Nondestructive Evaluation of Lumber and Cross-Laminated Timber from Pine Trees Felled for up to One Year

Sona Azad Laya Khademibami Troy Bowman Iris Montague
Kozma Naka Seyed A. Fatemi Rubin Shmulsky

Abstract

The use of downed timber from felled pine trees presents an opportunity to reduce economic losses and enhance sustainability in the forestry and construction industries. This study investigates the mechanical properties of lumber and cross-laminated timber panels from pine trees that were felled and then remained on the ground for up to 1 year. Time intervals included 0, 6, 9, and 12 months. Acoustic velocity (AV) and dynamic modulus of elasticity (D_{MOE}) were used for nondestructive evaluation. Additional properties of interest included moisture content and density. After equilibration, moisture content across time intervals differed statistically but not practically. Density varied slightly across time intervals, but differences were more likely a function of variations in parent trees rather than the result of time on the ground. The AV and D_{MOE} remained largely stable in lumber, suggesting minimal structural degradation over time. Cross-laminated timber panels demonstrated consistently higher AV and D_{MOE} values compared with lumber, underscoring the effectiveness of cross-lamination in enhancing mechanical performance. The cross-lamination process mitigated the effects of aging and environmental exposure, with no significant variations in density or AV over the study period. These findings suggest that storm-damaged timber retains much of its structural viability for up to 1 year. The study highlights the potential of using downed timber to promote sustainability in wood-based construction while reducing waste and economic losses.

The southeastern United States is rich in timber supply and conversion operations (Prestemon et al. 2010, Rutledge et al. 2021). Severe weather events (e.g., tornadoes, hurricanes) are prevalent in this region and can be highly destructive toward forestland, which leads to substantial economic losses of timber resources (Prestemon et al. 2010). During the past century, more than 160 hurricanes located in the Atlantic and Gulf coasts have caused the aforementioned damages, particularly in 2005 when hurricanes Katrina and Rita, on August 29 and September 24, respectively, resulted in the worst timber damage to occur during recent decades (Blake et al. 2007). Prestemon et al. (2010) estimated that the value of timber losses from Katrina and Rita in Alabama, Louisiana, Mississippi, and Texas was \$2.25 billion. This amount was approximately twice that of hurricane Hugo, which hit South Carolina in 1989. More recently, approximately \$4.4 billion in economic losses were estimated from another hurricane in Louisiana, Mississippi, Alabama, and Georgia in October 2020 (Yao et al. 2022).

In addition to direct timber and infrastructure losses, forest landowners are concerned about subsequent potential problems, including bark beetles and wildfire (Long et al. 2005). If fallen trees stay in the forest for extended periods without processing, the wood quality declines. Natural degradation agents, such as blue stain, beetle infestations, and ultimately wood decay, affect downed timber (Sellers 1985). Additionally, unprocessed timber can increase wildfire risks, disrupt wildlife habitats, and add costs and delays

The authors are, respectively, graduate student and assistant research professor, Dept. of Sustainable Bioproducts, Mississippi State University, MS (sa1934@msstate.edu; lk475@msstate.edu [corresponding author]; associate professor, Dept. of Natural Resources and Environmental Sciences, Alabama A&M University, Normal, AL (troy.bowman@aamu.edu); research forester, USDA Forest Service, Forest Products Lab., 201 Lincoln Green, Starkville, MS (iris.b.montague@usda.gov); associate professor, Dept. of Natural Resources and Environmental Sciences, Alabama A&M University, Normal, AL (kozma.naka@aamu.edu); postdoctoral associate, Dept. of Sustainable Bioproducts, Mississippi State University, MS (Sf1006@msstate.edu); and Dept. Head and Warren S. Thompson professor, Dept. of Sustainable Bioproducts, Mississippi State University, MS (rs26@msstate.edu). This paper was received for publication in July 2025. Article no. 25-00038.

Forest Prod. J. 75(4):433–440.
doi:10.13073/FPJ-D-25-00038

to harvesting (Wade 1993, Davis 1996, Long et al. 2005). Thus, using timber from fallen trees not only minimizes waste but also enhances forest management efficiency. This recovery reduces economic losses and supports sustainable practices by minimizing waste and ecological effect (Eleuterio et al. 2020). Salvaging downed timber also reduces disease risks and maximizes resource sustainability (Ruslim et al. 2023).

To efficiently use downed timber, new products and markets must be developed. This process requires wood-quality assessments, with particular attention to moisture content (MC), density, decay, and mechanical properties. Despite the potential resource value of downed timber after storms, minimal research regarding the mechanical performance of recovered lumber is available.

