Nondestructive Evaluation of 2 by 10 Southern Pine Lumber

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Abstract

Efficient use of the available wood resources is necessary to sustainably meet the long-term demand for wood products. This paper presents research about the potential of using transverse and longitudinal vibration techniques to evaluate the bending modulus of elasticity MOE (E_b) and tensile properties (E_t and UTS) of 2 by 10 No. 2 grade southern pine (*Pinus* spp.) lumber. A total of 285 lumber pieces were first nondestructively tested using longitudinal vibration (Director HM 200), transverse vibration (Metriguard E-computer), and proof-loading bending tests (Universal Instron Machine). Each specimen was then destructively tested in tension parallel to the grain to determine tension modulus of elasticity (E_t) and ultimate tensile stress (UTS). Correlations between growth characteristics, physical, and mechanical properties were analyzed. Excellent correlative relationships between longitudinal and transverse dMOE with the elastic properties E_b, and E_t were found. A strong correlation was also found between the elastic properties E_b and E_t. The prediction of E_b was improved after adding density to the model. The estimation of UTS was also improved with the addition of density and a secondary nondestructive measurement. Nondestructive techniques are recommended to assess the mechanical properties of southern pine 2 by 10 lumber.

Using wood as a building material is highly desirable because it is durable, cost-effective, renewable, and environmentally friendly. Wood can store CO_2 for decades and requires less energy to be manufactured. When wood is compared with other building materials, wood has the lowest impact on the environment (Falk 2009, Sutton 2010). Researching and sharing information about the mechanical properties of wood while highlighting its environmental benefits helps promote wood as the material of choice in the construction industry.

Southern pine (*Pinus* spp.) is a group of species primarily composed of loblolly (*P. taeda*), longleaf (*P. palustris*), slash (*P. elliottii*), and shortleaf pine (*P. echinata*). Southern pine is one of the most commercially used groups of species in North America. The wood from these species comes from plantations located across southern regions of the United States. Studying the properties of wood is crucial for the lumber industry to ensure accurate and reliable design values for construction (Southern Forest Products Association 2021).

Tension parallel to the grain is one of the fundamental properties of wood (Doyle and Markwardt 1967). When a piece of lumber is pulled away from the ends, tensile stress is generated resulting in an elongation of the material in the direction of the applied force. The high level of strength exhibited by a piece of wood when exposed to a tension force is related to its anatomical features such as fiber orientation, fiber arrangement, and thickness of cell walls (Record 1914).

The work done by Doyle and Markwardt in 1967 is considered one of the most extensive compilations of tensile properties of full-size dimensional lumber southern pine. The authors evaluated properties from 496 specimens (2 by 4, 2 by 6, and 2 by 8 sizes) and correlated the results with the ones obtained from flatwise nondestructive bending tests. A more recent study was conducted by Senalik et al. (2020) to understand how wood's natural occurring effects and the acoustic properties of wood can be of help in the estimation of ultimate tension stress (UTS).

Nondestructive testing (NDT) techniques are commonly used in the study of the physical and mechanical properties of wood. NDT is also known as Nondestructive Evaluation

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Table 1.—Dimensions of 2 by 10 southern pine dimensional lumber.

Size (in.)	Thickness (in.)	Width (in.)	Nominal length (ft.)	Length (m)	Quantity
2 × 10	1.5	9.25	14	4.29	85
	—	—	16	4.90	200

(NDE). Using NDE techniques allows the evaluation of an array of materials without affecting the structure and capabilities. Currently, different testing technologies have been developed and widely adopted because of their accuracy to assess the mechanical properties of a variety of wood-based products (Ross 2008, Brashaw et al. 2009).

One of the technologies used in this study is the longitudinal vibration technique, which allows the measurement of the acoustic properties of wood. Measuring the speed of acoustic waves generated by a physical impact that travels on a lumber specimen permits the determination of the dynamic modulus of elasticity (dMOE; Ross 2015). The dMOE can be used to estimate the modulus of rupture (MOR). An improvement in the estimation of UTS using dMOE (longitudinal vibration) and additional parameters such as the time-domain area (TDA) and frequency-domain area (FDA) as predictor variables was done in an experimental study by Senalik et al. (2020).

Another technology used to evaluate the properties of wood products is the transverse vibration technique (Ross 2015). This method allows the evaluation of dMOE by measuring the oscillation frequency in the vertical direction generated after a lumber piece is slightly deflected at the midspan of the lumber piece (França et al. 2018a, 2019b). Several authors have found excellent correlative relationships between MOE and dMOE using the longitudinal and transverse vibration technique (Wang et al. 1993; Yang et al. 2015; França et al. 2018a, 2020b).

