variables evaluated in the logs

Variables	Mean	Min	Max	SD	CV (%)
Major diameter (mm)	428	324	553	50.12	11.69
Minor diameter (mm)	379	283	521	46.49	12.26
Taper (mm/m)	11	2	24	5	45
Length (cm)	421	418	430	2.93	0.69
Vfakopp (m/seg)	3519	2808	4217	346	10.7
Vsylvatest (m/seg)	4053	2492	5134	614.98	15.17
VHitman (m/seg)	2811	2384	3574	300	10.68
Basic density (kg/m3)	543.93	438.79	618.75	39.87	7.3
Green density (Kg/m ³)	931.10	799.90	1014.37	57.47	6.17

3.2 Differences in longitudinal wave velocity

Significant differences in velocity are observed between the classes (Figures 2 left), where logs without CW had significantly higher longitudinal velocities than logs with CW, for all sampled equipment. The stress wave equipment allows to differentiate between the three measurements (Figure 2 right), but it does not allow to differentiate between the severity of CW.

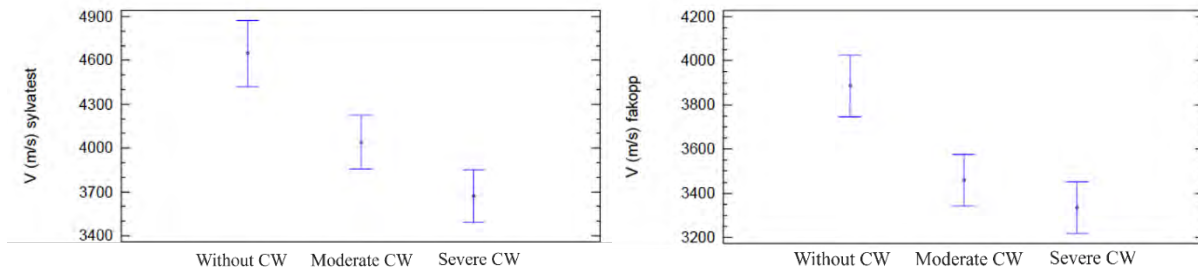


Figure 2—Mean test of velocity obtained with ultrasound equipment (left) and stress wave (right). The data correspond to average values of the three log orientations.

The results obtained are improved by using the velocities obtained in the CW zone. However, considering a standing tree measurement, where we do not know the CW orientation, it is necessary to apply a protocol with measurements in different orientations and work with the mean value of these measurements. Thus, the best technique to classified would be ultrasound, whose mean value between the three measurements in three orientations was able to significantly differentiate logs identified visually in three classes (Figure 2).

Regarding the wood basic density on the external zone extracted with increment borer, there are no significant differences between the classes without CW, moderate CW and severe CW.

3.3 Correlations between variables evaluated on logs

A significant negative correlation of taper with longitudinal velocity was observed, with a tendency that the more tapered the log, the lower the speed and the higher the CW (Table 2). The diameter does not show a negative correlation with the ultrasound or stress wave, but it does with the vibration signal (hitman). Density not correlated with either taper or diameter.

Table 2—Correlation matrix. Coeficients in bold indicate p-value<0.05.

	Major diameter	Taper	Mean hitman	Mean fakopp	Mean sylvatest	Basic density
Major diameter						
Taper	0,4519					
Mean hitman	-0,4310	-0,6110				
Mean fakopp	-0,1873	-0,5567	0,8523			
Mean sylvatest	-0,3096	-0,6510	0,9116	0,8846		
Basic density	-0,2522	0,0805	-0,0916	-0,3170	-0,2060	

3.4 Ultrasonic and acoustic wave propagation

Looking at the parameters evaluated on those 18 logs of final selection, there were significant differences in the ultrasonic and vibration waves, among the three classes of CW, while the stress waves was not able to differentiate between moderate and severe CW (Figure 3).

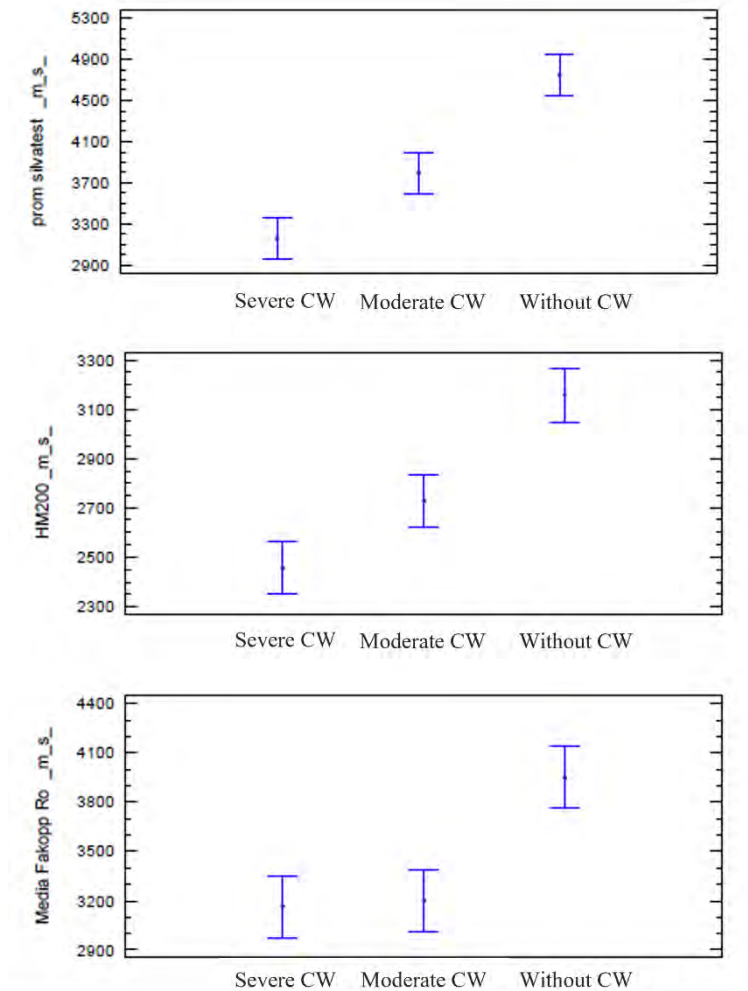


Figure 3—Mean test of velocity speed in the logs identified as representative of interest for this study with severe CW, moderate CW and without CW.

Based on this result, it could remark that the ultrasound NDT has more sensitivity to differentiate the types of CW. In addition, it would be possible to define ranges to classify CW: with velocities greater than 4300 m/s, there is no CW; between 3600 and 4300 m/s, there will be moderate CW; and if the velocity is less than 3600 m/s, then there is severe CW, that can cause problems in the sawmill. It would be necessary to find the equivalence with the ultrasound velocity in the tree with respect to the velocity obtained in the log, in order to define the discriminatory velocity ranges on the standing tree.

Also, measurements with longitudinal vibration allow to differentiate the classes of CW, allowing an effective discrimination between severe CW, moderate CW and absence of CW, and it is more convenient to use in log. The measurement should be made 3 times, averaging the three times.

3.5 Drilling resistance with resistograph

The resistograph was able to significantly differentiate discs with and without CW. Thus, if mean drilling resistance values is greater than 32, on the external part of the log wood (the last 10 cm), it could be indicate that there is severe CW in the log (Figure 4). Also, it would be necessary to validate the relationship of this result with measurements on standing trees.

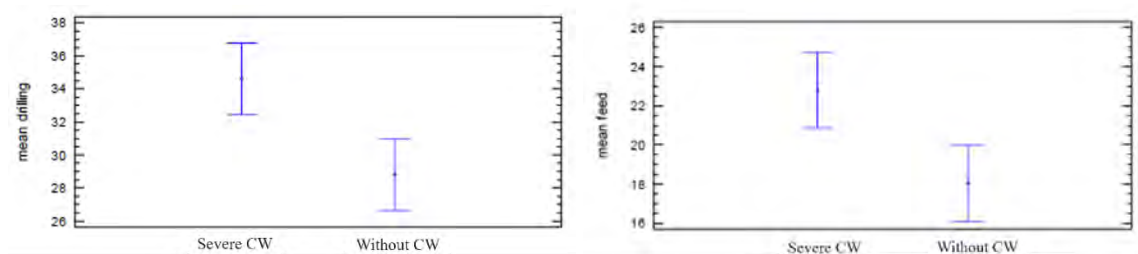


Figure 4—Mean test of the average value of Drilling Amplitude (left) and Feed Amplitude (right) obtained with resistograph on the external part of the discs (10-15 cm).

However, it is important to emphasize that these limiting values can only be considered for the fixed parameters of rotational and feed speed used in these measurements and chosen based on the density of the species.

3.6 Near infrared spectroscopy MicroNIR

The chemometric analysis of the spectra taken with MicroNIR on the cambium in the longitudinal zone of the log in the maximum MC orientation was used in the prediction model of boards with problems during sawing (Table 3). A prediction model of these problematic boards has also been obtained from the spectrum taken with MicroNIR on the discs. The fit statistics and predicted vs. observed plot are shown in Figure 5.

Table 3. Fit statistics for prediction model of boards with problems during sawing

Transformation	R ²	R ² _{CV}	RMSE	RMSE _{CV}	n	NC
SNVSG1	0.87	0.80	7.94	9.82	36	5

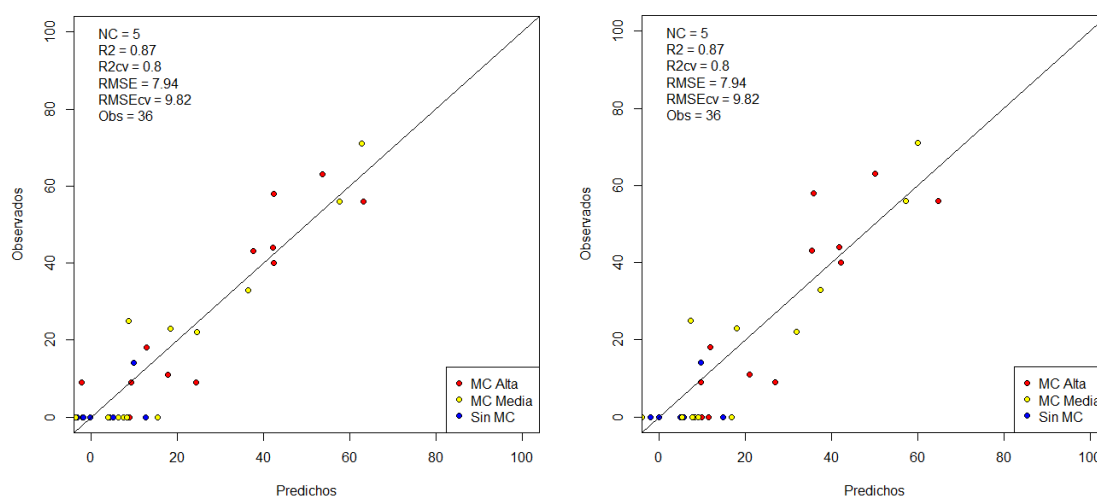


Figure 5—Observed vs. predicted plots for the SNVSG1 transformation (on the left: model plot; on the right: cross-validation plot).

Regarding measurements on the discs, the spectral differences between the CW zone and the CW-free wood are analyzed. For this purpose, a spectrum taken on different discs with and without CW was used and a chemometric analysis is performed by developing a discriminant analysis. The spectra are taken on planed and no planed discs. The confusion matrices with the results are shown below (Figure 6).

No planed discs					
Training			Test		
	NO	YES		NO	YES
NO	204	3	NO	85	0
YES	5	207	YES	4	94
Accuracy: 99.56%			Accuracy: 97.75%		
Precision: 100%			Precision: 95.51%		
Recall: 99.09%			Recall: 100%		
Number of components (LV): 6					
Transformation: SNV					
Planed discs					
Training			Test		
	NO	YES		NO	YES
NO	392	0	NO	168	0
YES	0	290	YES	0	123
Accuracy: 100%			Accuracy: 100%		
Precision: 100%			Precision: 100%		
Recall: 100%			Recall: 100%		
Number of components (LV): 3					
Transformation: SNVSG1					

Figure 6—Confusion matrices with the results obtained on planed and no planed discs.

4. Conclusions

This work shows the feasibility of some of NDT such as ultrasound wave propagation, drilling resistance and near infrared spectroscopy to infer the presence of problematic CW for the industry.

Values of velocity obtained with ultrasound and values of drilling resistance on the external part are provided, which are proposed to discriminate the presence of severe CW. That must be corroborated and validated in a new sampling on standing trees, to obtain correlation models of log and trees velocity to establish a characterization methodology. The portable NIR shows an interesting potential as CW characterization in the supply chain.

5. Acknowledgments

Our thanks to the funding agency National Agency for Research and Innovation (ANII) (Proyecto **ART_X_2021_1_170389**) and all companies that strongly collaborated in this research (FYMNSA, LUMIN, ARBOREAL SA, AGROEMPRESA FORESTAL).