Nondestructive testing (NDT) is effective at measuring the quality of wood products in various forms, such as small samples, logs, lumber, or standing trees. It can provide valuable mechanical properties information without damaging the subject wood products (Wang et al. 2001; Mora 2009; Legg and Bradley 2016). NDT techniques have been used to detect the presence of discontinuities, voids, or inclusions embedded in the material (Stephen 1991, Ross and Pellerin 1994, Bucur 1995, Dubey et al. 1997, Tanasoiu et al. 2002, Wang et al. 2004). Among various NDT methods, acoustic velocity (AV) is one of the most common techniques for evaluating stiffness and strength of different wood products (Bucur and Archer 1984; Bucur 1995, 2003). The AV is defined as the speed of sound waves traveling through a subject material such as wood, and it can be influenced by density, elasticity, and MC (Grabianowski et al. 2006). This technique has also gained popularity in the field of quality control and inspection of materials. It has several advantages over traditional testing techniques because it is rapid, relatively inexpensive, reliable, and not labor intensive (Bucur and Böhnke 1994).

The relationship between sound propagation and the mechanical properties of wood has been examined in several studies (Haines et al. 1996, Wang et al. 2003, Ross et al. 2004, Kotlínová et al. 2006, Bucur 2010). Nondestructive stress-wave techniques use a mechanical impulse to determine the dynamic modulus of elasticity (D_{MOE}) for assessment of stiffness of wood (Jung 1979, Smulski 1991, Bucur 2010). These can also be used for strength property estimation (Pellerin and Ross 2002, Wang et al. 2007). Such techniques, therefore, present an opportunity to evaluate the quality of downed timber for salvaging and conversion into new products such as cross-laminated timber (CLT; Ma et al. 2021).

CLT is a structural wood composite material comprising perpendicular layers of structural lumber. The crosswise orientation increases the rigidity and stability of the panels. In many applications, CLT construction can compete with concrete, steel, and masonry. CLT panels can be used for entire buildings as selected elements, such as roof underlayment along with floor and load-bearing walls (Brandner et al. 2016).

Peng et al. (2024) investigated the potential of using downed loblolly pine trees felled by hurricanes and tornadoes as wood fibers in wood polymer composite manufacturing. They investigated the effect on pine trees of varying ages (15, 30, and 39 yr) that were felled by hurricanes and tornadoes and remained in the forest for 0, 6, and 12 months. That research suggested that as time-on-ground increased, the wood fibers became rougher. In addition, longer exposure has been shown to reduce the fibers' density and their ability to dissolve in sodium hydroxide in younger felled trees. However, older trees behaved differently, wherein lower MC and heat stability were observed in the heartwood of 39-year-old trees. Furthermore, higher AV was observed in larger and older 12-month felled trees, indicating their stronger wood quality (Musah et al. 2022).

D_{MOE} is associated with how wood products elastically deform under dynamic loading. More recently, no significant differences in AV or D_{MOE} were noted in lumber from felled pine timber at 0 to 6 months' time on ground. For CLT panels, D_{MOE} was lower at 6 months on-ground as compared with 0 to 5 months (Khademibami et al. 2024).

Changes in the mechanical properties of felled pine trees over a 1-year period, particularly in the southeastern United States, are not well investigated. Unlike earlier studies that examined short-term changes in felled pine or limited product forms, this study uniquely evaluates nondestructive performance (AV and D_{MOE}) of both lumber and CLT panels fabricated from felled pine trees left on the ground for up to 1 year in the southeastern US climate. Both the extended time frame and the dual-product analysis investigated herein provide novel insights into storm-damaged timber use. It was hypothesized that NDT could help assess the wood quality of lumber and CLT made from felled pine trees, which remained on the ground for up to 1 year. Therefore, the objective of this study was to assess changes in NDT responses in lumber and CLT from felled pine trees at times up to 1 year.

Materials and Methods

Wood sample preparation

Approximately 20 to 25 loblolly pine (*Pinus taeda*) trees from the Alabama A&M University Winfred Thomas Agricultural Research Station in Hazel Green, Alabama, were marked for this study. All trees were felled on the same date (June 28, 2023), which marks the starting point (time zero). These felled trees were left on the ground in the forest at this site for varying times (0, 6, 9, and 12 mo) to simulate environmental exposure post high wind-type storm events. Environmental exposure in this study refers to natural outdoor conditions, including seasonal fluctuations in temperature (−5°C to 35°C), relative humidity (55% to 95%), and rainfall typical of the southeastern United States. These factors influenced the timber while left on the ground before processing. At these preselected times, five trees were removed from the forest and further processed (Table 1). At each time interval, felled trees were bucked into 8-foot-long logs with a minimum top diameter, inside bark, of 7 to 8 inches (17.8 to 20.3 cm). Lumber was then sawn into 2 by 6-inch rough green lumber and hauled to the Sustainable Bioproducts Department at Mississippi State University in Starkville, Mississippi.