NDT provides meaningful information that helps in the decision-making to assign the proper use of wood. With wood being a biological material, the influence of anatomical structure and naturally occurring defects such as knots, grain angle, reaction wood, decay, etc., can cause a reduction in the strength properties of wood. This, in combination with the possible processing defects, constitutes challenges for manufacturers and end-users (Ross 2015). NDT also contributes to broadening the knowledge of the structural potential of wood despite the variability inherent in the material.

The objectives of this study were (1) to evaluate the mechanical properties of 2 by 10 No. 2 (grade) southern pine lumber; (2) to investigate the relationships between the growth characteristics, and dynamic modulus of elasticity (dMOE) from longitudinal and transverse vibration with the mechanical properties; (3) to evaluate the accuracy and reliability of the NDT tools that are commercially available to assess bending MOE (E_b), tension MOE (E_t), and ultimate tensile stress (UTS); (4) to obtain a better understanding on the variability of bending and tensile properties of southern pine lumber along with the ability of current NDT tools to identify and measure this variability.

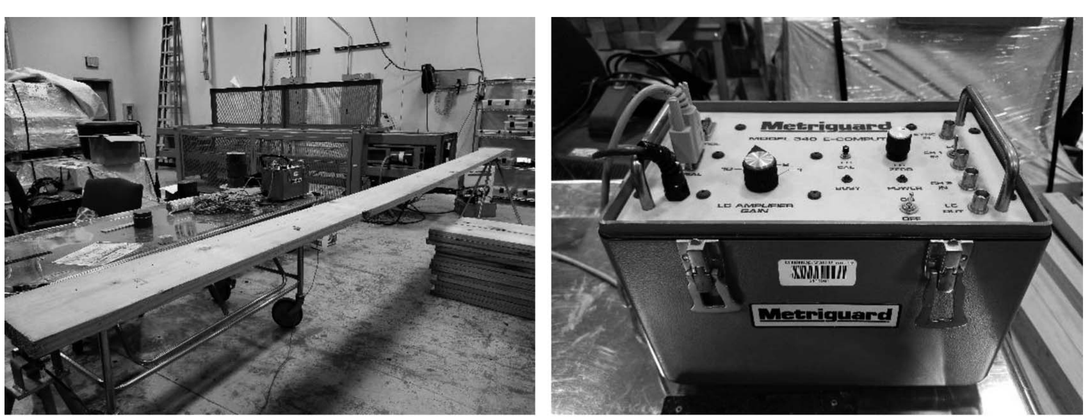
Materials and Methods

The sample size for the study consisted of 285 pieces of 2 by 10 No. 2 – KD southern pine structural lumber with two length sizes 4.29 m and 4.90 m (14 ft. and 16 ft.; Table 1). Lumber was obtained from the 18 original regions of southern pine growth regions in the United States (Southern pine growth region boundaries map can be viewed in França et al. 2018b). All lumber pieces were conditioned to 12 percent moisture content prior to testing.

From each specimen, the following variables were recorded: specimen dimensions, percentage moisture content (MC), density, percentage of latewood (LW), rings per inch (RPI), dynamic modulus of elasticity ($dMOE_{tv}$ and MOE_{long}), frequency-domain area (FDA), static bending modulus of elasticity (E_b), tension modulus of elasticity (E_t), and ultimate tensile stress (UTS).

Moisture content and density

Clear moisture specimens were cut from neat the tension failure. Specimens were labeled and weight recorded. Oven-dry weight was also recorded after specimens stopped losing weight. To evaluate density, each lumber piece was measured using a caliper (thickness and width) and a calibrated measuring tape for the length. Lumber pieces were weighted. Density was measured in kg per m^3.



(A) (B)

Figure 1.—(A) Transverse vibration technique setup. (B) E-Computer Metriguard.