6. References

- Bucur, V. 2003. Nondestructive characterization and imaging of wood. Springer Science & Business Media.
- Gardiner, B., Barnett, J., Saranpää, P., Gril, J. (Eds.). 2014. The Biology of Reaction Wood. Springer Berlin Heidelberg. <https://doi.org/10.1007/978-3-642-10814-3>

McLean, J. P., Jin, G., Brennan, M., Nieuwoudt, M. K., & Harris, P. J. (2014). Using NIR and ATR-FTIR spectroscopy to rapidly detect compression wood in *Pinus radiata*. *Canadian Journal of Forest Research*, 44(7), 820-830.

Meder, R., Trung, T., & Schimleck, L. 2010a. Seeing the wood in the trees: unleashing the secrets of wood via near infrared spectroscopy. *Journal of Near Infrared Spectroscopy*, 18(6), v-vii.

Meder, R., Marston, D., Ebdon, N., & Evans, R. 2010b. Spatially-resolved radial scanning of tree increment cores for near infrared prediction of microfibril angle and chemical composition. *Journal of Near Infrared Spectroscopy*, 18(6), 499-505.

Meder, R., & Schimleck, L. (2011). Has the time finally come for NIR in the forestry sector?. *Journal of Near Infrared Spectroscopy*, 19(5), v-v.

Moulia, B., Bastien, R., Chauvet-Thiry, H., & Leblanc-Fournier, N. (2019). Posture control in land plants: growth, position sensing, proprioception, balance, and elasticity. *Journal of Experimental Botany*, 70(14), 3467-3494.

Palma, S. S. A., Gonçalves, R., Trinca, A. J., Costa, C. P., Reis, M. N., Martins, G. A. 2018. Interference from Knots, Wave Propagation Direction, and Effect of Juvenile and Reaction Wood on Velocities in Ultrasound Tomography. *BioResources*, 13(2), 2834-2845.

Saadat-Nia, M., Brancheriau, L., Gallet, P., Enayati, A. A., Pourtahmasi, K., & Honavar, F. (2011). Ultrasonic wave parameter changes during propagation through poplar and spruce reaction wood. *BioResources*, 6(2), 1172-1185.

Sierra-de-Grado, R., Pando, V., Martínez-Zurimendi, P., Peñalvo, A., Bascónes, E., & Moulia, B. (2008). Biomechanical differences in the stem straightening process among *Pinus pinaster* provenances. A new approach for early selection of stem straightness. *Tree Physiology*, 28(6), 835-846.

Sierra-de-Grado, R., Pando, V., Voltas, J., Zas, R., Majada, J., & Climent, J. (2022). Straightening the crooked: intraspecific divergence of stem posture control and associated trade-offs in a model conifer. *Journal of Experimental Botany*, 73(4), 1222-1235.

Thumm, A., Riddell, M., Nanayakkara, B., Harrington, J., & Meder, R. (2010). Near infrared hyperspectral imaging applied to mapping chemical composition in wood samples. *Journal of Near Infrared Spectroscopy*, 18(6), 507-515.

Structural Diagnosis of Trees Using Resistography: A Non-Destructive Assessment for Internal Issues Identification

Matheus Barreto de Góes *

Departamento de Tecnologia das Construções, Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais, Brasil, matheusbarretog@hotmail.com

Edgar Vladimiro Mantilla Carrasco

Departamento de Tecnologia das Construções, Universidade Federal de Minas Gerais, Belo Horizonte, Minas Gerais, Brasil, mantilla@gmail.com

* Corresponding author

Abstract

Resistography is a non-destructive technique used in assessing the health and integrity of trees. This approach is based on the analysis of internal properties of the tree trunk, allowing for detection of imperfections without the need for cuts or substantial damage to the tree. The method involves the insertion of a very fine drill (3 mm in diameter) transversely into the trunk, checking the resistance to wood penetration, thereby enabling the evaluation of the extent of structural damage, identification of pathologies, and guidance for appropriate interventions. The aim of this study was to utilize resistography to examine the internal structure of Alfeneiro (*Ligustrum lucidum*) and identify potential structural issues, such as cavities, damage caused by pests, or areas of deterioration. For the assessment, individuals visually classified as healthy, without apparent structural damage, were randomly selected in the city, along with a second group classified as at risk, exhibiting characteristics such as visible structural damage and a predisposition to falling. The resistograph assessment was conducted on all individual trees from both groups, at various heights of the trunk, from base to chest height. Results were categorized into three groups: the first for visually healthy trees with no internal damage, the second for the critical group with detected internal damage, and the third for cases where graph results differed from the initial visual assessment. The findings indicate that resistography is a suitable tool for the structural evaluation of living urban trees. However, its effectiveness is enhanced when combined with other non-destructive techniques.

Keywords: resistography, urban arborization, non-destructive testing, security engineering

Residual Resistance Model for Wooden Poles in Electrical Distribution Networks Using Non-Destructive Technology

Julia Sáenz-Baute¹; Andrés Baietto¹; Silvia Böthig²; Stephany Arrejuría²; Yamila Delgado²; Marcelo Pérez³; Jaime González-Tálice¹; Ana Paula Coelho^{1*}

¹ Departamento Forestal, Facultad de Agronomía, Universidad de la República, Montevideo, Uruguay

² Fundación Latitud, Laboratorio Tecnológico del Uruguay (LATU), Montevideo, Uruguay,

³ Gerencia de Distribución, Administración Nacional de Usinas y Transmisiones Eléctricas (UTE), Montevideo, Uruguay

* Corresponding author: paula.coelho@fagro.edu.uy

Abstract

This study investigates the residual strength of *Eucalyptus grandis* wood poles in Uruguay using non-destructive technologies (NDT) such as Polux5[®], Fakopp[®], and Xylohygrometer. Poles were classified according to their location and years of use (ranging from 1 to 25 years). Tests for flexural strength, bulk density, and moisture content were carried out on the same poles that had previously been assessed using non-destructive methods. Data obtained from devices were compared with the results obtained by destructive methods using a generalized linear mixed model (GLMM). Both devices were effective, but Polux5[®] was more efficient than Fakopp[®]. Including visual inspection in models did not significantly improve the results, but can be used as a safety margin for estimation bias.

Keywords: in-service wood assessment, utility poles, strength estimation, MOR

Introduction

In-service structural timber

Often, wood elements in service show various structural anomalies, such as cracks, discoloration or stains, decay, and insect damage, which remain more or less hidden, losing their resistant capacity (Dietsch and Köhler, 2010; Kasal, 2014). For this reason, it is necessary to inspect them regularly, aiming to detect their internal condition or conservation status (Nowak et al., 2016). Through the use of non-destructive techniques, it is possible to assess the loss of strength of wood during its service life, which can be useful for prevention of failures and improvement of safety and efficiency of elements of this material that make up various structures.

The safety analysis of wood in service is performed by inspecting the structure and estimating damage and its extent, according to Frühwald et al. (2013). This process takes into account defects and heterogeneities found in components that make up the structure, using a combination of different assessment techniques. Therefore, safety analyses vary according to wood classification, strength, elasticity, density, and the evaluation of anomalies found in pieces (Carballo et al., 2009).

There are several methods used to assess the deterioration of an existing structure. These methods can be direct or indirect, qualitative or quantitative, and can consider the whole wooden element or only a part of it, as explained by Dietsch and Köhler (2010) and Kasal (2014). They also comment that they can be destructive, semi-destructive, or non-destructive with respect to the element being assessed. In fact, each of these methods makes it possible to evaluate different types of failure, so the authors mention that to obtain a good level of confidence regarding the performance of the evaluated element, it's necessary to combine different methods.

In-service wood assessment methods

Each technique used to evaluate timber in service has advantages and disadvantages. In fact, visual inspection, percussion probing, electrical moisture measurement, and dowel extraction are some of the most commonly used (Nowak et al., 2021). At the same time, these methods have the disadvantage of collecting information from a reduced section of elements, limited to the measurement point. As a result, it is necessary to increase the number of measurement points, which in turn may be insufficient for very large structural elements, and damage caused to the structure may be counterproductive (Frühwald et al., 2013; Kasal, 2014).

In general, these methods are considered subjective because they only provide information on existence and location of defects or damage, depending on experience of evaluator (Datla and Pandey, 2006; Freeman and Ragon, 2010; Gezer et al., 2015). For this reason, they are used as a complement to other non-destructive techniques, as they alone do not provide accurate data for evaluating the strength properties of the inspected element (Nowak et al., 2016).

For timber in service, assessing its physical and strength properties cannot be done using laboratory methods (destructive testing), as they require taking samples that would disrupt the structure continuity (Nowak et al., 2016). Thus, the difference in assessment level of structures will depend on the detection range of different equipment. This can range from very local to global (Palma and Steiger, 2020).

Non-destructive methods aim to obtain indexes that can be related to the internal characteristics of wood, aiming to avoid altering it physically, chemically, mechanically, or dimensionally (Íñiguez, 2007). In addition, these indicators lead to the estimation of mechanical and physical properties of a timber element and help in the deduction of its internal state and residual strength.

Different technologies have been developed (Nguyen et al., 2004). However, there are no established standards with regard to equipment and methods of use, as in the case of laboratory methods. As a result, the use of NDT techniques remains limited to specific instruments, which cannot be correlated with another instrument, even if they have the same operating principle (Kasal, 2014). Thus, although the results of these techniques are subjective, some of these techniques offer significant results for assessing wood in-service (Bandara et al., 2021).

Wooden poles in electricity distribution networks

Power distribution services consist of a network of high-voltage lines, called transmission systems, through which electricity moves from generators to substations. Subsequently, an underground or overhead distribution system carries medium and low-voltage electricity from transformer stations to distribution networks (Tallavó, 2009).

For overhead distribution networks, usually in rural areas, utilities use wooden poles to support cables, transformers, and other equipment for service users (Bandara et al., 2021). These elements need to be durable enough to maintain original quality and characteristics for minimum service life (Kumode et al., 2013).

Inspection plans for distribution network poles are carried out by utility management companies. These inspections aim to identify which poles remain in service, which need to be maintained or repaired, and which are at or near the end of their life (Seale et al., 2016). The indicator used to determine whether a pole requires re-treatment or substitution is the residual strength of wood.

For wooden poles, the risk of degradation is concentrated in the area of the pole collar or ground line, which is defined by ANSI O5.1 as part of the pole between one foot above and two feet below the ground level line (ANSI, 2017). Here wood has direct contact with soil, creating favorable conditions for decay to occur. This tissue damage occurs when several factors combine, including humidity above 20%, temperatures above 10°C, the presence of decaying organisms, soil nutrients, and oxygen (Freeman and Ragon, 2010). It is also the zone where the highest mechanical stress of an element is focused (Gezer et al., 2015).

Methodology

Fieldwork

Seventy working poles installed in active distribution lines in three departments located in central and southwestern Uruguay - Durazno, Flores, and San José - were randomly selected. Sectors studied are differentiated according to their location - S1, S2, and S3. Total number of poles per sector was 25, 22 and 23, respectively. By classifying poles according to years of use, three categories were obtained. The first group includes poles from 1 to 10 years (C1) -21 poles-, the second group of poles from 11 to 20 years (C2) -34 poles- and the third group of poles older than 21 years in use (C3) -15 poles-. All poles in the sample were inspected while working in distribution lines before they were removed. On the ground line section of poles required parameters were measured. Three devices were used: a wood hygrometer - Xylohygrometer- to determine the moisture content at the time of inspection, a microsecond timer - Fakopp® - to measure the speed of wave transmission between inspection points, and a device that simultaneously measures penetration resistance (strength) and wood moisture Polux 5®. In addition, the presence, location, and quantity of defects/damage observed were recorded. These included knots, holes, cracks, decay, mechanical damage, and insects. Assessed poles were then removed from service and transferred to facilities for mechanical testing. Each pole was subjected to a static bending test. In addition, basic bulk density and moisture content were determined using standard laboratory procedures on discs taken from the same poles that had been tested.

Statistical analysis

Polux 5® and Fakopp® instruments were compared. A Xylohygrometer was added to the latter. The estimation parameters considered - MOR, DAB, and CH - were analyzed using the R package 'lme4' (Bates et al., 2015) by fitting generalized linear mixed models -GLMM-. Random effects were defined as years in use category and sector of origin of the pole. Values obtained from NDT measurements -strength, moisture content, and wave propagation speed- were treated as continuous variables. Spearman's correlation (Rho) was used to analyze the visual defects of each element, both along the pole and on the ground line. These defects were treated as fixed effects, transforming them into discrete variables - NO, SLIGHT, YES - according to their quantity and degree of affecting pole. To compare statistical models, we looked for models with lower values of Akaike's (AIC) and Bayes' (BIC) information criteria. Additionally, the highest value of R_p^2 suggested by Nakagawa et al. (2017) was added to understand what percentage of total variance was explained by fixed and random effects of found models. Finally, an evaluation of the effectiveness of the proposed optimal models for each NDT equipment used was performed. This analysis was performed by examining the percentage of total predictions generated by each model in relation to false negatives and false positives. All statistical analyses were performed using R statistical software (version 4.3.1) (R Foundation for Statistical Computing, Vienna, Austria). The p-value was set at 0.05.