Lumber was then kiln dried, planed, and moisture equilibrated in a protected outdoor environment. Lumber was

Table 1.—Log collection time (after the felling).

Time identification	Month	Number of logs	Number of lumber	Color
1	0	5	80	No color
2	6	5	80	Blue
3	9	5	80	Green
4	12	5	80	Black

planed to a thickness of 1 5/8 inches for moisture equilibration. After the final set of lumber was delivered and initially processed, all lumber was moisture-equilibrated for an additional 3 months (Fig. 1). For further processing, approximately 80 pieces from each time interval were selected (Table 1). The primary criteria for further processing included minimal wane, minimal 98-inch length, not more than 2 inches of bow, and not more than 1 inch of crook.

MC and density

Lumber MC was measured using a Wagner L601-3 Quick Scanning Moisture Meter (Wagner Meter, Rogue River, Oregon) designed for nominal 2-inch-thick pine lumber. The MC was calculated using Equation 1:

$$\mathrm{MC}\% = \frac{m2 - m1}{m1} \times 100\ (\%) \tag{1}$$

where MC is moisture content, m_2 is the initial mass (g), and m_1 is the dry mass (g).

Density (ρ) was determined by measuring specimen dimensions and weight, using Equation 2:

$$\rho = \frac{W}{V} \tag{2}$$

where ρ is density (kg per m^3), W is weight (kg; air dry at the time of testing), and V is volume (m^3).

Figure 1.—Lumber sorting according to the time arrival 0 (left side-down), 6 (left side-up), 9 (right side-down), and 12 (right side-up): no color, blue, green, and black colors, respectively.

Nondestructive testing

Following MC and density measurement, NDT was performed. NDT was conducted on individual lumber specimens and on resultant CLT panels. After lumber was evaluated by AV, it was sorted into high and low groups. Constituent lumber, approximately 24 pieces from the high AV sort and 24 pieces from the low AV sort, were then selected for CLT production.

AV and D_{MOE}

A Hitman Director HM220 (Fiber-gen, Christchurch, New Zealand) instrument was used to measure time-of-flight for both lumber and CLT panels, and the AV value was subsequently calculated according to the method described by Wang (2011). The time-of-flight was measured by the sensor and placed at one end of the lumber specimen; then, the opposite end was tapped with a hammer to generate a sound wave. The device recorded the time-of-flight that traveled from one end to the other.

The D_{MOE} was computed using Equation 3:

$$D_{\mathrm{MOE}} = \rho \times (AV^2) \tag{3}$$

where D_{MOE} is the dynamic module of elasticity (Pa), ρ is density (kg per m^3), and AV is acoustic velocity (m per s). In the "Results" section, the data of D_{MOE} with unit of Pa were converted to million psi.

NDT was conducted on both the initial lumber and on the resultant panels.

CLT production

For production, the candidate lumber, sorted by AV, was finished by planing each face. Final lumber thickness was 1.5 inches. The widths of individual finish boards were 6 inches. As such, 24 boards were used to manufacture 4 by 8-foot, three-ply, CLT panels. Cold-setting polyurethane adhesive was used. Two panels (one high AV and one low AV) were manufactured from each of the time intervals (0, 6, 9, and 12 months).

Statistical analysis

All experiments were set as completely randomized designs. Experimental units were either individual boards or individual CLT specimens. Nondestructive evaluation data were analyzed for each piece of lumber and CLT using one-way analysis of variance (ANOVA) with general linear mixed models (PROC GLIMMIX) in SAS 9.4 (SAS Institute 2013). In addition, the two-way ANOVA was used to evaluate the main and interactive effects between lumber and CLT panel groups within each time interval. Treatment differences were deemed significant at $\alpha = 0.05$ level. Fisher's protected least significant difference was used for the separations of treatment means (Steel and Torrie 1981).

The following statistical models were used for one- and two-way ANOVA:

One-way ANOVA:

$$Y_{ij} = \mu + P_i + e_{ij} \tag{4}$$

where μ was the population mean; P_i was the effect of time intervals ($j = 1$ to 4); and E_i was the residual error.

Two-way ANOVA:

$$Y_{ij} = \mu + T_i + P_j + (\mathrm{TP})_{ij} + e_{ij} \tag{5}$$

where μ was the population mean; T_i was the effect of lumber or CLT group treatments ($i = 1$ to 2); P_j was the effect of time intervals treatments ($j = 1$ to 4); $(\mathrm{TP})_{ij}$ was the interaction of each lumber or CLT group treatments with each of the time intervals treatments; and E_{ij} was the residual error.

