Nondestructive Evaluation of 2 by 8 and 2 by 10 Southern Pine Dimensional Lumber

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Abstract

This study investigated the use of two nondestructive testing (NDT) methods to evaluate the mechanical properties of No. 2 grade: 2 by 8 and 2 by 10 southern pine lumber. The dynamic modulus of elasticity (dMOE) of each specimen was evaluated nondestructively by using longitudinal vibration and transverse vibration in edgewise and flatwise directions. After the NDT evaluation, the specimens were destructively tested and correlations between static bending MOE with modulus of rupture (MOR) and dMOE were developed. The overall MOE values were 11.14 and 10.96 GPa for 2 by 8 and 2 by 10, respectively. For MOR, the overall value for 2 by 8 was 42.59 MPa, and for 2 by 10 was 43.05 MPa. As expected, results showed statistically significant correlations between static MOE and dMOE (with *r* ranging from 0.87 to 0.96 for both sizes tested). Also as expected, weaker correlations were found between MOR and the dMOE values (with *r* ranging from 0.42 to 0.57 for both sizes tested). The lower correlations are largely explained by the difference between the NDT tools analyzing each specimen's global stiffness versus MOR, which is influenced heavily by localized characteristics. Perhaps this finding occurred because larger strength-reducing characteristics are permitted in larger section pieces (2 by 8 vs. 2 by 10) and thus they have opportunity for greater variability. The continuation of studies to develop more reliable NDT is crucial to improve the evaluation of mechanical properties of southern pine lumber and is beneficial to the southern pine timber industry.

Efficient use of the available wood supply is essential to sustainably meet the long-term demand for wood products and to ensure their economic viability. Improvement of solid sawn wood use for structural applications depends on the ability to understand and accurately predict the mechanical behavior of each piece.

The efficient use of structural lumber depends largely on accurate, reliable, and conservative evaluation of each piece's mechanical properties. Unlike many other construction materials, wood is produced by a living tree, which results in a high variability in its properties in function of the environment, genetics, and growth conditions (Panshin and de Zeeuw 1980). In the United States, wood is a major material used for construction and it has many advantages when compared with steel and concrete, which include considerable ductility and fatigue resistance, favorable strength-to-weight ratios, cost efficiency, ready availability, and relative ease of construction. In addition, wood is a sustainable, renewable, and biodegradable material. However, the use of wood as a structural material requires a reliable strength evaluation via grading (Frese 2008).

Sorting wood pieces with similar mechanical properties into stress classes is a simple way to minimize the variability of the material and ensure its reliable strength properties. The sorting of wood into these classes can be done using one or more visual and/or mechanical sorting criteria, a set of basic properties for engineering design, or a unique grade name (Kretschmann 2010).

The southern pine group is composed of four major species (*Pinus taeda, P. palustris, P. echinata,* and *P. elliottii*) and is known for its high density, favorable

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mechanical properties, rapid drying, and ease of preservative treatment (Gaby 1985). Southern pine is the single largest species group from which domestic structural lumber is produced. The southeastern US region is considered a very productive forested area and its lumber production can be traced back over 150 years. Approximately 60 percent of the wood used in the United States and 15 percent of the wood consumed globally is produced in this region (Wear and Greis 2002, McKeand et al. 2003). Southern pine timber and wood products make a major contribution to economic activity in the region (American Wood Council 2012, Coyle et al. 2015).

Advances in structural design methods and potential changes in the timber resource over time have brought focus on the performance of the traditional visual grading system. The US Department of Agriculture Forest Service Forest Products Laboratory has worked cooperatively with the American Lumber Standards Committee (ALSC) and various agencies that write grade-rules for many years to assess and monitor published design values for lumber products. Within the past 15 years, research indicated that a change in southern pine design values was appropriate and that a more rigorous resource monitoring program was warranted (Southern Forest Products Association 2005). Modulus of elasticity (MOE) is a frequently used indicator of load resistance and is one of the most important mechanical properties when sorting wood into stress classes (Nzokou et al. 2006, Amishev and Murphy 2008).

Visual and mechanical grading are the two methods used to grade structural lumber. The classification of lumber by visual grading is based on human inspection or by automated imaging with systems that can identify various characteristics such as knots, warp, splits, wane, and others (Bharati et al. 2003). Machine grading systems, including machine stress rating and machine evaluated lumber, are grading methods based on nondestructive testing (NDT) techniques. Flatwise bending, transverse vibration, and acoustic NDT techniques are the foundation for many of the commercially available machine grading technologies (Ross 2015). Machine grading systems rely on statistical relationships between a nondestructive parameter, such as frequency of vibration, and static mechanical properties.

NDT is a method that evaluates physical and mechanical properties of a piece of material without changing its characteristics. The assessment of the quality of wood materials has become a crucial issue in the operational value chain as forestry and the wood processing industry are increasingly under economic pressure to maximize its extracted value (Ross et al. 1991, Brashaw et al. 2009). Techniques such as ultrasound, transverse vibration, longitudinal vibration, and x-ray have been investigated and adopted by industry because of their fast responses and high correlations with mechanical properties (Senft et al. 1962, McKean and Hoyle 1964, Ross 1985, Ziegler 1997, Galligan and McDonald 2000, Simpson and Wang 2001, Yang et al. 2015, França et al. 2018a).

