Destructive and Nondestructive E-Rating of Red Maple Veneers

Dalila Belaidi Mostafa Mohammadabadi Frederico França
Rubin Shmulsky Xiping Wang R. Daniel Seale

Abstract

In this study, the modulus of elasticity of red maple (*Acer rubrum*) veneer, a native species abundant in eastern North America, was evaluated. These veneer sheets were 3.5 mm thick by 304 mm wide by 2.44 m long. Over 500 specimens were visually graded and subjected to a nondestructive stress wave test to determine the dynamic modulus of elasticity (MOE_d). Subsequently, 60 specimens were selected for tensile testing to measure the static modulus of elasticity (MOE_s). The average MOE_d was 19.10 GPa, while the MOE_s obtained from tensile testing was 11.88 GPa. This tension-based MOE value was very close to the bending test value for red maple lumber reported in *the wood handbook* (11.31 GPa). A regression analysis was conducted to evaluate the effects of density and defects on MOE. The results showed that density has a greater effect on MOE_d than defects. A correlation was also developed between MOE_d and MOE_s. The results showed that the MOE_d was 60 percent higher than the MOE_s, with a weak positive correlation ($r = 0.40$). The stress wave velocity, as affected by different factors such as density, defects, and fiber orientation, strongly correlated with MOE_d.

The mechanical properties of wood are critical for its application in construction, ranging from conventional residential buildings to modern large-scale structures (Arriaga et al. 2023). Understanding these properties is essential for predicting wood performance, especially in engineered wood products, where specific strength characteristics are required (Mohamed 2023, José Marini et al. 2018). In this context, corrugated panels made from wood fibers and veneers have emerged as an innovative approach, enhancing the structural integrity and efficiency of engineered wood products (Lamichhane et al. 2025).

One of the most rapid and cost-effective methods for estimating these properties has been wood density testing (Tsoumis 1991, Izekor et al. 2010, Ponneth et al. 2014, Baar et al. 2015). Increasing wood density through processes like densification has also been shown to improve mechanical properties such as stiffness and elasticity (Pradhan et al. 2024).

However, the usability of this test is often limited to clear, straight-grained wood, which does not align with practical applications (Baar et al. 2015).

Similarly, the modulus of elasticity (MOE) is also a crucial predictive parameter, as it represents the mechanical properties and stiffness of the material (Divós and Tanaka 2005, Oberhofnerová et al. 2016, Chen et al. 2021). Because it helps designers and engineers predict deflection under load, its use in construction is critical. It varies by grain direction and is important in a wide range of wood types/products (Izekor et al. 2010, Baar et al. 2015, Oberhofnerová et al. 2016, Fathi et al. 2020, Turkot et al. 2020). This elastic parameter has been evaluated by two different methods: static and dynamic, denoted MOE_s and MOE_d, respectively (Ettelaei et al. 2019). The static method involves different mechanical tests, such as tensile, bending, and compressive tests (Mohamed 2023). While the static bending test is the most common approach for measuring MOE_s, it is often impractical, time-consuming, expensive, and destructive (Liu et al. 2006, Fedyukov et al. 2017, Ettelaei et al. 2019). Destructive tests increase costs for users, as specimens cannot be reused after testing (Turkot et al. 2020). Due to these factors, several techniques have been

The authors are, respectively, PhD Student (db3049@msstate.edu), Assistant Professor (mm5132@msstate.edu [corresponding author]), Assistant Professor (fn90@msstate.edu), and Professor and Head (rs26@msstate.edu), Dept. of Sustainable Bioproducts, Forest and Wildlife Research Center, College of Forest Resources, Mississippi State Univ., Starkville; Research Forest Products Technologist, USDA Forest Serv., Forest Products Lab., US Dept. of Agric., Madison, Wisconsin (xiping.wang@usda.gov); Warren S. Thompson Professor of Wood Sci. and Technol., Dept. of Sustainable Bioproducts, Forest and Wildlife Research Center, College of Forest Resources, Mississippi State Univ. (rds9@msstate.edu). This paper was received for publication in March 2025. Article no. 25-00015.

Forest Prod. J. 75(2):195–205.
doi:10.13073/FPJ-D-25-00015

developed for rapid, cost-effective, and nondestructive evaluation of mechanical properties (Mvolo et al. 2022). Considering their advantages, nondestructive test (NDT) methods have been widely applied in the wood industry, ranging from evaluating the structural performance of wood-based products and grading and sorting structural wood products to inspecting wood structures in situ and detecting decay in wood-based components (Ross 1992, Miclea et al. 2002).

Generally, a stress wave moves quickly through dense, solid materials, but the presence of voids, cracks, or decay can slow down and redirect the waves (Dackermann et al. 2014). Besides defects, various structural and chemical factors play a significant role in affecting stress wave velocity and the overall stiffness of the material. These factors include the wood's density, moisture content, and fiber orientation. For example, de Oliveira and Sales (2006) reported that ultrasonic wave velocity increased with an increase in density, while Baar et al. (2012) reported in their study that velocity and density are interdependent parameters.

Several studies have also demonstrated the effect of moisture content on sound wave propagation velocity. As the moisture content of wood decreases, a significant increase in wave velocity occurs (Simpson and Wang 2001, Kang and Booker 2002). Furthermore, Bucur (2006) found that, as the fiber length increases, the velocity of the acoustic wave in the longitudinal direction also increases.

Numerous studies have been conducted to evaluate the wood properties of various wood species using different NDT methods, with a specific emphasis on comparing destructive and nondestructive techniques, as summarized in Table 1.

Although various wood species have been assessed in previous studies, as shown in Table 1, red maple (*Acer rubrum*), a native hardwood abundant in eastern North America (Alderman et al. 2005), has not been extensively studied. Red maple is known for its high mechanical properties and significant potential as a structure material (Ross et al. 2004b). Furthermore, most of these studies have primarily focused on the nondestructive evaluation of lumber products, often comparing them to bending tests. In contrast, wood veneers, which are commonly used in the production of plywood, laminated veneer lumber, and mass plywood, remain largely unexplored.

Table 1.—Summary of studies evaluating wood properties through destructive and nondestructive (NDT) approaches.

Authors	Species	Destructive methods	Nondestructive methods	Findings
Birinci et al. (2024)	Spruce, alder	Static bending	Acoustic test Screw withdrawal force	Strong correlation between screw withdrawal and bending strength ($0.6135 < R^2 < 0.9997$). Strong correlation between NDT and static bending ($0.7076 < R^2 < 0.9997$).
Utami et al. (2020)	Sukun, munggur, mahogany, Sonokeling, acacia, teak	Static bending	Longitudinal stress wave	High correlation between the dynamic modulus of elasticity (MOE_d) values and static modulus of elasticity (MOE_s) values ($R^2 = 0.898$).
Chen and Guo (2016)	Chinese fir, elm	Compression parallel and static bending	Stress wave timing Resistance drilling machine	Stress wave timing combined with resistance drilling test was effective at predicting wood's mechanical properties.
Goia et al. (2002)	Cupiúba (C-30), Jatobá (C-40)	Static bending	Ultrasonic waves	Ultrasonic wave-predicted mechanical properties showed the influence of humidity control in wood testing.
França et al. (2020)	Southern pine	Static bending	Longitudinal vibration and transverse vibration	Significant correlations between MOE_S and MOE_d. Weaker correlations between modulus of rupture (MOR) and MOE_d.
Llana et al. (2020)	Alder, ash, birch, sycamore	Static bending	Acoustic stress waves and resonance testing	Reliable estimation of mechanical properties using acoustic and resonance methods with tree species and diameter.
Mvolo et al. (2022)	Lodgepole pine, white spruce	Three-point bending	SilviScan (SS), time of flight (TOF), stress wave speed (SWS)	Stress wave speed (SWS) had highest R^2 (89%) for lodgepole pine, MOE(SS) had the lowest R^2 (47%). MOE(TOF) had a lower R^2 for lodgepole pine than white spruce, but the opposite was true for SWS.
Turkot et al. (2020)	Red oak, white oak	Three-point bending	Acoustic NDT methods	The MOE was best predicted by NDT methods.
Divós and Tanaka (2005)	Spruce	Three-point bending	Longitudinal vibration	Shorter characteristic times yield higher MOE values. Small (1.7%) change in MOE was seen with order of magnitude change in characteristic time.
Baar et al. (2015)	Doussié, Merbau, Wengé, Zebrano, Muira-catiara	Static bending	Longitudinal and flexural resonance and ultrasound	The weakest correlation was found for the ultrasound method. MOE_d provided less accurate predictions of MOR compared to MOE_s.
Wang et al. (2003)	Red maple	Ultrasonic wave	Bending test (flatwise and edgewise)	Edgewise MOE_s had positive relationship with veneer layup patterns and ultrasonic rating. Low-value red maple sawlogs produced high-quality laminated veneer lumber products with improved performance when ultrasonically rated.

