Nondestructive Assessment of Hardwood Cross-Laminated Timber

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Abstract

This study investigated the use of longitudinal vibration technique to evaluate the mechanical properties of cross-laminated timber (CLT) of four species of lumber—red oak (*Quercus rubra*), sweetgum (*Liquidambar* spp.), yellow poplar (*Liriodendron* spp.), and southern pine (SYP; *Pinus* spp.). The hardwood CLTs for this study were made from low-grade lumber; SYP CLT was industrially manufactured. The dynamic modulus of elasticity (dMOE) was assessed using the Fakopp device. After nondestructive testing (NDT) evaluation, samples were then destructively tested and correlations between various properties were developed. These properties included bending modulus of elasticity (MOE), modulus of rupture (MOR), density, and dMOE. There was moderate correlation between MOE and dMOE for three of the species tested—red oak, sweet gum, and SYP; however, a weaker relationship was observed between MOR and dMOE for all species tested. The coefficient of correlation for MOE against density showed that 30 to 64 percent of tested samples fit into the linear relationship. The coefficient of correlation result suggests that NDT could be reliable for predicting the bending MOE of CLT. The NDT result for hardwood samples also showed that CLT from low-value hardwood lumber could be used for construction purposes, with 95 of 96 hardwood samples exceeding 8,300 MPa, the minimum allowable strength value specified in American National Standards Institute/The Engineered Wood Association for softwood CLT. This research shows that NDT techniques can be used for estimation of mechanical properties of hardwood CLT and are able to improve the grading of mass timber products.

The mechanical properties of an engineering material in service are critical to evaluating its serviceability. Correctly predicting the mechanical properties of these materials, in this case, wood and engineered wood products (EWPs), leads to an estimation of the total lifespan of the wood products while in service. Generally, the mechanical properties of a material are those that involve a reaction to an applied load. The removal of the applied load to a material under bearable stress takes deformations on the material back to a completely recoverable state (Senalik and Farber 2021). Of the various subproperties of mechanical properties, strength properties are of utmost concern in the wood and wood products industry. The most common strength properties are modulus of elasticity (MOE), modulus of rupture (MOR), compressive strength (parallel and perpendicular), tensile strength (parallel and perpendicular), and hardness. The traditional method of determining these properties is through a static bending test, which is destructive and poses usability risks to materials being tested. The evaluation of these properties using a static test comes with the risk of permanent damage to the material being tested, thus leading to wastage of materials, environmental concerns, and loss of money (Franca et al. 2020).

To curtail the risks associated with static bending, nondestructive testing (NDT) is an alternative method of estimating the properties of a material in such a way that preserves the integrity of the material being tested. Ross (2015) defines nondestructive evaluation (NDE) as the science of identifying the physical and mechanical properties of a

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piece of material without altering its end-use capabilities and then using this information to make decisions regarding appropriate applications. This technique estimates the strength of the material by generating a dynamic modulus of elasticity (dMOE) through vibration produced across (transverse) or along (longitudinal) the length of the material being tested. In a force vibration testing of hybrid cross-laminated timber (CLT)–concrete, Quang et al. (2018) found that dynamic properties generated are good indicators of the wood quality. This indicates that NDT could be very beneficial for quality-control purposes in the wood products industry. Franca et al. (2020) stated that these two types of NDT techniques—longitudinal stress wave and transverse vibration—are the most widely used in structural lumber evaluation.

Some authors (Jayne 1959, Kaiserlik and Pellerin 1977, Gerhards 1982, Falk et al. 1990; Wang 2013, Franca et al. 2020) have previously emphasized how the use of longitudinal stress waves to predict the MOE of lumber has been extensively studied. This technique relies on the principle of time-of-flight measurement systems to determine the speed required for the propagated stress wave to travel along the length of the material being tested. In these measurement systems, a mechanical or ultrasonic impact is used to transmit longitudinal waves into a member. Piezoelectric sensors are placed at two points on the member and used to sense the passing of the wave. The time required for the wave to travel between sensors is measured and used to compute wave propagation speed, which is then used to calculate the dMOE. This principle has been used by different authors in previous studies. Prakash (1980), Franca et al. (2018), and Lee et al. (2021) used various NDT techniques to estimate the mechanical properties of lumber and composite material. The advantages of using the longitudinal vibration waves as a tool to determine the MOE over some other types of NDT are the simplicity, affordability, and suitability across applications (Turkot et al. 2020).

