In: Wang, X.; Sauter, U.H.; Ross, R.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. pp 250-261.

Nondestructive Evaluation of Tensile Properties of Structural Lumber from the Spruce–Pine–Fir Species Grouping: Phase 1. Evaluation of Modulus of Elasticity

Nusret As
Istanbul University, Istanbul, Turkey, nusretas@istanbul.edu.tr

Robert J. Ross
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA, robert.j.ross@usda.gov
Michigan Technological University, Houghton, Michigan, USA
Mississippi State University, Starkville, Mississippi, USA

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

Christopher Adam Senalik
USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin, USA, christopher.a.senalik@ usda.gov

Abstract

The study summarized in this report was conducted to examine the relationships between nondestructive evaluation parameters and the modulus of elasticity (MOE) of spruce–pine–fir structural lumber. A random sample of lumber was obtained from a local lumber yard and conditioned to approximately 10% equilibrium moisture content in the laboratory. Static bending and vibration (transverse and longitudinal) nondestructive tests were conducted on each specimen, and MOE was calculated. The relationship between static and dynamic modulus values was examined, and empirical models were developed using statistical regression analysis techniques. Results revealed excellent correlative relationships between MOE values. Coefficients of determination obtained were 0.92, 0.96, and 0.93 for MOE of static–transverse vibration, MOE of static–longitudinal vibration, MOE of longitudinal–transverse vibration, respectively.

Keywords: nondestructive evaluation, modulus of elasticity, spruce–pine–fir lumber

Introduction

The tensile strength of wood and lumber products is important in the design of engineered components and structural systems. For example, the bottom chord of a wood truss is stressed in tension as are the undersides of large glued-laminated timbers. The tensile strength of wood is 20 to 50 times greater along the grain (fibers generally aligned with the long axis of a lumber specimen) than in the radial or tangential directions for softwood species and species groupings that are commonly used in structural applications. The grain angle is the angle between the wood fibers and the edges of a piece of wood. Variations in grain orientation are especially great around knots and are a major factor governing the ultimate strength of a piece of lumber in tension.

A search of the literature in the USDA Forest Products Laboratory's library collection, Web of Science, and Engineering Index yielded several technical papers that summarize attempts to investigate the use of nondestructive testing (NDT) techniques to predict the tensile strength of structural lumber.

Hoyle (1968) summarized early research efforts from a variety of laboratories that resulted in the technology referred to as machine stress rating (MSR) of lumber. He presented results from several studies specifically designed to examine the relationship between the modulus of elasticity (MOE) (measured in a flat-wise orientation, utilizing a center span dead load) and the corresponding strength of softwood structural lumber. He reported that the statistical models relating MOE and tensile strength yielded correlation coefficients ranging from 0.74 to 0.82.

Orosz (1977) and Green and McDonald (1993a, 1993b) utilized transverse vibration NDT techniques to measure the MOE of structural lumber. Green and McDonald reported correlation coefficients for the models relating MOE to tensile strength that ranged from 0.46 to 0.60.

Kaiserlik and Pellerin (1977) examined the use of a longitudinal vibration NDT method to evaluate the tensile strength of softwood lumber. They reported a correlation coefficient of 0.84 when MOE was compared with tensile strength values. It is interesting to note that in addition to measuring the longitudinal MOE, they measured the attenuation rate of the stress wave as it travelled through the lumber specimens. When incorporating this additional parameter in their prediction equation, they reported a correlation coefficient of 0.90.

Cramer and Fohrell (1990) reported on a series of studies that developed fundamental information on the physical and mechanical properties of wood in knots and fiber deviation observed around knots. Knots significantly reduce the tensile strength of structural lumber. Although this work provided excellent information on stress distributions in the vicinity of knots, it did not provide a commercially useful methodology for evaluating lumber properties.

Rajeshwar et al. (1997) provided details on the use of an ultrasonic technique for estimating the strength of Southern Pine structural lumber. Ultrasounds through transmission measurements were made at several locations in the vicinity of knots and used to predict strength.