This research aimed to deepen current understanding of the relationship between nondestructive and destructive methods for evaluating the mechanical properties of red maple veneer. Specifically, this study examined the correlation between the dynamic modulus of elasticity (MOE_d), determined using the stress waves method, and the static modulus of elasticity (MOE_s), measured through the tensile test. The study also investigated how wood density and veneer defects influence these two properties. The goal was to provide valuable insights into the effectiveness and reliability of nondestructive testing for predicting the elastic modulus of red maple veneers. The findings from this study are expected to improve the sorting process of red maple veneers by incorporating nondestructive testing methods, aid in the development of high-performance veneer-based products, optimize production processes, and reduce waste in the industry.

Materials and Methods

Full-size red maple veneer sheets, measuring 1.21 by 2.44 m (4 by 8 ft), were supplied by Great Lake Veneer (Marion, Wisconsin). Each full-size veneer sheet was first ripped into 304-mm-wide pieces, resulting in a total of 553 veneer specimens. Table 2 shows the average thickness, width, length, weight, and density of all 553 specimens. The density was evaluated using a scale to determine the weight (kg), a tape measure was used to determine width and length (m), and a caliper was used for the thickness (m) measurement.

Of these, 60 veneer specimens were selected for mechanical evaluation using a destructive tensile test. The width and thickness of each specimen were measured at multiple points, and the average values were calculated. The length of these specimens, 2.43 m (8 ft), represents the grain (longitudinal) direction. Prior to both nondestructive and destructive evaluations, all veneer specimens were conditioned in a controlled environment to achieve an equilibrium moisture content of 12 percent.

Visual grading of veneers

The veneer specimens were first visually graded based on the International Hardwood Veneer Grading Rules (Adam Redman 2020). This process involved visually inspecting each veneer specimen for defects and classifying them into four different grades: Grades A, B, C, and D. Key factors considered during the visual grading included the number and size of knots, type of knots, checks, holes, insect attack, and decay. The grading process followed the following established guidelines:

Grade A: Veneers with minimal or no defects, as shown in Figure 1a.

Table 2.—Dimensions of red maple veneers used for nondestructive and destructive evaluation. The numbers in parentheses represent the coefficients of variation (COV), expressed as percentages.

	Total samples	Thickness (mm)	Width (mm)	Length (mm)	Density (kg/m^3)
Nondestructive	553	3.5 (5.77)	304 (1.40)	2442 (0.11)	584 (8.17)
Destructive	60	3.5 (5.76)	292 (2.54)	2442 (0.12)	587 (8.96)

Grade B: Veneers with moderate defects, including small- to medium-sized knots and minor splits, as shown in Figure 1b.

Grade C: Veneers with significant defects, such as large knots, moderate splits, or minor decay, as shown in Figure 1c.

Grade D: Veneers with severe defects, including large holes, insect attack, or advanced decay, as shown in Figure 1d.

Stress wave E-rating

A portable stress wave timer (Fakopp Enterprise, Hungary) was used to measure the elastic modulus, nondestructively, along the longitudinal direction. As shown in Figure 2a, each veneer specimen was clamped at a single point on each end using a specialized fixture, with additional support provided beneath the specimens to maintain straightness and prevent damage at the contact points (Ross 2015).

A flat board was used to support the specimens, resulting in a clamping distance of 2.39 m (94 in.).

The stress wave was generated by a single strike from an impactor built into one of the specialized clamps, as shown in Figure 2b. To determine the longitudinal dynamic modulus of elasticity direction, for each piece of veneer, three measurements from different locations were taken. A Fakopp Microsecond Timer was used to measure the time it took for the stress wave to travel from one end to the other.

According to Ross et al. (2004a), all commercially available timing devices, such as the Fakopp Microsecond Timer, provide similar results when properly calibrated and used according to the manufacturer's instructions.

The stress wave velocity v (m/s) was calculated according to Equation 1:

$$\nu = L/t \quad (1)$$

where L represents the distance between the clamping points, and t is the time measured using the Fakopp device. After calculating the velocity, the dynamic modulus of elasticity (MOE_d) was determined according to Equation 2.

$$MOE_d = \rho^* \nu^2 \quad (2)$$

where ρ is the density of the veneer (kg/m^3), and ν is the velocity (m/s).

Tensile test

The tensile test method was conducted using the Metriguard 422 Tension Proof Tester (Fig. 3a), which is primarily used for evaluating lumber. As a result, the minimum specimen thickness required for a secure connection in the grips was approximately 25 mm (1 in.). To test thin veneers with an average thickness of 3.5 mm using this Metriguard machine, the two ends of each of the 60 destructive specimens were sandwiched between two 17.46-mm-thick particleboard blocks (Fig. 3b). This schema resulted in a gripping length of 140 mm (5.5 in.) at each end and an actual tensile length of 2,159 mm (85 in.). To facilitate specimen loading, all 60 tensile specimens were trimmed from 304 to 292 mm (12 to 11.5 in.) widths. To secure the ends of the veneer in the grips, particleboard blocks

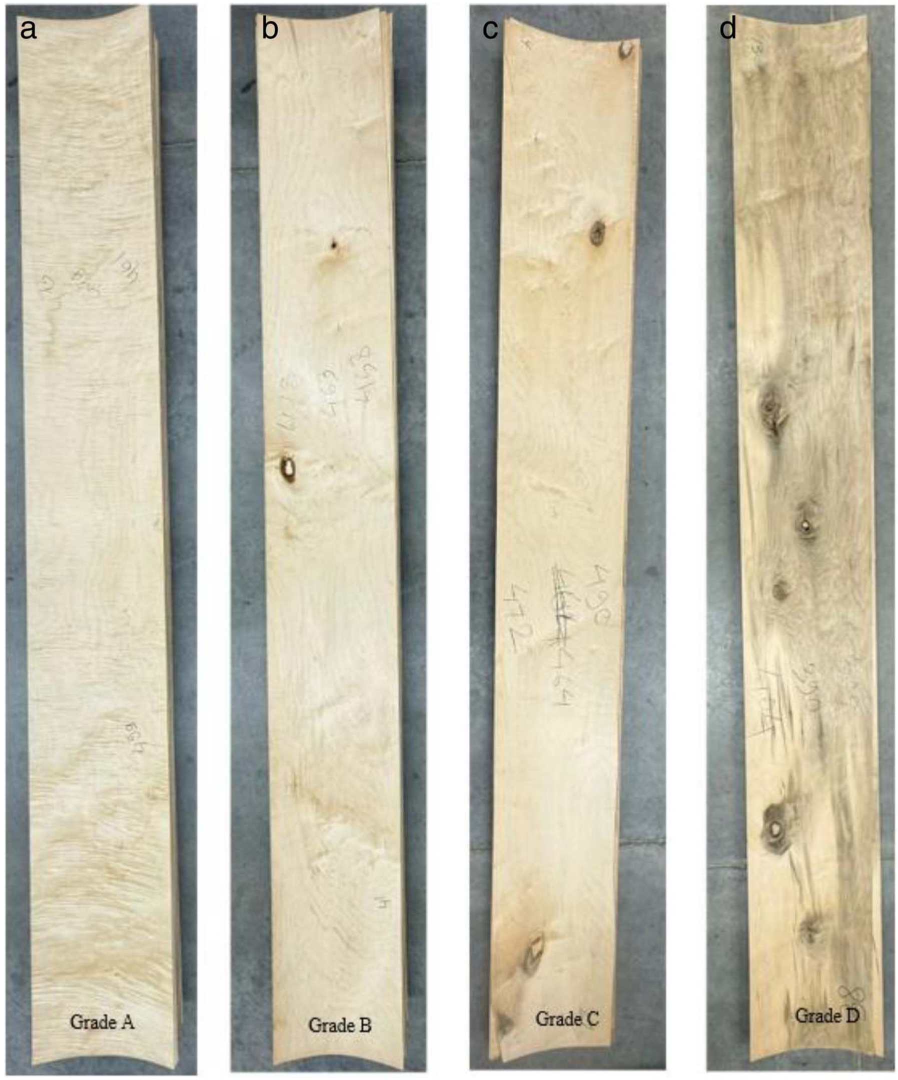

Figure 1.—Visually graded veneer specimens: (a) Grade A, (b) Grade B, (c) Grade C, and (d) Grade D.