Results and Discussion

Lumber properties over time

MC and density.—Equilibrated MC of lumber (after sawing, planing, drying, and equilibration) varied slightly from 9.6 percent for time zero lumber to 10.2 percent for the lumber after 12 months on the ground (Table 2). This difference was statistically significant ($P = 0.0048$) but not considered practically significant. As such, any differences in MC were not considered influential because a variation that was less than 1 percent (9.6% to 10.2%) falls within the industry tolerance range and does not affect mechanical performance. Furthermore, ASTM D1990-16 Annex A1 provides a method for adjusting mechanical properties based on MC differences that are 1 percent or greater but does not provide guidance for adjusting values in cases where MC differences are less than 1 percent (ASTM International 2025).

Lumber density fluctuated during the 1-year period ($P = 0.0002$). No real trend occurred upward or downward in density over time. As such, it was estimated that the statistical differences in density were attributable primarily to variability in the parent trees rather than time on ground.

AV and D_{MOE}

The AV of lumber remained relatively stable across time intervals, with values ranging from 4,753 m/s to 4,776 m/s ($P = 0.9978$; Table 2). This consistency suggests that the structural integrity (namely stiffness) of lumber was not significantly compromised during the 1-year period. This finding supports the notion of using downed timber for construction applications (Khademibami et al. 2024). These findings are consistent with Bucur and Archer (1984), who demonstrated that AV is strongly correlated with wood stiffness and is minimally affected by short-term moisture fluctuations. In addition,

Table 2.—Mean physical and mechanical properties of downed tree lumber in different time intervals.

	Month					
	0	6	9	12	SEM	*P* value
Moisture content (%)	9.6^b	9.3^b	9.6^b	10.2^a	0.25	**0.0048**
Density (kg/m^3)	473^c	509^a	498^{ab}	485^{bc}	8.4	**0.0002**
AV (m/s)[d]	4,765	4,753	4,759	4,776	113.23	0.9978
D_{MOE} (million psi)[d]	1.58	1.70	1.66	1.65	0.093	0.6298

[a–c] Treatment means within the same column within the effect with no common superscripts are significantly different.

[d] AV = acoustic velocity; D_{MOE} = dynamic modulus of elasticity.

the constant D_{MOE} across time intervals suggests lumber stiffness and load-bearing properties did not degrade over time. Previous studies have shown that although AV and D_{MOE} are sensitive to internal structural changes, minor variations in moisture and density over short periods may not cause significant mechanical degradation (Ross 2008, Wang 2011).

CLT properties over time

Density and structural stability.—The density of CLT panels did not differ across all time intervals ($P = 0.9326$). Values ranged from 490 to 494 kg/m^3 (Table 3). This finding suggests that the composite effect and randomization of constituent material in CLT manufacturing helps minimize density variation. Llana et al. (2022) demonstrated that engineered wood products, particularly CLT, show minimal density variation due to the adhesive bonding process, which mitigates the effects of moisture absorption and biological degradation.

AV and D_{MOE}

AV values for CLT ranged from 6,418 to 6,733 m/s, with no statistically significant differences across time intervals ($P = 0.6567$), indicating that the cross-lamination process may enhance structural stability and mitigate the effects of wood aging (Ma et al. 2021). The enhanced AV values in CLT compared with lumber confirm findings by Bucur (2010), which highlight the benefits of engineered wood products in maintaining acoustic and mechanical performance over time.

The D_{MOE} values for CLT panels did not significantly differ ($P = 0.5817$) within the 1-year period and ranged from 2.97 to 3.26 million psi (Table 3). This finding was similar to that in a separate study conducted by Khademibami et al. (2024) on CLT from felled trees that remained on the ground from 0 to 6 months. This trend suggests that possible degradation within a 1-year time period may have a negative effect on lumber quality, but the CLT panels manufactured therefrom remained relatively unchanged and potentially viable for construction applications (Llana et al. 2022).

Comparative analysis of lumber and CLT

No statistically significant interactive effects occurred between wood products and time interval; however, a significant effect for AV and D_{MOE} was found between lumber and CLT panels (Table 4). CLT panels exhibited higher AV and lower D_{MOE} in comparison with lumber (Fig. 2). Other studies have also indicated that engineered wood products often outperform solid wood in

Table 3.—Mean mechanical properties of CLT panels in four different time intervals.[a]

	Month					
	0	6	9	12	SEM	P value
Density (kg/m^3)	494	490	495	494	7.9	0.9326
AV (m/s)[a]	6,733	6,527	6,693	6,418	281.1	0.6567
D_{MOE} (million psi)[a]	3.26	3.04	3.22	2.97	0.243	0.5817

[a] CLT = cross-laminated timber; AV = acoustic velocity; D_{MOE} = dynamic modulus of elasticity.