Results and discussion

Defect analysis

Knots and cracks, representing more than 85% and 90% of the total sample, respectively, were found to be the most common defects in the evaluated poles. Therefore, these poles would be expected to have lower resistance in areas where knots are located, as described by Lima (2018), and greater damage due to degradation in areas affected by cracks, as reported by Kumode et al. (2013).

Nevertheless, 46% of observed knots were located in the active length of the pole, but far from the evaluated zone (ground line). Therefore, as in Torrán et al. (2009), the relationship between these knots and the pole resistance in the evaluation zone would be very low.

As mentioned by Iejavs et al. (2021) and Seng Hua et al. (2022), the presence of cracks in sample poles can be attributed to characteristics of fast-growing *E. grandis*. Also, according to Kartal (2000), to quality of wood and harvesting, drying, and impregnation processes to which they were subjected. Now, it is important to mention that cracks found in the ground line had an average depth of 75 mm (data not shown), which exceeds the sapwood thickness impregnated with CCA (25 mm) allowed by UTE (2018) for wooden poles used for power lines.

On the other hand, half of the evaluated poles showed holes. This was attributed to woodpecker activity. This defect increased along the active length for categories C2 and C3, that is, after 10 years of use, which is in agreement with Bandara et al. (2021) and (Kumode et al., 2013) with regard to the deterioration of this type of structure once it is in service.

In addition, 65% of the poles inspected showed signs of rot. Of these, half showed deep rot. Like holes, deep rot was mainly found in poles over 10 years old (categories C2 and C3). This situation could be because poles in this study were exposed to high humidity conditions (Gezer et al., 2015), which could have been conducive to the growth of decay fungi. These fungi could have entered through deep cracks and also proved to be resistant to preservatives (CCA) used to immunize them (Walker et al., (2006).

The results of this part of this study are presented in Table 1. With the exception of the decay defect, there is a low correlation between the visual defects evaluated and modulus of rupture calculated by the flexural test. These results are consistent with those obtained by Zhang et al. (2024) and Íñiguez (2007) regarding the low influence of knots when they are located far from the point of loading. The holes also did not affect the evaluated risk section; however, Morrel (2012) points out that this defect can cause failures in other sections of pole, away from the ground line.

Table 1— Relationship of MOR to defects present in poles

Property	Defect	Rho	p-value
General Visual			
MOR	Soil Moisture	0.13	0.2765
	Mechanical Damage	0.20	0.0954
	Knots	-0.28	0.0203*
	Holes	-0.28	0.0197*
	Cracks	-0.14	0.2321
	Presence of Insects	0.08	0.5048
	Detailed Visual at Ground Line		
	Rot Coverage	-0.42	0.0003*
	Crack Coverage	-0.03	0.7822
	Knot Coverage	-0.05	0.6870
	Rot Depth	-0.33	0.0058*
	Crack Depth	-0.16	0.1976

Note: Spearman's Rho. *p<0.05

On the other hand, decay was significant for resistance at the ground line (Rho of -0.42) (table 1). This means that even if the degree of internal decay is not known, the presence of this condition in wood could cause a decrease in its resistance. The results are consistent with what has been stated in other studies, which refer to the difficulty of relating deterioration detected by a simple visual inspection to the level of internal deterioration of wood (Gezer et al., 2015; Kasal and Anthony, 2004).

Predictive models

The defect with the highest Rho obtained was included in the estimation based on the results of defect analysis (table 2). However, it did not significantly improve the before model found without the inclusion of visual defects.

Table 2— Predictive models of MOR, including visual evaluation, with non-destructive equipment

Model 11 (Polux5®)					Model 12 (Fakopp®+Hygrometer)				
Fixed Effects									
	Coef.	AIC	BIC	R_p^2	Coef.	AIC	BIC	R_p^2	
I	2.7605* (0.1931)	508.4	524.1	0.62	3.1469* (0.2424)	518.7	534.5	0.61	
F/V	0.0079* (0.0011)				0.0006* (0.0001)				
M	-0.0045* (0.0016)				-0.0180* (0.0061)				
CR	-0.2428* (0.1092)				-0.2461* (0.1147)				
Random Effects									
	σ								
C:S	0.0170								
R	0.0714								

Note: Coef. = coefficient. I = intercept. F|V = force or velocity, depending on the equipment used. M = humidity. CR = rot cover. C:S = variance by category and sector. R = residual variance. AIC and BIC = values of Akaike's and Bayes', respectively. R_p^2 = Pseudo R². *p < 0.05

Both proposed models overestimated low MOR (<20 kg) and underestimated high MOR (<50 kg) (figure 1). However, the consequences of this bias in estimates pose different risks. An overestimation of MOR in a replacement pole (false negative) poses a risk of service interruption and could lead to serious accidents, in addition to an increase in operating costs of the distribution network caused by the necessary replacement after pole breakage (Nguyen et al., 2004). On the other hand, an underestimation of poles with high MOR values would not have major consequences since it does not imply any decision other than to maintain the pole.

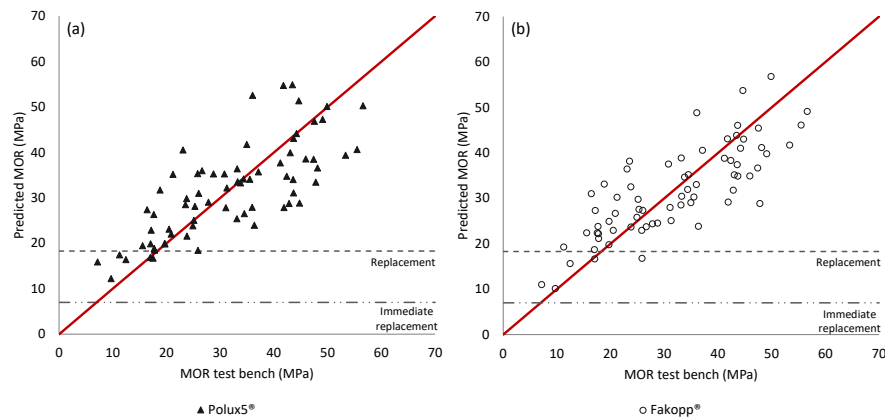


Figure 1— Predicted and observed values of nondestructive equipment including visual inspection data on the ground line.

Model 11, proposed for Polux 5[®], seems to be more accurate in predicting wood strength for both false negatives (10%) and false positives, while model 12 (Fakopp[®] + Xylohygrometer) is slightly less accurate for both measures (13% false negatives). However, both models seem to be useful. It depends on whether underestimation or overestimation of wood strength is the priority.

According to the results, the choice between the instruments could be determined by measurement method and the number of data sets of each instrument to be included in prediction models. In particular, devices with a lower number of measurements will have an easier time in the field. However, pole management requires the general addition of visual defects, in line with recommendations mentioned by Bandara et al. (2021), Frühwald et al. (2013), and Kasal (2014). These authors present pole assessment methods, known by service management companies worldwide and considered essential for distribution networks' safety and efficiency.

Conclusions

Both techniques were effective in the estimation of residual wood strength. For the mechanical technique, only the measurement orientation perpendicular to the transmission line proved useful. To achieve accuracy comparable to the mechanical technique, the acoustic technique required measurements in both orientations.

Knots and holes were the most common defects along the pole. Rot was the predominant defect at the ground line of the pole. However, its correlation with residual strength in the evaluated risk area can be considered moderate to low, even though rot coverage had the greatest effect on wood strength estimation.

Finally, contrary to expectations, including visible pole features did not significantly affect the accuracy of predictive models. However, managing a distribution network also depends on identifying and dealing with such defects. Thus, the entire pole needs to be inspected, not just the ground line.

Acknowledgments

Our thanks to the Scientific Research Sector Commission (CSIC) of the University of the Republic (UdelaR), the National Administration of Power Plants and Electric Transmissions (UTE), and the National Agency for Research and Innovation (ANII).

References

- ANSI. 2017. ANSI O5.1 Wood Poles: Specifications and Dimensions. (Version 2017). American National Standard for Wood Utility Products.
- Bandara, S., Rajeev, P. and Gad, E. 2021. Structural health assessment techniques for in-service timber poles. *Structure and Infrastructure Engineering*, 19(4), 439–459. <https://doi.org/10.1080/15732479.2021.1951775>
- Bates, D., Maechler, M., Bolker, B. and Walker, S. 2015. Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, 67(1), 1–48. <https://doi.org/10.18637/jss.v067.i01>
- Carballo, J., Hermoso Prieto, E. and Díez Barra, M. R. 2009. Ensayos no destructivos sobre madera estructural. Una revisión de 30 años en España. *Revista Forestal Mesoamericana Kurú*, 6(17), 26–41.
- Datla, S. V. and Pandey, M. D. 2006. Estimation of life expectancy of wood poles in electrical distribution networks. *Structural Safety*, 28(3), 304–319. <https://doi.org/10.1016/j.strusafe.2005.08.006>
- Dietsch, P. and Köhler, J. 2010. Assessment of Timber Structures. European Science Foundation. https://www.researchgate.net/profile/Philipp-Dietsch-2/publication/273131514_Assessment_of_Timber_Structures/links/5c507139458515a4c7481d9f/Assessment-of-Timber-Structures.pdf
- Freeman, M. H. and Ragon, K. W. 2010. A Review of Wood Pole Testing Equipment Compared to Visual and Excavation Techniques Used in Test and Treat Programs. 2010 Southeastern Utility Pole Conference - Technical Forum (pp. 178-188). https://poles.com/WebRoot/Store4/Shops/08fd78c5-abfa-4217-9263-68fec9605ccc/MediaGallery/Internal_Treatment_Data__Doc/SEPOLECONF20112CMikeFreemanInspectionDevices2CCostBenefitAnalysis.pdf
- Frühwald, K., Hasenstab, A. and Osterloh, K. 2013. Detection of Incipient Decay of Wood with Non- and Minor-Destructive Testing Methods. En O. Güneş & Y. Akkaya (Eds.), *Nondestructive Testing of Materials and Structures* (Vol. 6, pp. 353–358). Springer Netherlands. https://doi.org/10.1007/978-94-007-0723-8_51
- Gezer, E. D., Temiz, A. and Yükses, T. 2015. Inspection of Wooden Poles in Electrical Power Distribution Networks in Artvin, Turkey. *Advances in Materials Science and Engineering*, 2015, 1–11. <https://doi.org/10.1155/2015/659818>
- Iejavs, J., Podnieks, M. and Uzuls, A. 2021. Some physical and mechanical properties of wood of fast-growing tree species eucalyptus (*Eucalyptus grandis*) and radiata pine (*pinus radiata* d.don). *Agronomy Research*, 19(2), 434–443. <https://doi.org/10.15159/AR.21.038>
- Íñiguez, G. 2007. Clasificación mediante técnicas no destructivas y evaluación de las propiedades mecánicas de la madera aserrada de coníferas de gran escuadría para uso estructural [Tesis doctoral]. E.T.S.I. Montes (UPM). <https://oa.upm.es/415/>
- Kartal, S. N. 2000. The leachability, fungal resistance, and mechanical properties of wood treated with CCA and CCB wood preservatives. *İstanbul Üniversitesi Orman Fakültesi Dergisi. Seri A*, 50(2), 177–194. <https://www.cabdirect.org/cabdirect/abstract/20073276319>
- Kasal, B. 2014. Structural health assessment of in situ timber: An interface between service life planning and timber engineering. *Wood Material Science & Engineering*, 9(3), 134–138. <https://doi.org/10.1080/17480272.2014.903298>
- Kasal, B. and Anthony, R. W. 2004. Advances in situ evaluation of timber structures. *Progress in Structural Engineering and Materials*, 6(2), 94–103. <https://doi.org/10.1002/pse.170>