An NDT method for measuring the grain orientation is based on the difference in dielectric constant (permittivity) of wood between the parallel direction (lower dielectric constant) and the perpendicular direction (higher dielectric constant) to the grain. The dielectric constant is simply the ability of a material to concentrate an applied electric field. Measuring a material's dielectric constant can be as simple as measuring the current flow between two conductors with an alternating voltage applied. At low moisture content levels, wood can be considered a dielectric material (Kellogg 1981, James and Hamill 1965, Lin 1967, Skaar 1948). The dielectric constant of a nonconducting material determines the amount of electric potential energy that is stored in a given volume of the material within an electric field. It is expressed as the ratio of the dielectric permittivity of the material relative to that of a vacuum or dry air. Experimentally, it is determined as the ratio of the capacity of a condenser with the material acting as the dielectric relative to the capacity of the condenser when the space between the plates is dry air. The dielectric constant for wood varies with grain (fiber) direction, and commercial equipment has been developed that utilizes this fact to determine fiber orientation in wood products. Knots, spiral grain, and other defects can be detected by measuring dielectric properties.

Pellerin and Ross (2015) provided a review of the concept and development of tension proof loading, a technology that focuses on testing each piece of lumber to a predetermined load level near its design load.

Pieces of lumber having a strength below the set design load would fail, thereby eliminating them from the lumber to be used.

The preceding review reveals the following: 1. There has not been a systematic evaluation of the relationships between widely used NDT parameters and the tensile properties of structural lumber. 2. There is no reported research focused on the potential of using combinations of these techniques to predict the strength of structural lumber.

The overarching objective of our cooperative work is to systematically evaluate relationships between several NDT parameters and the tensile properties of softwood structural lumber. This report summarizes the first phase of our work. It summarizes our examination of the relationships between several measurements of MOE of a sample of spruce–pine–fir lumber.

Materials and Methods

Materials

One hundred nominal 2- by 4-in. (38- by 89-mm), 12-ft- (3.66-m-) long lumber specimens (visual grade No. 2 or better, spruce–pine–fir species group) were obtained from a local lumber yard. All specimens were stickered and equilibrated at a temperature of 70 °F (21 °C) and relative humidity (RH) of 50% (Figure 1).

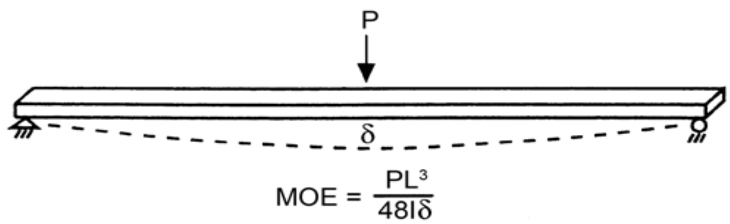
Figure 1—Lumber specimens used in this study.

Nondestructive test methods

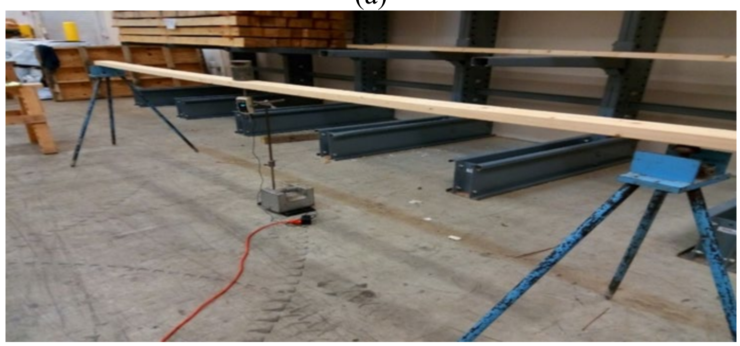
The following briefly describes the test setups that were used for measurement of MOE. Detailed descriptions of each setup, and subsequent analysis, are presented in Ross (2015).

Flatwise bending

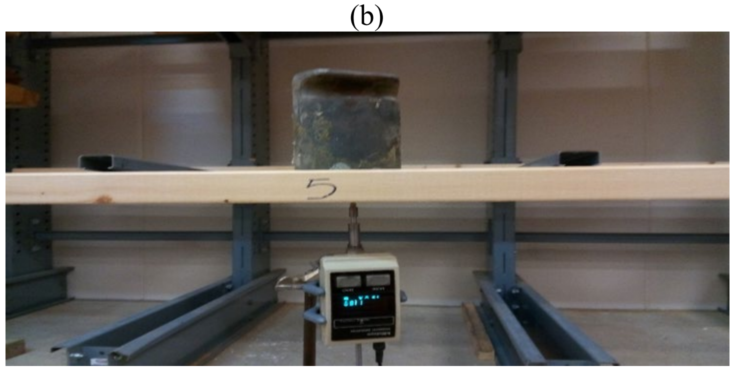
Figure 2 illustrates the center-point loading test setup that was used. Each specimen was simply supported at both ends, a load applied, and the midspan deflection that resulted from the load measured. A span of 3.5 m was used. A load of 4.54 kg was applied at midspan, and the specimen's corresponding deflection was measured.