Table 4.—Mean AV and D_{MOE} of lumber and CLT panels made from downed trees in four different time intervals.[a]

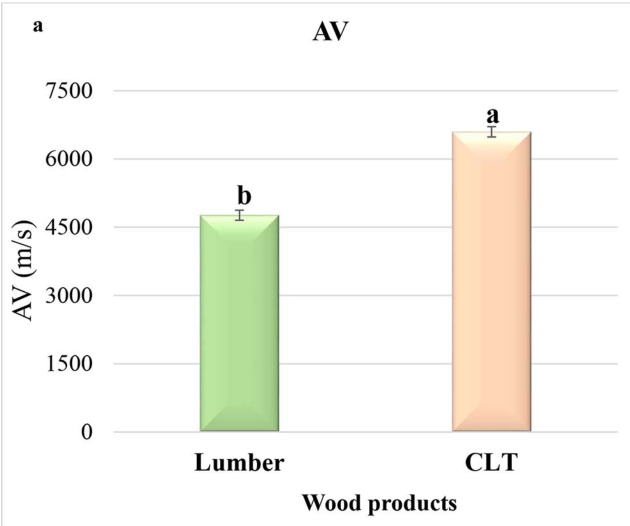
Time intervals	AV (m/s)	D_{MOE} (million psi)
Month		
0	5,753	2.41
6	5,640	2.36
9	5,742	2.44
12	5,597	2.31
SEM	224.4	0.183
Wood products		
Lumber	4,766[b]	1.64[b]
CLT	6,600[c]	3.10[c]
SEM	112.2	0.129
Wood products by months		
Lumber		
0	4,773	1.56
6	4,754	1.70
9	4,759	1.66
12	4,776	1.65
CLT		
0	6,733	3.26
6	6,526	3.03
9	6,724	3.22
12	6,418	2.96
SEM	317.4	0.258
	P value	
Month	0.8722	0.8929
Wood products	**<0.0001**	**<0.0001**
Wood products by month	0.8654	0.681

[a] CLT = cross-laminated timber; AV = acoustic velocity; D_{MOE} = dynamic modulus of elasticity.

[b,c] Treatment means within the same column within effect with no common superscripts are significantly different.

mechanical performance (Ross - 2008, Wang - 2011). Furthermore, previous studies have emphasized that CLT panels, due to their cross-laminated structure, exhibit improved resistance to mechanical degradation compared to traditional lumber (Karacabeyli and Douglas 2013, Espinoza et al. 2018). This structural advantage suggests that CLT panels may be a promising material and market in regions prone to natural disasters, where salvaged timber could be used efficiently (Ashley and Strader 2016).

The findings of this study suggest that lumber obtained from downed pine trees may remain functionally viable for 12 months. The lack of significant deterioration in AV and D_{MOE} supports the potential for using storm-damaged timber for structural applications. Such use would reduce waste and support sustainable forest management practices (Eleutério et al. 2020). From a sustainability perspective, salvaging downed trees for CLT production contributes to the reduction of construction waste while promoting responsible forest management (Ramage et al. 2017). Future research is needed to determine the long-term durability and environmental effects of using salvaged timber beyond 12 months and salvaged timber from various woody species that are commercially used for engineered wood products to further enhance resource efficiency in the forestry and construction industries.



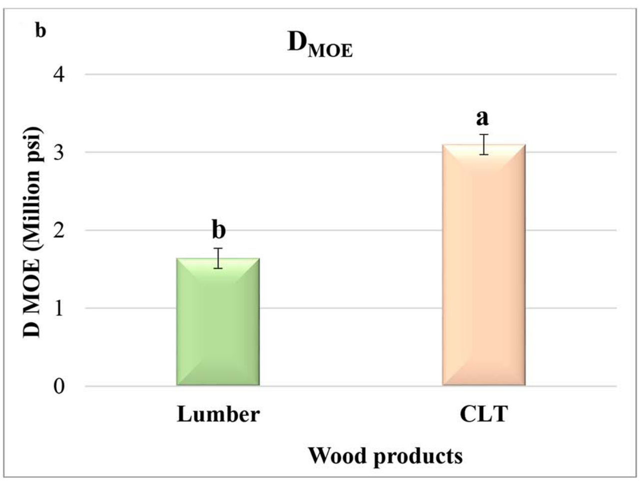


Figure 2.—(a), (b) Mean acoustic velocity (AV) (2.a) and dynamic modulus of elasticity (D_{MOE}) (2.b) of lumber and cross-laminated timber (CLT) panels made from downed timber. (a), (b) Treatment means within the same column within effect with no common superscripts are significantly different. P value AV = <0.0001; SEM = 112.2; P value D_{MOE} = <0.0001; SEM = 0.129.

Conclusions

The aim of the current study was to investigate the NDT characteristics of lumber and CLT panels from felled loblolly pine trees over a 1-year time period. Findings showed that equilibrated lumber MC varied with treatment time, but differences were of no practical significance. Density varied among time intervals, but the differences seemed more attributable to parent tree density than to time on the ground. The incorporation of more trees into each treatment time and perhaps more randomization in the forest would have minimized any statistical differences in density.