- Kumode, M. M. N., Moreschi, J. C., Muñiz, G. I. B. de, Nisgoski, S., Ferracin, R. J. and Tanobe, V. O. de A. 2013. Análise das causas da deterioração dos postes de madeira da Ilha do Mel, Paraná, Brasil. *Ciência Florestal*, 23(1), 213–221. <https://doi.org/10.5902/198050988455>
- Lima, L. J. 2018. La madera como material estructural. *Certezas, Conjeturas, Incógnitas y Perspectivas (Monografías, p. 59)*. LEMEJ-UNNOBA. https://lemej.unnoba.edu.ar/wp-content/uploads/publicaciones/Luis_Lima-La_madera_como_material_estructural.pdf
- Morrell, J. J. 2012. Wood Pole Maintenance Manual: 2012 Edition, Research Contribution 51; College of Forestry. Forest Research Laboratory, Oregon State University
- Nakagawa, S., Johnson, P. C. D. and Schielzeth, H. 2017. The coefficient of determination R² and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. *J. R. Soc. Interface*, 14: 20170213. <http://dx.doi.org/10.1098/rsif.2017.0213>
- Nguyen, M., Foliente, G. and Wang, X. M. 2004. State-of-the-Practice & Challenges in Non-Destructive Evaluation of Utility Poles in Service. *Key Engineering Materials*, 270–273, 1521–1528. <https://doi.org/10.4028/www.scientific.net/KEM.270-273.1521>
- Nowak T, Patalas F and Karolak A 2021 Estimating Mechanical Properties of Wood in Existing Structures—Selected Aspects. *Materials*. doi:10.3390/ma14081941
- Nowak, T. P., Jasieńko, J. and Hamrol-Bielecka, K. 2016. In situ assessment of structural timber using the resistance drilling method – Evaluation of usefulness. *Construction and Building Materials*, 102, 403–415. <https://doi.org/10.1016/j.conbuildmat.2015.11.004>
- Palma, P. and Steiger, R. 2020. Structural health monitoring of timber structures – Review of available methods and case studies. *Construction and Building Materials*, 248, 118528. <https://doi.org/10.1016/j.conbuildmat.2020.118528>
- R Core Team (4.3.1). 2023. [R: A Language and Environment for Statistical Computing]. R Foundation for Statistical Computing. <https://www.R-project.org/>
- Seale, R. D., Shmulsky, R., Entsminger, E. D., Bartuli, A. and Belalami, S. 2016. Field Test of a Novel Nondestructive Testing Device on Wood Distribution Poles. *Wood And Fiber Science*, 48(3), 156-161.
- Seng Hua, L., Wei Chen, L., Antov, P., Kristak, L. and Md Tahir, P. 2022. Engineering Wood Products from Eucalyptus spp. *Advances in Materials Science and Engineering*, 2022, 1–14. <https://doi.org/10.1155/2022/8000780>
- Tallavó, F. J. 2009. New Methodology for the Assessment of Decayed Utility Wood Poles Using Ultrasonic Testing [Tesis doctoral]. University of Waterloo.
- Torrán, E. A., Sosa Zitto, M. A., Cotrina, A. D. and Piter, J. C. 2009. Bending strength and stiffness of poles of argentinean Eucalyptus grandis. *Maderas. Ciencia y Tecnología*, 11(1). <https://doi.org/10.4067/S0718-221X2009000100006>
- UTE. 2018. NO-DIS-MA 2502 Postes de Eucaliptus preservados (Versión 3). Normas de Distribución, Administración Nacional de Usinas y Transmisiones Eléctricas.
- Walker, J. C., Archer, K. and Lebow, S. 2006. Wood preservation. En Springer (ed), *Primary wood processing: Principles and practice* (pp. 297–338). New Zealand.
- Zhang, X., Sun, H., Xu, G., Duan, Y., Jan, J., Joris, J. and Shi, J. 2024. Understanding the Effect of Knots on Mechanical Properties of Chinese Fir under Bending Test by Using X-ray Computed Tomography and Digital Image Correlation. *Forests*, 15(1), 174. <https://doi.org/10.3390/f15010174>

A Review of Ground Penetrating Radar for Inspecting Wood Structures

Brunela Pollastrelli Rodrigues *

Clemson University, Clemson, South Carolina, USA, brunelr@clemson.edu

Christopher Adam Senalik

USDA-Forest Products Laboratory, Madison, WI, USA, christopher.a.senalik@usda.gov

Xi Wu

Jiangnan University, Wuxi, China, 7161905006@vip.jiangnan.edu.cn

James Wacker

USDA-Forest Products Laboratory, Madison, WI, USA, james.p.wacker@usda.gov

* Corresponding author

Abstract

This review aims to identify knowledge gaps that need to be addressed for GPR to be a more effective tool for inspecting wood structures. Over the past two decades, ground penetrating radar (GPR) has gained popularity as an inspection tool for wood and wooden structures. GPR is classified as a nondestructive technique based on the electromagnetic (EM) theory, and the EM properties of a dielectric material such as wood govern its propagation wave. The several characteristics that make GPR an attractive nondestructive evaluation (NDE) tool for wood will be discussed, as well as its limitations. One of these gaps is the ability to distinguish between internal features and internal decay based on GPR output. In summary, GPR is a powerful tool for inspecting wood and wood structures due to its portability and ability to detect moisture pockets, voids, and metal connectors. It can be used to locate internal features, but identifying them is difficult. Further research is needed to locate and identify internal decay independent of moisture.

Keywords: ground penetrating radar, wood inspection, nondestructive testing, wood moisture, wood decay.

Radial Variation of Wood Density along the Trunk of *Astronium lecointei* (Ducke) Trees in Eastern Amazon

Bruna Hornink*

Department of Plant Biology, Institute of Biology, University of Campinas – UNICAMP, Campinas, São Paulo, Brazil, bhornink@gmail.com

Claudia Fontana

Departament of Forest Resource, Escola Superior de Agricultura Luiz de Queiroz – ESALQ, Universidade de São Paulo - USP, Piracicaba, São Paulo, Brazil, claudiafontanabio@gmail.com

João Gabriel Leal Martins

Department of Plant Biology, Institute of Biology, University of Campinas – UNICAMP, Campinas, São Paulo, Brazil, joaogabriellemartins@gmail.com

Nicole Riatto Victor

Department of Plant Biology, Institute of Biology, University of Campinas – UNICAMP, Campinas, São Paulo, Brazil, n186204@dac.unicamp.br

Mario Tomazello-Filho

Departament of Forest Resource, Escola Superior de Agricultura Luiz de Queiroz – ESALQ, Universidade de São Paulo - USP, Piracicaba, São Paulo, Brazil, mtomazel@usp.br

Amy E. Zanne

Department of Biology, University of Miami, Miami, Florida, EUA, aezanne@gmail.com

Peter S. Groenendijk

Department of Plant Biology, Institute of Biology, University of Campinas – UNICAMP, Campinas, São Paulo, Brazil, bhornink@gmail.com

* Corresponding author

Abstract

Understanding the radial variation of wood density is crucial for optimizing wood usage in various industries and estimating wood biomass storage in trees. By understanding how density changes across radial axes at different heights along the tree trunk, manufacturers can better tailor their processing methods, resulting in more efficient and sustainable use of wood resources. In this study, we evaluated *Astronium lecointei*, a commercially important wood (common name in Brazil – muiracatiara), to assess patterns and potential drivers of radial wood density variation across the tree trunk. We obtained disks at three heights along the commercial trunk (Base, Middle - at 6 meters, and the Top) of six felled trees in the FLONA do Tapajós logging concession. We assessed the radial wood density variation (WD, $U_{12\%}$) using X-ray densitometry. This technique allows for precise measurements of radial wood density profiles. Wood density decreases axially along the trunk (Base = 1.07 ± 0.16 ; Middle = 0.90 ± 0.16 ; Top = 0.87 ± 0.15 ; $F = 0.02191$, $p < 0.001$) and increases along the radial profile (from pith to bark). The position along the trunk is the driver that explains 31% of the total WD ($U_{12\%}$) variation, while the tree (individual) and radii contributions were minimal (3.6%). Understanding these patterns in the structural characteristics of *A. lecointei* wood may improve forest management practices and harvest strategies for the wood industry and can help improve forest biomass estimates.

Keywords: Anacardiaceae, forest management, muiracatiara, X-ray densitometry

Prediction of the Strength of Wood Products with Nondestructive Evaluation Techniques—A Review

Laurice M. Spinelli Correa

Department of Sustainable Bioproducts, Mississippi State University, Starkville, MS, USA,
ls2090@msstate.edu

Robert J. Ross

USDA Forest Service, Forest Products Laboratory, Madison, WI, USA, robert.j.ross@usda.gov

Abstract

One of the most significant contributions of the science of nondestructive evaluation to the forest products industry is the prediction of strength of wood products. Being a biological material, wood has inherent variability that other engineering materials do not. The ability to use various nondestructive techniques to predict the strength of wood products is the foundation for structural lumber grading programs, ultrasonic veneer grading methods, and in-place condition assessment procedures. Recently, Mississippi State University and the USDA Forest Products Laboratory conducted a series of studies to investigate strength prediction of wood products using a range of nondestructive techniques. Bending and tension modulus of elasticity, proof loading, transverse vibration, acoustic, and the use of dielectric properties have been investigated in these recent studies. This paper presents findings from our literature review and reported results from these studies.

Keywords: lumber, composites, wood products, structural, strength, nondestructive evaluation

Introduction

The first efforts to develop nondestructive tests to estimate the strength of wood products focused on structural lumber. Early development of machine lumber grading was marked by worldwide involvement and a commitment of Federal, State, and commercial funding. A 1968 compilation of research and development efforts estimated an accumulated 36 years of lumber-related research at seven national research laboratories worldwide between 1961 and 1968, 28 years at U.S. universities, 15 years between Potlatch Corporation, Inc., and the Western Pine Association (late 1950s and early 1960s), 13 years among five machinery companies (Galligan and Moyer 1968) and internationally by the Commonwealth Scientific and Industrial Research Organization (Melbourne, Australia) and the Timber Research Unit of the Council for Scientific and Industrial Research in South Africa. Several of these organizations produced commercial grading machines in the early years of machine stress grading (1960–1970), using essentially the same principles of the relationship between lumber stiffness and bending strength, which permit a grading system less oriented to species than is the visual grading system.

The foundation for machine grading of structural lumber are the statistical relationships between various properties of wood that can be measured nondestructively and strength (Ross 2015). Most used parameters are measurements of the modulus of elasticity (MOE) of wood. Recently a series of studies have been conducted by Mississippi State University (MSU) and USDA Forest Products Laboratory (USDA-FPL) to investigate these relationships, to explore the use of additional nondestructive parameters, and to examine their use with mass timber products. This paper provides a review of the

current state-of-the-art of strength prediction with nondestructive evaluation (NDE) and presents a summary of recent efforts on strength prediction of lumber and mass timber.

Methods

We conducted a literature review which focused on NDE of lumber and wood products. Our review included an in-depth analysis of Ross (2015) and proceedings from the International Nondestructive Testing and Evaluation of Wood Symposium series, which dates to 1964 (Ross and Wang 2012; Ross and Wang 2013; Ross and et al. 2015; Wang and et al. 2017; Wang and et al. 2019; Wang and Ross 2022). Entsminger and et al. (2020) provided background information. We also examined papers from USDA-FPL's library and MSU's library collection. Papers were individually reviewed, specifically focusing on the statistical models presented. In the following, we present simple “goodness-of-fit” statistical parameters, typically correlation coefficient or coefficient of determination. Our rationale was that these parameters are widely used and reported. The reader is encouraged to examine individual, cited publications for more details on the statistical models presented.

Results and Discussion

Foundation Research

Flatwise bending modulus of elasticity as NDE parameter

The ability to use MOE to predict the strength of lumber was thoroughly investigated and results served as the basis for mechanical grading under investigation at Potlatch Corporation (Lewiston, Idaho, USA) and the Western Pine Association (Portland, Oregon, USA) (McKean and Hoyle 1964). Much of the foundation research reviewed focused on examining the relationship between flatwise bending MOE and strength (bending, compression, and tension) of softwood structural lumber. Table 1 summarizes the results of these studies for MOE and flatwise bending strength of softwood lumber. Note all studies used large samples of lumber and that relatively strong relationships were observed, with reported correlation coefficients of 0.6 to 0.87.

Transverse and Longitudinal Vibration Characteristics as NDE Parameters

Early Research with Softwood Products

The use of transverse vibration NDE techniques was also reported in the literature. These techniques were investigated for use with small, clear wood specimens, glued-laminated timbers, and structural lumber. Strong relationships were observed between vibration and static bending MOE values. Statistical relationships were also observed with bending strength.

Hardwood Lumber

Transverse vibration techniques were used to examine applying machine grading concepts to hardwood lumber in the 1990's. Relationships like those observed for softwood species were found to also exist for hardwood lumber. Kaiserlik and Pellerin (1977) examined the use of longitudinal vibration techniques to estimate the tensile stiffness and strength of a small sample of lumber and observed good statistical relationships. Based on their results, a comprehensive examination of the use of longitudinal vibration NDE techniques to evaluate the strength of wood composite materials was conducted at Washington State University (Ross and Pellerin 1988). Strong relationships were observed, and a statistical model was developed and verified with a broad range of wood composite materials.

Table 1—Research on the correlation between modulus of elasticity (tested flatwise) and flatwise bending strength of softwood lumber.

Reference	Species	Nominal moisture content (%)	Grade ^a	Nominal width (in) ^b	Growth location	Correlation coefficient <i>r</i>
Hoyle (1961)	Douglas-fir	12	SS, C, U	4, 6, 10	Western Oregon, Washington, Idaho	0.79
					Washington	0.72
	Western hemlock	12	SS, C, U	4, 6, 10	Western Oregon, Washington	0.74
	Western larch	12	SS, C, U	4, 6, 8	Idaho, Washington	0.70
Hoyle (1962)	Grand fir	12	C, S, U	8	Idaho	0.75
Hofstrand and Howe (1963)	Grand fir	12	C, S	4, 6, 8	Idaho	0.75
Pellerin (1963b)	Douglas-fir	12	Combination of visual grades	4, 8	Idaho	0.76
Hoyle (1964)	Southern Pine	12	1D, 1, 2D, 2, 3	4, 6, 8	Southeastern United States	0.76
Kramer (1964)	Southern Pine	12	1D, 2, 3	4, 6, 10	Southeastern United States	0.88
Johnson (1965)	Douglas-fir	10	SS, C, U	6	Western Oregon, Washington	0.85
	Western hemlock	10	SS, C, U	6	Western Oregon, Washington	0.86

^aGrades are by regional rules in use at time of research. Western Products Association and West Coast Lumber Inspection Bureau Grades: SS, Select Structural; C, Construction; S, Standard; U, Utility. Western Wood Products Association Grades: 1, 2, 3. Southern Pine Inspection Bureau Grades: 1D, No. 1 Dense; 1, No. 1; 2D, No. 2 Dense; 2, No. 2; 3, No. 3. 1

^b1 in. = 25.4 mm.