(a)



(b)



(c)

Figure 2—Flatwise bending test setup: (a) test setup; (b) specimen being tested; and (c) load being applied and corresponding deflection measurement.

The flatwise bending MOE of a specimen was calculated using the following formula:

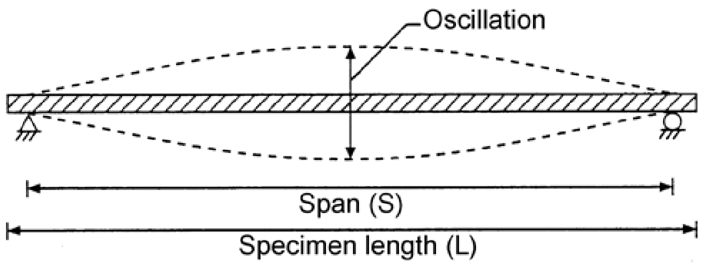
$$\text{MOE} = \frac{PL^3}{48I\delta}$$

where

P is applied load (N),
L is span (mm),
I is moment of inertia (mm^4), and
δ is midspan deflection (mm).

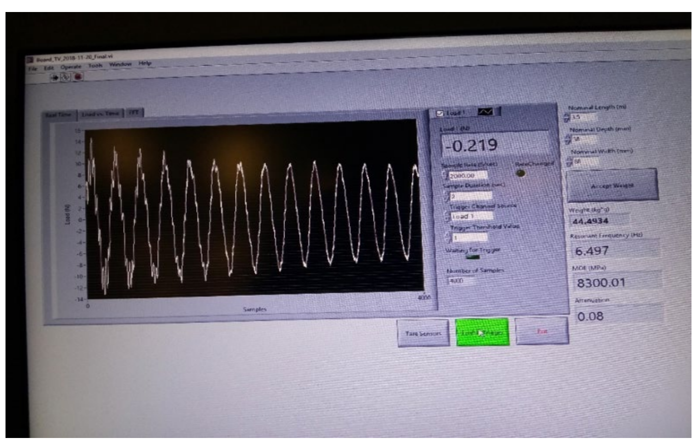
Transverse vibration

Figure 3 illustrates the free transverse vibration test setup we used. A specimen was simply supported at both ends. A slight deflection was introduced at the midspan of the specimen. The specimen was then allowed to freely oscillate in the vertical (transverse) direction. Frequency of oscillation was measured, coupled with the specimen's weight and dimensions, and used to compute MOE.



(a)

(b)



(c)

Figure 3—Transverse vibration test setup used in this study: (a) transverse vibration test setup; (b) specimen being tested; and (c) typical signal observed in response to transverse vibration.

Transverse vibration MOE was calculated using the following formula:

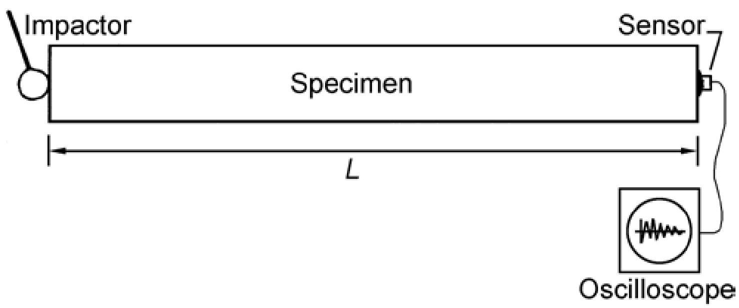
$$\text{MOE} = \frac{F_r^2 W L^3}{2.46 I g}$$

where

MOE is dynamic modulus of elasticity (Pa),
F_r is resonant frequency (Hz),
W is beam weight (kg),
L is beam span (m),
I is beam moment of inertia (m^4), and
g is acceleration due to gravity (9.8 m/s^2).

Longitudinal vibration

Figure 4 illustrates the pulse echo test setup utilized in this study. An impact or “pulse” on one end of the specimen induced a wave to flow along its length. The pulse “echoed” from the opposite end of the specimen. A fibre-gen Model HM 200 Hitman NDT tool (fibre-gen, Ltd., Christchurch, New Zealand) was used for conducting the tests. Frequency of oscillation was determined and, along with a specimen’s weight and dimensions, was used to compute MOE.