Seasonal variations (i.e., rainfall, humidity, temperature) were inherent in the outdoor exposure. However, within 1 year, no significant effects on AV or D_{MOE} were detected. No meaningful differences in AV and D_{MOE} were observed across the time intervals. These results indicate that although some level of change in the structural variable of downed lumber may take place within a 1-year time period, their nondestructive mechanical performance remained stable, possibly due to limited degradation. Extended multi-year monitoring may reveal stronger seasonal influences.

Observed AV and D_{MOE} were higher in CLT panels compared with lumber. This finding indicates that the composite action associated with these engineered panels minimized variability and improved overall properties.

The significant enhancement in structural properties observed in CLT panels compared to solid lumber underscores the advantages of engineered wood materials in mitigating the effects of aging and environmental exposure. These findings support the feasibility of using salvaged timber for construction, contributing to sustainable forestry practices and reducing economic losses from storm-damaged trees.

Future research is needed to investigate the long-term durability of CLT panels made from salvaged wood, particularly in varying climatic conditions. Additionally, analyses of chemical composition and decay resistance of downed timber can provide deeper insights into optimization of their application for high-performance construction materials. By promoting the efficient use of natural resources, this research aligns with broader goals of sustainability and resilient infrastructure development.

Acknowledgments

This publication is a contribution of the Forest and Wildlife Research Center, Mississippi State University. This project was supported by the subrecipient agreement 22-00379 from United States Endowment for Forestry and Communities, Inc. The Endowment is a not-for-profit corporation that works collaboratively with partners in the public and private sectors to advance systemic, transformative, and sustainable change for the health and vitality of the nation's working forests and forest-reliant communities. This research was conducted in cooperation with the USDA Forest Service. The authors acknowledge Alabama A&M University staff and students for their contribution in providing the loblolly pine lumber.

Literature Cited

ASTM International. 2025. Standard practice for establishing allowable properties for visually graded dimension lumber from in-grade tests of full-size specimens. ASTM D1990-16. ASTM International, West Conshohocken, Pennsylvania.

Ashley, W. S. and S. M. Strader. 2016. Recipe for disaster: How the dynamic ingredients of risk and exposure are changing the tornado disaster landscape. *Bull. Amer. Meteor. Soc*. 97(5):767–786. https://doi.org/10.1175/BAMS-D-15-00150.1

Blake, E. S., E. N. Rappaport, and C. W. Landsea. 2007. The deadliest, costliest, and most intense United States tropical cyclones from 1851 to 2006. Tech. Memorandum NWS TPC-4, National Oceanic and Atmospheric Administration, Washington, DC. 45 p.

Brandner, R., G. Flatscher, A. Ringhofer, G. Schickhofer, and A. Thiel. 2016. Cross laminated timber (CLT): Overview and development. European Journal of Wood and Wood Products, 74(3):331–351.

Bucur, V. 2010. *Acoustics of Wood.* 2nd ed. Springer-Verlag, Berlin, Germany. 454 pp.

Bucur V. 2003. Nondestructive characterization and imaging of wood. Springer-Verlag, Berlin, p 354.

Bucur, V. and R. R. Archer. 1984. Elastic constants for wood by an ultrasonic method. *Wood Sci Technol*. 18:255–265.

Bucur, V. and I. Böhnke. 1994. Factors affecting ultrasonic measurements in solid wood. *Ultrasonics*. 32(5):385−390. https://doi.org/10.1016/0041-624X(94)90109-0

Bucur V. 1995. Acoustics of wood. CRC Press Inc., New York, p 284.

Davis, G. E. 1996. *Effects of Hurricane Andrew on Natural and Archeological Resources: Big Cypress National Preserve, Biscayne National Park, Everglades National Park*. 96(2). US Department of the Interior, National Park Service, Natural Resource Program Center, Natural Resource Information Division.

Dubey, Y. M., Sachin Gupta, N. K. Shukla. 1997. Estimation of modulus of elasticity of Populus deltoides by vibration test method. *J Timb Dev Assoc India*. 43(4):5−9.

Eleuterio, A. A., M. Aparecida de Jesus, and F. E. Putz. 2020. Stem decay in live trees: Heartwood hollows and termites in five timber species in eastern Amazonia. *Forests*. 11(10):1087. https://doi.org/10.3390/f11101087

Espinoza, O., U. Buehlmann, M. F. Laguarda-Mallo, and V. Rodríguez Trujillo. 2018. Status of cross-laminated timber in North America. *In:* 2016 World Conference on Timber Engineering, WCTE 2016. Vienna University of Technology, Vienna.