measuring 292 mm wide by 140 mm long were bonded to the veneers using a polyurethane adhesive, LOCTITE UR 5153, supplied by Henkel, with a gel time of 30 minutes and a cure time of 60 minutes (Belaidi et al. 2025). Bonding the particleboard to the veneers was necessary to prevent slippage during the tensile test. Simply placing the boards on both sides of the veneers increased the thickness but did not address the slippage issue effectively. An extensometer with a gauge length (L_i) of 1,282.7 mm (50.5 in.) was used to measure the extension (ΔL) of the veneers as shown in Figure 3c. The static modulus of elasticity (MOE_s) was then calculated using Equation 3.

$$MOE_s = \frac{P}{\Delta L} * \frac{L_i}{A} \xrightarrow{m = P/\Delta L} MOE_s = \frac{mL_i}{A} \quad (3)$$

where P is the tensile load, ΔL is the extension corresponding to the tensile load of P, A is the cross-section area of the

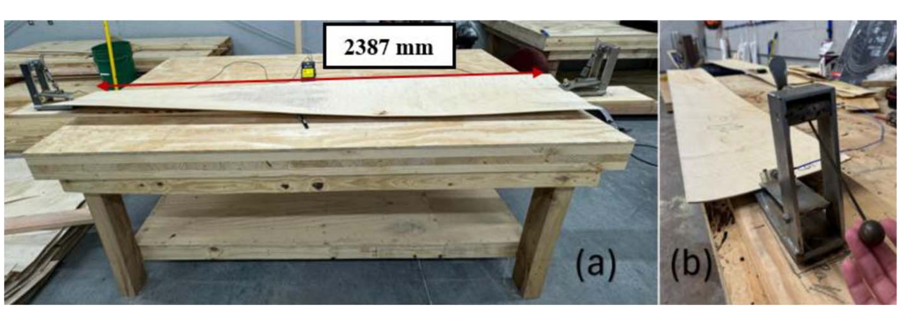

Figure 2.—(a) Setup for the stress wave measurement. (b) Built-in pendulum.

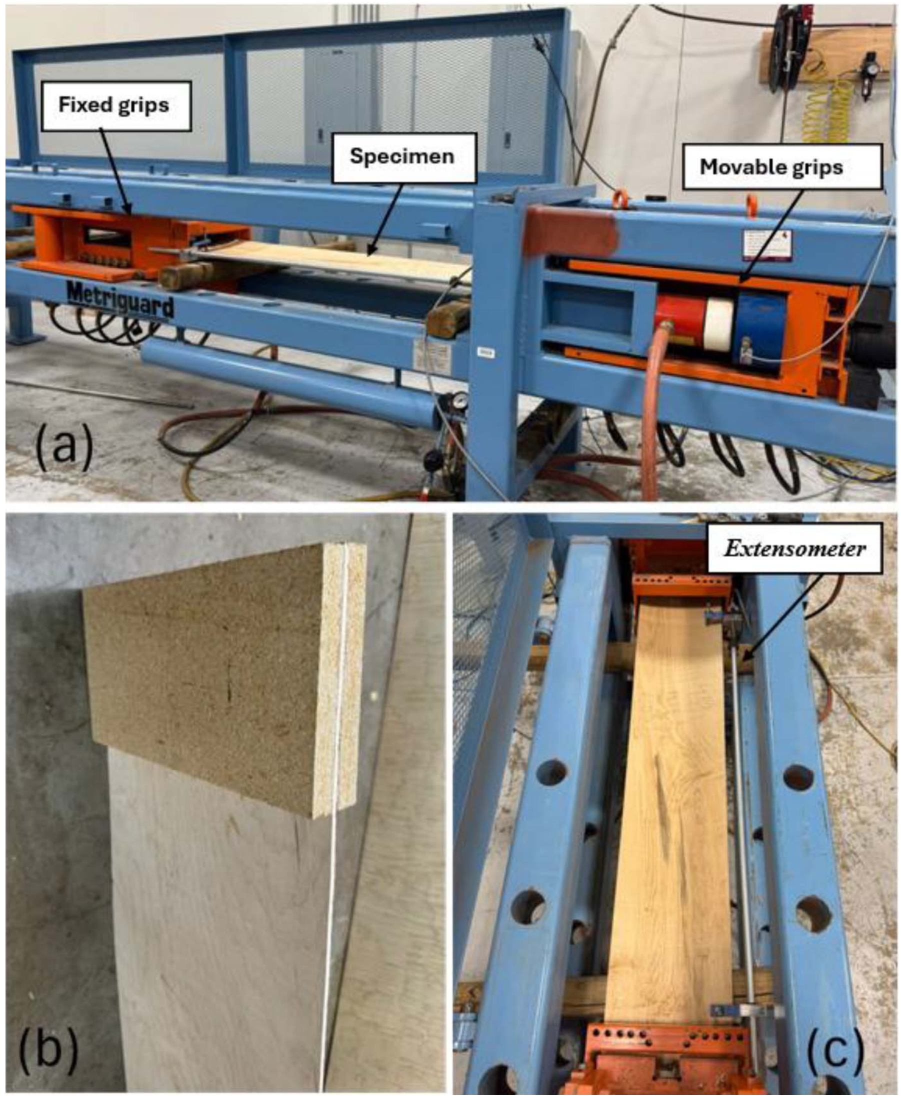

Figure 3.—(a) Metriguard 422 Tension Proof Tester. (b) Veneer specimen sandwiched between particle boards. (c) Extensometer used for measuring the extension.

veneer, and m is the slope of the tensile load versus extension graph in the elastic region.

The tensile test was selected as a destructive method for this study to determine the experimental MOE of 8-ft-long veneers. In contrast, the bending test requires a large span-to-depth ratio, approximately 24 to 30, or even up to 60, similar to dimensional lumber, to reduce the effect of shear deformation and obtain an accurate MOE for the veneers. This would have necessitated cutting 4- to 7-inch-long bending specimens from 96-inch-long veneers. Given that small specimens may not accurately reflect the properties of full-length veneers, tensile testing was considered to be a more suitable approach for assessing the mechanical properties of the veneers.

Results and Discussion

Stress wave properties of red maple veneer specimens

The distribution of the MOE_d for the 553 veneer specimens, ranging from 10 GPa to 29 GPa, is presented in Figure 4. A Kolmogorov-Smirnov normality test was conducted on the MOE_d values using OriginPro software version 2025. The resulting p-value was 0.79 (>0.05), indicating that MOE_d values are normally distributed. The mean MOE_d of the red maple veneer was 19.10 GPa, with a standard deviation of 2.95 GPa and a coefficient of variance (COV) of 15.44 percent.

The density of the veneer specimens is presented in Figure 5a, ranging from 436 to 765 kg/m^3, with a mean of 584.26 kg/m^3, a standard deviation of 47.79 kg/m^3, and COV of 8.18 percent. The Kolmogorov-Smirnov test for density resulted in a p-value of 0.25 (>0.05), indicating that the density distribution also follows a normal distribution.

In contrast, stress wave velocity varied between 4,496 and 6,551 m/s, as shown in Figure 5b, with an average of 5,710.07 m/s, a standard deviation of 440.14 m/s, and COV of 7.70 percent. This relatively low COV value can be attributed to the anatomical structure of red maple.