(a)

(b)

Figure 4—Longitudinal vibration test setup used in this study: (a) test setup; (b) fibre-gen model HM 200 Hitman equipment used to conduct longitudinal vibration tests.

Velocity (C, speed of sound transmission) was measured. MOE was computed using velocity (C) and density (ρ) of a specimen using the following formula:

$$MOE = C^2 \rho$$

Statistical analysis

Linear regression analysis techniques were used to examine the relationship between MOE values obtained.

Results and Discussion

A summary of results obtained is given in Table 1. Note that the sample had an average moisture content of 10.7% (oven-dry basis). Flatwise static bending MOE values ranged from 4.6 to 13.4 GPa, with an average value of 8.8 GPa. Transverse vibration MOE values ranged from 9.9 to 15.5 GPa, and longitudinal vibration MOE values ranged from 5.2 to 15.4 GPa.

Table 1—Summary of some physical and mechanical properties of the lumber sample used in this study

			Dimension					Longitudinal vibration		Transverse vibration	
Statistics	MC (%)	Weight (kg)	Thickness (mm)	Width (mm)	Length (m)	Density (g/cm^3)	Static MOE (GPa)	Velocity (m/s)	MOE (GPa)	f (Hz)	MOE (GPa)
Mean	10.7	5.4	38	88	3.68	0.43	8.79	4,596	9.24	6.48	9.91
Std. dev.	0.37	5.4	0.4	0.9	0.004	0.043	1.95	487.8	2.07	0.662	2.10
Max.	11.8	7.3	39	91	3.68	0.58	13.43	5,491	15.35	7.71	15.47
Min.	9.7	4.1	37	86	3.66	0.34	4.61	3,461	5.20	4.96	5.60
COV (%)	3.5	10.0	1.1	1.1	0.11	10.0	22.2	10.6	22.4	10.2	21.2

Results obtained from our statistical analyses are illustrated in Figures 5 through 7. Strong correlative relationships were observed between flatwise static bending, transverse vibration, and longitudinal vibration MOE values. It is important to note that both transverse and longitudinal vibration MOE values were found to be greater than corresponding flatwise bending MOE values. This phenomenon has been observed in similar studies conducted with lumber from different species of wood.

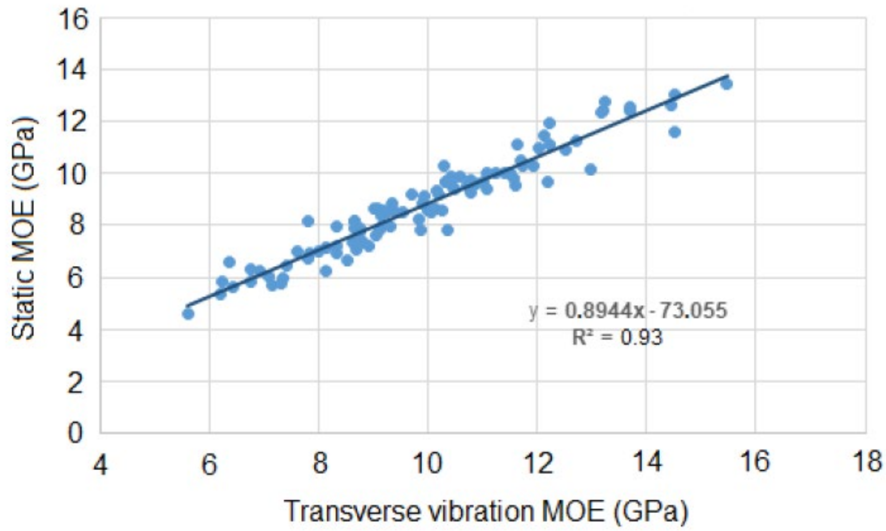


Figure 5—Observed relationship between transverse vibration and flatwise bending modulus of elasticity (MOE) values for the spruce–pine–fir lumber specimens used in this study.

