Assessing 2 by 6 Southern Pine Lumber Flexural and Tensile Properties with Nondestructive Techniques

Marly G. C. Uzcategui Frederico José Nistal França
R. Daniel Seale Robert J. Ross C. Adam Senalik

Abstract

The objective of this study was to assess the flexural and tensile properties of 702 pieces of No. 2 grade 2 by 6 southern pine lumber using nondestructive testing (NDT) techniques. Longitudinal and transverse vibration techniques were used to test each specimen. The mean dynamic modulus of elasticity in the longitudinal direction was 11,246 MPa, and the mean transverse vibration dynamic modulus of elasticity was 11,491 MPa. Proof-loading bending tests were conducted on each specimen. The mean bending modulus of elasticity (MOE) was 10,615 MPa. Each specimen was then destructively tested in tension parallel to the grain to determine tension MOE (E_t) and ultimate tensile stress (UTS). The overall mean for E_t was 11,339 MPa and the UTS mean was 28.54 MPa. Correlations between growth characteristics, and physical and mechanical properties were analyzed. From the linear regression analysis, a strong relationship between E_t and dynamic MOE was found using both NDT tools. Multivariable regression models were developed to improve UTS estimation. NDT techniques are recommended for the estimation of mechanical properties of No. 2 grade 2 by 6 southern pine lumber.

Ensuring the efficient use of timber resources requires accurate sorting into grades of lumber. Part of lumber's utility value depends on the stiffness, or modulus of elasticity (MOE), and bending strength, or modulus of rupture (MOR), of the material. Assessing the stiffness and strength of lumber is done during the grading process. Visual stress rating (VSR) and machine stress rating (MSR) are current methods for grading structural lumber. VSR uses the size of visual effects such as knots to predict stiffness and strength; however, a visual grade may not always reflect the accurate strength or stiffness of lumber. In the case of MSR, a combination of edge-knot size and stiffness is the traditional method used (Rajeshwar et al. 1997, Entsminger et al. 2020, França et al. 2021).

Most MSR lumber is based on the relationship between MOE and MOR (Galligan et al. 1979). MOE is known as one of the main predictor variables of MOR but other characteristics such as density and acoustic wave speed can be used to assist in the grading of lumber. Developing correlation relations between MOE and MOR helps to establish design values or working stresses. Improving the precision of these correlations is still a subject of study (Doyle et al. 1967, Ross 2015, Entsminger et al. 2020, Senalik et al. 2020).

Nondestructive testing (NDT) principles are the base of MSR systems. Machine grading is an increasingly used method to grade lumber in North America. The use of MSR helps to maintain or improve the quality of the product in sawmills. Machines determine the MOE in the entire lumber piece using a transverse wave vibration method (Entsminger et al. 2020). Evaluating and improving the prediction of the mechanical properties of southern yellow pine (SYP) lumber informs landowners about the quality of the currently produced lumber. The value of SYP lumber depends on guaranteeing this quality to the customers (França et al. 2021).

Longitudinal and transverse vibration techniques are the most widely used NDT techniques to investigate the physical and mechanical properties of lumber and wood-based products. Both techniques assess wood properties based on the stress wave and frequency oscillation. The study of acoustic wave behavior is used to improve the prediction of MOR. More recently, there is an interest in applying NDT techniques to evaluate tensile properties,

The authors are, respectively, Graduate Research Assistant, Assistant Research Professor, and Professor, Mississippi State Univ., Starkville, Mississippi (mgc273@msstate.edu, fn90@msstate.edu [corresponding author], rds9@msstate.edu); and Supervisory Research General Engineer and Research General Engineer, USDA Forest Serv., Forest Products Lab., Madison, Wisconsin, (rjross@fs.fed.us, christopher.a.senalik@usda.gov). This paper was received for publication in August 2022. Article no. 22-00055.

Forest Prod. J. 73(1):75–81.
doi:10.13073/FPJ-D-22-00055

especially since there is not enough research on the subject (As et al. 2020). Another nondestructive evaluation to assess MOE is through proof-loading bending tests (Ross 2015). This method offers a reliable evaluation to assure the strength of full-size dimensional lumber (Woeste et al. 1987).

The use of linear regression models to investigate correlative relationships between dynamic MOE (dMOE) and other physical and mechanical properties is a widely accepted method. Nonetheless, previous investigations show that using dMOE as a sole predictor variable is not sufficient to predict MOR or ultimate tensile stress (UTS) from lumber, as MOE accounts for only 50 to 55 percent of the variation in both properties. The difficulty in predicting MOR and UTS has been associated with strength-reducing effects such as knots. Hence, examining the acoustic wave behavior to find potential factors such as time domain and frequency domain seems promising to enhance estimations of lumber strength (França et al. 2018a, 2019a, 2020; Senalik et al. 2020; Correa et al. 2022).