As a diffuse-porous species with small, uniform vessels and fine ray structures, red maple provides a more

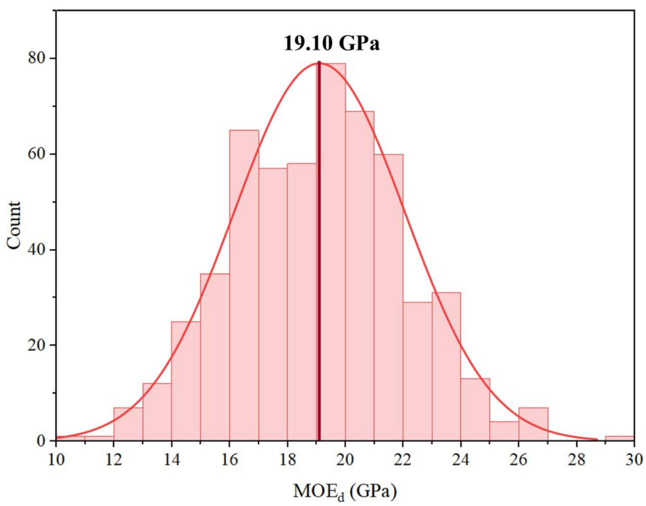

Figure 4.—Distribution of the dynamic modulus of elasticity (MOE_d) of 553 red maple veneer specimens.

consistent material composition, which likely contributes to stable acoustic velocity values across repeated measurements. However, the Kolmogorov-Smirnov test for velocity yielded a *p*-value of <0.0001, indicating a non-normal distribution. The skewness of velocity was -0.27, suggesting a slight negative skew.

These findings were compared with previous studies on hardwood species that showed close mean values, where Del Menezzi et al. (2013) reported an average velocity of 4,432 m/s and an average density of 467 kg/m^3 for 64 *Schizolobium parahyba* veneer samples. Similarly, Ross et al. (2004b) conducted a study on red maple logs, where they assessed the yield of ultrasonically graded veneer from logs obtained from eastern and Great Lake states in the United States. The study reported that the average density for veneer from Great Lake states logs was 578.2 kg/m^3, and average density for veneer from eastern states logs was 561.6 kg/m^3. While Van Duong and Hasegawa (2024) found a mean acoustic velocity of 4,183 m/s and density of 450 kg/m^3 for black wattle (*Acacia*) logs, Sharma and Shukla (2012) reported a velocity of 4,100 m/s for the same species.

The variation in velocity and density values across these studies can be explained by several factors, including differences in the specific species, the number of samples used, and the type of material tested (veneer, logs, or solid lumber).

The 60 veneer specimens for the destructive tensile test in this study were selected to represent the bell-shaped distribution of MOE_d values. Therefore, all 553 veneer specimens were rank sorted by MOE_d in ascending order, from low to high, and assigned numerical labels accordingly. One veneer specimen was randomly selected from every group of nine specimens using a random number generator method.

The distribution of the MOE_d of the 60 veneer specimens selected for the nondestructive test is presented in Figure 6. The bell-shaped histogram also indicates a normal distribution of MOE_d for these 60 specimens, ranging from 12 GPa to 29 GPa, similar to that of the 553 veneer parent population. The mean MOE_d of these 60 specimens was 19.12 GPa, with a standard deviation of 3.10 GPa and a COV of 16.21 percent, which is nearly identical to that of the entire population of 553 specimens (19.12 GPa).

Impact of veneer density and stress wave velocity on MOE_d.—This section present the effect of veneer density and stress wave velocity on MOE_d through regression analysis, as shown in Figure 7. The analysis was conducted using OriginPro software.

Table 3 provides a comprehensive overview of the statistical results. MOE_d is influenced by both density and velocity, but the strength of their relationships differs significantly. Wood density and MOE_d are two key predictors of the mechanical properties of wood (Tsoumis 1991, Divós and Tanaka 2005, Izekor et al. 2010, Baar et al. 2015, Oberhofnerová et al. 2016). Typically, an increase in density results in greater material stiffness, leading to a higher MOE_d (Baar et al. 2015).

The regression analysis for density showed a weak but positive correlation ($r = 0.27$) and low coefficient of

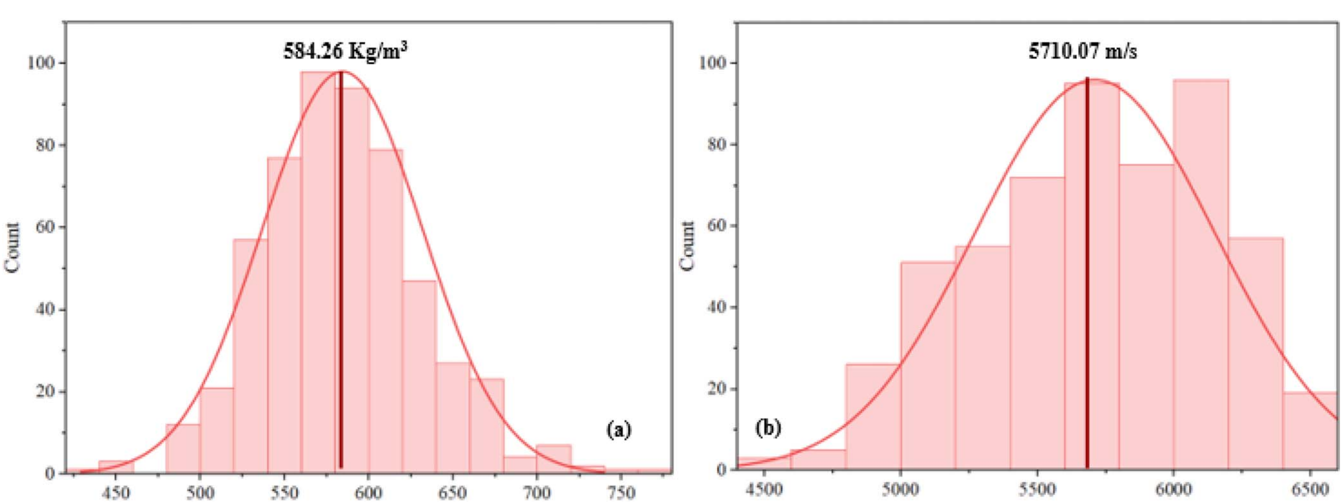

Figure 5.—Distribution of the stress wave properties of 553 red maple veneer specimens: (a) density and (b) velocity.

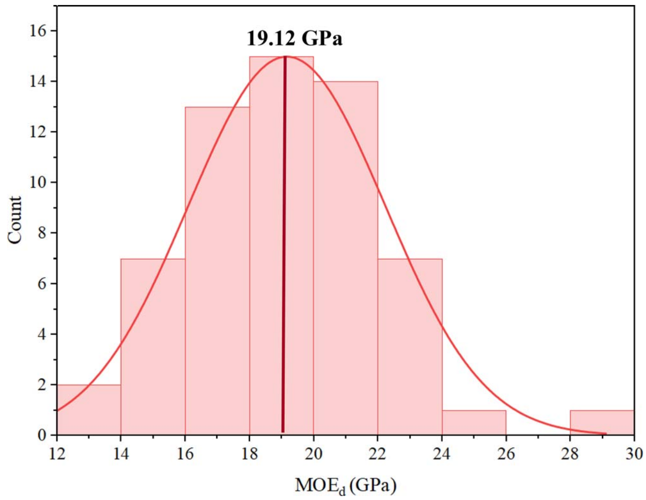

Figure 6.—Distribution of the dynamic modulus of elasticity (MOE_d) of 60 red maple veneer specimens.

determination ($R^2 = 0.074$), indicating that 7.4 percent of the variability in MOE_d can be explained by density. The analysis of variance (ANOVA) test results indicated a statistically significant relationship between density and MOE_d. Given a low p-value <0.0001 and a moderate F-value of 44.35, it can be confidently concluded that the density influences MOE_d. Therefore, while the results suggest statistical significance, the low R^2 value (0.074) and weak positive correlation ($r = 0.27$) indicate that the relationship is not strong enough to reliably predict the MOE_d based solely on the density.

To further demonstrate the weak correlation between density and MOE_d, three different specimens of veneer with low, medium, and high MOE_d were selected, all exhibiting very close density, as shown in Table 4. Although all three samples had nearly identical densities with an average of 528 kg/m^3, their MOE_d values showed significant variation, ranging from 16.99 GPa to 21.99 GPa. These specimens demonstrate that density alone cannot fully account for the variations observed in MOE_d.