Research Results from Mississippi State University and FPL Collaboration

The research program conducted jointly by MSU and FPL examined a variety of NDE parameters for the prediction of Southern pine lumber, spruce-pine-fir lumber, and mass timber strength. The use of flatwise bending, transverse vibration, and longitudinal vibration techniques were examined. In addition, measurement of slope-of-grain (fiber alignment) using dielectric properties were investigated.

Softwood Lumber

As et al. (2020a) conducted a study with spruce-pine-fir lumber specimens to examine the relationship between lumber grain angle (fiber alignment) and energy loss characteristics from transverse vibration nondestructive tests. Grain angle was measured at numerous locations for each specimen with equipment that uses a dielectric nondestructive testing technique. A commonly used free transverse vibration test, in which the specimens were simply supported in a flatwise bending mode, was used to determine energy loss characteristics of the specimens. Increases in grain angle resulted in greater energy loss. A statistically significant positive correlative relationship was found between grain angle and energy loss.

Anderson et al. (2020) reported on a study that used several techniques to measure MOE and grain angle measurements (obtained using a dielectric nondestructive testing technique) to evaluate the strength of Southern pine structural lumber. Static bending, transverse vibration, and longitudinal stress wave techniques were used to measure the MOE of the specimens. The specimens were tested to failure in bending.

As et al. (2020b) investigated using NDE parameters to determine the tensile MOE and strength of spruce–pine–fir structural lumber. Static bending and vibration (transverse and longitudinal) nondestructive tests were conducted on each specimen and MOE was calculated. Results revealed excellent correlative relationships among MOE values. Coefficients of determination obtained were 0.92, 0.96, and 0.93 for MOE of static transverse vibration, MOE of longitudinal vibration, and MOE of longitudinal transverse vibration, respectively. Correlative relationships were also observed between NDE parameters and tensile strength. Coefficients of determination were like those observed for strength predication models developed for other species.

Yang et al. (2015) conducted a study that used transverse vibration techniques to evaluate southern yellow pine structural lumber in flatwise and edgewise orientations, with both yielding comparable results to earlier studies.

Franca et al. (2018) reported on a comprehensive study they conducted to examine the use of transverse vibration nondestructive testing techniques to estimate the strength and stiffness of southern pine lumber. The study's sample was large (2,039 specimens). It consisted of visual grade No. 2, nominal dimension lumber in four widths–2x4, 2x6, 2x8, and 2x10. Transverse vibration tests were performed, in both flatwise and edgewise orientations, prior to static testing in bending. Strong relationships were observed between MOE values. Relationships between MOE values and strength were comparable to those reported in other studies.

Uzcategui et al. (2023a, 2023b) report on a large study designed to evaluate the properties of southern pine structural 2x6 and 2x10 lumber, including correlations between growth characteristics, mechanical, and physical properties. They found a strong relationship between transverse and longitudinal dMOE with elastic properties, confirming that NDE is adequate to assess the mechanical properties of southern pine 2x6 and 2x10 lumber.

Composite Materials (Cross-laminated timber)

Nondestructive evaluation of cross-laminated-timber (CLT) strength was investigated by Spinelli Correa et al. (2022). They used a longitudinal vibration technique to measure the MOE of CLT specimens. Results from this study were encouraging, as a generic model relating stiffness and strength was proven to be accurate for a broad spectrum of wood composite materials. As expected, the MOE prediction was higher ($R^2 = 0.90$) than the modulus of rupture (MOR) prediction ($R^2 = 0.33$), as the latest can have stronger influence from wood defects and stress concentration.

Advanced Signal Analysis and Modeling

Investigation of the use of longitudinal stress wave NDE for predicting the properties of structural lumber initially used stress wave MOE as the primary prediction parameter. Kaiserlik and Pellerin (1977) is the first reported use of an additional parameter, stress wave attenuation. They noted that stress wave attenuation may be a useful additional parameter.

Recently, Senalik et al. (2020a, 2020b) presented work that focused on a systematic investigation of stress wave behavior in wood, including an in-depth analysis of signals recorded during stress wave testing of a large sample of wood specimens. After stress wave testing the specimens were tested to failure in tension. The statistical model using dynamic MOE to predict ultimate tensile stress (strength) yielded a coefficient of determination of 0.52. Additional parameters related to energy loss resulted in an improved model, with a coefficient of determination of 0.71.

Concluding Comments

This paper presents a summary of research efforts aimed at using NDE techniques to predict the strength of wood products. Strong correlative relationships were reported between various measurement of MOE. Relationships between nondestructive parameters and strength were found.

Acknowledgments

The authors acknowledge the support from USDA Forest Service Forest Products Laboratory (FPL) in Madison, Wisconsin, as a major contributor of technical assistance, advice, and guidance to this research. This publication is a contribution of the Forest and Wildlife Research Center, Mississippi State University.

References

- Anderson, G.C.; Owens, F.C.; Franca, F.; Ross, R.J.; Shmulsky, R. 2020. Correlations between grain angle meter readings and bending properties of mill-run southern pine lumber. *Forest Products Journal* 70(3):275-278.
- As, N.; Senalik, C.A.; Ross, R.J.; Wang, X. 2020 (a). Nondestructive Evaluation of the Tensile Properties of Structural Lumber from the Spruce–Pine–Fir Species Grouping-Relationship between Grain Angle and Energy Loss. Research Note. FPL-RN-0382. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 12 p.
- As, N.; Senalik, C.A.; Ross, R.J.; Wang, X.; Farber, B. 2020 (b). Nondestructive Evaluation of Tensile Properties of Structural Lumber from the Spruce–Pine–Fir Species Grouping-Relationship between Modulus of Elasticity and Ultimate Tension Stress. Research Note. FPL-RN-0383. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 12 p.
- Corder, S.E. 1965. Localized deflection related to bending strength of lumber. In: *Proceedings, 2nd nondestructive testing of wood symposium*; 1965 April; Spokane, WA. Pullman, WA: Washington State University: 461–472.
- Doyle, D.V.; Markwardt, L.J. 1966. Properties of Southern Pine in relation to strength grading of dimension lumber. Res. Pap. FPL–RP–64. Madison WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
- Entsminger, Edward D.; Brashaw, Brian K.; Seale, R. Daniel; Ross, Robert J. 2020. Machine grading of lumber—practical concerns for lumber producers. General Technical Report FPL-GTR-279. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 62 p.
- Franca, F.; Seale, R.D.; Ross, R. J; others. 2018. Using transverse vibration nondestructive testing techniques to estimate stiffness and strength of southern pine lumber. Research Paper. FPL-RP-695. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 6 p.
- Galligan, W.L.; Moyer, L. 1968. A status report: Nondestructive testing of lumber. In: *Proceedings, symposium “Focus 70”*; 1968 September; Vancouver, B.C., Canada: Council of Forest Industries.
- Green, D.W.; McDonald, K.A. 1993a. Investigation of the mechanical properties of red oak 2 by 4’s. *Wood and Fiber Science*. 25(1): 35–45.
- Green, D.W.; McDonald, K.A. 1993b. Mechanical properties of red maple structural lumber. *Wood and Fiber Science*. 25(4): 365–374.
- Hoerber, G.F. 1962. A study of modulus of elasticity and modulus of rupture in Douglas-fir dimension lumber. Lewiston, ID: Potlatch Forests, Inc.

- Hofstrand, A.D.; Howe, J.P. 1963. Relationship between modulus of elasticity and compression strength of white fir. Lewiston, ID: Potlatch Forests, Inc.
- Hoyle, R.J. 1961. A nondestructive test for stiffness of structural lumber. *Forest Products Journal*. 11(6): 251–254.
- Hoyle, R.J. 1962. Analysis of relationship between stiffness and strength of 2" x 8" white fir (*Abies grandis*) used as joist and plank. Lewiston, ID: Potlatch Forests, Inc.
- Hoyle, R.J. 1964. Research results on machine stress rated Southern Pine lumber. Lewiston, ID: Potlatch Forests, Inc.
- Hoyle, R.J. 1968. Background to machine stress rating. *Forest Products Journal*. 18(4): 87–97.
- Jayne, B.A. 1959. Vibrational properties of wood as indices of quality. *Forest Products Journal*. 9(11): 413–416.
- Johnson, J.W. 1965. Relationships among moduli of elasticity and rupture. In: *Proceedings, 2nd nondestructive testing of wood symposium*; 1965 April; Spokane, WA. Pullman, WA: Washington State University: 419–457.
- Kaiserlik, J.H.; Pellerin, R.F. 1977. Stress wave attenuation as an indicator of lumber strength. *Forest Products Journal*. 27(6): 39–43.
- Kramer, P.R. 1964. Correlation of bending strength and stiffness of Southern Pine. *Forest Products Journal*. 14(10): 495–496.
- Littleford, T.W. 1965. Mechanical stress rating of western Canadian species. In: *Proceedings, 2nd nondestructive testing of wood symposium*; 1965 April; Spokane, WA. Pullman, WA: Washington State University: 475–485.
- McKean, H.B.; Hoyle, R.J. 1962. Stress grading method for dimension lumber. Special Tech. Pub. 353. Philadelphia, PA: American Society for Testing Materials.
- Miller, D.G. 1965. In: *Proceedings, 2nd Nondestructive testing of wood symposium*. 1965 April, Spokane, Washington. Pullman: Washington: Washington State University. 485–491.
- O'Halloran, M.R. 1969. Nondestructive parameters for lodgepole pine dimension lumber. Fort Collins, CO: Colorado State University. M.S. thesis.
- Pellerin, R.F. 1963a. Compression parallel to grain versus modulus of elasticity for Douglas-fir dimension lumber. Washington State University, Division of Industrial Research. Lewiston, ID: Potlatch Forest, Inc.
- Pellerin, R.F. 1963b. Correlation of Strength properties of 1-inch lumber. Washington State University, Division of Industrial Research. Lewiston, ID: Potlatch Forests, Inc.
- Pellerin, R.F. 1965a. The contributions of transverse vibration grading to design and evaluation of 55-foot laminated beams. In: *Proceedings, 2nd nondestructive testing of wood symposium*; 1965 April; Spokane, WA. Pullman, WA: Washington State University: 337–347.
- Pellerin, R.F. 1965b. A vibrational approach to nondestructive testing of structural lumber. *Forest Products Journal*. 15(3): 93–101.
- Ross, R.J. 2015. *Nondestructive Evaluation of Wood*. Second Edition. General Technical Report. FPL–GTR–238. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 167 p.
- Ross, R.J. Geske, E.A.; Larson, G.L.; Murphy, J.F. 1991. Transverse vibration nondestructive testing using a personal computer. Res. Pap. FPL–RP–502. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

- Ross, Robert J.; Gonçalves, Raquel; Wang, Xiping, eds. 2015. Proceedings: 19th International Nondestructive Testing and Evaluation of Wood Symposium. General Technical Report FPL-GTR-239. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 688 p.
- Ross, R.J.; Pellerin, R.F. 1988. NDE of wood-based composites with longitudinal stress waves. *Forest Products Journal* 38(5): 39-45.
- Ross, Robert J.; Wang, Xiping. 2012. Nondestructive Testing and Evaluation of Wood—50 Years of Research: International Nondestructive Testing and Evaluation of Wood Symposium Series. General Technical Report FPL-GTR-213. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 6,702 p.
- Ross, Robert J.; Wang, Xiping, eds. 2013. Proceedings: 18th International Nondestructive Testing and Evaluation of Wood Symposium. General Technical Report FPL-GTR-226. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 808 p.
- Senalik, C.A.; Franca, F.; Seale, R.D.; Ross, R.J.; Shmulsky, R. 2020a. Estimating lumber properties with acoustic-based technologies. Part 1: modeling acoustic (stress) wave behavior in clear wood and lumber. *Wood and Fiber Science* 52(4): 380-389.
- Senalik, C.A.; Franca, F.; Seale, R.D.; Ross, R.J.; Shmulsky, R. 2020b. Estimating lumber properties with acoustic-based technologies. Part 2: Ultimate tension stress estimation from time and frequency domain parameters. *Wood and Fiber Science* 52(4): 390-399.
- Spinelli Correa, Laurice M; Franca, Frederico J. Nistal; Shmulsky, R.; Seale, R.D.; Wang, X.; Ross, R.J. 2022. Nondestructive evaluation of cross-laminated timber panels. Research Paper. FPL-RP-714. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 9 p.
- Sunley, J.G.; W.M. Hudson. 1964. Machine-grading lumber in Britain. *Forest Products Journal*. 14(4): 155–158.
- Uzcategui, M.G.C.; Franca, F.J.N.; Seale, R.D.; Senalik, C.A.; Ross, R.J. 2023 (a). Nondestructive evaluation of 2 × 10 southern pine lumber. *Forest Prod. J.* 73(3):186–193. doi:10.13073/FPJ-D-22-00054.
- Uzcategui, Marly G. C.; Franca, Frederico Jose Nistal; Seale, R. Daniel; Ross, Robert J.; Senalik, C. Adam. 2023 (b). Assessing 2 by 6 Southern Pine Lumber Flexural and Tensile Properties with Nondestructive Techniques. *Forest Products Journal*. 73(1): 75-81. <https://doi.org/10.13073/FPJ-D-22-00055>.
- Wang, Xiping; Ross, Robert J., eds. 2022. Proceedings: 22nd International Nondestructive Testing and Evaluation of Wood Symposium. General Technical Report FPL-GTR-290. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 324 p.
- Wang, Z.; Ross, R.J.; Murphy, J.F. 1993. A comparison of several NDE techniques for determining the modulus of elasticity of lumber. *Wood Forestry Research*. 6(4): 86–88. (In Chinese).
- Wang, Xiping; Sauter, Udo H.; Ross, Robert J., eds. 2019. Proceedings: 21st International Nondestructive Testing and Evaluation of Wood Symposium. General Technical Report FPL-GTR-272. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 724 p.
- Wang, Xiping; Senalik, C. Adam; Ross, Robert J., eds. 2017. Proceedings: 20th International Nondestructive Testing and Evaluation of Wood Symposium. General Technical Report FPL-GTR-249. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 539 p.
- Yang, B.Z.; Seale, R.D.; Shmulsky, R.; Dahlen, J.; Wang, X. 2015. Comparison of nondestructive testing methods for evaluating No. 2 southern pine lumber: Part A, modulus of elasticity. *Wood and Fiber Science*. 47(4) 375-384.