Some studies about the relationships between tensile properties and dMOE or MOE are documented in the literature. One of the earliest and most extensive studies was that of Doyle et al. (1967) for SYP full-size dimensional lumber. The authors studied the relationship between flexural and tensile properties for lumber of different grades and sizes. More recent studies were conducted by Senalik et al. (2020) and As et al. (2019). Studies about the application of bending proof-load to ensure tensile strength are also found in the literature. Woeste et al. (1987) studied the effect of edgewise bending proof-loads on the tensile and bending strength of 2 by 4 structural lumber.

This research aims to assess No. 2 southern pine 2 by 6 lumber flexural and tensile properties using nondestructive techniques. There were four specific objectives. (1) Investigate the relationships between the dMOE from longitudinal and transverse vibration and the mechanical properties (bending MOE [E_b], tension MOE [E_t], and UTS). (2) Evaluate the accuracy and reliability of the NDT tools that are commercially available on tensile properties. (3) Obtain a better understanding of 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. (4) Investigate the length influence on the flexural and tensile properties.

Materials and Methods

Materials

The lumber tested in this study consisted of 702 pieces of 2 by 6 No. 2–KD southern pine (*Pinus* spp.), 14 and 16 feet in length (4.27 and 4.88 m) (Table 1). For this study, No. 2 lumber was selected because it accounts for the largest percentage of SPY production by grade (França et al. 2018b), and it is the most common grade used in structural applications such as trusses, light frame construction, engineered applications, concrete forms. The lumber was obtained from the 18 commercial growing regions of SYP in the United States (Southern pine growth regions map can be viewed in França et al. 2018b). The specimens were conditioned to 12 percent moisture content (MC) prior to testing. Data collected prior to testing on each specimen included specimen dimensions, MC, density, percentage of latewood (LW), and rings per inch (RPI). The average MC when specimens were tested was 12.20 percent.

Table 1.— Dimensions of 2 by 6 southern pine dimensional lumber.

Size	Thickness (in.)	Width (in.)	Nominal length	Length (m)	Quantity
2 × 6	1.5	5.5	14 ft	4.27	168
			16 ft	4.88	534

RPI and percentage of LW

The rings at the ends of each specimen were counted following 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 in which direction the rings were counted (radial or tangential direction). The percentage of LW was measured using a small plastic dot grid (25.4 × 25.4 mm) made of 64 dots in total. The dot 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 zone were counted and recorded. The calculation procedure is described by Uzcategui et al. (2020).

Testing

The specimens were first nondestructively tested with the longitudinal and transverse vibration techniques. The longitudinal vibration technique was conducted using the Director HM 200 (Fibre-gen, Christchurch, New Zealand) tool (Fig. 1). The test consisted of placing each specimen horizontally over two supports and generating an impact with a hammer into one of the ends. This impact produced an acoustic longitudinal vibration that traveled through the entire length of the piece and was recorded by the director's tool. This procedure was done following the ASTM E 1876 (ASTM 2021b) standard. Calculation of the dMOE in the longitudinal direction ($dMOE_{long}$) is given by Equation 1.

$$dMOE_{long} = \rho v^2 \quad (1)$$

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

An additional variable was evaluated after examination of the frequency-domain signal. The area under the natural frequency peak was calculated as described by Senalik et al. (2020) and in concordance with Correa et al. (2022).

To assess all specimens with the transverse vibration technique, each specimen was put in a flatwise direction over two supports and the center of the span was tapped to generate an oscillation wave. The oscillation frequency was captured by the E-computer Model 340 Transverse Vibration (Metriguard, Pullman, Washington, USA). Tests were conducted in accordance with ASTM E 1876 (2021b). The equation used to calculate the transverse vibration dynamic modulus of elasticity ($dMOE_{tv}$) is given in Equation 2.

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

Where $dMOE_{tv}$ is the transverse vibration dynamic MOE (MPa), f is the resonant frequency (Hz), W is the mass of the