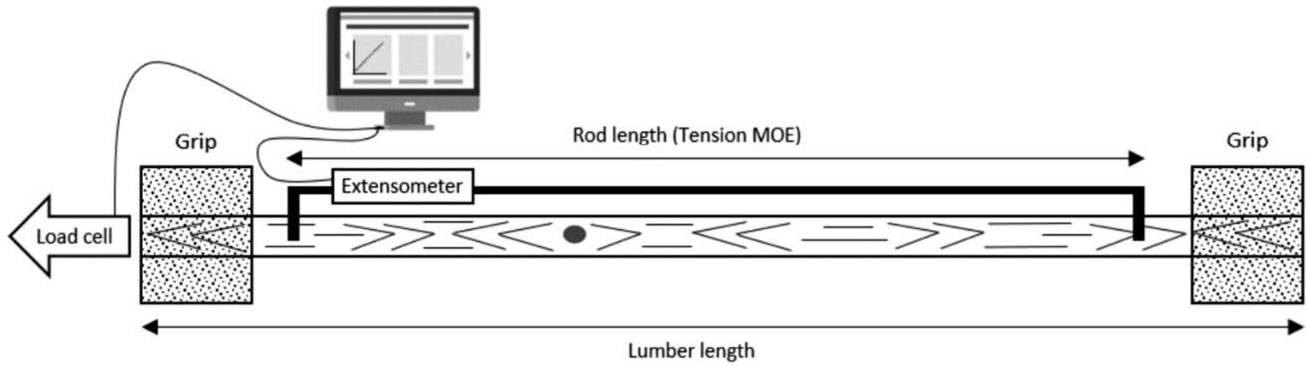


Figure 2.—Test setup used to determine tension parallel to the grain properties.

Rings per inch and percentage of latewood

To evaluate RPI, the visible rings at the ends of each piece of lumber were counted according to the procedures from Southern Pine Inspection Bureau grading rules (SPIB 2014). Then, the total rings counted were divided by the thickness or the width depending on the grain direction of the piece (radial or tangential direction). The LW percentage was measured using a small plastic dot grid (25.4 mm by 25.4 mm). The grid was placed at both ends of the lumber piece, aligning the dotted rows to the growth rings. The dots that matched with the latewood regions were counted and recorded. Then, the total of dots counted was divided by the total amount of dots on the dotted grid (64 dots). Procedure is described by França et al. (2018b).

Transverse vibration

All pieces were evaluated using the transverse vibration technique with the E-computer Model 340 Transverse Vibration (Metriguard, Pullman, Washington, USA; Fig. 1). This technique consists of putting the lumber piece in a flatwise direction over two metal tripods and then tapping in the center of the span to generate an oscillation wave. The oscillation frequency was captured by the equipment to calculate the dynamic MOE. This test followed American Society for Testing and Material E1876 (ASTM 2021b). The equation used to calculate the transverse vibration dynamic modulus of elasticity ($dMOE_{tv}$) is given in Equation 1.

$$dMOE_{tv} = \frac{f^2 W s^3}{2.46 I} \quad (1)$$

where $dMOE_{tv}$ is the transverse vibration dynamic MOE (MPa), f is the resonant frequency (Hz), W is the mass of the lumber piece (kg), s is the span (m), and I is the moment of inertia (m^4).

Table 2.—Results per nominal length and overall for moisture content (MC) percentage, density, rings per inch (RPI), and percentage of latewood (LW).

	Nominal length (ft.)	Mean	Min.[a]	Max.[a]	COV (%)[a]
MC (%)	14	12.27	7.60	20.70	20.09
	16	11.66	7.20	18.80	17.82
	Overall	11.82	7.20	20.70	18.60
Density (kg/m^3)	14	554.58	435.91	753.94	10.57
	16	546.77	448.86	707.46	9.42
	Overall	547.02	436.00	754.00	9.79
RPI	14	3.74	2.08	12.67	44.01
	16	3.95	1.67	15.67	49.70
	Overall	3.82	1.67	15.67	48.24
LW (%)	14	45.77	25.78	72.66	21.06
	16	44.96	21.09	76.56	21.12
	Overall	45.02	21.09	76.56	21.07

[a] Coefficient of variation; Min. = minimum; Max. = maximum.

Longitudinal vibration

All pieces were evaluated using the longitudinal vibration technique with the Director HM 200 (Fibre-gen, Christchurch, New Zealand) tool. This technique consists of putting the lumber piece over two sawhorses in flatwise orientation, then touching one of the ends of the specimen with the sensor of the acoustic tool and immediately hitting it with a hammer. This impact produces an acoustic longitudinal vibration wave that travels through the length of the piece. The velocity of the wave is recorded for each specimen.