X-ray Densitometry in the Evaluation of Medium Density Fiberboard Bonded with Urea Formaldehyde Resin and Industrial Boiler Ash

Alexsandro Bayestorff da Cunha

Department of Forestry Engineering, Santa Catarina State University, Lages, Santa Catarina, Brazil,
alexsandro.cunha@udesc.br

Débora Caline de Melo

Department of Forestry Engineering, Santa Catarina State University, Lages, Santa Catarina, Brazil,
debora.mello.eng@hotmail.com

Joelson Lima Ferreira

Department of Forestry Engineering, Santa Catarina State University, Lages, Santa Catarina, Brazil,
joelsonlimaf@hotmail.com

Camila Alves Corrêa

Department of Forestry Engineering, Santa Catarina State University, Lages, Santa Catarina, Brazil,
camialvesc@gmail.com

Tarcisio Francisco de Camargo

Department of Forestry Engineering, Santa Catarina State University, Lages, Santa Catarina, Brazil,
tarcisiofcamargo@gmail.com

Polliana D'Angelo Rios

Department of Forestry Engineering, Santa Catarina State University, Lages, Santa Catarina, Brazil,
polliana.rios@udesc.br

Abstract

The objective was to analyze the apparent density and density profile of medium-density fiber panels manufactured with *Pinus taeda*, using urea-formaldehyde as an adhesive and ammonium sulfate and boiler ash as additives. The treatments were characterized by the presence or absence of ammonium sulfate and the addition of 0%, 1%, 3%, and 5% ash to the adhesive. The density was determined by the gravimetric method, and the density profile was assessed using an X-ray densitometer. The percentage of ash in the adhesive and the inclusion of ammonium sulfate did not influence the density by the gravimetric method and had no effect on the density of the layers by the X-ray method. It is concluded that the panels presented a typical density profile, making it viable to use ash as an additive, regardless of the application of ammonium sulfate.

Keywords: *Pinus taeda*, wood panels, density profile, forest biomass.

Introduction

Medium-density fiberboard (MDF) panels are produced from dry wood fibers, sprayed with synthetic adhesives, and bonded using pressure and high temperatures. Various adhesives can be used in their manufacture, depending on the product's intended use. Among the most used by the fiberboard industry is

urea-formaldehyde (UF) (Melo et al. 2010). Additionally, various additives can be incorporated into the adhesive composition, such as catalysts, which accelerate the curing of the adhesive, and inert fillers, which aim to enhance technological properties (Iwakiri 2005).

Due to a series of environmental concerns, the forest-based industry is increasingly focused on sustainability in its production processes, including the final disposal of solid waste generated. The cellulose, paper, and wood panel industries are major contributors to waste production in the form of bark, sanding dust, chips, sawdust, shavings, and other by-products, which are already extensively reused within the companies themselves to generate thermal and electrical energy. The process of burning biomass to generate energy results in the production of coal (boiler ash) (IBÁ 2019). This waste is typically disposed of in landfills, and due to the large volumes generated, it occupies significant storage areas, reducing the useful life of landfills.

In the literature, several studies have been conducted to find environmentally friendly destinations for biomass burning residues, such as soil amendment (Wittmann 2010); in the production of mortars (Vasconcellos et al. 2004); and as a raw material for manufacturing activated carbon (Werlang et al. 2013).

At the same time, studies have focused on developing adhesives with the inclusion of low-cost alternative additives. For example, Kim (2009) applied volcanic pozzolan to MDF panels in proportions of 1%, 3%, 5%, and 10% of UF resin, finding that the technological properties of the panel were not affected. Similarly, Kumar et al. (2013) added activated carbon to UF resin in proportions of 0.20%, 0.52%, and 1.04% of the adhesive weight, resulting in reduced curing time and increased internal bonding properties and modulus of rupture of MDF panels.

Considering these studies, the application of by-products, such as boiler ash, in adhesives may be advantageous due to their availability in large quantities and low cost. In addition to economic benefits, the reuse of boiler ash would be environmentally beneficial by reducing its accumulation in landfills, thus enhancing the industry's competitiveness through its positive environmental impact. Consequently, using boiler ash as an alternative additive in panel manufacturing, mixed with adhesive, could be promising. However, studies are needed to ensure that the panels meet quality standards regarding their physical and mechanical characteristics.

One of the most important properties of the panels is apparent density, as it significantly influences other physical and mechanical properties. Additionally, density is associated with process parameters such as pressing cycle (pressure, temperature, and time), adhesive, and wood (species, particle geometry, etc.) (Maloney 1993). The profile and variation of apparent density values throughout the thickness of wooden panels are crucial in evaluating process and raw material variables, determining their quality and final use (Wang et al. 2006). Researchers have reported using X-ray densitometry to obtain the apparent density profile in panels (Belini et al. 2009; Gonçalves et al. 2018; Surdi et al. 2014) because it is a non-destructive and quick-to-obtain data technique. Moreover, the X-ray technique can determine the quality of the panel by demonstrating the density distribution at various points and detecting anatomical and physical changes (Tomazello Filho et al. 2010).

The objective of this study was to determine the apparent density and vertical density profile of MDF panels produced with UF resin, ammonium sulfate, and boiler ash as an alternative additive.

Material and Methods

Raw materials

The raw material used to produce the panels comprised *Pinus* spp. fibers, urea-formaldehyde resin, and paraffin emulsion supplied by Sudati – MDF (Otacílio Costa, SC), a catalyst (ammonium sulfate) from Berneck (Curitibanos, SC), and forest biomass ash from the Engie boiler (Lages, SC).

The fibers were collected after the thermomechanical defibration process, and the only pre-treatment applied before producing the panels was drying in an oven with forced air circulation at a temperature of 80°C until reaching 4% humidity. According to the company's technical bulletin, the resin and paraffin had the following characteristics: (i) resin: molar ratio of 1.08, 220 cP viscosity, 60% solids content, 75 to 80 seconds of gel time, and a pH of 7.6; (ii) paraffin: 58.3% solids content and a pH of 8.9.

The ash used had, according to Gonçalves (2018), the following characteristics: moisture content of 5%; organic chemical composition with 72.85% carbon, 2.57% hydrogen, 0.28% nitrogen, and 0.02% sulfur. Upon arrival of the boiler ash in the laboratory, it was ground and classified using a 60-mesh sieve, considering the need for low particle size for effective incorporation into the adhesive.

Panels production

The panels were produced with a density of 750 kg.m⁻³, dimensions of 40 cm x 40 cm x 1.5 cm, 12% urea-formaldehyde resin, and 1% paraffin emulsion, with three repetitions per treatment. The treatments used in the study were characterized by incorporating different percentages of coal ash into the adhesive and using a catalyst in an aqueous solution of ammonium sulfate (24%) in an amount of 5% of the resin weight, as shown in Table 1.

Table 1— Experimental plan.

Treatment	Ash (%)	Catalyst
T1	0	Yes
T2	1	Yes
T3	3	Yes
T4	5	Yes
T5	0	No
T6	1	No
T7	3	No
T8	5	No

The adhesives were prepared by simply mixing the UF resin with the ash in a beaker, and homogenization was done manually with a glass rod for 15 minutes for each composition.

The adhesive application was carried out in a rotating drum gluing machine, where the pre-calculated quantity of fibers was deposited. A gun containing the adhesive was positioned in the center of the drum, driven by an air compressor as the drum rotated at a speed of 20 rpm. The produced mass (fibers + adhesive) was randomly placed in a forming box with internal dimensions of 40 cm x 40 cm x 25 cm, pre-pressed at room temperature under a pressure of 5 kgf.cm⁻² for 5 minutes, and then hot-pressed in a Marconi MA 098 hydraulic press for 10 minutes at a pressure of 40 kgf.cm⁻² and a temperature of 180°C.

Upon leaving the press, the panels were conditioned in a climatic chamber at a temperature of 20°C ± 3°C and relative humidity of 65% ± 3% until reaching a constant mass. Subsequently, the panels were trimmed to dimensions of 38 cm x 38 cm to reduce edge effects.

X-ray densitometry and gravimetric apparent density test

The size of the specimens and the test procedures were defined in accordance with the NBR 15316 standard (ABNT 2019). Twelve samples were extracted from each panel, with six designated for the gravimetric density test and six for X-ray densitometry, totaling 18 specimens measuring 50 mm x 50 mm for each treatment in both tests.

To determine the vertical density profile, the specimens were inserted into the sample holder of the IMAL DPX300 X-ray densitometer. They underwent irradiation in a sequential operation by a collimated X-ray beam with precisely controlled scanning speed. This process provided readings of the apparent density at a constant interval (40 μm linear distance) along the thickness of the specimen. These readings allowed for the determination of the average density, maximum density, and minimum density.



Figure 1 — X-ray densitometer (A); specimens at the time of testing (B); graphic result of the panel density profile (C).

The gravimetric density of the panel specimens was determined by measuring their volume (length, width, and thickness) with a 0.1 mm digital caliper and their mass using a 0.001 g precision digital scale.

Statistical analysis

The experiment was conducted following a completely randomized design with a two-factor arrangement, comprising four ash concentrations (0%, 1%, 3%, and 5%) and two levels of catalyst (presence and absence). The obtained values were subjected to verification of normality of data distribution using the Shapiro-Wilk test and homogeneity of variances using the Levene test. With the assumptions of parametric statistics met, analysis of variance and the Tukey test were performed to compare means at the 5% level of significance. Statistical analyses were conducted using the R program within the RStudio version 4.1.3 interface.

Results

In Table 2, it is observed that there was no statistically significant difference between the treatments, neither for the variation in the percentage of ash incorporated into the adhesive nor in the use of catalyst. Additionally, densities higher than the nominal value (750 kg.m^{-3}) are observed, but within the limits established by NBR 15316 (ABNT 2019) for classification as a medium-density panel, which is between 651 and 800 kg.m^{-3} .

Table 2— Average apparent density values using the gravimetric method.

Ash percentage (%)	Density (kg.m^{-3})	
	Without catalyst	With catalyst
0	T1 783 _(0,56) Aa	T5 785 _(1,21) Aa
1	T2 783 _(0,40) Aa	T6 784 _(1,09) Aa
3	T3 783 _(0,94) Aa	T7 783 _(0,83) Aa
5	T4 782 _(0,84) Aa	T8 783 _(0,57) Aa
Reference	750	

Density values higher (783 to 785 kg.m⁻³) than the nominal density (750 kg.m⁻³), as observed, reflect the number of fibers deposited in the mattress, which exceeded the calculated amount. This excess may have resulted from material spreading beyond the projected area during hot pressing. However, the fibers were well intertwined with each other and with the adhesive in the mattress, reducing expansion during the process. According to Dacosta et al. (2005), small variations are common in the manual manufacturing process of panels in the laboratory, particularly during mattress assembly phases and in the addition of resins and other additives. Similar deviations from nominal density in laboratory-produced panels have been observed in previous studies. Eugênio (2016) projected a density of 750 kg.m⁻³ but obtained 790 kg.m⁻³ for MDF panels with PVA adhesive in different concentrations. Sanches (2012) conducted a study with panels composed of various forest species (*Pinus taeda*, *Eucalyptus saligna*, *Mimosa scabrella*, and *Hovenia dulcis*), where the nominal density was 665 kg.m⁻³, but values varied up to 680 kg.m⁻³.

The homogeneity of average density values among treatments is attributed to the uniform distribution of fibers with adhesive during the mattress formation process. This behavior has been described by several authors, such as Ribeiro (2015), who evaluated the technological properties of MDF panels with wood from *Schzolibium amazonicum* and residues from Amazonian species, and Pereira (2014), who studied particleboard panels from *Pinus patula* and *Pinus* spp. with four levels of urea formaldehyde resin.