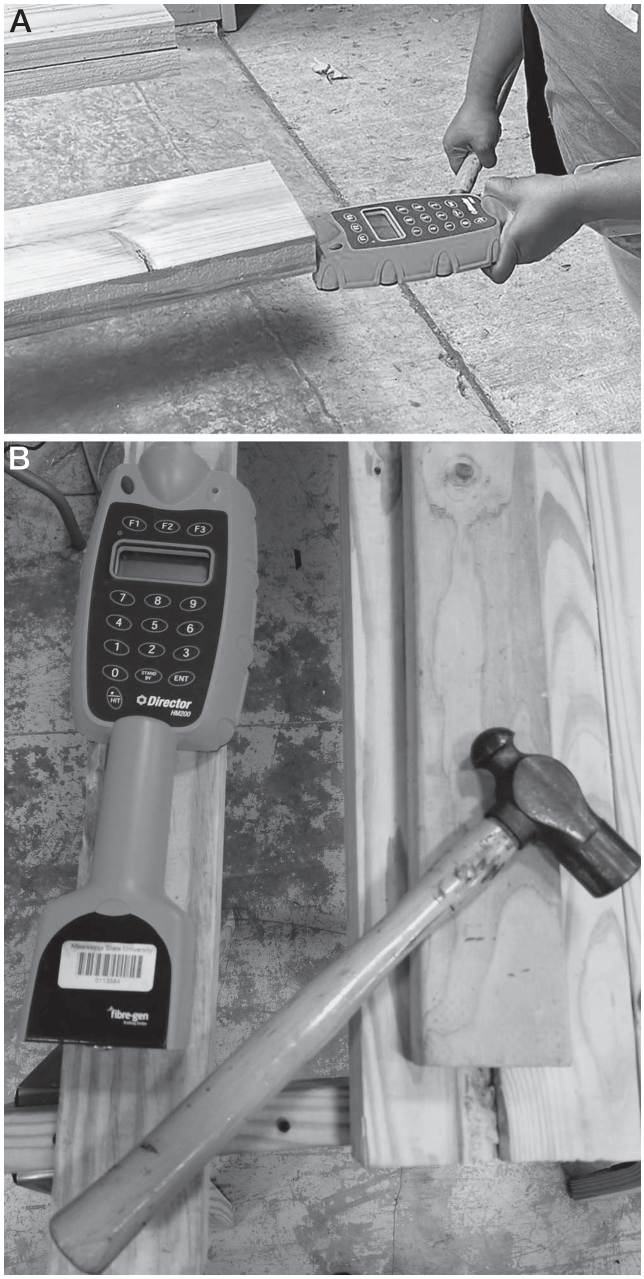

Figure 1.—(A) Longitudinal vibration technique setup. (B) Director HM 200.

lumber piece (kg), s is the span (m), I is the moment of inertia (m^4), and g is the acceleration due to gravity (9,807 $m \cdot s^{-2}$).

After $dMOE_{long}$ and $dMOE_{tv}$ were obtained, proof-load bending tests were conducted for all the specimens. The static MOE values were obtained via four-point static tests in edgewise bending using a span-to-depth ratio of 17:1 following the standard ASTM D 198-21 (ASTM 2021a), where the ratio span was 3.99 m (13.09 ft). The rate of the load was $0.02 m \cdot min^{-1}$ (0.80000 in.$\cdot min^{-1}$), and the maximum load was 3,336 N. The procedure followed ASTM D 4761-19 (ASTM 2019).

Once all NDT was performed, all pieces were destructively tested in tension parallel to the grain using a Tension Proof Loader Model 422 (Metriguard). To conduct tension tests, each specimen was placed horizontally in the tension machine (Fig. 2). Each specimen was held by metallic grips at both ends while the test was performed.

Tests were monitored from the beginning of the test until failure occurred. Tension stress and strain were recorded in the Blue Hill system (Instron, Norwood, Massachusetts, USA). The span of testing was 96 inches (2.43 m) for the shorter lumber (14 ft [4.27 m]) and 117 inches (2.97 m) for the longer pieces (16 ft [4.88 m]). E_t and UTS were calculated for each piece specimen. All tests were performed following the standard D 198-21 (ASTM 2021a).

Statistical analysis

Descriptive statistics, analysis of variance (ANOVA), and models were generated using SAS version 9.4 (SAS Institute; Cary, NC). ANOVA was calculated at the $\alpha = 0.05$ significance level. Linear regression models were created for E_b, E_t, and UTS with $dMOE_{long}$ and $dMOE_{tv}$ as predictor variables. Data to generate models were organized taking into consideration the length of each specimen. The coefficient of determination (r^2) was calculated. The standard D 2915-17 (ASTM 2022) was followed for the statistical analyses and associated graphs.

Table 2 shows descriptive statistics for MC (%), density, RPI, and LW (%) from 2 by 6 structural lumber. RPI and LW (%) values are consistent with the results published by the authors França et al. (2018b, 2019a, 2019b). For density, the mean, minimum, maximum, and coefficient of variation

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

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

	Nominal length (ft)	Mean	Median	Minimum	Maximum	COV (%)[a]
% MC %	14	12.23	12.10	7.40	19.8	17.68
	16	12.19	12.30	6.60	20.10	17.06
	Overall	12.20	12.20	6.60	20.10	17.20
Density ($kg \cdot m^{-3}$)	14	561.89	548.15	437.00	725.00	11.10
	16	559.56	557.60	416.00	763.00	10.40
	Overall	560.12	554.74	416.00	763.00	10.57
RPI	14	5.34	4.67	1.02	18.33	49.67
	16	4.66	4.33	1.48	15.67	45.86
	Overall	4.82	4.33	1.02	18.33	47.40
% LW	14	45.89	45.31	22.66	72.66	23.98
	16	45.87	45.31	18.75	82.81	23.51
	Overall	45.88	45.31	18.75	82.81	23.62

[a] COV = coefficient of variation.