Because longitudinal vibration testing is applicable to many situations, it can be used on structural lumbers and EWPs such as CLT. Succinctly, NDE seeks to predict how stiff or strong an individual member will be. Although the ultimate strength of solid sawn lumber varies more than that of composites, the prediction of the mechanical properties of each can be improved with the application of NDE (Franca et al. 2020).

CLT is a multilayer wood composite material manufactured from structural lumber (Mohamadzadeh and Hindman 2015). Broadly speaking, there is no stringent number of layers, as well as dimensions, for CLT. Though Hiziroglu (2019) reported that CLT is typically manufactured as a ply consisting of three to seven layers of lumber, there can be a greater number of layers depending on specifications. The ideal thickness of the constituent lumber would usually range from 15 mm (0.59 in) to 50 mm (1.96 in). According to APA—The Engineered Wood Association (APA), the assembly of lumber yields a panel of up to 610 to 3,048 mm (2 to 10 ft) wide and up to 508 mm (20 in) thick. Through finger jointing, higher dimensions of CLT are attainable.

Previous studies have been carried out to predict mechanical properties of lumber using diverse NDTs. França et al. (2018) evaluated the stiffness and strength properties of southern pine (SYP) lumber using transverse vibration technique in both flatwise and edgewise directions. The authors reported R^2 ranging from 0.794 to 0.887 for all their correlations between dMOE and MOE. This showed excellent relationships and hence NDT can be a good indicator for estimating mechanical properties.

A study by Opazo-Vega et al. (2021) assessed the dMOE of *Eucalyptus nitens* timber using two types of NDT. The study found that both NDT techniques are good predictors of stiffness and fast alternatives for mechanical evaluation. The mean longitudinal and transverse vibrations and static bending were 12,500, 10,480, and 11,500 MPa respectively and a positive correlation existed between the results, with $R^2 = 0.98$.

Despite the number of studies available on NDTs for lumber strength prediction, just a few studies have estimated CLT strength properties using NDTs. A study by Llana et al. (2022) was focused on evaluating structural properties of European oak CLT made from recovered timber from a demolition sector. Longitudinal vibration was used to estimate the dMOE. The dMOE obtained for CLT made from recovered European oak ranged between 9,417 and 9,423 MPa. In the United States, low-value hardwoods are gaining interest for their potential use as structural materials by remodeling them into CLT. It is therefore a requisite to be cognizant of the attributes of this modified material as a load-bearing material. In this study, the mechanical properties were evaluated with a two-step approach. The longitudinal vibration method was first performed on low-value hardwoods and industrially manufactured softwood CLT, followed by the static bending test. The objective of this study was to evaluate the precision of nondestructive methods in predicting mechanical properties of CLT made with underutilized hardwood species.

Materials and Methods

Materials

For this study, CLT from four different species were used. The hardwood species used were red oak (*Quercus rubra*), sweetgum (*Liquidambar* spp.), and yellow poplar (*Liriodendron* spp.); the softwood species used was SYP (*Pinus* spp.).

Hardwood CLT

The hardwood lumber that was used to manufacture the CLT panels was acquired from two sawmills in Mississippi. A total of 382 hardwood lumber pieces in the dimensions of 50 by 152 mm (approximately 2 by 6 in) was obtained from these suppliers. Table 1 shows the summary of lumber pieces used for this study. Before manufacturing CLT panels, the lumber pieces were air dried in an outdoor setting for approximately 18 months. During this time, the moisture

Table 1.—Lumber pieces for cross-laminated timber manufacturing.

	Red oak		Sweetgum		Yellow poplar		
Grade	Core	Faces	Core	Faces	Core	Faces	Total
2	0	79	0	75	8	76	238
3	38	0	10	0	28	0	76
4	18	0	30	0	20	0	68
Total	135		115		132		382

content (MC) was periodically read using a pinless moisture meter known as the Wagner meter MMC 220 and all samples were dried to about 12 percent MC. This is to ensure that the lumber pieces met the required MC for CLT manufacturing (12% ± 3%) according to ANSI/APA PRG 320-2019 (2020) standard.

Air drying was followed by visual strength grading, which was conducted by a certified grader from Timber Products inspection. This was done following Northeastern Lumber Manufacturing Association (NELMA 2021) rules. Upon inspection of lumber, grades were assigned by using numbers from 1 to 4, with 1 being the strongest and 4 being the weakest.