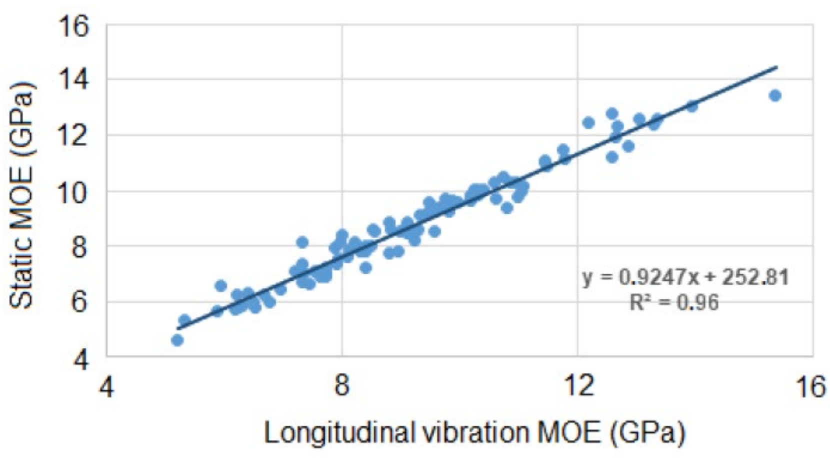


Figure 6—Observed relationship between longitudinal vibration and flatwise bending modulus of elasticity (MOE) values for the spruce–pine–fir lumber specimens used in this study.

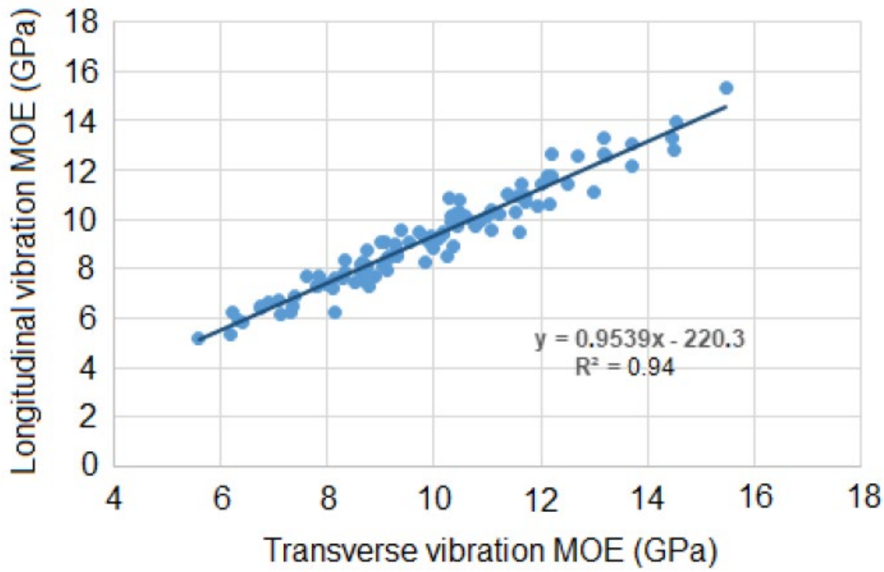


Figure 7—Observed relationship between transverse and longitudinal vibration modulus of elasticity (MOE) values for the spruce–pine–fir lumber specimens used in this study.

Summary

A systematic investigation on the use of NDT techniques to evaluate the tensile strength of structural lumber is being conducted using lumber from several species groupings in the United States. Scientists from Mississippi State University, Istanbul University, and the USDA Forest Service, Forest Products Laboratory, have begun to examine the use of transverse vibration, longitudinal vibration, and dielectric permittivity to derive a robust methodology for estimating the tensile strength of structural lumber.

The first phase of their efforts was to examine the relationship between vibration and flatwise bending MOE values for structural lumber. This report summarizes a study that examined the relationship between flatwise bending and vibration moduli for spruce–pine–fir lumber specimens. Excellent correlative relationships were found to exist.

Acknowledgments

This project was conducted through research cooperation between the USDA Forest Service, Forest Products Laboratory (FPL), and Istanbul University, Turkey, and was supported in part by TUBITAK, Turkey (1059B191601491).

Literature Cited

Cramer, S.M.; Fohrell, W.B. 1990. Method for simulating tension performance for lumber members. Journal of Structural Engineering. 116(10): 2719-2745.

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.

Hoyle, R.J. 1968. Background to machine stress rating. Forest Products Journal. 18(4): 87-97.

James, W.L.; Hamill, D.W. 1965. Dielectric properties of Douglas-fir measured at microwave frequencies. Forest Products Journal. 15(2): 51-56.

Kaiserlik, J.H.; Pellerin, R.F. 1977. Stress wave attenuation as an indicator of lumber strength. Forest Products Journal. 27(6): 39-43.

Kellogg, R.M. 1981. Physical properties of wood. In: Wood — Its structure and properties. Volume 1. Clark C. Heritage Memorial Series on Wood. F.F. Wangaard, ed. Educational Modules for Materials Science and Engineering, Materials Research Laboratory, The Pennsylvania State University, University Park, PA. pp. 195-223.