(COV) were 560 $kg \cdot m^{-3}$,416 $kg \cdot m^{-3}$, 763 $kg \cdot m^{-3}$, and 10.57 percent respectively.

Results and Discussion

The mean RPI was 4.82, ranging from 1.02 to 18.33 with a COV of 47.40 percent. The mean percentage of LW mean was 45.88 percent and it ranged from 18.75 percent to 82.81 percent. The LW (%) COV was 23.62 percent. Density values from the present study are within the range of the results obtained by several authors (França et al. 2018a, 2018b, 2019a; Irby et al. 2020).

According to SPIB grading rules, southern pine dense lumber should have four or more annual RPI on either one end and at least ½ or more LW (%). Pieces averaging fewer than four RPI are also accepted if they meet an average of 1/3 or more LW (%). Our results show that the specimens evaluated meet the SPIB RPI and LW (%) requirements for No. 2 grade lumber.

The overall results for the mechanical properties evaluated are shown in Table 3. For $dMOE_{long,}$ the mean value (both lengths included) was 11,246 MPa, with a range from 3,659 to 22,402 MPa with a COV of 26.60 percent. The $dMOE_{long}$ results obtained are comparable to the values reported by França et al. (2019b). The overall mean for $dMOE_{tv}$ (both lengths combined) was 11,491 MPa with a minimum of 3,665 MPa, a maximum of 22,168 MPa, and a COV of 26.70 percent. These results are comparable with the results obtained by previous authors (França et al. 2018a; 2019b).

The E_b mean was 10,615 MPa and it ranged between 3,994 and 18,547 MPa with a COV equal to 24.34 percent. The E_b mean values are slightly lower than E_t and dMOE mean values. These results are comparable to those reported by França et al. (2018b) and França et al. (2019b). The overall mean for E_t was 11,339 MPa, with a minimum of 3,942 MPa, a maximum of 22,088 MPa, and a COV of 28.30 percent. The UTS mean was 28.54 MPa and it ranged between 5.33 MPa and 80.14 MPa. The UTS COV was 49.45 percent. The mean and range values for UTS reported in this study are comparable to the ones reported by Doyle et al. (1967).

Table 4 summarizes the ANOVA results for E_b, E_t, and UTS evaluated individually against the length, RPI, and LW (%) factors. A statistically significant difference ($\alpha = 0.05$) was found in the means of bending and tensile properties with respect to the means of the visual characteristics (RPI and LW %). The evaluation of the effect of length revealed no statistically significant difference among bending and tensile properties of southern pine at $\alpha = 0.05$ significance level. The effect of length on the tensile properties of SYP lumber (8 and 10 ft [2.44 and 3.05 m] long) was investigated previously by Showalter et al. (1987). In contrast to our results, these authors found that tensile strength was significantly lower in the longer specimens.

Bivariate correlations among the variables under investigation are presented in Table 5. Strong correlations were found between E_b and $dMOE_{tv}$ ($r = 0.92$) and between E_b

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 6 (14 ft,16 ft, and combined) southern pine dimensional lumber.

	Nominal length (ft)	Mean (MPa)	Median (MPa)	Minimum (MPa)	Maximum (MPa)	COV (%)[a]
$dMOE_{long}$	14	11,199	10,916	3,858	21,293	27.49
	16	11,261	11,142	3,659	22,402	26.35
	Overall	11,246	11,126	3,659	22,402	26.60
FDA	14	8,187	7,826	2,310	15,738	33.18
	16	7,253	6,777	1,476	16,543	34.08
	Overall	7,477	7,056	1,476	16,543	34.27
$dMOE_{tv}$	14	11,524	11,359	3,858	22,168	27.34
	16	11,481	11,436	3,665	21,309	26.51
	Overall	11,491	11,414	3,665	22,168	26.70
E_b	14	10,523	10,497	4,601	17,114	24.27
	16	10,644	10,520	3,994	18,547	24.38
	Overall	10,615	10,514	3,994	18,547	24.34
E_t	14	11,109	10,784	3,983	20,622	28.63
	16	11,411	11,215	3,942	22,088	28.20
	Overall	11,339	11,059	3,942	22,088	28.30
UTS	14	29.10	24.11	6.08	72.33	52.49
	16	28.36	25.17	5.33	80.14	48.43
	Overall	28.54	24.55	5.33	80.14	49.45

[a] COV = coefficient of variation.

Table 4. —Values of analysis of variance for bending modulus of elasticity (MOE) (E_b), tension MOE (E_t), and ultimate tensile stress (UTS) depending on the length of the specimen, the rings per inch (RPI), and the percentage of latewood (LW).