It is noteworthy that the incorporation of ash or catalyst into the adhesive did not alter the apparent density of the produced panels, which is a positive result. The consistency of density values among treatments is crucial in the technological evaluation of panels, as this variable significantly influences others, such as dimensional stability and properties of resistance and stiffness (Saldanha and Iwakiri, 2009; Mendes et al. 2008; Protásio et al. 2012).

Table 3 presents the values for the density profile, where the variable can be observed in three different portions throughout the panel thickness (upper, central, and lower layers), as well as the average density. The table demonstrates equivalence in density values for all treatments, irrespective of the percentage of ash incorporated into the adhesive. However, there is a significant difference between the external and central layers, which is attributed to the greater compaction of the fibers.

Density differences between the outer layers of the panel and the central one, as noted by Maloney (1993), occur during the pressing process. In this phase, the heated press plates meet the mattress, transmitting heat that causes the humidity of the panel to evaporate. This process results in the plasticization of the wood lignin and greater ease of compression in the outer layers. Conversely, the center of the panel receives less heat, hindering such compression. By the time the temperature reaches the central layer, the panel has already attained the desired thickness, meaning that the central layer does not have sufficient time to become as compacted as the outer layers. As a result, the classic graph for the density profile of reconstituted wood panels exhibits an "M" shape.

The greater compaction of the external layers enhances the dimensional stability and resistance to static bending of the panels (Kollmann et al. 1975) due to lower porosity (Belini et al. 2009) and reduces formaldehyde emission rates (Marutzky et al. 1992). Maloney (1993) adds that low density values in the central portion of the panel can compromise the resistance properties to top screw pullout and perpendicular traction. Among the process variables that can influence the density profile of the panels, Suchsland and Woodson (1986), as well as Maloney (1993), cite the press closing time, the moisture content of the external layers in relation to the center, and the pressure and temperature used during the process. Factors intrinsic to wood, such as the species of wood used, the geometry, and distribution of fibers, also play a role (Kollmann et al. 1975).

Table 3— Average values of the panel density profile using the X-ray densitometry method.

Without catalyst						
Ash percentage (%)	Density (kg.m ⁻³)					
	Average	Upper maximum		Core	Lower maximum	
0	784 A	(+14%) 894	(+49%) Aa	(-23%) 601 Ab	(+13%) 890	(+48%) Aa
1	781 A	(+13%) 886	(+55%) Aa	(-27%) 572 Ab	(+12%) 875	(+53%) Aa
3	783 A	(+11%) 866	(+55%) Aa	(-28%) 560 Ab	(+10%) 863	(+54%) Aa
5	780 A	(+11%) 864	(+57%) Aa	(-29%) 552 Ab	(+10%) 857	(+55%) Aa
With catalyst						
Ash percentage (%)	Density (kg.m ⁻³)					
	Average	Upper maximum		Core	Lower maximum	
0	786 A	(+14%) 899	(+49%) Aa	(-23%) 603 Ab	(+13%) 889	(+47%) Aa
1	785 A	(+13%) 890	(+49%) Aa	(-24%) 598 Ab	(+12%) 878	(+47%) Aa
3	788 A	(+10%) 869	(+48%) Aa	(-26%) 585 Ab	(+10%) 871	(+49%) Aa
5	785 A	(+9%) 855	(+48%) Aa	(-26%) 579 Ab	(+10%) 867	(+50%) Aa

Superscript: percentage difference in layer densities in relation to the average density. Subscript: percentage difference in the densities of the upper and lower layers in relation to the core layer; means followed by the same capital letter in the column do not differ statistically from each other for ash percentage; means followed by the same lowercase letter on the same line do not statistically differ from each other for different layers along the panel thickness, both by Tukey's test at a 5% significance level.

According to Suchsland and Woodson (1986), the influence of the density profile, i.e., the differences between the densities of the external and central layers, is more significant in thick panels than in thin ones. They also highlight that the higher the contrast, the better the resistance properties to static bending and screw pullout. Trianoski (2010) suggests that the difference between the maximum and minimum densities in reconstituted wood panels for industrial conditions should be between 20% and 35%. In this context, it is observed that the differences for all treatments ranged between 47% and 57%, thus exceeding the suggested range. Torquato et al. (2010) also found similar variations for MDF panels made from *Pinus* spp., with an average of 57%.

Regarding the difference between the density of the layers and the average density, it is observed that the values varied from a 9% to 14% increase for the surfaces in relation to the average, and from a 23% to 29% reduction for the central layer, also in relation to the average. These results are consistent with those obtained by Ferreira (2020), who recorded an average variation of 24.6%, and by Torquato et al. (2010), who found a variation of around 19% for MDF panels made from *Pinus* spp.

Conclusion

The panels were classified as medium density and exhibited a density profile typical of MDF panels, with more compacted outer layers. The application of the catalyst and boiler ash to the adhesive did not significantly influence the analyzed density properties, suggesting that boiler ash can be incorporated into the UF adhesive as an alternative additive, regardless of the use of ammonium sulfate catalyst.

For future research, it is recommended to evaluate the influence of ash inclusion in the adhesive on other physical and mechanical properties of the panels.

Acknowledgments

We extend our gratitude to Engie Brasil, Berneck S.A., and Sudati MDF for their support and provision of materials that enabled the completion of this study. Special thanks to Mr. Gefferson Costa de Liz for his invaluable assistance throughout the research process.

References

- Associação Brasileira de Normas Técnicas. 2019. NBR 15316 - Painéis de fibra de média densidade. Rio de Janeiro.
- Belini, U.L., Tomazello Filho, M., Chagas, M.P. 2009. Densitometria de raios X aplicada na avaliação tecnológica de painéis MDF de eucalipto. *Sci. For.* 37(84): 343-350.
- Dacosta, L.P.E.; Haselein, C.R.; Santini, E.J.; Schneider, P.R.; Calegari, L. 2005. Qualidade das chapas de partículas aglomeradas fabricadas com resíduos do processamento mecânico da madeira de *Pinus elliottii* Engelm. *Ciência Florestal*. 15(4): 311-322.
- Eugênio, R.A.P. 2016. Painéis de medium density fiberboard produzidos com adesivo alternativo. Bauru, SP: Universidade Estadual Paulista. 126 p. M.S. thesis
- Gonçalves, F.G.; Lelis, R.C.C.; Carvalho, A.M.; Tomazello Filho, M. 2018. Densitometria de raios x na avaliação da densidade em painéis de partículas. *Ciência Florestal*. 28(3): 1151–1162.
- Indústria Brasileira de Árvores – IBÁ. 2019. Relatório anual 2019. São Paulo, Brasil. <https://iba.org/datafiles/publicacoes/relatorios/iba-relatorioanual2019.pdf> [accessed July 30, 2018].
- Iwakiri, S. Painéis de madeira reconstituída. Curitiba: FUPE, 2005. 254 p.
- Kollmann, F.P.; Kuenzi, E.W; Stamm, J. 1975. Principles of wood science an technology wood based material. New York, USA: Springer – Verlag.
- Kumar, A.; Gupta, A.; Sharma, K.V.; Nasir, T.A. 2013. Influence of activated charcoal as filler on the properties of wood composites. *International Journal of Adhesion and Adhesives*. 46: 34-39.
- Kim, S. 2009. The reduction of indoor air pollutant from wood-based composite by adding pozzolan for building materials. *Construction and Building Materials*. 23(9): 2319-2323.
- Marutzky R.; Flentge, A.; Boehme, C. 1992. Dependence of formaldehyde emission of MDF on the density profile. *Holz als Roh und Werkstoff*. 50(6): 239-240.
- Maloney, T.M. 1993. Modern particleboard and dry-process fiberboard manufacturing. San Francisco: Miller Freeman. 688 p.
- Melo, R.R. et al. 2010. Resistência de painéis aglomerados produzidos com diferentes proporções de madeira e casca de arroz a fungos e cupins xilófagos. *Ciência Florestal*. 20(3): 501-511.
- Mendes, R.F. 2008. Influência da densidade do painel e da composição em camadas nas propriedades físico-mecânicas de painéis OSB de clones de *Eucalyptus* spp. *Cerne*. 14(4): 379-385.
- Pereira, G.F. 2014. Comparação das propriedades físicas de painéis de madeira aglomerada de *Pinus patula* e *Pinus* sp. de origem industrial. Curitiba, SC: Universidade Federal de Santa Catarina. 56 p. thesis.
- Protásio, T.P.; Guimarães Jr, J.B.; Mendes, R.F.; Mendes, L.M.; Guimarães, B.M.R. 2012. Correlações entre as propriedades físicas e mecânicas de painéis aglomerados de diferentes espécies de *Eucalyptus*. *Floresta e Ambiente*. 19(2): 123-132.

Sanches, F.L. 2012. Qualidade de painéis aglomerados produzidos com mistura de madeira de quatro espécies florestais. Irati, PR: Universidade Estadual do Centro-Oeste. 93 p. M.S. thesis.

Ribeiro, V.C.N. 2015. Caracterização anatômica da matéria-prima e avaliação das propriedades tecnológicas de painéis MDF de madeira de *Schizolobium amazonicum* Huber ex Ducke e de resíduos de espécies da Amazônia. Piracicaba, SP: Universidade de São Paulo Escola. 123 p. M.S. thesis.

Saldanha, L. K.; Iwakiri, S. 2009. Influência da densidade e do tipo de resina nas propriedades tecnológicas de painéis OSB de *Pinus taeda*. Floresta. 39(3): 571-576.

Suchsland, O., Woodson, G.E. (1986). Fiberboard manufacturing practices in the United States. United States: U.S. Department of Agriculture, Forest Service. 263 p.

Surdi, P.G.; Bortoletto Jr. G.; Castro, V.R.; Mendes, R.F.; Almeida, N.F.; Tomazello Filho, M. 2014. Relação entre Perfil de Densidade e Ligação Interna de Painéis OSB de *Pinus* spp. Floresta e Ambiente. 21(3): 349-357.

Torquato, L.P.; Iwakiri, S.; Bonduelle, G. M.; Albuquerque, C. E. C.; Matos, J. L.M. 2010. Avaliação das propriedades físicas e mecânicas de painéis de fibras de média densidade (MDF) produzidos pelas indústrias brasileiras. Floresta. 40(2): 275-280.

Tomazello Filho, M. et al. 2010. Avaliação tecnológica da madeira e de painéis MDF de eucalipto por densitometria de raios X. Madeira: Arquitetura & Engenharia. 11 (27): 45-58.

Trianoski, R. 2010. Avaliação do potencial de espécies florestais alternativas, de rápido crescimento, para produção de painéis de madeira aglomerada. Curitiba, PR: Universidade Federal do Paraná. 252 p. M.S. thesis.

Vasconcellos, C.B.; Leal, C.L.D.; França, M.P.; Castro, P.F. 2004. Aproveitamento da Cinza de Caldeira na Construção Civil. Vértices. 6(1).

Wang, X. et al. 2006. Evaluation of density distribution in wood-based panels using X-ray scanning. The e-Journal of Nondestructive Testing. 11(4).

Werlang, E.B.; Schneider, R.C.S.; Rodriguez, A.L.; Niedersberg, C. 2013. Produção De Carvão Ativado A Partir De Resíduos Vegetais. Revista Jovens Pesquisadores. 3 (1):v156-167.

Wittmann, A.L. 2010. Proposta para tratamento e destinação dos resíduos sólidos orgânicos do Grupo Santa Maria. Curitiba, PR: Universidade Federal do Paraná. 75 p. thesis.

Quality Journey: ISO 9001 and Benefits Perception in Croatian Wood Companies

Kristina Klarić

Department of Production Organization, Faculty of Forestry and Wood Technology University of Zagreb, Zagreb, Croatia, kklaric@sumfak.unizg.hr

Andreja Pirc Barčić *

Department of Production Organization, Faculty of Forestry and Wood Technology University of Zagreb, Zagreb, Croatia, apirc@sumfak.unizg.hr

Karla Vukman

Department of Production Organization, Faculty of Forestry and Wood Technology University of Zagreb, Zagreb, Croatia, kkremenj1@sumfak.unizg.hr

Jelena Obranković

Department of Production Organization, Faculty of Forestry and Wood Technology University of Zagreb, Zagreb, Croatia, jelena.obrankovic@gmail.com

Petar Ćurić

Department of Production Organization, Faculty of Forestry and Wood Technology University of Zagreb, Zagreb, Croatia, petar.curic@gmail.com

* Corresponding author

Abstract

In order to meet customer needs, wood industry companies are forced to invest in the quality of their products, processes and services. Quality management is a set of management actions that determines quality policy, goals and responsibility, and is achieved through planning, monitoring, ensuring, and improving quality. ISO 9001, the most widespread quality management standard, requires the implementation of a monitoring and performance measurement system. Furthermore, this standard can facilitate certificate holders the integration of non-destructive testing techniques to achieve greater compliance in the processes of design, manufacturing, and quality assurance. The research objective is to explore the perception of benefits from ISO 9001 certification within companies in the Croatian wood industry. Based on the research objective, a questionnaire was developed. The first part consisted of questions to gather companies' general profiles. The second part related to the ISO 9001 quality management system benefits perception. The sample frame was 233 wood manufacturing companies (according to NACE rev. 2 classified in the field C 16 - the manufacture of wood and of products of wood and cork and C 31 – furniture manufacturing) in Croatia. The first survey process was conducted in the 2014 and the second one in 2023. In 2014 the total number of usable surveys received was 41 (response rate of 17,6%) and in 2023 was 33 (response rate of 14,2%). The results showed that the number of certificates in wood industry companies increased in 2024 compared to 2013. Respondents have continued to recognize similar major benefits of implementing the ISO 9001 system, emphasizing the ability to anticipate errors, improve product and service quality, and enhance customer satisfaction and trust. This confirms the significance of the standard's requirement related to measurement and monitoring.