The regression analysis revealed a strong correlation ($r = 0.86$) between velocity and the dynamic modulus of elasticity.

Table 3.—Regression results of velocity and density on dynamic modulus of elasticity (MOE_d).

MOE_d	Equation of regression	Pearson's r	R^2	F value	p-value
Density (kg/m^3)	$Y = 9.26 + 0.017x$	0.27	0.074	44.35	<0.0001*
Velocity (m/s)	$Y = -13.667 + 0.0057x$	0.86	0.74	1579.22	<0.0001*

* Significant at $P \leq 0.05$.

A coefficient of determination (R^2) of 0.74 indicates that 74 percent of the variability in MOE_d is explained by velocity. The results were highly significant ($F = 1{,}579.22$, $p < 0.0001$), confirming that velocity is a stronger predictor of MOE_d.

Overall, this comparison revealed that while density and velocity influence the MOE_d, velocity had a more significant impact on MOE_d compared to density. This is likely due to several factors affecting the stress wave velocity in the veneer, such as density, defects, and fiber orientation. As a result, velocity demonstrated a statistically significant relationship with MOE_d, accounting for the combined effect of these factors. As shown in Table 4, density could not explain the variation in the MOE_d of three selected veneer specimens; however, the grading of veneers, primarily based on defects, may account for this variation. The veneer with a higher grade (Grade A) exhibited an MOE_d of 21.99 GPa, while the one with a lower grade (Grade D) corresponds to a lower MOE_d of 16.99 GPa. Therefore, in the following section, the effect of defects on the MOE_d is thoroughly investigated.

Effects of natural defects on stress wave velocity and MOE.—According to Bucur (2006), natural defects such as knots, cracks, and fiber deviation can significantly affect the stiffness of wood material (Bucur 2006).

Based on the visual grading system, veneers with low MOE_d values are expected to be graded as Grades C and D, indicating a greater presence of defects. Conversely, the MOE_d for veneers graded as Grades B and C is expected to be around the mean MOE_d, reflecting moderate defects. Finally, veneers with high MOE_d values will

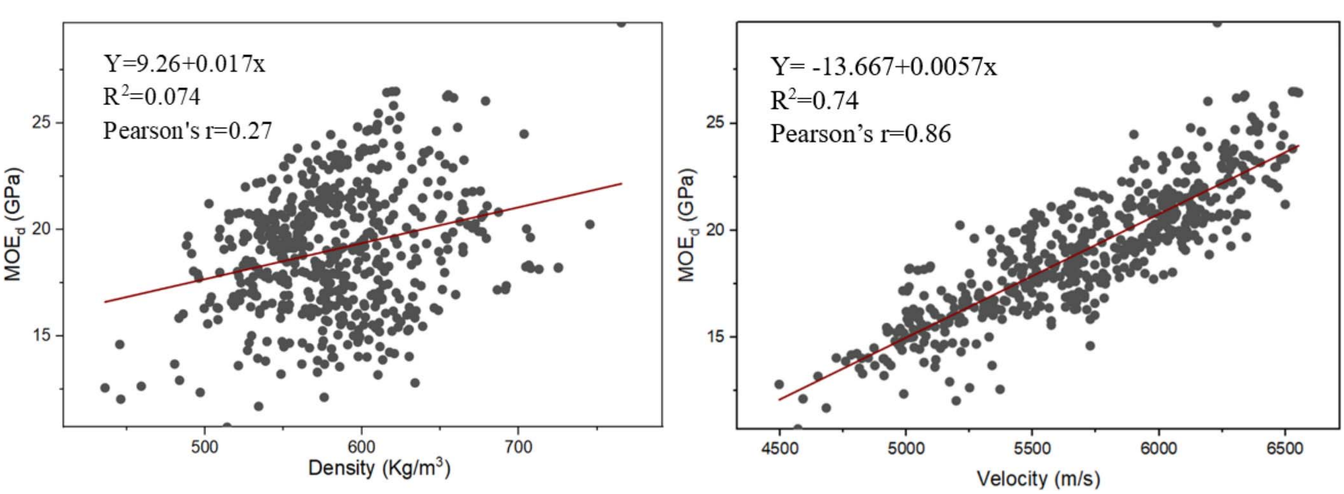

Figure 7.—Regression analysis of density and velocity with the dynamic modulus of elasticity (MOE_d).

Table 4.—Wave propagation time, density, dynamic modulus of elasticity (MOE_d), and grade of three selected veneer specimens.

Sample	MOE_d (GPa)	Transmission wave time (s)			Density (kg/m^3)	Grade
1	16.99	428	411	441	531	D
2	20.73	392	379	384	528	B
3	21.99	381	371	367	526	A

likely fall between Grades A and B, suggesting minimal to no defects.

The regression analysis of veneer grades with respect to MOE_d and velocity is presented in Figure 8. Results revealed that Grade A veneers were distributed across the entire range of MOE_d values. Overall, the grading results do not align with the hypothesis that veneers with fewer defects demonstrate higher stiffness only, as indicated by their MOE_d.

Some researchers have identified other factors beyond the presence of knots that may impact MOE_d. Qin et al. (2018) highlighted that it is very challenging to locate and quantify defects in wood, mainly when the defects, such as knots, are located away from the center of the specimen. Fiber and microfiber angles, though beyond the scope of this study, are other factors that can significantly affect the stiffness and strength of wood materials (Kollmann 1951, Eberhardsteiner 1995).

Mechanical properties of red maple veneer

The distribution of the MOE_s of the 60 veneer specimens, as determined from the destructive tensile test, is shown in Figure 9. Using OriginPro software, a Shapiro-Wilk normality test was carried out on the MOE_s values. The resulting *p*-value was 0.051, indicating a near-normal distribution of MOE_s for these 60 specimens, with results ranging from 6 GPa to 16 GPa.

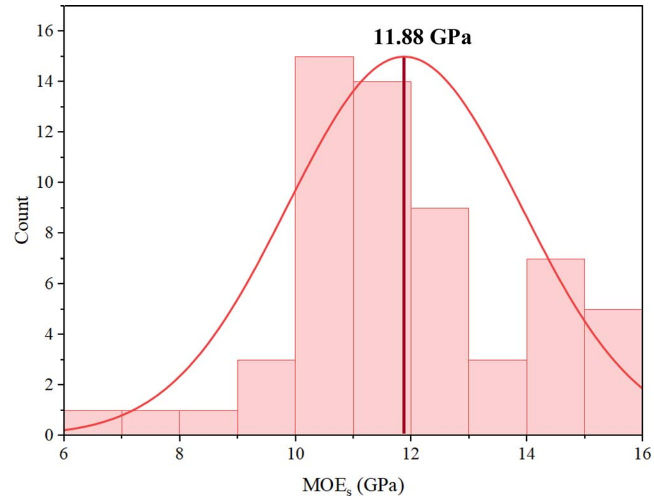

Figure 9.—Distribution of the static modulus of elasticity (MOE_s) of 60 red maple veneer specimens.

The mean MOE_s was 11.88 GPa, with a standard deviation of 2.01 GPa, and a COV of 16.91 percent, indicating moderate variability. The loading rate applied during testing was 126.73 N/s. It should be mentioned that the *Wood Handbook* (USDA 2021) reports a typical MOE_s of 11.31 GPa for red maple dimensional lumber.

The tensile strength of the veneer specimens is given in Figure 10, showing a right-skewed distribution with a mean of 27,410 kPa, a standard deviation of 13,155 kPa, and a coefficient of variance of 48 percent. The tensile strength ranged from 5,600 to 68,000 kPa. In comparison, the bending strength reported in the *Wood Handbook* (USDA 2021) for red maple is 92,390 kPa. The difference in results can be attributed to variations in testing methods—tensile testing in this study versus bending testing in the *Wood Handbook* (USDA 2021)—as well as differences in material form, with this study examining veneers while the *Wood Handbook* data are based on lumber.