Property	Factor	DF[a]	SS	MS	F	P
E_b	Length	1	1,741,647	1,741,647	0.39	0.53
	RPI	1	710,144,978	710,144,978	157.44	<0.001
	% LW	1	777,853,006	777,853,006	172.45	<0.001
	Error	690	3,112,336,049			
$E_{t\%}$	Length	1	12,722,924	12,722,924	1.85	0.17
	RPI	1	1,208,425,285	1,208,425,285	175.96	<0.001
	% LW	1	1,179,010,711	1,179,010,711	171.68	<0.001
	Error	690	4,738,571,103			
UTS	Length	1	73.58	73.58	0.53	0.47
	RPI	1	17,568.63	17,568.63	125.58	<0.001
	% LW	1	23,163.67	23,163.67	165.57	<0.001
	Error	690	96,531.32			

[a] DF = degrees of freedom; SS = the sum of squares; MS = mean sum of squares; F = Fisher's F test; P = significance level.

Table 5.—Pearson's bivariate correlation (r) among length, rings per inch (RPI), percentage of latewood (% LW), density, dynamic modulus of elasticity transverse and longitudinal vibration ($dMOE_{tv}$ and $dMOE_{long}$, respectively), frequency-domain area (FDA), bending MOE (E_b), tension MOE (E_t), and ultimate tensile stress (UTS).

	Length	RPI	% LW	density	$dMOE_{tv}$	$dMOE_{long}$	FDA	E_b	E_t	UTS
Length	1	−0.12760 (0.0007)	−0.00047 (0.9900)	−0.01678 (0.6571)	−0.00607 (0.8725)	0.00886 (0.8146)	−0.15572 (<.0001)	0.02003 (0.5962)	0.04024 (0.2871)	−0.02229 (0.5554)
RPI		1	0.48825 (<0.0001)	0.33936 (<0.0001)	0.48119 (<0.0001)	0.50086 (<0.0001)	0.02089 (0.5806)	0.39946 (<0.0001)	0.42565 (<0.0001)	0.31741 (<0.0001)
LW (%)			1	0.54409 (<0.0001)	0.52485 (<0.0001)	0.51246 (<0.0001)	−0.19405 (<0.0001)	0.47442 (<0.0001)	0.46194 (<0.0001)	0.46366 (<0.0001)
density				1	0.72889 (<0.0001)	0.70814 (<0.0001)	−0.26283 (<0.0001)	0.73175 (<0.0001)	0.64561 (<0.0001)	0.62565 (<0.0001)
$dMOE_{tv}$					1	0.97586 (<0.0001)	−0.19834 (<0.0001)	0.92406 (<0.0001)	0.90009 (<0.0001)	0.62432 (<0.0001)
$dMOE_{long}$						1	−0.18547 (<0.0001)	0.89726 (<0.0001)	0.89077 (<0.0001)	0.60814 (<0.0001)
FDA							1	−0.24502 (<0.0001)	−0.18403 (<0.0001)	−0.39374 (<0.0001)
E_b								1	0.85915 (<0.0001)	0.64851 (<0.0001)
E_t									1	0.57172 (<0.0001)
UTS										1

and $dMOE_{long}$ ($r = 0.90$). França et al. (2018a, 2019b) and Yang et al. (2015) also reported strong correlations between E_b and dMOE for 2 by 6 lumber. França et al. (2018a) found correlations between $dMOE_{tv}$ and E_b equal to 0.92. For MOE_{long} and E_b, the same authors reported a correlative relationship equal to 0.91. Their results are similar to the ones presented in this study.

A strong correlation was found between E_b and E_t ($r = 0.86$). This result was slightly lower than the ones obtained by Doyle et al. (1967). For 2 by 6 lumber, the authors reported a correlation coefficient of 0.94. The E_t was also closely related with the two NDT techniques ($r = 0.90$; $dMOE_{tv}$) and ($r = 0.89$; $dMOE_{long}$). The excellent correlations found between dMOE and E_b and dMOE and E_t prove that both NDT techniques can be used to accurately predict E_b and E_t of southern pine 2 by 6 lumber.

Density was found to be moderately correlated with elastic and tensile properties. The correlation coefficient obtained for density and E_b was 0.73 and for density and E_t was 0.65. The highest correlation found for UTS was with the E_b variable ($r = 0.65$). Nondestructive method correlations with UTS were 0.62 for $dMOE_{tv}$, and 0.61 for $dMOE_{long}$. Doyle et al. (1967) found a correlation of 0.55 between E_b and UTS.

A potential relationship was found between the frequency-domain area (FDA) and UTS ($r = -0.39$). RPI were found to have weak to moderate correlation with density ($r = 0.34$), $dMOE_{tv}$ ($r = 0.48$), $dMOE_{long}$ ($r = 0.50$), E_b ($r = 0.40$), and E_t ($r = 0.42$). Similarly, LW (%) was found moderately correlated with density ($r = 0.54$), $dMOE_{tv}$ ($r = 0.52$), $dMOE_{long}$ ($r = 0.51$), E_b ($r = 0.47$), and E_t ($r = 0.46$). Lower correlations were found between growth characteristics and UTS ($r = 0.31$, RPI; $r = 0.46$, LW %).