This procedure was done following the ASTM E1876 (ASTM 2021b) standard. Calculation of the dynamic modulus of elasticity ($dMOE_{long}$) in the longitudinal direction is given by Equation 2.

$$dMOE_{long} = \rho v^2 \quad (2)$$

where $dMOE_{long}$ is the longitudinal vibration dynamic MOE (MPa), ρ is the density of the lumber piece (kg/m^3), and v is the longitudinal wave velocity (m/s^1).

The longitudinal vibration signal from each lumber piece was also recorded. It was possible to measure a secondary variable obtained from the frequency-domain signal. The area under the natural frequency peak was calculated as described by Senalik et al. (2020) and utilized by Correa et al. (2022).

Proof-loading bending test

The E_b values were obtained for all lumber pieces via four-point static tests in edgewise direction using a span-to-depth ratio of 17:1 per ASTM D198-21 (ASTM 2021a), where the span was 3.99 m. The rate of the load was 0.300 inches/minute and the maximum load was 4,000 N. Procedure followed ASTM D 4761-19 (ASTM 2019).

Table 3.—Overall results for longitudinal and transverse dynamic modulus of elasticity ($dMOE_{long}$ and $dMOE_{tv}$), frequency-domain area (FDA); bending MOE (E_b), tension MOE (E_t), and ultimate tensile stress (UTS) parallel to the grain on 2 by 10 (14 ft.,16 ft., and combined) southern pine dimensional lumber.

Variable[a]	Nominal length (ft.)	Mean (MPa)	Min. (MPa)	Max. (MPa)	COV (%)[b]
$dMOE_{long}$	14	10,450	5,836	19,635	25.79
	16	9,943	4,614	17,175	24.18
	Overall	10,094	4,614	19,635	24.77
FDA	14	7,897	2,584	14,814	30.63
	16	7,235	2,639	17,675	36.32
	Overall	7,433	2,584	17,675	34.73
$dMOE_{tv}$	14	10,883	5,257	19,658	25.62
	16	10,262	4,850	16,786	24.34
	Overall	10,447	4,850	19,658	24.87
E_b	14	13,080	7,919	22,103	21.45
	16	13,487	7,162	21,472	22.03
	Overall	13,365	7,162	22,103	21.88
E_t	14	9,749	4,800	18,548	27.30
	16	9,730	4,415	17,551	24.93
	Overall	9,735	4,415	18,548	25.62
UTS	14	25.59	7.40	72.97	51.00
	16	23.93	7.67	72.31	45.93
	Overall	24.42	7.40	72.97	47.67

[a] $dMOE_{long}$: longitudinal vibration dynamic modulus of elasticity; FDA: frequency-domain area; $dMOE_{tv}$: transverse vibration dynamic modulus of elasticity; E_b: static bending modulus of elasticity; E_t: tension modulus of elasticity; UTS: ultimate tensile stress.

[b] Coefficient of variation.

Tension test

Following nondestructive tests, all pieces were destructively tested in tension parallel to the grain using a Tension Proof Loader Model 422 (Metriguard, Pullman, Washington, USA). Before starting the test, each specimen was placed horizontally in the tension machine (Fig. 2). Metal grips held both ends of the specimen while the test was performed.

Over time, these grips pull the specimen apart until it fails. The span of testing was 2.44 m (96 in.) for the shorter specimens (14 ft.) and 2.97 m (117 in.) for the longer ones (16 ft.). Testing allowed the measurement of the E_t by recording the tension stress and strain. The calculation of UTS is at the maximum tensile stress for each piece. Tension tests were conducted according to the standard D198-21 (ASTM 2021a).

Statistical analysis

All statistical analyses and associated graphs were completed according to the standard D2915-17 (ASTM 2022) using SAS version 9.4 (SAS Institute 2013). Descriptive statistics were used to summarize the visual characteristics, physical, and mechanical properties of the evaluated material.

Bivariate correlations among variables were evaluated. The variables E_b, E_t, and UTS were used as multiple linear functions of density and NDT properties. To predict E_b, E_t, and UTS, a stepwise procedure was used for fitting models. For each relationship obtained, the coefficient of determination (R^2) was calculated. The following equations were used to predict E_b, E_t, and UTS:

Table 4.—Pearson's bivariate correlation (r) among length, rings per inch (RPI), percentage of latewood (%), density, dynamic modulus of elasticity (dMOE; transverse and longitudinal vibration), frequency-domain area (FDA), bending MOE (E_b), tension MOE (E_t), and ultimate tensile stress (UTS).