After the completion of visual grading, the CLT panels were assembled. For this study, all panels were manufactured in accordance with the CLT handbook (Karacabeyli and Douglas 2013). The individual lumber was arranged into three-ply CLT panels and glued with Loctite UR 5151 adhesive, which is a one-component polyurethane adhesive. The glue was applied to the laminates of the panels by moving already-layered-up lumber through an adhesive laminar flow. The spread rate of the flow was calibrated to 0.03 lb/ft^2 (165 g/m^2) for each of the two glue lines of the CLT panels. This adhesive was selected on the basis of its suitable properties for hardwood species. These glue characteristics also meet the requirements for CLT manufacturing specified by ANSI/APA PRG 320-2019 (2020) for softwood CLT. The manufacturing conditions for the CLT panels are presented in Figure 1.

For each hardwood species, four CLT panels were manufactured, resulting in 12 panels. Each panel had a final dimension of 102 mm (4 in) thick, 1,200 mm (≈ 48 in) wide, and 2,100 mm (≈ 84 in) long. These panels were then stripped to approximately 152 mm (6 in) wide, with the thickness and the length remaining the same. Each panel produced 8 strips, resulting in 32 strips per species and 96 strips in all.

Softwood CLT

The softwood CLT panels used in this study were manufactured industrially as a three-ply panel and were acquired to be used for testing purposes. The dimensions of SYP CLT panels were approximately 152 mm (6 in) by 2.1 m (84 in) by 2.7 m (108 in). These panels were then stripped into equivalent sizes as the hardwood CLT strips. The glue used for the SYP CLT is a moisture-cure adhesive based on polyurethane technology and the spread rate was 0.03 lb/ft^2 (165 g/m^2).

Density

Density measurements of all samples were conducted at approximately 12 percent MC. The density of the samples was calculated in accordance with ASTM D4052-15 (ASTM 2015).

Nondestructive evaluation

Longitudinal vibration test procedures followed the ASTM E1876 (ASTM 2022) standard. Figure 2 shows the nondestructive setup of specimens. The specimens were placed horizontally on two rigid sawhorses. The sawhorse supports were placed at one-quarter length to the specimen's right- and left-hand sides. The NDT was then conducted using the Fakopp microsecond timer (Fakopp Enterprise Bt. 2005). A straight-peen hammer is used to produce vibration by hitting the start terminal of the Fakopp device. The vibration generated is transmitted along the specimen's length all the way to the end terminal of the device. This device then generates the time of flight (in microseconds) using a fast Fourier vibration analyzer. The velocity it took for the vibration to travel and the dMOE were then calculated using Equations 1 and 2:

$$v = \frac{d}{t} \tag{1}$$

where v is the longitudinal wave velocity (m·s^{-1}), d is the length of the sample in meters, and t is time of flight in seconds.

$$\text{dMOE}_{\text{long}} = \rho v^2 \tag{2}$$

where dMOE$_{\text{long}}$ is the longitudinal vibration dMOE (MPa), ρ is the density of samples (kg·m^{-3}), and v is the longitudinal wave velocity (m·s^{-1}).

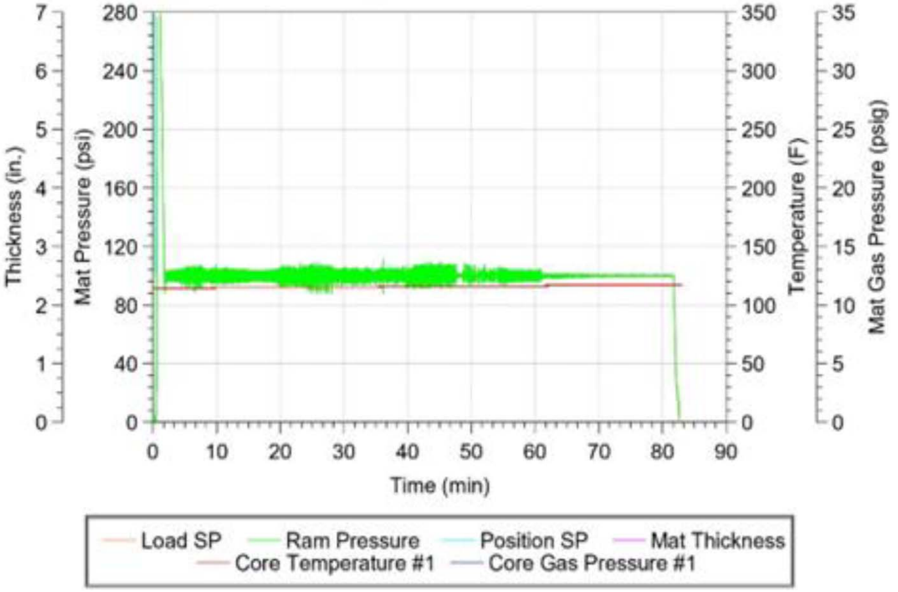

Figure 1.—Cross-laminated timber manufacturing conditions.