Keywords: quality, wood industry, ISO 9001, Croatian.

Nondestructive Evaluation Approach: Analysis of Quality Data Information about Wood Products in Retail Shops in Croatia

Andreja Pirc Barčić *

Department of Production Organization, Faculty of Forestry and Wood Technology University of Zagreb, Zagreb, Croatia, apirc@sumfak.unizg.hr

Petar Ćurić

Department of Production Organization, Faculty of Forestry and Wood Technology University of Zagreb, Zagreb, Croatia, petar.curic@gmail.com

Jelena Obranković

Department of Production Organization, Faculty of Forestry and Wood Technology University of Zagreb, Zagreb, Croatia, jelena.obrankovic@gmail.com

Danijela Domljan

Department of Furniture and Wood in Construction, Faculty of Forestry and Wood Technology University of Zagreb, Zagreb, Croatia, ddomljan@sumfak.hr

* Corresponding author

Abstract

Checking the quality of a product before making a purchase is essential to ensure that consumer gets value for the money and avoids any potential disappointment. The consumer protection documents have the main role in protecting consumers from unfair, unreasonable and/or improper trade practices, which means they protect consumers from misleading, deceptive, unfair or fraudulent conduct and/or actions. For an example, in the European Directive 2019/2161 is aiming to provide the better enforcement and modernization of Union consumer protection rules strengthening consumer rights by giving consumers the same rights across the EU. Additionally, national authorities in individual countries are responsible for the enforcement of EU consumer protection laws. The aim of this paper to analyze quality, quantity, transparency and accuracy of information on wood products in Croatian retail shops. Furthermore, improperly and incorrectly defined and highlighted documents and declarations of wood products can mislead the consumer in its purchasing decision so an additional aim was to provoke and maybe motivate the professional and scientific community to consider which non-destructive methods and procedures could be applied to evaluate quality of wood products in stores and retail shops. Based on the research objective, a questionnaire was developed. The first part consisted of questions to gather retail profiles. The second part related to gathering information about wood products - information about materials (etc. is it made of wood or some material similar to wood); country of origin; product safety; eco-labels, etc. Research was conducted within 20 wood product retail shops in 2023 in Croatia including 9 categories of wood products. Overall, more than 180 wood products were analyzed. Results show that quality and transparency of information regarding wood products in retail shops are incomplete and sometimes incorrect, which is not in line with rules defined in consumer protection documents.

Keywords: nondestructive evaluation approach, wood-based products, quality data information, Croatia

Combined Effect of Wood Temperature and Moisture Content on Drilling Resistance Measurements

Evgenii Sharapov *

Volga State University of Technology, Yoshkar-Ola, Mari El Republic, Russian Federation,
sharapoves@volgatech.net

Aleksandr Korolev

Volga State University of Technology, Yoshkar-Ola, Mari El Republic, Russian Federation,
korolevas@volgatech.net

Oleg Egoshin

Volga State University of Technology, Yoshkar-Ola, Mari El Republic, Russian Federation,

* Corresponding author

Abstract

Drilling resistance (DR) measurements is a widely used nondestructive method to evaluate the quality and internal defects of wood. Due to climate conditions, assessment of wood in growing trees and timber structures can be conducted at low temperatures, for example, below the freezing point of water. The amount of moisture in the wood can have an additional significant influence on the DR measurements. The objective of the study was to determine a combined influence of the temperature and moisture content (MC) of wood on DR. Laboratory tests were carried out on defect-free specimens of Scots pine (*Pinus sylvestris* L.) conditioned at 20°C/40% RH (mean MC=7.4%), 20°C/65% RH (MC=11%), 20°C/98% RH (MC=23.5%) for ensuring EMC and vacuum-impregnated in water (MC=147.9%). Subsequently, the specimens were kept at temperatures of 20°C, 2°C, –2°C and –10°C in plastic bags. An IML-RESI PD 400 tool and a standard spade drill bit (IML System GmbH, Wiesloch, Germany) were used to measure the DR and feeding resistance (FR). In total, 256 DR and FR laboratory measurements were made with 16 repetitions for each factor combination. Additional tests were carried out on 33 growing trees at +18°C and –15°C. Statistical differences between the mean DR and FR were assessed using ANOVA, Tukey's HSD, and t-test. The significant influence of temperature on the mean DR and FR was found for the specimens with MC 11% and higher. The water saturated specimens tested at –10°C had a drastic increase in DR and FR. Frozen free moisture had an impact on the mechanical properties of wood and the drill bit penetration process (drilling process). Control of temperature and wood MC can be recommended for evaluation of wood properties by DR and possible adjustment of DR profiles. The research work was supported by the Russian Science Foundation (RSF, No 23-16-00220), <https://rscf.ru/en/project/23-16-00220/>.

Keywords: in-situ assessment, nondestructive testing, structural timber, growing tree, wood properties.

Sugarcane Culm Radiographs: Methodology and Potential Applications

Bruna Hornink*

Department of Plant Biology, Institute of Biology, University of Campinas – UNICAMP, Campinas, São Paulo, Brazil, bhornink@gmail.com

João Paulo R. Marques

Department of Basic Sciences, Faculdade de Zootecnia e Engenharia de Alimentos, Universidade de São Paulo - USP, Pirassununga, São Paulo, Brazil, joaoanatomia@gmail.com

Gabriel de Assis-Pereira

Department of Forest Resource, Escola Superior de Agricultura Luiz de Queiroz – ESALQ, Universidade de São Paulo - USP, Piracicaba, São Paulo, Brazil, gabriel_assispereira@hotmail.com

Mario Tomazello-Filho

Department of Forest Resource, Escola Superior de Agricultura Luiz de Queiroz – ESALQ, Universidade de São Paulo - USP, Piracicaba, São Paulo, Brazil, mtomazel@usp.br

* Corresponding author

Abstract

Sugarcane is globally recognized as an agricultural crop with a wide range of applications beyond sugar and ethanol production, including use as a source of fiber for animal feed, biogas, pellets, paper, packaging, panels, and more. Despite its importance, there is a notable lack of literature on methods for analyzing sugarcane culms and their correlation with technological properties. This study evaluates sugarcane culms from three commercial varieties using X-ray imaging and densitometry. The process involved immersing culm internodes in a fixative solution (FAA), followed by cutting 3 mm-thick cross sections using a Buehler Isomet 5000. The sections were hydrated in a Petri dish, then dehydrated in an acetone gradient (30% to 100%, 15 min per step), and finally dried ($U_0\%$) using a Leica CPD 300 critical point dryer to prevent shrinkage during X-ray exposure with a Faxitron LX-60. This preparation facilitated the acquisition of digital radiographic images for anatomical analysis and culm density determination using WindendroTM software. The study characterized the anatomical structures of three sugarcane varieties, noting differences in vascular bundle concentration and parenchyma tissue distribution. A consistent variation pattern was observed across the varieties: higher vascular bundle concentration and lower parenchyma tissue density in the outermost regions compared to the innermost. The ratio of parenchyma to vascular bundles correlated with the mean culm density, which was higher in the peripheral areas due to greater vascular bundle concentration. The potential applications of this methodology span various fields, including nutrition, irrigation, genetics, pest and disease management, biomass production, and carbon sequestration, in addition to technological characterization of sugarcane culms.

Keywords: X-ray densitometry, crop technological properties, CO₂ critical point, anatomical structure

Annual Tree-Rings Wood Density of *Pera glabrata* Trees Trunk Occurring in the Cerrado Biome Applying X-Ray Densitometry

Gabriel Assis-Pereira *

Department of Forest Sciences, ESALQ, University of São Paulo, Piracicaba, Brazil,
Instituto de Pesquisas Ambientais do Estado de São Paulo, Assis, Brazil,
gabriel_assispereira@hotmail.com

Victor César da Silva Oliveira

Department of Forest Sciences, ESALQ, University of São Paulo, Piracicaba, Brazil, victorcesar@usp.br

Davi Neves de Lemos

Department of Forest Sciences, ESALQ, University of São Paulo, Piracicaba, Brazil, davinl@id.uff.br

Maycon da Silva Teixeira

Department of Forest Sciences, ESALQ, University of São Paulo, Piracicaba, Brazil, mayconst@usp.br

Tiago Marcilio Gomes Pinto

Department of Forest Sciences, ESALQ, University of São Paulo, Piracicaba, Brazil,
tiagomarcilio@usp.br

Mario Tomazello-Fo

Department of Forest Sciences, ESALQ, University of São Paulo, Piracicaba, Brazil, mtomazel@usp.br

Giselda Durigan

Instituto de Pesquisas Ambientais do Estado de São Paulo, Assis, Brazil, giselda.durigan@gmail.com

* Corresponding author

Abstract

New methodologies for the qualitative and quantitative analysis of different parts of plants have been presented in the literature. However, the tree trunk stands out in the analyses, and, more frequently with the wood density determination, applying allometric equations. With this objective, in the present work, the X-ray densitometry methodology was applied to determine the tree-rings wood density of the trunk of 11-*Pera glabrata* trees occurring in the Cerrado biome, in Águas de Santa Bárbara, SP, Brazil. The analysis of the radial wood density profiles allowed the tree-rings delimitation and, in this way, the *Pera glabrata* trees age determination, from 23 to 47 years old. Based on the tree trunk diameter, mean annual trunk growth of 1.24 ± 0.30 cm/year were obtained; the radial profiles indicated mean wood apparent density of 0.77 ± 0.04 g/cm³. The results of the age, annual increase and mean trunk wood density of *Pera glabrata* trees make it possible to reconstruct its growth dynamics in the Cerrado and relate to climatic variables, incidence of natural fires and other factors. Based on the results, the work discusses sustainable management practices of numerous tree species in the Cerrado, including their resilience in the face of extreme climatic events (Funding: FAPESP project 2020/01378-0 and 2023/14668-5)

Keywords: trunk analysis, age determination, growth dynamics, climatic variables.

Advancing Biomass Characterization: Near-Infrared Spectroscopy and Chemometrics in Modern Non-Destructive Wood Analysis

Iris Beatriz Vega Erramuspe *

College of Forestry, Wildlife & Environment, Auburn University, AL, USA, ibv0002@auburn.edu

Laura Michelle Nieto Arciniegas

College of Forestry, Wildlife & Environment, Auburn University, Auburn, AL, USA,
lzn0032@auburn.edu

Christian Rivera Caicedo

College of Forestry, Wildlife & Environment, Auburn University, AL, USA

Astrid Melissa Rojas Marquez

College of Forestry, Wildlife & Environment, Auburn University, Auburn, AL, USA,
amr0201@auburn.edu

Mathew Smidt

USDA Forest Service, Southern Research Station, Auburn, AL, USA, mathew.smidt@usda.gov

Brian Via

College of Forestry, Wildlife & Environment, Auburn University, AL, USA, brianvia@auburn.edu

* Corresponding author

Abstract

Wood's significance across industries like construction, furniture, and paper manufacturing underscores the need for precise analysis to ensure quality and sustainable management. Near-infrared spectroscopy (NIRS) combined with advanced chemometric models offers a powerful non-destructive tool for this purpose, providing rapid analysis, minimal sample preparation, and accurate prediction of wood properties through techniques like principal component analysis (PCA) and partial least squares regression (PLS).

In this study, we present the results of our efforts in developing chemometric models combining the power of NIR spectroscopy and traditional chemical analysis. These models have shown potential applications in the analysis of carbon content in wood, detection of fungal infection in pine needles, and assessment of wood decay. In our study focused on estimating carbon content in woody samples using NIRS coupled with chemometric models, the correlation between the C-content obtained by elemental analysis and the NIR spectra of standard samples was used to build the chemometric model, enabling the prediction of C-content in unknown samples with low error. In the context of fungal infection detection, NIR spectroscopy combined with chemometric models can discriminate between healthy and infected pine needles based on subtle spectral differences associated with biochemical changes induced by fungal pathogens, such as the increment in lignin content. NIR spectroscopy coupled with chemometric models has also shown great potential in assessing wood decay, enabling rapid identification and quantification of decay extent in wooden structures. Traditional wet chemical analysis was essential in developing the chemometric model for this purpose.

In conclusion, the integration of near-infrared spectroscopy with advanced chemometric models presents a promising approach for non-destructive wood analysis, offering rapid and accurate insights into wood quality, composition, and health across various applications and industries.