Variable[a]	Length	RPI	LW (%)	Density	$dMOE_{tv}$	$dMOE_{long}$	FDA	E_b	E_t	UTS
Length	1	0.047 (0.4331)	−0.060 (0.3154)	−0.08 (0.1773)	−0.110 (0.0648)	−0.093 (0.1174)	−0.118 (0.0474)	0.064 (0.2833)	−0.0345 (0.9538)	−0.065 (0.2735)
RPI		1	0.410 (<0.0001)	0.362 (<0.0001)	0.567 (<0.0001)	0.579 (<0.0001)	−0.079 (0.1851)	0.461 (<0.0001)	0.520 (<0.0001)	0.310 (<0.0001)
LW (%)			1	0.523 (<0.0001)	0.445 (<0.0001)	0.390 (<0.0001)	−0.197 (0.0008)	0.508 (<0.0001)	0.375 (<0.0001)	0.323 (<0.0001)
Density				1	0.615 (<0.0001)	0.591 (<0.0001)	−0.262 (<0.0001)	0.642 (<0.0001)	0.514 (<0.0001)	0.576 (<0.0001)
$dMOE_{tv}$					1	0.976 (<0.0001)	−0.192 (0.0011)	0.865 (<0.0001)	0.885 (<0.0001)	0.554 (<0.0001)
$dMOE_{long}$						1	−0.184 (0.0019)	0.826 (<0.0001)	0.887 (<0.0001)	0.542 (<0.0001)
FDA							1	−0.251 (<0.0001)	−0.208 (0.0004)	−0.383 (<0.0001)
E_b								1	0.785 (<0.0001)	0.546 (<0.0001)
E_t									1	0.544 (<0.0001)
UTS										1

[a] RPI: rings per inch; LW (%): percent of latewood; $dMOE_{tv}$: dynamic modulus of elasticity from transverse vibration; $dMOE_{long}$: dynamic modulus of elasticity from longitudinal vibration; FDA: frequency-domain area; E_b: static bending modulus of elasticity; E_t: tension modulus of elasticity; UTS: ultimate tensile stress.

Table 5.—Results of regression analyses relating static bending modulus of elasticity (MOE [E_b]), tension MOE (E_t), and ultimate tensile stress (UTS) with transverse vibration ($dMOE_{tv}$) and density for 2 by 10 southern pine structural lumber.

Property	NDT technique[a]	β_0[b]	β_1[b]	β_2[b]	R^2[c]	P value	Standard error (μ)
E_b	$dMOE_{tv}$	3,199.65	0.97	—	0.75	<0.001	1,472.61
	$dMOE_{tv}$ + density	−823.04	0.85	9.70	0.77		1,416.66
E_t	$dMOE_{tv}$	864.92	0.85	—	0.78	<0.001	1,164.49
	$dMOE_{tv}$ + density	1,876.75	0.88	−2.44	0.78		1,161.95
UTS	$dMOE_{tv}$	−1.52	0.002	—	0.31	<0.001	9.71
	Density	−43.98	0.13	—	0.33		9.54
	Density + $dMOE_{tv}$	−35.52	0.08	0.001	0.40		9.08

[a] NDT: nondestructive testing; $dMOE_{tv}$: dynamic modulus of elasticity from transverse vibration.
[b] β_0, β_1, and β_2 are used in the generalized models: Property = $\beta_0 + \beta_1 \cdot [dMOE_{tv}\ (MPa)] + \beta_2 \cdot [density\ (kg/m^3)]$.
[c] R^2: coefficient of determination.

$$MOE_b = f(dMOE, density) + \varepsilon_1 \quad (3)$$

$$MOE_t = f(dMOE, density) + \varepsilon_2 \quad (4)$$

$$UTS = f(dMOE, density, FDA) + \varepsilon_3 \quad (5)$$

Results and Discussion

Statistical analyses for MC (%), density, RPI, and LW (%) from 2 by 10 structural lumber are listed in Table 2. The overall density mean, minimum, and maximum were 547 kg/m^3, 436 kg/m^3, and 754 kg/m^3, respectively. Density values from the present study are within the range of the results obtained by several authors (Irby et al. 2020; França et al. 2018a, 2018b, 2019a). The average moisture content (MC) when pieces were tested was 11.82 percent.

The mean, minimum, and maximum for RPI were 3.82, 1.67, and 15.67, respectively. For LW (%), the mean was 45.02 percent; the minimum was 21.09 percent, the maximum was 76.56 percent and the coefficient of variation (COV) was 21.07 percent. RPI and LW (%) values are consistent with the results published by the authors Irby et al. (2020) and França et al. (2018b, 2019a).