Grabianowski, M., B. Manley, and J. C. F. Walker. 2006. Acoustic measurements on standing trees, logs and green lumber. *Wood Sci. Tech*. 40(3):205−216.

Haines, D. W., J. M. Leban, and C. Herbe. 1996. "Determination of Young's modulus for spruce, fir and isotropic materials by the resonance flexore method with comparisons to static flexure and other dynamic methods." *Wood Science and Technology*. 30(4): 253−263.

Jung, L. 1979. "Stress grading techniques on veneer sheets," USDA Forest Service General Tech. Rep. FPL 27. USDA, Madison.

Karacabeyli, E. and B. Douglas, eds. 2013. CLT Handbook: Cross-Laminated Timber. U.S. edition. Special Publication SP-529E. FPInnovations, Pointe-Claire, Québec, Canada; co-published by U.S. Department of Agriculture, Forest Products Laboratory, and Binational Softwood Lumber Council. 488 pp.

Khademibami, L., R. Shmulsky, F. J. N. Franca, R. J. Ross, X. Wang, and S. A. Fatemi. 2024. Impact of time-on-ground of felled pine trees on quality of mass timber. *In:* R. Gonçalves, X. Wang, and R. J. Ross (Eds.), Proceedings of the 23rd International Nondestructive Testing and Evaluation of Wood Symposium. General Technical Report FPL–GTR–305. Campinas, São Paulo, Brazil: US Department of Agriculture, Forest Service, Forest Products Laboratory.

Kotlínová, M., M. Kloiber, G. Vasconcelos, P. B. Lourenço, and J. Branco. 2006. "Comparison of nondestructive and semi-destructive methods used on two types of wood," in: In situ Evaluation & Non-destructive Testing of Historic Wood and Masonry Structures, Institute of Thermomechanics Academy of Sciences Czech Republic, 66−76.

Legg, M. and S. Bradley. 2016. Measurement of stiffness of standing trees and felled logs using acoustics: A review. *J. Acoust. Soc. Amer*. 139(2):588−604. https://doi.org/10.1121/1.4940210

Llana, D. F., V. González-Alegre, M. Portela, and G. Íñiguez-González. 2022. Cross laminated timber (CLT) manufactured with European oak recovered from demolition: Structural properties and non-destructive evaluation. *Constr. Build. Mater*. 339:127635. https://doi.org/10.1016/j.conbuildmat.2022.127635

Long, A., J. Nowak, C. Demers, R. Williams, N. Strong, J. Davidson, and J. Holzaepfel. 2005a. Assessment and management of hurricane damaged timberland: SS-FOR 22/FR154, 1/2005. EDIS 2005, 4. https://doi.org/10.32473/edis-fr154-2005

Long, A. J., R. Williams, C. Demers, J. Nowak, N. Strong, J. Davidson, and J. Holzaepfel. 2005b. Assessment and Management of Hurricane Damaged Timberland. EDIS Publication FR154 / SS-FOR 22. University of Florida, IFAS Extension.

Ma, Y., R. Si, M. Musah, Q. Dai, X. Xie, X. Wang, and R. J. Ross. 2021. Mechanical property evaluation of hybrid mixed-species CLT panels with sugar maple and white spruce. *J. Mater. Civil Eng*. 33(7):04021171. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003760

Mora, C. R. 2009. Rapid techniques for screening wood properties in forest plantations (Doctoral dissertation, university of Georgia). University of Georgia.

Musah, M., J. H. Diaz, A. O. Alawode, T. Gallagher, M. Soledad Peresin, D. Mitchell, M. Smidt, and B. Via. 2022. Field assessment of downed timber strength deterioration rate and wood quality using acoustic technologies. *Forests*. 13(5):752. https://doi.org/10.3390/f13050752

Pellerin, R. and R. J. Ross. 2002. Inspection of timber structures using stress wave timing nondestructive evaluation tools. *In:* Inspection of Timber Structures. pp. 135−151. Forest Products Society. Roy F. Pellerin & Robert J. Ross (Eds.). ISBN 1-892529-26-2

Peng, Y., D. Pokhrel, X. Wang, T. Elder, N. Stark, B. Via, T. Gallagher, M. Smidt, and D. Mitchell. 2024. Wood fiber production from downed timber for manufacturing wood polymer composite: Fiber property characterization. *Wood Mater. Sci. Eng*. 19(2):541−555. https://doi.org/10.1080/17480272.2023.2266832

Prestemon, J. P., T. P. Holmes, J. M. Pye, H. M. Rauscher, Y. Sands, D. C. Lee, and J. S. Beatty. 2010. Economic impacts of hurricanes on forest owners. *In:* Advances in Threat Assessment and Their Application to Forest and Rangeland Management. pp. 207−221. U.S. Department of Agriculture, Forest Service, Pacific Northwest & Southern Research Stations.