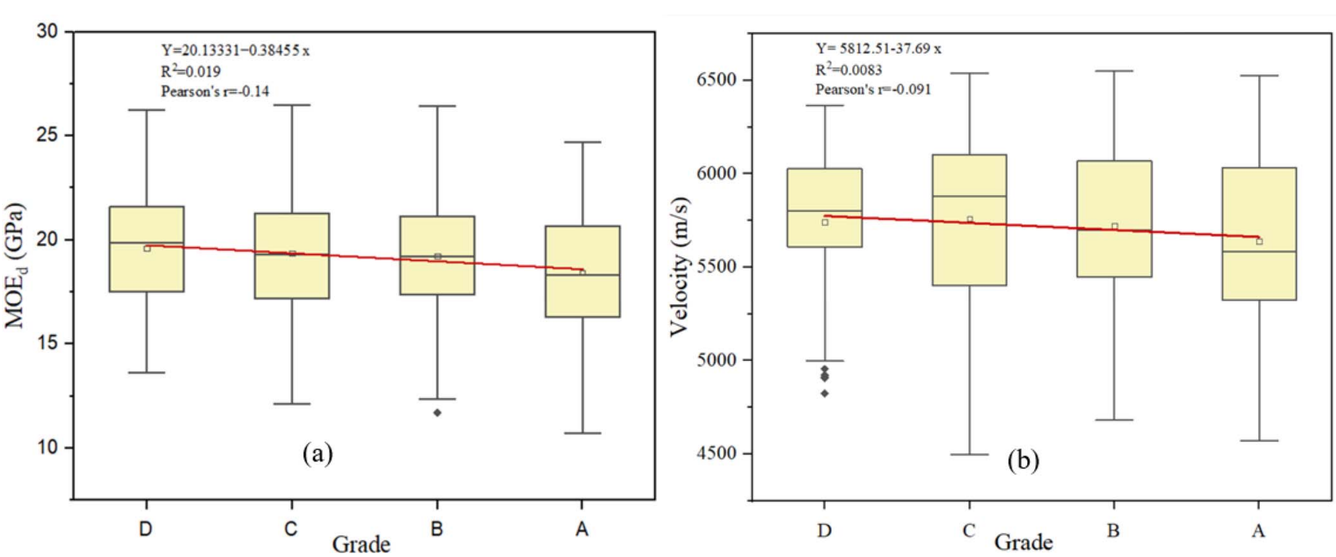

Figure 8.—Regression analysis of veneer grades across: (a) low, medium, and high dynamic modulus of elasticity (MOE_d) and (b) velocity. (A: high grade and D: low grade.)

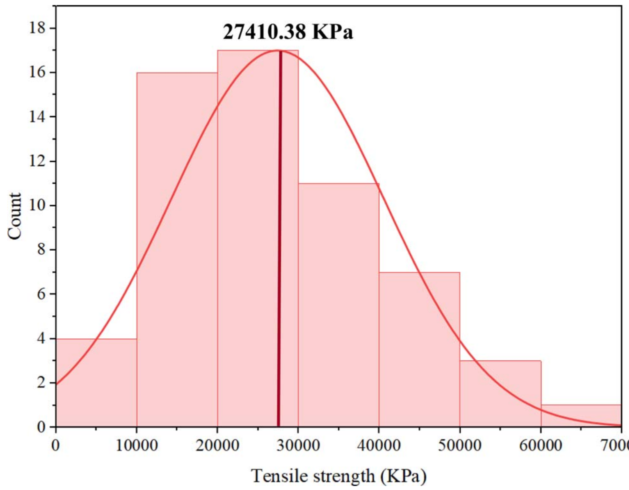

Figure 10.—Distribution of the tensile strength of 60 red maple veneer specimens.

Unlike MOE_d, natural strength-reducing defects, such as knots and checks, significantly impacted the MOE_s and the tensile strength of these veneers, as shown in Figure 11. High-grade veneers, such as Grades A and B, exhibit higher MOE_s and tensile strength, ranging from 10 to 15 GPa and 0.04 to 0.47 GPa, respectively, offering superior strength and stiffness due to the absence of natural defects.

Relation between stress wave and MOE_s of red maple veneer

Figure 12 presents the regression analysis of the relationship between MOE_d and MOE_s of the 60 veneer specimens tested destructively. The results revealed a positive correlation of 0.40 between MOE_d and MOE_s, with a p-value of 0.00156, indicating a statistically significant relationship. However, the coefficient of determination (R^2) was 0.1622, suggesting a weak linear relationship.

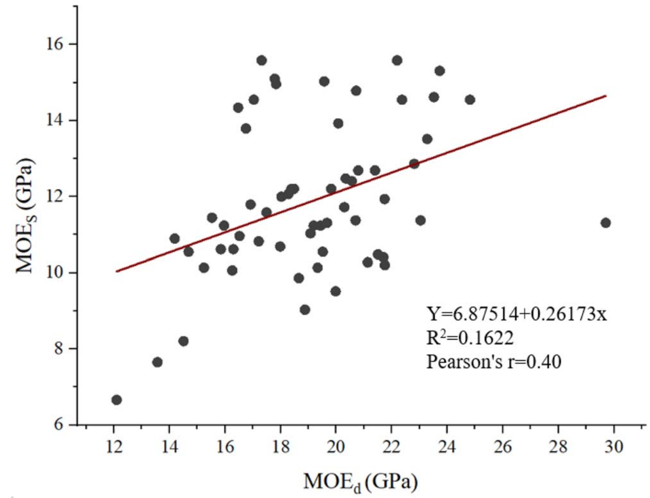

Figure 12.—Regression analysis of the relationship between dynamic modulus of elasticity (MOE_d) and static modulus of elasticity (MOE_s).

The MOE_d and MOE_s values and their descriptive statistics are presented in Table 5.

The results in Table 5 indicate that the mean value of the MOE_d was significantly (60%) higher than that of the MOE_s, with averages of 19.12 GPa and 11.88 GPa, respectively.

To investigate whether this difference was influenced by the presence of defects, a regression analysis was conducted between the MOE_d/MOE_s ratio and visual grades of only the 60 specimens, yielding an R^2 value of 0.0066 and Pearson's r of 0.081, as shown in Figure 13.

Considering the slope of the regression line, this ratio slightly increases for veneers with fewer defects and better grades. However, this increase is negligible and suggests that veneer grade does not have a significant effect on the MOE_d/MOE_s ratio to explain the difference between the MOE_d and MOE_s. Additionally, a one-way

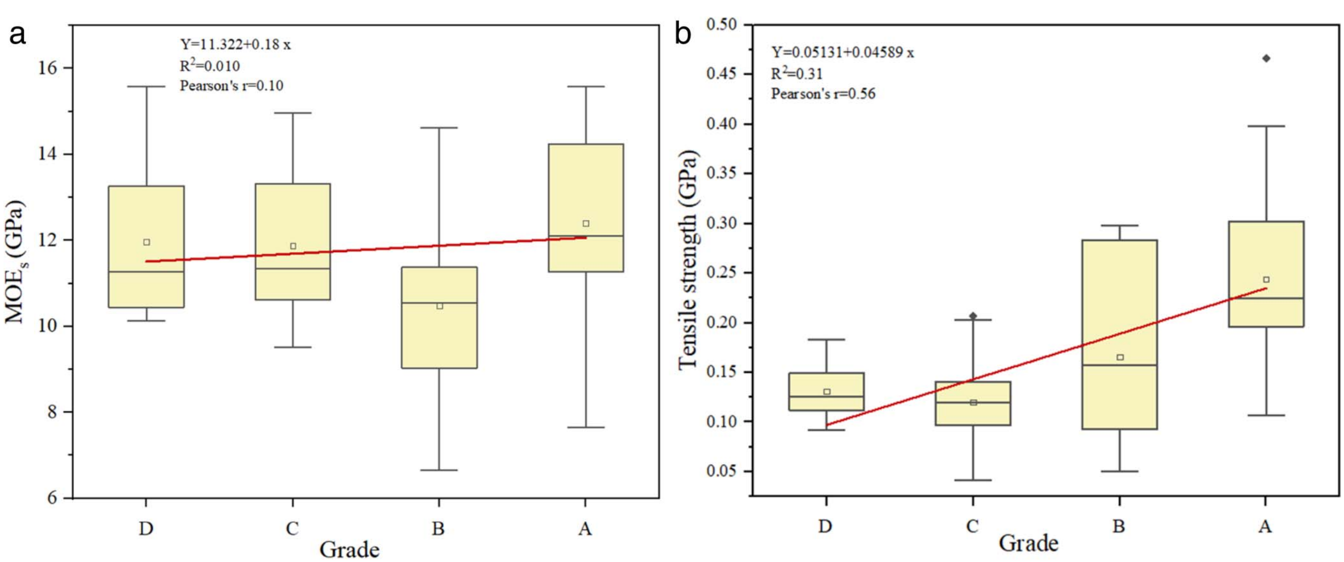

Figure 11.—Regression analysis of veneer grades across (a) low, medium, and high static modulus of elasticity (MOE_s) and (b) tensile strength.