SPIB guidelines specify that southern pine lumber should have four or more annual rings per inch on either one end or the other of the piece to be considered a No. 2 grade. Our results show that the specimens evaluated meet the SPIB No. 2 grade lumber RPI and LW percentage requirements.

The dMOE mean values for longitudinal and transverse vibration are shown in Table 3. The overall $dMOE_{long}$ mean value for both lengths tested was 10,094 MPa, with a range from 4,614 to 19,635 Mpa with a COV of 24.77 percent. The $dMOE_{long}$ mean value is slightly lower but within the range of the values reported by França et al. (2020a, 2020b).

The overall mean for $dMOE_{tv}$ tested (both lengths combined) was 10,447 Mpa with a minimum of 4,850 Mpa, a maximum of 19,658 Mpa, and a COV of 24.87 percent. The $dMOE_{tv}$ values shown in Table 3 are slightly lower but within the range of the results obtained by previous authors (França et al. 2018a, 2020a, 2020b). The $dMOE_{tv}$ mean value was found to be slightly higher than the $dMOE_{long}$ mean value. Previous authors (França et al. 2020a) noted the same difference among techniques.

The overall mean for E_b was 13,365 Mpa. The minimum and maximum values ranged between 7,162 Mpa and 22,103 Mpa, with a COV of 21.88 percent. E_b mean values are higher than E_t and dMOE values. For E_t, the overall mean was 9,735 Mpa, ranging between 4,415 Mpa and 18,548 Mpa with a COV of 25.62 percent. The mean for UTS was 24.42 Mpa, ranging from 7.40 to 72.97 Mpa with a COV of 47.67 percent.

In 1967, Doyle and Markwardt found an overall mean of 23.44 for UTS obtained from No. 2 KD southern pine lumber (sizes 2 by 4, 2 by 6, and 2 by 8). A preliminary evaluation (results not shown) demonstrated no statistically significant differences between bending or tensile properties (alpha = 0.05), and the length factor (14 ft. and 16 ft.)

Bivariate correlations among the variables under investigation are presented in Table 4. For E_b, the highest correlations were seen for dMOE ($dMOE_{tv}$ = 0.865 and

Table 6.—Results of regression analyses relating static bending modulus of elasticity (MOE [E_b]), tension MOE (E_t), and ultimate tensile stress (UTS) with density, longitudinal dynamic MOE, and frequency-domain area (FDA) for 2 by 10 southern pine structural lumber.

Property	NDT technique[a]	β_0[b]	β_1[b]	β_2[b]	β_3[b]	R^2[c]	P value	Standard error (μ)
E_b	$dMOE_{long}$	3,614.23	0.97	—	—	0.68	<0.001	1,651.39
	$dMOE_{long}$ + density	−1,800.79	0.80	12.92	—	0.72		1,556.51
E_t	$dMOE_{long}$	806.17	0.88	—	—	0.79	<0.001	1,153.09
	$dMOE_{long}$ + density	1,191.01	0.90	−0.92	—	0.79		1,154.44
UTS	FDA	37.27	−0.001	—	—	0.15	<0.001	10.77
	$dMOE_{long}$	−1.03	0.002	—	—	0.29		9.80
	Density	−43.98	0.13	—	—	0.33		9.54
	Density + $dMOE_{long}$	−36.79	0.09	0.001	—	0.39		9.10
	Density + $dMOE_{long}$ + FDA	−21.49	0.07	0.001	−0.001	0.45		8.70

[a] NDT: nondestructive testing; $dMOE_{long}$: dynamic modulus of elasticity from transverse vibration.
[b] β_0, β_1, and β_2 are used in the generalized models: Property = $\beta_0 + \beta_1 \cdot [dMOE_{long}\ (MPa)] + \beta_2 \cdot [density\ (kg/m^3)] + \beta_3 \cdot [FDA]$.
[c] R^2: coefficient of determination.