Figure 2.—Nondestructive evaluation setup using Fakopp microsecond timer.

Static bending test

The static bending tests were done following ASTM D198-22 (ASTM 2022). Figure 3 shows the static bending test setup. The third-point loading test was performed on the Instron universal testing machine, with a bending capacity of 600 kN. The tested samples had a span-to-depth ratio of 17:1 for midspan CLT and were placed in a flatwise manner on the testing machine. The strips were supported with two bearing plates—a fixed plate and the other a roller plate. The rate of load applied was set to ensure that the time of failure occurred in 3 to 5 minutes. The deflection was measured by placing a deflectometer at the midspan of each sample. Deflection readings were automatically captured by the computer connected to the Instron universal testing machine. The load-deflection graph generated for each test was then used for the determination of the MOE and MOR values. The MOE and MOR were calculated using Equations 3 and 4 respectively:

$$\text{MOE} = (PL^3)/(48\,EI) \tag{3}$$

$$\text{MOR} = (P_{\max}L)/(bd^2) \tag{4}$$

where P = load below proportional limit (N), $P_{\max}$ = failure load (N), L = test span (mm), b = width of sample (mm), d = thickness of sample (mm), E = center deflection (mm), and I = moment of inertia (mm^4). MOE and MOR, MPa.

Results and Discussion

Table 2 shows the summary of results obtained from 126 specimens tested. The mean densities obtained for red oak, sweetgum, yellow poplar, and SYP were 748, 592, 515, and 562 kg·m^{-3}, respectively. The mean densities reported for hardwood CLT are similar, although slightly lower than the findings of Ogunruku et al. (2024) in the study of underutilized hardwood for CLT industrial mats, with 707, 607, and 519 kg·m^{-3} for red oak, sweetgum, and yellow poplar, respectively. However, higher values of coefficients of variation (COVs) were observed for each species of hardwood CLT reported by the authors as compared with this study. A possible reason for the difference in densities observed from both studies could be the specific gravity at which the densities

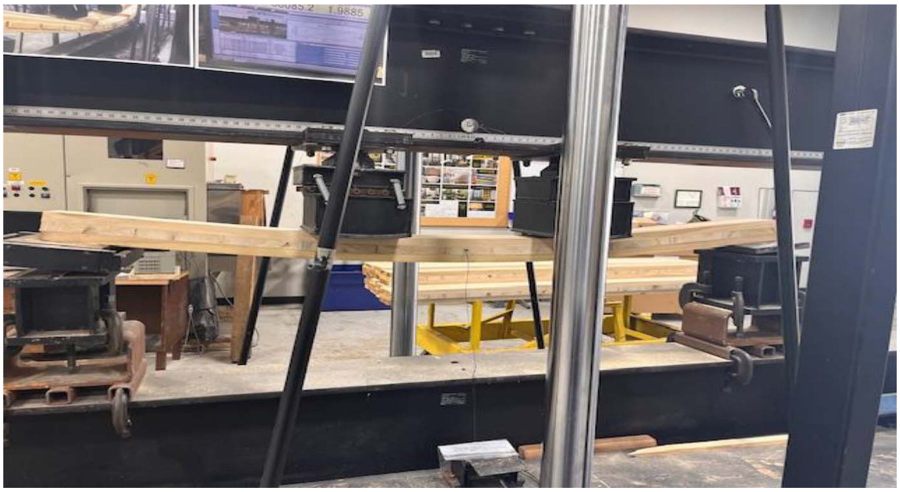

Figure 3.—Static bending setup using Instron 600 KN universal testing machine.

Table 2.—Density, static bending modulus of elasticity (MOE), modulus of rupture (MOR), and dynamic MOE (dMOE) of cross-laminated timber strips from red oak, sweetgum, yellow poplar, and southern pine species. COV = coefficient of variation.