A stepwise regression technique was employed to determine the best-fit multiple regression equation for E_b, E_t, and UTS. Tables 6 and 7 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 similar R^2 value ($R^2 = 85$) when compared to the value obtained with a single predictor ($dMOE_{tv} = 0.86$); however, the combination of the two variables reduced the standard

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 transverse vibration and density for 2 by 6 southern pine structural lumber.

Property	NDT technique[a]	β_0[b]	β_1	β_2	R^2	P	SE (μ)
E_b	$dMOE_{tv}$	1,671.26	0.78	—	0.85	<0.001	988.30
	$dMOE_{tv}$ + density	−488.48	0.70	5.42	0.86		964.22
E_t	$dMOE_{tv}$	517.82	0.94	—	0.81	<0.001	1,399.33
	$dMOE_{tv}$ + density	999.23	0.96	−1.21	0.81		1,399.47
UTS	$dMOE_{tv}$	−4.46	0.003	—	0.39	<0.001	11.03
	Density	−54.99	0.15	—	0.39		11.02
	Density + $dMOE_{tv}$	−39.03	0.09	0.02	0.45		10.46

[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 [$kg \cdot m^{-3}$]).

Table 7.—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 6 southern pine structural lumber.

Property	NDT technique[a]	β_0[b]	β_1	β_2	β_3	R^2	P	SE (μ)
E_b	$dMOE_{long}$	1,901.63	0.77	—	—	0.81	<0.001	1,141.51
	$dMOE_{long}$ + density	−1,494.02	0.66	8.44	—	0.82		1,086.37
E_t	$dMOE_{long}$	593.99	0.96	—	—	0.79	<0.001	1,459.49
	$dMOE_{long}$ + density	−54.77	0.93	1.61	—	0.79		1,458.98
UTS	FDA	44.75	−0.002	—	—	0.16	<0.001	12.98
	$dMOE_{long}$	−3.72	0.003	—	—	0.37		11.21
	Density	−54.99	0.149	—	—	0.39		11.02
	Density + $dMOE_{long}$	−41.24	0.093	0.002	—	0.45		10.52
	Density + $dMOE_{long}$ + FDA	−22.43	0.08	0.002	−0.001	0.50		9.97

[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).

error. On the contrary, the combination of these variables did not improve the prediction of E_t ($R^2 = 0.81$) or reduce the error in comparison to the results obtained with a single predictor. The combination of $dMOE_{long}$ with density presented a similar coefficient of determination ($R^2 = 0.82$) when compared to a single predictor ($dMOE_{long}$) ($R^2 = 0.81$).

For E_t, the models with either NDT technique combined with density did not improve the prediction ($R^2 = 0.81$, MOE_{tv}; and $R^2 = 0.79$, $dMOE_{long}$). Using $dMOE_{tv}$ or $dMOE_{long}$ as a single predictor is suggested to estimate E_t. The best single predictor for UTS was density ($R^2 = 0.39$). The models for UTS with either density or $dMOE_{tv}$ generated the same R^2. The R^2 obtained from $dMOE_{long}$ and UTS was slightly lower ($R^2 = 0.37$) than the one found between MOE_{tv} and UTS. The best prediction for UTS was found when combining two or more variables: density and $dMOE_{tv}$ ($R^2 = 0.45$), or density with $dMOE_{long}$, and FDA ($R^2 = 0.50$), with the last model being the one with the highest coefficient of determination and the smallest error.

Linear regression plots for 2 by 6 lumber using the models from Tables 6 and 7 are shown in Figures 3, 4, and 5. E_b is predicted using the generated models (dMOE + density). Slight improvements were found for E_b estimation (from $R^2 = 0.85$ to $R^2 = 0.86$ using transverse vibration and from $R^2 = 0.81$ to $R^2 = 0.82$ using longitudinal vibration) (Fig. 3).

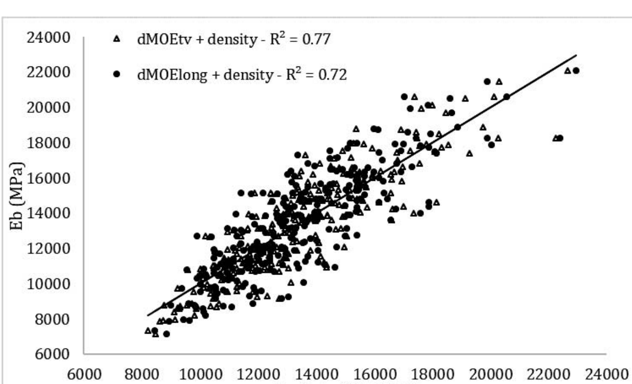

Figure 3.—Linear regression plots (from Tables 6 and 7) for predicted bending modulus of elasticity (MOE) (E_b) versus static bending MOE (E_b).