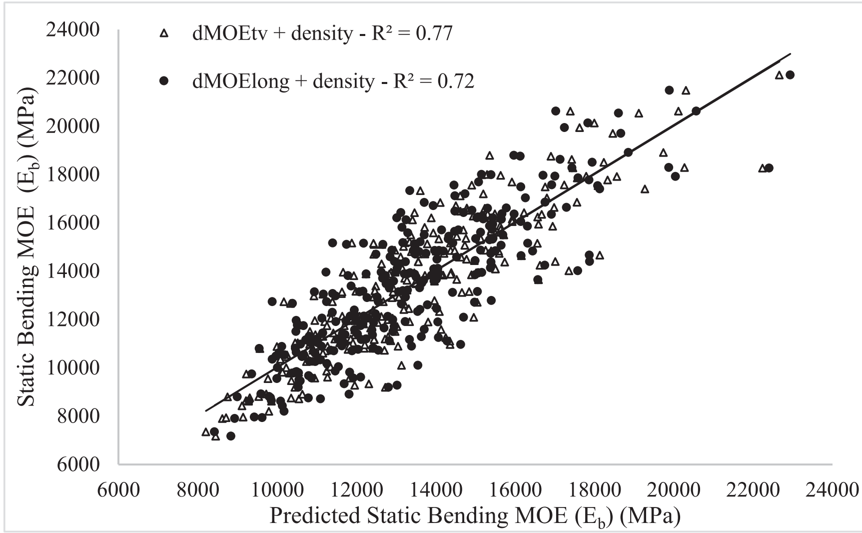


Figure 3.—Linear regression plots (from Tables 5 and 6) for predicted bending modulus of elasticity (MOE [E_b]) vs. E_b.

$dMOE_{long}$ = 0.826). These results are similar to the ones reported by Yang et al. (2015) and França et al. (2018a). A strong correlation was found between E_b and E_t ($r = 0.785$). The NDT techniques also exhibited high correlations with E_t ($dMOE_{tv} = 0.885$ and $dMOE_{long} = 0.887$). Results for both nondestructive techniques confirm that dMOE is an excellent predictor of E_b and E_t for southern pine 2 by 10 lumber.

Density had notable correlations with all three mechanical properties. For E_b and E_t the correlation with density was moderate (r = 0.642 and r = 0.514, respectively). Density exhibited the highest correlation with UTS (r = 0.576). Nondestructive methods also showed moderate correlation with UTS (r = 0.554, $dMOE_{tv}$; r = 0.542, $dMOE_{long}$).

FDA presented a potential relationship with UTS (r = –0.383). RPI had moderate correlations with density (r = 0.362), dMOE ($dMOE_{tv} = 0.567$; $dMOE_{long} = 0.579$), E_b (r = 0.461), and E_t (r = 0.520). LW (%) also presented moderate correlations with density (r = 0.523), dMOE ($dMOE_{tv} = 0.445$; $dMOE_{long} = 0.390$), E_b ($r = 0.508$), and E_t ($r = 0.375$). RPI and LW (%) showed low correlation with UTS ($r = 0.310$, and $r = 0.323$, respectively).

Table 5 and Table 6 show the regression model coefficients, coefficient of determination (R^2), P value, and standard error of the regression models for E_b, E_t, and UTS. For E_b, the combination of $dMOE_{tv}$ with density presented a slightly higher coefficient of determination (R^2 = 0.77) when compared with a single predictor ($R^2 = 0.75$; $dMOE_{tv}$).

The use of $dMOE_{long}$ to predict E_b generated a slightly lower coefficient of determination ($R^2 = 0.68$) than the one obtained using the transverse vibration technique. However, the combination of $dMOE_{long}$ with density improved the E_b estimation ($R^2 = 0.72$; see Table 6).

The E_t estimation using $dMOE_{tv}$ or $dMOE_{long}$ as single predictors generated an R^2 equal to 0.78 and 0.79, respectively. Nevertheless, the addition of density did not

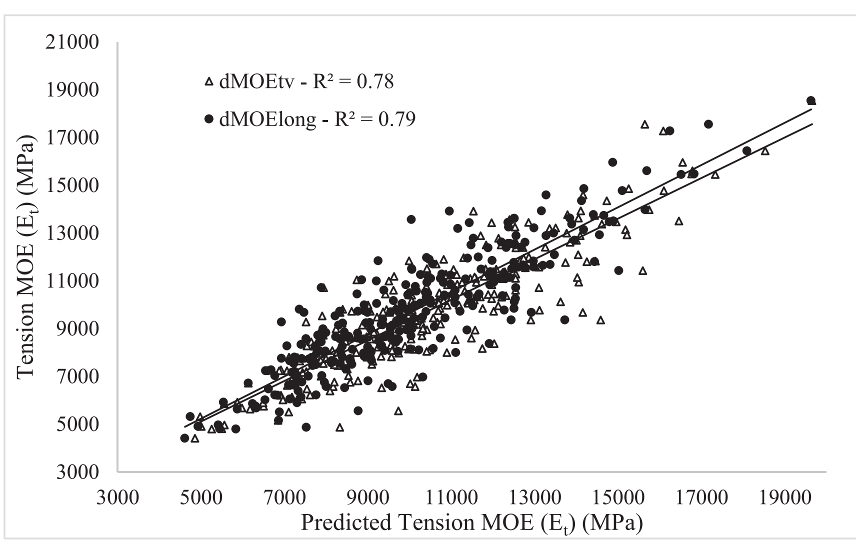


Figure 4.—Linear regression plots (from Tables 5 and 6) for predicted tension modulus of elasticity (MOE [E_t]) vs. E_t.