Table 5.—Descriptive statistics for destructive and nondestructive tests.[a]

	N total	Mean (SD)	COV (%)	Minimum	Maximum
MOE_d (GPa)	60	19.12 (3.10)	16.21	12.09	29.7
MOE_s (GPa)	60	11.88 (2.01)	16.92	6.66	15.58

[a] MOE_d = dynamic modulus of elasticity; MOE_s = static modulus of elasticity; COV = coefficient of variance.

Table 6.—Oneway analysis of variance (ANOVA) comparison of dynamic modulus of elasticity (MOE_d)/static modulus of elasticity (MOE_s) ratio across veneer grades.

Visual grading	Mean[a] (GPa)
B	1.78a
A	1.62a
D	1.59a
C	1.54a

[a] Means that do not share the same letter are significantly different.

ANOVA test (Table 6) was also conducted using OriginPro software, and it indicated the same finding, i.e., no statistically significant difference in the MOE_d/MOE_s ratio across grades.

This difference aligns with findings in the literature, where dynamic testing methods often yield higher values than static testing methods (Van Duong and Hasegawa 2024). Goia et al. (2002) showed that the results of the dynamic tests were 17 percent higher than those of static tests. Van Duong and Ridley-Ellis (2021) reported that the MOE obtained by the bending test was about 15 percent lower than the value of MOE obtained by the stress wave method. The results obtained by Horáček et al. (2012) showed that the MOE_d results of Scots pine (*Pinus sylvestris*) were also higher than the MOE_s values.

The weak correlation between the MOE_d and MOE_s could be due to methodological differences between the two testing approaches. According to Divós and Tanaka (2005), this difference can be also attributed to the time-dependent behavior of wood, also known as creep. This difference has been explained by describing wood as a damping and viscoelastic material (Halabe et al. 1997). Wood acts more like a stiff material when a force is applied quickly, such as during impact loading or dynamic tests. However, in longer-duration tests, like the creep test, the wood tends to behave more like a flexible material due to its viscoelastic properties.

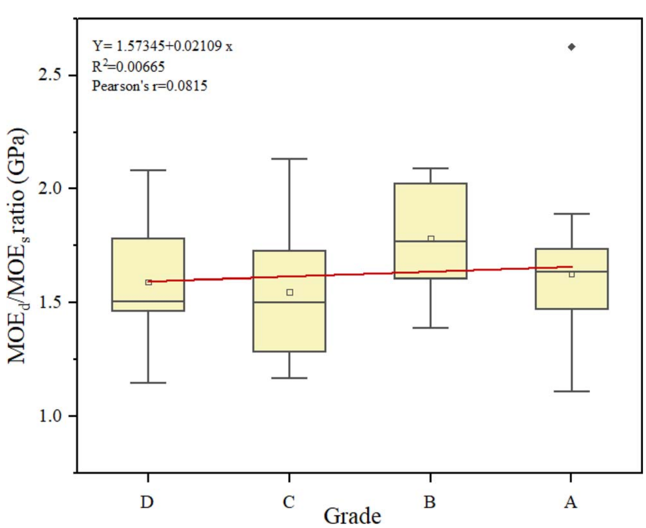

Figure 13.—Regression analysis of the relationship between dynamic modulus of elasticity (MOE_d)/static modulus of elasticity (MOE_s) ratio and grades.

Conclusions

This study investigated the relationship between the dynamic and static modulus of elasticity of red maple veneer, evaluating the mechanical properties using destructive and nondestructive methods. The key findings from this study are summarized as follows:

1. The MOE_d was significantly higher than the MOE_s, with mean values of 19.12 GPa and 11.88 GPa, respectively.
2. Density and naturally occurring strength-reducing defects such as knots had a statistically significant effect on the MOE_d. However, the impact was negligible on the MOE_d compared to MOE_s.
3. The modulus of elasticity for red maple veneer obtained from the tensile test (11.88 GPa), was closely aligned with the bending test value (11.31 GPa) reported in the *Wood Handbook* (USDA 2021).
4. Velocity showed a strong positive correlation of 0.86 and R^2 of 0.74 with the MOE_d, compared to density, which showed a weak correlation of 0.27 and low R^2 (0.074).
5. Samples with defects were found to have a lower MOE_s and tensile strength compared to those with fewer or no defects.

Acknowledgments

The authors acknowledge the support from the USDA Forest Service Forest Products Laboratory (FPL) in Madison, Wisconsin, as a major contributor of technical assistance, advice, and guidance to this research. The authors also acknowledge support from Great Lake Veneer and Henkel for supplying wood veneers and adhesives.

Literature Cited

Adam Redman, International Hardwood Veneer Grading Rules (2020)

Alderman, D. R., Jr., M. S. Bumgardner, and J. E. Baumgras. 2005. An assessment of the red maple resource in the northeastern United States. *North. J. App. Forestry* 22(3):181–189.

Arriaga, F., X. Wang, G. Íñiguez-González, D. F. Llana, M. Esteban, and O. Niemz. 2023. Mechanical properties of wood: A review. *Forests* 14(6). https://doi.org/10.3390/f14061202

Baar, J., J. Tippner, and V. Gryc. 2012. The influence of wood density on longitudinal wave velocity determined by the ultrasound method in comparison to the resonance longitudinal method. *Eur. J. Wood Wood Prod.* 70(5):767–769. https://doi.org/10.1007/s00107-011-0550-2

Baar, J., J. Tippner, and P. Rademacher. 2015. Prediction of mechanical properties—modulus of rupture and modulus of elasticity—of five tropical species by nondestructive methods. *Maderas: Cienc. Tecnol.* 17(2):239–252. https://doi.org/10.4067/S0718-221X2015005000023

Belaidi, D., A. Lamichhane, S. Pradhan, M. Mohammadabadi, R. Shmulsky, and X. Wang. 2025. Effect of adhesives on bonding performance of softwood and hardwood plywood. *Forest Prod. J.* 75(1):17.

Birinci, A. U., Ozturk, H., Demir, A., Ilhan, O., Gezer, E. D., & Demİrkir, C. (2024). Determining the effects of timber strength and wood species on the mechanical properties of CLT using non-destructive and destructive methods. *Nondestructive Testing and Evaluation*, 1–16. https://doi.org/10.1080/10589759.2024.2389942

Bucur, V. 2006. Acoustics of Wood. 2nd ed. Springer, Berlin.

Chen, A., Y. Liang, Z. Jiang, and J. Sun. 2021. Prediction of elastic modulus and mid-span deflection of bamboo-wood composites. *BioResources* 16(4):7784–7798.

Chen, Y. and W. Guo. 2016. Mechanical properties evaluation of two wood species of ancient timber structure with nondestructive testing. *BioResources* 11(3):6600–6612.

Dackermann, U., K. Crews, B. Kasal, J. Li, M. Riggio, F. Rinn, and T. Tannert. 2014. In-situ assessment of structural timber using stress-wave measurements. *Mater. Struct*. 47(5):787–803. https://doi.org/10.1617/s11527-013-0095-4

Del Menezzi, C., L. Mendes, M. de Souza, and G. Bortoletto. 2013. Effect of nondestructive evaluation of veneers on the properties of laminated veneer lumber (LVL) from a tropical species. *Forests* 4(2):270–278. https://doi.org/10.3390/f4020270

de Oliveira, F. G. R., & Sales, A. (2006). Relationship between density and ultrasonic velocity in Brazilian tropical woods. *Bioresource Technology*, 97(18), 2443–2446. https://doi.org/10.1016/j.biortech.2005.04.050

Divós, F. and T. Tanaka. 2005. Relation between static and dynamic modulus of elasticity of wood. *Acta Silv. Lign. Hung.* 1(1):105–110.