Figure 4 shows linear regression plots for predicted E_t and E_t. As previously stated, the combination of density with dMOE did not improve the estimation of E_t. Although both NDT techniques are excellent to predict E_t, the highest R^2 was found with the transverse vibration technique.

The results show that multivariable regression models can enhance the prediction of UTS (Fig. 5). For UTS the combination of density with $dMOE_{tv}$ increased the ability to estimate tensile stress (from $R^2 = 0.39$ to $R^2 = 0.45$). As

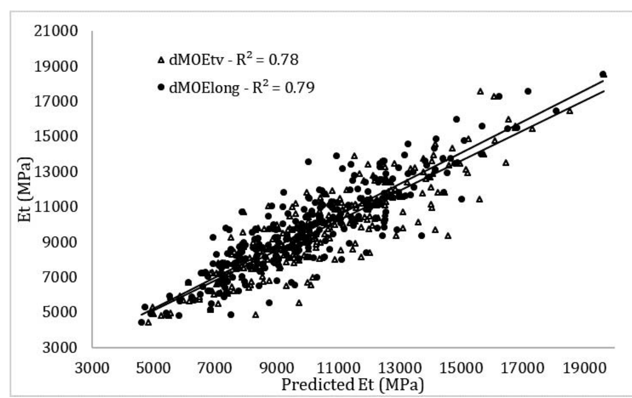

Figure 4.—Linear regression plots (from Tables 6 and 7) for predicted tension modulus of elasticity (MOE) (E_t) versus tension MOE (E_t).

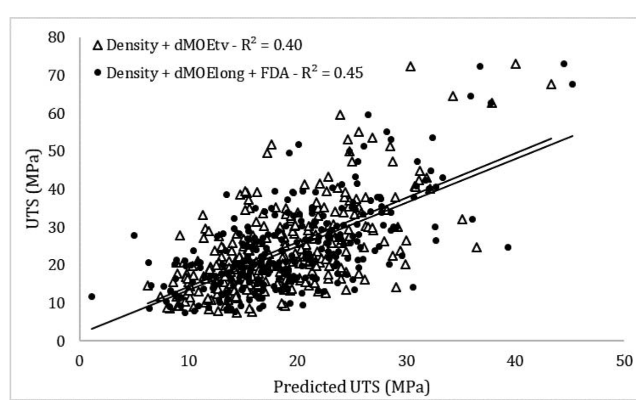

Figure 5.—Linear regression plots (from Tables 6 and 7) for predicted ultimate tensile stress (UTS) versus (UTS).

described above, the best prediction was found when adding density, $dMOE_{long}$, and FDA ($R^2 = 0.50$). These results are comparable to the ones found by Senalik et al. (2020) and Correa et al. (2022).

Conclusions

This study evaluated the flexural and tensile properties of 2 by 6 (14 and 16 ft [4.27 and 4.88 m]) No. 2 visually graded southern pine lumber. Transverse and longitudinal vibration techniques were implemented to determine the dMOE ($dMOE_{tv}$ and $dMOE_{long}$). The results are based on the evaluation of 702 specimens. The MC when specimens were tested was around 12 percent. Linear and multiple regression models were developed to analyze the relationships between dMOE and the flexural and tensile properties of SYP. The authors conclude the following:

- The length (14 and 16 ft [4.27 and 4.88 m]) did not significantly affect the flexural and tensile properties of 2 by 6 lumber.
- The $dMOE_{tv;}$ and $dMOE_{long}$ were excellent predictors of E_b and E_t.
- The prediction of E_b was improved with the combination of $dMOE_{tv}$ + density in the model.
- Density was the best single predictor for UTS.
- The best model to predict UTS was the one combining density, $dMOE_{long}$, and FDA.

Literature Cited

American Society for Testing and Material (ASTM). 2019. ASTM D 4761-19: Mechanical properties of lumber and wood-based structural material. *In:* Annual Book of ASTM Standards. ASTM International, West Conshohocken, Pennsylvania.

American Society for Testing and Material (ASTM). 2021a. ASTM D 198-21: Standard test methods of static tests of lumber in structural sizes. *In:* Annual Book of ASTM Standards. ASTM International, West Conshohocken, Pennsylvania.

American Society for Testing and Material (ASTM). 2021b. ASTM E 1876-21: Standard test method for dynamic Young's modulus, shear modulus, and Poisson's ratio by impulse excitation of vibration. *In:* Annual Book of ASTM Standards. ASTM International, West Conshohocken, Pennsylvania.

American Society for Testing and Material (ASTM). 2022. ASTM D 2915-17: Standard for sampling and data-analysis for structural wood and wood-based products. *In:* Annual Book of ASTM Standards. ASTM International, West Conshohocken, Pennsylvania.

As, N., C. A. Senalik, R. J. Ross, X. Wang, and B. Farber. 2020. Nondestructive evaluation of the tensile properties of structural lumber from the spruce-pine-fir species grouping: Relationship between modulus of elasticity and ultimate tension stress. Res. Note FPL-RN-0383. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 14 pp.