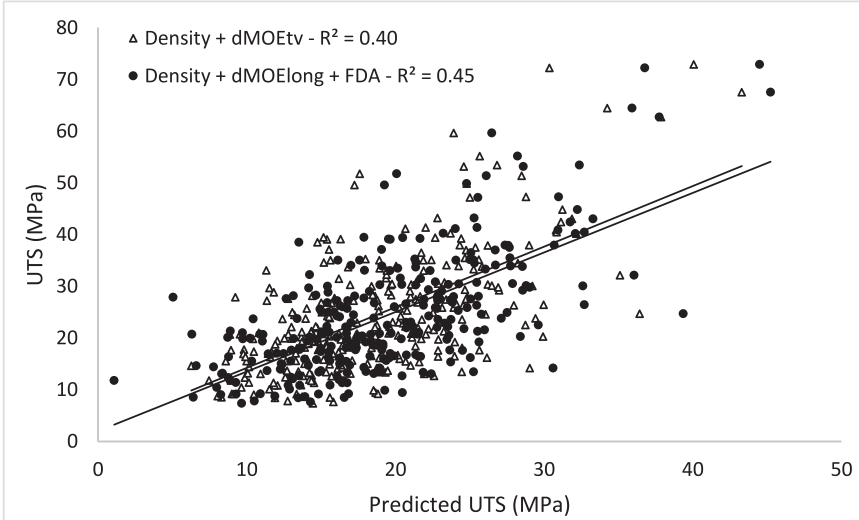


Figure 5.—Linear regression plots (from Table 5 and Table 6) for predicted ultimate tensile stress (UTS) vs. UTS.

improve the E_t estimation with either NDT technique. For UTS, density was the best single predictor variable ($R^2 = 0.33$). The inclusion of density and $dMOE_{tv}$ increased the R^2 to 0.40. In contrast, density, MOE_{long}, and FDA was the best combination to predict UTS ($R^2 = 0.45$).

Figures 3, 4, and 5, show linear regression plots for 2 by 10 lumber using the models from Table 5 and Table 6. Predicted E_b using the generated models (dMOE + density) slightly improved the E_b estimation (from $R^2 = 0.75$ to $R^2 = 0.77$ with transverse vibration and from $R^2 = 0.68$ to $R^2 = 0.72$ with the longitudinal vibration technique).

Although E_b is best estimated when using either MOE_{tv} or MOE_{long} combined with density, the highest coefficient of determination is found when using the transverse vibration technique (see Fig. 3). On the other hand, the combination of variables did not enhance the estimation of E_t. Thus, one predictor variable ($dMOE_{tv}$ or $dMOE_{long}$) is suggested (see Fig. 4).

As previously stated, the combination of density and $dMOE_{tv}$ or of density, $dMOE_{long}$, and FDA increased the ability to estimate UTS (see Fig. 5). The improved R^2 found for UTS in this study is comparable to the ones reported by Senalik et al. (2020) and Correa et al. (2022). Our results show that the prediction of UTS can be improved when two or more variables are included in the model.

Conclusions

This study evaluated the potential of using nondestructive techniques to predict bending MOE (E_b), tension MOE (E_t), and ultimate tensile stress (UTS) using longitudinal and transverse vibration techniques (NDT). From these analyses, we found that:

- The length (14 ft. and 16 ft.) does not significantly affect the bending and tensile properties of 2 by 10 southern pine lumber.
- The combination of $dMOE_{tv}$ + density improved the prediction of E_b but did not improve that of E_t.
- Transverse vibration ($dMOE_{tv}$) was the best single predictor for E_b.
- Longitudinal vibration ($dMOE_{long}$) was a slightly better predictor for E_t.
- Density was the best single predictor for UTS.
- The combination of density, $dMOE_{long}$, and frequency-domain area (FDA) improved the UTS prediction.

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