Lin, R.T. 1967. Review of the dielectric properties of wood and cellulose. Forest Products Journal. 17(7): 61-66.

Orosz, I. 1977. Relationships between transverse free vibration E and other properties as affected by knots. Forest Products Journal. 27(1): 23-27.

Pellerin, R.F.; Ross, R.J. 2015. Proof loading. In: Nondestructive evaluation of wood. Second Edition. Gen. Tech. Rep. FPL-GTR-238. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 53-57. Chapter 4.

Rajeshwar, B.; Bender, D.A.; Brey, D.E.; McDonald, K.A. 1997. An ultrasonic technique for predicting tensile strength of southern pine lumber. Transactions of the American Society of Agricultural Engineers. 40(4): 1153-1159.

Ross, R.J. 2015. Nondestructive evaluation of wood. Second Edition. Gen. Tech. Rep. FPL-GTR-238. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 167 p.

Skaar, C. 1948. The dielectric properties of wood at several radio frequencies. NY State College of Forestry Technical Publication No. 69.

Additional References

Athey, T.W. 1982. Measurement of RF permittivity of biological tissues with an open-ended coaxial line. IEEE Trans. MTT. 30: 82-86.

Beall, F.C. 2007. Industrial applications and opportunities for nondestructive evaluation of structural wood members. Maderas: Ciencia y Tecnologia. 9(2): 127-134.

Daval, V. 2015. Automatic measurement of wood fiber orientation and knot detection using an optical system based on heating conduction. Optics Express. 23(26): 33529.

Divos, F.; Tanaka, T. 2005. Relation between static and dynamic modulus of elasticity of wood. Acta Silvatica Lignaria Hungarica. 1: 105-110.

Gupta, R. 2012. Effect of grain angle on shear strength of Douglas-fir wood. Holzforschung. 66: 655-658.

Hollertz, R. 2014. Dielectric properties of wood fibre components relevant for electrical insulation applications. Stockholm: KTH Royal Institute of Technology. 38 p.

Ilic, J.; Ozarska, B. 1996. Nondestructive evaluation of properties of reconstituted wood products used in Australia. In: 10th International Symposium on Nondestructive Testing of Wood. Swiss Federal Institute of Technology, Lausanne, Switzerland: 269-278.

Jayne, B.A. 1959. Vibrational properties of wood as indices of quality. Forest Products Journal. 9: 413-416.

Kabir, M.F. 1997. Dielectric properties or rubber wood at microwave frequencies measured with an open-ended coaxial line. Wood and Fiber Science. 29(4): 319-324.

Kabir, M.F. 2001. Temperature dependence of the dielectric properties of rubber wood. Wood and Fiber Science. 33(2): 233-238.

Kliger, R.; Perstorper, M.; Johansson G. 1992. Stiffness in structural timber - effect according to position in the stem. In: Proc. IUFRO S5.02 Timber Engineering Meeting, Laboratorie de Rheologie du Bois de Bordeaux, Bordeaux, France.

Schajer, G.S. 2006. Measurement of wood grain angle, moisture content and density using microwaves. Holz als Roh-und Werkstoff. 64: 483-490.

Shupe, T.E. 1998. Effect of wood grain and veneer side on loblolly pine veneer wettability. Forest Products Journal. 48(6): 95-97.

Simonaho, S-P. 2004. Determination of wood grain direction from laser light scattering pattern. Optics and Lasers in Engineering. 41: 95-103.

Perstorper, M. 1994. Strength and stiffness prediction of timber using conventional and dynamic methods. In: Proc. first European symposium on nondestructive evaluation of wood. University of Sopron, Sopron, Hungary.

Ross, R.J. 2015. Nondestructive evaluation of wood. Second edition. Gen. Tech. Rep. FPL-GTR-238. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Ross, R.J.; Pellerin, R.F. 1994. Nondestructive testing for assessing wood members in structures: A review. Gen. Tech. Rep. FPL-GTR-70 (Rev.). Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Tanaka, T.; Nagao, H.; Nakai, T. 1991. Nondestructive evaluation of bending and tensile strength by longitudinal and transverse vibration of lumber. Proc. 8th international symposium on nondestructive testing of wood. Conferences and Institutes, Washington State University, Pullman, USA.

Winning, M. 2005. Transition between low and high angle grain boundaries. Acta Materialia. 53: 2901-2907.

Yapici, F. 2011. The effect of grain angle and species on thermal conductivity of some selected wood species. BioResources. 6(3): 2757-2762.