Prestemon, J. P. and T. P. Holmes. 2010. Economic impacts of hurricanes on forest owners vol 2. General Technical Report PNW-GTR-802.

Ramage, M. H., H. Burridge, M. Busse-Wicher, G. Fereday, T. Reynolds, D. U. Shah, G. Wu, L. Yu, P. Fleming, D. Densley-Tingley, J. Allwood, P. Dupree, P. F. Linden, and O. Scherman. 2017. The wood from the trees: The use of timber in construction. *Renew. Sustain. Energy Rev*. 68:333−359. https://doi.org/10.1016/j.rser.2016.09.107

Ross, R. J. and R. F. Pellerin. 1994. Nondestructive testing for assessing wood members in structures: a review. Gen Tech Report, FPLGTR-70. US Department of Agriculture, Forest Service, Forest Products Laboratory, Madison.

Ross, R. J. 2008. Transverse vibration techniques: Logs to structural systems. In Proceedings of the 15th International Symposium on Nondestructive Testing of Wood: September 10–12, 2007. Madison, WI: Forest Products Society, c2008: p. 13–15.

Ross, J. R., K. B. Brashaw, X. Wang, H. R. White, and F. R. Pellerin. 2004. Wood and Timber Condition Assessment Manual, Forest Products Society Madison, WI.

Ruslim, Y., N. M. Astuti, and D. R. Sari. 2023. Potential waste from felling of Eucalyptus pellita trees using Komatsu PC130F-7 in industrial plantation forest. *In:* IOP Conference Series: Earth and Environmental Science. Vol. 1282, no. 1, p. 012002. IOP Publishing. https://doi.org/10.1088/1755-1315/1282/1/012002

Rutledge, B. T., et al., 2021. Tree, stand, and landscape factors contributing to hurricane damage in a coastal plain forest: post-hurricane assessment in a longleaf pine landscape. Forest Ecology and Management, 481. https://doi.org/10.1016/j.foreco.2020.118724

SAS Institute. 2013. SAS proprietary software release, version 9.4. SAS Institute Inc., Cary, North Carolina.

Sellers, T. 1985. Plywood and Adhesive Technology. CRC Press.

Smulski, S. 1991. "Relationship of stress-wave and static bending determined properties of four northeastern hardwoods", *Wood and Fiber Science*. 23(1):44−57.

Steel, R. G. D. and J. H. Torrie. 1981. Principles and Procedures of Statistics: A Biometrical Approach. No. Ed. 2, p. 633pp.

Stephen J. 1991. Relationship of stress wave and static bending determined properties of four northeastern hardwoods. Wood Fiber Sci. 23(1):44−57.

Tanasoiu V., C. Micleaa, and C. Tanasoiua. 2002. Nondestructive testing techniques and piezoelectric ultrasonic transducers for wood and built in wooden structures. *J Optoelectron Adv Mater*. 4(4):949−957.

Wade, D. D. 1993. Photo series for estimating post-hurricane residues and fire behavior in southern pine. Vol. 82. US Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Wade, D., J. Forbus, and J. Saveland 1993. Photo series for estimating post-hurricane residues and fire behavior in southern pine. General Technical Report, U.S. Forest Service, Asheville, NC.

Wang, X. 2011. Fundamentals of acoustic measurements on trees and logs and their implication to field application. *In:* Proceedings of the 17th International Symposium on Nondestructive Testing and Evaluation of Wood, 2011; pp. 25−33; 2011. (pp. 25–33)

Wang, X., F. Divos, C. Pilon, B. K. Brashaw, R. J. Ross, and R. F. Pellerin. 2004. Assessment of decay in standing timber using stress wave timing nondestructive evaluation tools: a guide for use and interpretation. Gen. Tech. Rep. FPL-GTR-147. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory, 2004. 12 pages, 147.

Wang, X., P. Carter, R. J. Ross, and B. K. Brashaw. 2007. Acoustic assessment of wood quality of raw forest materials: A path to increased profitability. *Forest Prod. J.* 57(5):6−14.

Wang, S. Y., C. J. Lin, and C. M. Chiu. 2003. “The adjusted dynamic modulus of elasticity above the fiber saturation point in Taiwanian plantation wood by ultrasonicwave measurement”. *Holzforschung*. 57(5):574–552.

Wang, X., R. J. Ross, M. McClellan, R. J. Barbour, J. R. Erickson, J. W. Forsman, and G. D. McGinnis. 2001. Nondestructive evaluation of standing trees with a stress wave method. *Wood Fiber Sci*. 522−533.

Yao, Q., et al. 2022. Nature versus humans in coastal environmental change: assessing the impacts of hurricanes zeta and Ida in the context of beach nourishment projects in the Mississippi river delta. Remote Sensing, 14. https://doi.org/10.3390/rs14112598