Property	Red oak	Sweet gum	Yellow poplar	Southern pine
Density (kg m^{-3})				
Mean	748	592	515	562
Minimum	709	554	479	502
Maximum	800	639	556	610
COV (%)	2.64	3.40	4.06	4.51
MOE (MPa)				
Mean	13,241	10,277	10,711	9,409
Minimum	10,951	6,747	8,895	5,108
Maximum	16,339	12,791	12,833	12,147
COV (%)	10.50	14.18	8.93	17.81
MOR (MPa)				
Mean	52.78	36.14	45.04	36.22
Minimum	30.08	9.33	26.31	22.37
Maximum	64.37	51.69	58.36	46.38
COV (%)	15.97	34.57	8.93	17.33
dMOE (MPa)				
Mean	12,654	9,909	9,430	9,616
Minimum	10,907	8,343	8,276	6,522
Maximum	15,497	11,018	10,860	11,875
COV (%)	9.60	7.33	6.06	13.47

were determined. For instance, a study by Kretschmann and Green (2008) found that the specific gravity for yellow poplar could range between 0.42 and 0.64, with an average of 0.51. Additionally, the percentage of earlywood to latewood also plays a significant role in density of wood material. Salvo et al. (2017) reported that average density of *E. nitens* has a positive correlation with latewood width. Cown et al. (2002) examined the density of a species of pine for a range of earlywood to latewood percentage between 16 and 42 percent, and they found that density on average increases with increased latewood percentage. Different percentages in this ratio for the species tested could also be a reason for the slight difference observed among densities of the species tested. Pradhan et al. (2023), in the study of effect of densification on rolling shear performance of SYP CLT, found the mean density of nondensified low-density SYP lumber to be 449.17 kg·m^{-3} and nondensified high-density SYP lumber 641.23 kg·m^{-3}. The mean density of SYP CLT in this study exhibited similarity with Pradhan et al. (2023), as it falls within the range reported for CLT constituent lumber by the authors in their study.

The MOE values obtained for red oak strips ranged from 10,951 to 16,339 MPa, with an average of 13,241 MPa. For sweetgum, the MOE ranged from 6,747 to 12,791 MPa, with a mean value of 10,277 MPa. The yellow poplar strips had minimum and maximum MOE values of 8,895 and 12,833 MPa respectively. The mean value of yellow poplar MOE was 10,711 MPa. SYP had a mean value of 9,409 MPa, and the minimum and maximum values were found to be 5,108 and 12,147 MPa, respectively. The COVs obtained for MOE values were 10.50, 14.18, 8.93, and 17.81 percent for red oak, sweetgum, yellow poplar, and SYP, respectively. Because of the anisotropic nature of wood, the MOE of the three different axes affect the overall stiffness of the boards constituting each panel. Also, Kretschmann (2010) reported that elastic constants within and across species are related to their equilibrium MC and specific gravity. These could be reasons for the observed COVs in MOE among different species.

When comparing the results of this study with Hassler et al. (2024), the results show that all red oak specimens tested in this study are suitable for structural purposes. All red oak CLT samples exceeded the minimum specified value by ANSI/PRG-320. In Hassler et al. (2024), >95 percent of 452 red oak lumber of Grade 2 and below tested surpassed the minimum threshold of 8,300 MPa. The mean, minimum, and maximum values reported by Azambuja et al. (2023) in the study that evaluated low-grade yellow poplar for CLT production were 9,550, 8,780, and 10,650 MPa respectively. These values are just slightly different from those reported in this study; however, the differences are negligible. A reason for this could be the number of layers constituting the panels for each study. In a study by Correa et al. (2022), the reported MOE minimum, mean, and maximum values for V3-grade SYP CLT were 5,755, 8,057, and 10,277 MPa, respectively. Although the values reported in this study are marginally different from Correa et al. (2022), they are nonetheless closely related.

The MOR values obtained for red oak varied between 30.08 and 64.37 MPa, with a mean value of 52.78 MPa. The COV obtained for red oak was 15.97 percent. For the sweetgum samples, the minimum value was 9.33 MPa, mean was 36.14 MPa, and the highest value observed was 51.69 MPa. The COV for sweetgum was 34.57 percent. For yellow poplar, the MOR values had a minimum of 26.31 MPa and a maximum of 58.36 MPa; the mean value was 45.04 MPa. The COV for yellow polar was 8.93 percent. SYP had a mean value of 36.22 MPa; minimum and maximum values were 22.37 and 46.38 MPa, respectively. The COV obtained for SYP was 17.33 percent. The mean values of red oak and yellow poplar specimens were quite higher than sweetgum and SYP CLT specimens; however, both sweetgum and SYP specimens were very similar. Ultimate failure of CLT can be associated with either wood failure or glue line failure. The better mean MOR value observed in red oak could be a result of higher stiffness values observed in red oak; however, glue line failure could not be certainly linked to failure since only one type of adhesive was used for this study. Despite varying mean MOR values across tested specimens, all specimens in this study exceeded the minimum requirement specified for Grade V3 (No. 2 and No. 3) CLT in ANSI/APA PRG-320 2019 (2020). More details and discussion on density, MOE, and MOR are presented in Omotayo et al. (in press).