Eberhardsteiner, J. (1995). "Biaxial testing of orthotropic materials using electronic speckle pattern interferometry," Measurement 16(3), 139-148. https://doi.org/10.1016/02632241(95)00019-4

Ettelaei, A., M. Layeghi, H. Zarea Hosseinabadi, and G. Ebrahimi. 2019. Prediction of modulus of elasticity of poplar wood using ultrasonic technique by applying empirical correction factors. *J. Int. Meas. Confed.* 135:392–399. https://doi.org/10.1016/j.measurement.2018.11.076

Fathi, H., V. Nasir, and S. Kazemirad. 2020. Prediction of the mechanical properties of wood using guided wave propagation and machine learning. *Constr. Build. Mater*. 262:120848. https://doi.org/10.1016/j.conbuildmat.2020.120848

Fedyukov, V., E. Saldaeva, and M. Chernova. 2017. Different ways of elastic modulus comparative study to predict resonant properties of standing spruce wood. *Wood Res.* 62(4):607–614.

França, F. J. N., T. S. F. A. França, R. Daniel Seale, and R. Shmulsky. 2020. Nondestructive evaluation of 2 by 8 and 2 by 10 southern pine dimensional lumber. *Forest Prod. J*. 70(1):79–87. https://doi.org/10.13073/FPJ-D-19-00051

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 pp.

Goia, F., R. De Oliveira, J. Anadia, O. De Campos, and A. Sales. 2002. Ultrasonic measurements in Brazilian hardwood. *Mater. Res.* 5(1):51–55.

Halabe, U. B., G. M. Bidigalu, H. V. S. Gangarao, and R. J. Ross. 1997. Nondestructive evaluation of green wood using stress wave and transverse vibration techniques. *Mater. Eval*. 55(9):1013–1018.

Horáček, P., J. Tippner, and K. T. Hassan. 2012. Nondestructive evaluation of static bending properties of Scots pine wood using stress wave technique. *Wood Res*. 57(3):359–366.

Izekor, D. N., J. A. Fuwape, and A. O. Oluyege. 2010. Effects of density on variations in the mechanical properties of plantation grown *Tectona grandis* wood. *Arch. Appl. Sci. Res.* 2(6):113–120.

José Marini, L., A. Luís Christoforo, and F. Antonio Rocco Lahr. 2018. Comparison of two methods to determine the bending modulus of elasticity of wood. *Int. J. Mater. Eng*. 8(6):162–166. https://doi.org/10.5923/j.ijme.20180806.05

Kang, H. and R. E. Booker. 2002. Variation of stress wave velocity with MC and temperature. *Wood Sci. Technol*. 36(1):41–54.

Kollmann, F. (1951). Technologie des Holzes und der Holzwerkstoffe [Technology of Wood and Wood-based Materials], Springer, New York, New York.

Lamichhane, A., S. Pradhan , D. Belaidi, & M. Mohammadabadi (2025). Engineered wood cellular beams: Influence of corrugated panels layout on structural performance. *Structures*, 73. https://doi.org/10.1016/j.istruc.2025.108460

Liu, Z., Y. Liu, H. Yu, and J. Yuan. 2006. Measurement of the dynamic modulus of elasticity of wood panels. *Front. Forestry China* 1(4):425–430. https://doi.org/10.1007/s11461-006-0048-y

Llana, D. F., I. Short, and A. M. Harte. 2020. Use of non-destructive test methods on Irish hardwood standing trees and small diameter round timber for prediction of mechanical properties. *Ann. Forest Sci.* 77:62. https://doi.org/10.1007/s13595-020-00957-x

Miclea, C., V. Tanasoiu, C. Miclea, and C. Tanasoiu. 2002. Nondestructive testing techniques and piezoelectric ultrasonics transducers for wood and built in wooden structures. *J. Optoelectron. Adv. Mater.* 4(4). https://www.researchgate.net/publication/253713113

Mohamed, A. 2023. Standard test methods for elastic and shear properties. *In:* Current Applications of Engineered Wood. J. Zhang (Ed.). InTech Open, London.55 - 68.

Mvolo, C. S., J. D. Stewart, and A. Koubaa. 2022. Comparison between static modulus of elasticity, non-destructive testing moduli of elasticity and stress-wave speed in white spruce and lodgepole pine wood. *Wood Material Sci. Eng.* 17(5):345–355. https://doi.org/10.1080/17480272.2021.1871949

Oberhofnerová, E., K. Arnetová, T. Holeček, V. Borůvka, and J. Bomba. 2016. Determination of correlation between destructive and nondestructive test methods applied on modified wood exposed to natural weathering. *BioResources* 11(2):5155–5168. https://doi.org/10.15376/biores.11.2.5155-5168

Ponneth, D., A. E. Vasu, J. C. Easwaran, A. Mohandass, and S. S. Chauhan. 2014. Destructive and non-destructive evaluation of seven hardwoods and analysis of data correlation. *Holzforschung* 68(8):951–956. https://doi.org/10.1515/hf-2013-0193

Pradhan, S., Lamichhane, A., Belaidi, D., & Mohammadabadi, M. (2024). The Effect of Different Densification Levels on the Mechanical Properties of Southern Yellow Pine. *Sustainability (Switzerland)*, 16(15). https://doi.org/10.3390/su16156662

Ross, R. J. 1992. Nondestructive testing of wood. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin.

Qin, J., Liu, X., Van Den Abeele, K., and Cui, G. (2018). "The study of wood knots using acoustic nondestructive testing methods," Ultrasonics 88:43–55. https://doi.org/10.1016/j.ultras.2018.01.004

Ross, R. J. 2015. Nondestructive evaluation of wood. 2nd ed. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. www.fpl.fs.fed.us (Accessed November 2024).

Ross, R. J., K. B. Brashaw, X. Wang, H. R. White, and F. R. Pellerin. 2004a. Wood and timber condition assessment manual. Forest Products Society, Madison, Wisconsin.

Ross, R. J., J. R. Erickson, B. K. Brashaw, X. Wang, S. A. Verhey, J. W. Forsman, and C. L. Pilon. 2004b. Yield and ultrasonic modulus of elasticity of red maple veneer. *Forest Prod. J*. 54(12):220–225. https://www.researchgate.net/publication/242425828

Sharma, S. K. and S. R. Shukla. 2012. Properties evaluation and defects detection in timbers by ultrasonic non-destructive technique. *J. Indian Acad. Wood Sci.* 9(1):66–71. https://doi.org/10.1007/s13196-012-0064-5

Simpson, W. T. and X. Wang. 2001. Relationship between longitudinal stress wave transit time and moisture content of lumber during kiln-drying. *Forest Prod. J*. 51(10):51–54.

Tsoumis, G. 1991. Science and technology of wood: Structure, properties, utilization. Chapman & Hall, New York.

Turkot, C. G., R. D. Seale, E. D. Entsminger, F. J. N. França, and R. Shmulsky. 2020. Nondestructive evaluation of red oak and white oak species. *Forest Prod. J*. 70(3):370–377. https://doi.org/10.13073/FPJ-D-20-00015

Utami, S. S., A. Mappuji, B. Achmad, A. Awaluddin, A. Ayutyastuti, Y. F. Luckyarno, and R. J. Yanti. 2020. Design of an acoustic-based nondestructive test (NDT) instrument to predict the modulus of elasticity of wood. *Eng. J.* 24(6):109–116. https://doi.org/10.4186/ej.2020.24.6.109

Van Duong, D. and M. Hasegawa. 2024. Relationship between acoustic wave velocity and mechanical properties in *Acacia mangium* wood. *Maderas: Cienc. Tecnol*. 26. https://doi.org/10.22320/s0718221x/2024.33

Van Duong, D. and D. Ridley-Ellis. 2021. Estimating mechanical properties of clear wood from ten-year-old *Melia azedarach* trees using the stress wave method. *Eur. J. Wood Prod*. 79:941–949. https://doi.org/10.1007/s00107-021-01664-8

Wang, X., R. J. Ross, B. K. Brashaw, S. A. Verhey, J. W. Forsman, and J. R. Erickson. 2003. Flexural properties of laminated veneer lumber manufactured from ultrasonically rated red maple veneer—A pilot study. Research Note FPL–RN–0288. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. https://www.fpl.fs.usda.gov/documnts/fplrn/fplrn288.pdf