Correa, L. M. S., F. J. N. França, R. Shmulsky, R. D. Seale, R. Ross, and C. A. Senalik. 2022. Evaluation of modulus of elasticity and modulus of rupture of cross-laminated timber with longitudinal vibration NDE techniques. Research Paper FPL-RP-714. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. https://www.fs.usda.gov/research/treesearch/64130. Accessed April 22, 2022.

Doyle, D. V., L. J. Markwardt, Forest Products Laboratory (U.S.), and U.S Forest Service. 1967. Tension parallel-to-grain properties of southern pine dimension lumber. Research Paper FPL 84. Forest Products Laboratory, Madison, Wisconsin. 39 pp.

Entsminger, E. D., B. K. Brashaw, R. D. Seale, and R. J. Ross. 2020. Machine grading of lumber—Practical concerns for lumber producers. General Technical Report FPL-GTR-279. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 66 pp.

França, F., R. Seale, R. Ross, R. Shumulsky, and T. França. 2018a. Using transverse vibration nondestructive testing techniques to estimate stiffness and strength of southern pine lumber. Research Paper FPL-RP-695. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. 8 pp. https://doi.org/10.2737/FPL-RP-695

França, T. S. F. A., F. J. N. França, R. D. Seale, and R. Shmulsky. 2018b. Bending strength and stiffness of no.2 grade southern pine lumber. *Wood Fiber Sci*. 50(20):1–15.

França, F. J. N., R. D. Seale, R. Shmulsky, and T. S. F. A. França. 2019a. Modeling mechanical properties of 2 by 4 and 2 by 6 southern pine lumber using longitudinal vibration and visual characteristics. *Forest Prod. J*. 68(3):286–294.

França, F. J. N., R. D. Seale, R. Shmulsky, and T. S. F. A. França. 2019b. Assessing southern pine 2 × 4 and 2 × 6 lumber quality: longitudinal and transverse vibration. *Wood Fiber Sci*. 51(1): 2–15. https://doi.org/10.22382/wfs-2019-002

França, F. J. N., T. S. F. A. França, S. R. Daniel, 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

França, F. J. N., R. Shmulsky, J. T. Ratcliff, B. Farber, C. A. Senalik, R. J. Ross, and R. D. Seale. 2021. Yellow pine small clear flexural properties across five decades. *Forest Prod. J*. 71(3):233–239. https://doi.org/10.13073/FPJ-D-20-00040

Galligan, W. L., Gerhards, C. C., & Ethington, R. L (1979) Evolution of tensile design stresses for lumber (Vol. 28) Forest Products Laboratory.

Irby, N. E., F. J. N. França, H. M. Barnes, R. D. Seale, and R. Shmulsky. 2020. Effect of growth rings per inch and density on compression parallel to grain in southern pine lumber. *BioResources* 15(2):2310–2325.

Rajeshwar, B., D. A. Bender, D. E. Bray, and K. A. McDonald. 1997. An ultrasonic technique for predicting tensile strength of southern pine lumber. *Trans. Am. Soc. Agric. Eng*. 40(4):1153–1160.

Ross, Robert J (2015) Nondestructive Evaluation of Wood: Second Edition. USDA Forest Service, Forest Products Laboratory, General Technical Report, FPL-GTR-238, 2015; 176 p.

Senalik, C., F. França, R. Seale, R. Ross, and R. Shumulsky. 2020. Estimating lumber properties with acoustic-based technologies—Part 2: Ultimate tension stress estimation from time- and frequency-domain parameters. *Wood Fiber Sci*. 52(4):390–399. https://doi.org10.22382/wfs-2020-037

Showalter, K. L., F. E. Woeste, and B. A. Bendtsen. 1987. Effect of length on tensile strength in structural lumber. Research Paper FPL-RP-482). USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin.

Southern Pine Inspection Bureau (SPIB). 2014. Standard Grading Rules for Southern Pine Lumber. Southern Pine Inspection Bureau, Pensacola, Florida.

Uzcategui, M. G. C., R. D. Seale, and F. J. N. Franca. 2020. Physical and mechanical properties of hard maple (*Acer saccharum*) and yellow poplar (*Liriodendron tulipifera*). *Forest Prod. J*. 70(3):326–334. https://doi.org/10.13073/FPJ-D-20-00005

Woeste, F. E., D. W. Green, K. A. Tarbell, and L. A. Marin. 1987. Proof loading to assure lumber strength. *Wood Fiber Sci*. 19(3):283–297.

Yang, B. Z., R. D. Seale, R. Shmulsky, J. Dahlen, and X. Wang. 2015. Comparison of nondestructive testing methods for evaluating no. 2 southern pine lumber: Part A, modulus of elasticity. *Wood Fiber Sci*. 47(4):375–384.