Dynamic MOE

The dMOE was obtained via longitudinal vibration for all samples and had mean values of 12,654; 9,909; 9,430; and 9,616 MPa for red oak, sweetgum, yellow poplar, and SYP, respectively. These mean values obtained for all species from NDT exceeded the minimum requirement for structural CLT specified by ANSI/APA PRG-320 2019 (2020) to be 8,300 MPa for the longitudinal layer on the basis of E1 layup standard. The minimum and maximum values for dMOE for red oak, sweetgum, yellow poplar, and SYP were 10,907 and 15,497; 8,343 and 11,018; 8,276 and 10,860; and 6,522 and 11,875 MPa respectively. The COVs obtained for

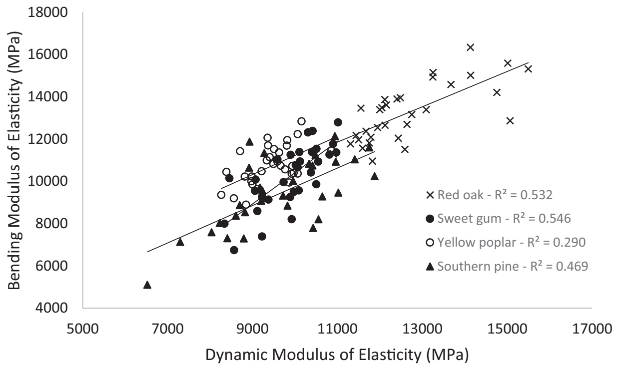

Figure 4.—Linear regression of bending modulus of elasticity against dynamic modulus of elasticity.

the red oak, sweetgum, yellow poplar, and SYP dMOE values were 9.6, 7.33, 6.06, and 13.47 percent respectively.

By comparison, the dMOE mean value for each hardwood CLT was slightly lower than the MOE mean value for the corresponding species; however, the ratio of dMOE to static MOE for all hardwood specimens was close, with a value ranging from approximately 0.85 to 1.1. The reason for this slightly lower mean value of dMOE compared with MOE could be because the NDT operation was performed using the middle layer, graded as No. 4, as the reference point as opposed the tensile layers, graded as No. 3, undergoing deformation upon loading. However, for the SYP CLT panels, which were industrially manufactured, the dMOE mean value was slightly higher than the obtained mean value for MOE. Correa et al. (2022) reported the mean dMOE of three-ply SYP CLT as 6,800 MPa, quite different from the value reported in this study. Though both studies used the longitudinal vibration technique, the reason for this difference could likely be the difference in the devices used for each study, as this study made use of the Fakopp device, whereas Correa et al. (2022) used Hitman HM 200.

Linear regression analysis

All relationships were assumed to be linear and take the form of the mathematical expression shown below:

$$y = (mX) + C + e$$

where y = tested parameters (MOE, MOR), m = slope, X = NDT parameter, C = intercept, and e = standard error of estimate.

Dynamic MOE versus static MOE

All specimens were analyzed by linear regression analysis using dMOE to predict static MOE to estimate the relationship between these two variables. Figure 4 shows the trend of all species tested. The coefficient of determination (R^2) values obtained for red oak, sweetgum, yellow poplar, and SYP were 0.532, 0.546, 0.290, and 0.469 respectively. This indicates that a good linear relationship exists for both red oak and sweetgum. However, for yellow poplar and SYP, the linear relationships were slightly lower, which is indicative of moderate correlation. These values indicate a fair regression model for red oak, sweetgum, and SYP as only approximately 50 percent of the specimens were rightly accounted for by NDT in the model; however, yellow poplar had a weak relationship, with just about 30 percent fitting into the model. In the study by Llana et al. (2022) for evaluating structural properties of European oak CLT made from recovered lumber, the R^2 of MOE against dMOE for oak CLT made from recovered lumber was reported to be 0.61. This is higher than reported by this study; however, both values are comparable as they moderately predict oak CLT specimens using NDT according to the regression model. Table 3 shows the correlation between dynamic MOE and static MOE.

Table 3.—Modulus of elasticity (MOE) against dynamic MOE correlation model.

	Slope (m)	Intercept (C)	SE of estimate (e)	Coefficient of determination (R^2)	P value
Red oak	0.6367	4,222.6	967.41	0.532	<0.0001
Sweetgum	0.3459	6,339.9	1,062.63	0.546	<0.0001
Yellow poplar	0.2137	7,118.3	1,170.57	0.290	0.0039
Southern pine	0.5244	4,635.0	1,242.79	0.469	<0.0001

Dynamic dMOE versus bending MOR

Figure 5 shows the trend of dMOE versus bending MOR for all species of CLT tested. The coefficient of correlation, R, for red oak, sweetgum, yellow poplar, and SYP were 0.43, 0.5, 0.46, and 0.41, respectively. This shows that only a moderate linear relationship existed between MOR and the dMOE for all species; hence a fair level of predictability was obtained from the line graphs. The R^2 obtained for bending MOR against dMOE for red oak, sweetgum, yellow poplar, and SYP were 0.185, 0.249, 0.214, and 0.172 respectively. These values indicated that the variability in MOR covered by the NDT was 18.5, 24.9, 21.4, and 17.2 percent respectively. Table 4 shows the correlation between dMOE and static MOR.

Static bending MOE versus bending MOR

Figure 6 shows the linear regression graph of bending MOE versus bending MOR. The R^2 values that existed between the two variables MOR and MOE were 0.129, 0.292, 0.194, and 0.233 for red oak, sweetgum, yellow poplar, and SYP respectively. Ogunruku et al. (2024) reported R^2 for four grades of lumber from red oak, sweetgum, and yellow poplar as 0.18 to

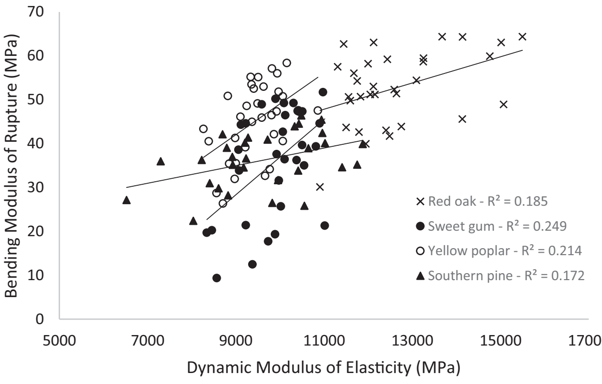

Figure 5.—Linear regression of bending modulus of rupture against dynamic modulus of elasticity.

Table 4.—Modulus of rupture against dynamic modulus of elasticity correlation model.

	Slope (m)	Intercept (C)	SE of estimate (e)	Coefficient of determination (R^2)	P value
Red oak	61.954	9,383.7	7.74	0.185	0.0140
Sweetgum	30.456	8,058.0	11.00	0.249	0.0036
Yellow poplar	29.013	8,860.7	7.83	0.214	0.0076
Southern pine	85.513	6,519.2	5.82	0.172	0.0228

0.45, 0.23 to 0.67, and 0.35 to 0.6 respectively. These values are higher than those reported by this study for hardwood CLT. This could be because MOE of CLT is significantly increased when compared with MOE of constituent lumber.

Density versus bending properties

Density was tested with static bending MOE and MOR. Figures 7 and 8 show the correlation between density versus bending MOE and bending MOR for all species of CLT. The R^2 values obtained for red oak, sweetgum, yellow poplar, and SYP were 0.413, 0.265, 0.312, and 0.096 respectively. Despite density being an important predictor of strength for lumber, only about 30 to 64 percent fit into the linear relationship for the CLT species that were examined. The reason for this can be associated with the presence of defects and irregular slope of grain in the constituent lumber making up each panel. This showed that density cannot be assumed as a good indicator of strength for CLT from low-grade lumber.

For density versus bending MOR, the R^2 values obtained for red oak, sweetgum, yellow poplar, and SYP were 0.015, 0.157, 0.290, and 0.469 respectively. The effect of density over strength varied on the basis of the number of observations. Density had a greater influence over the bending MOE when compared with its MOR.

The R^2 values observed for MOR against other properties (density, MOE, and dMOE) were considerably weak, especially for the hardwood species. This can likely be a result of reaction wood that might have constituted the panels. According to Clair et al. (2006b), microfibril angle (MFA) in tension wood is always lower than that of normal wood. Generally, lower MFA usually indicates higher strength for normal wood; even so, the case is not always the same for tension wood. This may thus model the stiffness (MOE) and dMOE (since NDT is known to also be reliant on MFA) as being higher, whereas ultimate strength is likely to be much less. This contrasting relationship can be associated with the higher spread seen in MOR graphs.

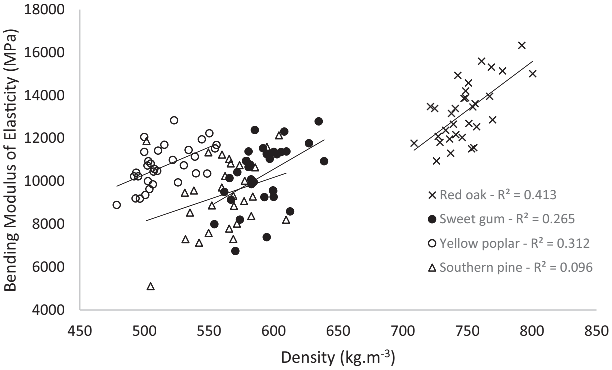

Figure 7.—Linear regression of bending modulus of elasticity against density.

Conclusions

This study investigated the use of longitudinal vibration, a type of nondestructive technique, to evaluate the mechanical properties of three low-grade hardwood CLT and an industrially manufactured softwood CLT. Density values of all CLT species were calculated and the mean density values obtained were closely related to values obtained from a previous study. The correlation of physical property against mechanical properties was done in which static bending properties were obtained in a flatwise manner. For density against MOE, moderate correlations were observed for all hardwood CLT and a weak correlation was observed for softwood CLT.

The correlation of static MOE against dMOE was also established. The correlation showed that dMOE could be reliable in the prediction of CLT MOE; however, improvement in technology is needed since the model from the correlation accounted for only a fair proportion of the specimens tested. This is also indicative of the benefits NDT would have for grading purposes and for the wood industry as its accuracy will be improved in the coming years.

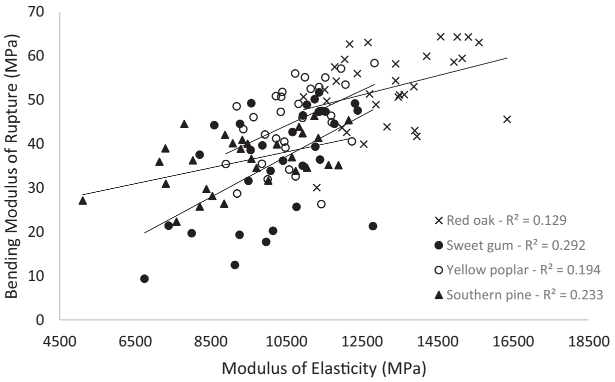

Figure 6.—Linear regression of bending modulus of rupture against modulus of elasticity.

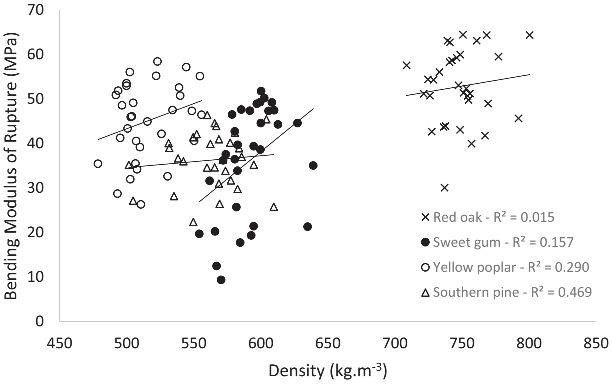

Figure 8.—Linear regression of bending modulus of rupture against density.

The linear correlations of MOR against both static MOE and dMOE were weak to slightly moderate. Regardless of these relationships, nonlinear correlations could be done to better develop a stronger relationship for a more accurate prediction.

Finally, from the static MOE results for hardwood CLT, all mean MOE values exceeded the specified minimum value, 8,300 MPa, specified in PRG-320 for softwood CLT. This affirms that low-grade hardwood lumber can be used as structural material through the manufacturing of CLT, hence maximizing its value.

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