Longitudinal stress wave and transverse vibration are the most widely used NDT techniques toward structural lumber evaluation. Predicting MOE of lumber with longitudinal stress wave has received considerable research efforts in recent years in terms of lumber grading or presorting (Jayne 1959, Kaiserlik and Pellerin 1977, Gerhards 1982, Falk et al. 1990, Wang 2013). Longitudinal vibration testing has proved to be an accurate method of mechanical property assessment. Transmission time of sound waves, or acoustic velocity, and attenuation of induced stress waves in wood materials are frequently used as NDT parameters (Ross 2015).

The transverse vibration method uses the relationship between MOE and low-frequency oscillation of a supported lumber beam, and this relationship is examined through fundamental mechanics (Timoshenko et al. 1974). This technique can be used on thicker specimens, panels, in situ structures, and samples with nonrectangular shape. Transverse vibration requires the weight and volume of each specimen, so density can also be calculated (Ross et al. 1991).

Continual development of NDT technologies is needed to improve the mechanical evaluation, and subsequently the economic valuation, of structural lumber. Greater NDT accuracy leads to wiser resource conservation and use as well as greater economic benefit. The objectives of this study were (1) to evaluate the mechanical properties of No. 2 grade 2 by 8 and 2 by 10 southern pine lumber using NDT tools and to develop correlations between dynamic MOE (dMOE) and static bending MOE and modulus of rupture (MOR); (2) to obtain more information on the variability of mechanical properties of southern pine lumber along with the ability of current NDT techniques to identify and measure this variability; (3) to expand the knowledge on NDT techniques; and (4) to improve the accuracy and reliability of the NDT tools that are widely used for grading and testing structural lumber.

Materials and Methods

A production-weighted sample of southern pine visually graded structural lumber was collected from 15 of the original 18 southern pine growth regions (Jones 1989). No. 2 grade lumber was selected because it represents the largest volume of southern pine produced. A total of 476 specimens of 2 by 8-in. (38 by 184-mm), and 306 specimens of 2 by 10-in. (38 by 235-mm) No. 2 structural lumber was collected (Table 1). This production-weighted sampling approximately followed the in-grade lumber sampling used to derive design values by rules-writing agencies such as Southern Pine Inspection Bureau (SPIB).

The variables recorded in this study included specimens' dimensions, weight, specific gravity, and moisture content. The presence of pith, number of annual growth rings per inch, percentage of latewood, and orientation of the board are described in França et al. (2018b). The average moisture content when tested was 11.3 percent, and the average air-dried density was 547 kg/m^3.

For this study, four commercially available NDT tools were used to evaluate the relationship between the mechanical properties tested (MOE and MOR) and dMOE.

Table 1.—Dimensions of 2 by 8 and 2 by 10 southern pine dimensional lumber.

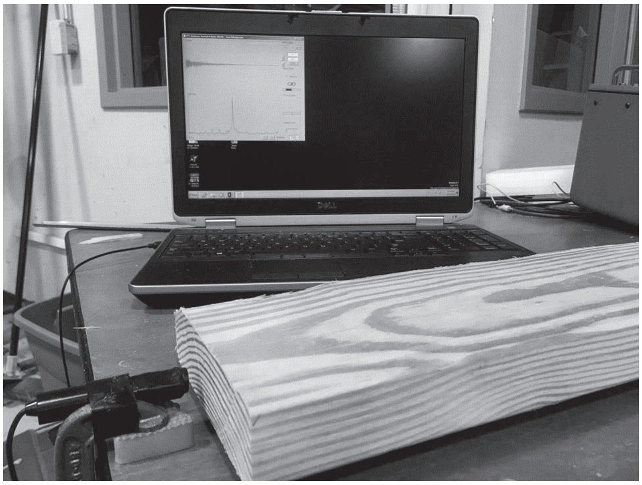
Size (in.)	Thickness (mm)	Width (mm)	Length (m)	Quantity by length
2 × 8	38	184	3.66 (144 in.)	142
	—	—	4.29 (169 in.)	202
	—	—	4.90 (193 in.)	132
2 × 10	38	235	4.29 (169 in.)	200
	—	—	4.90 (193 in.)	106

The longitudinal vibration was collected using the Fakopp, Falcon A-grader, and Director HM200 (Fig. 1). The Metriguard Model 340 Transverse Vibration E-Computer, shown in Figure 2, was the device used to capture the transverse vibration in flatwise and edgewise orientation.

Longitudinal vibration

For longitudinal vibration, the specimens were supported by two rigid sawhorses, positioned at one-quarter and three-quarters of the specimen's length. A thin foam cushion was placed between the sawhorses and specimen to reduce damping and increase accuracy during the test. A hammer was used to generate the vibration in the specimen. The specimens were oriented flatwise, with one end supported by a knife-edge and the other end supported by a point, permitting each specimen to vibrate in an unrestrained manner.

The Fakopp device, coupled with a microphone, was used to collect the longitudinal frequencies. The natural frequency of each piece was collected using a fast Fourier vibration analyzer (Fakopp 2005) and Falcon A-grader software. In addition, the portable device Director HM200 was used to test each specimen.



(a)

(b)

Figure 1.—Longitudinal stress wave technique: (a) microphone: Fakopp and Falcon A-Grader; and (b) Director HM 200.

Figure 2.—Transverse vibration technique: Metriguard E-Computer Model 340 (edgewise–flatwise).

For testing, an impact was applied on each specimen in the longitudinal direction per ASTM E1876 (ASTM International 2015a). The direction of the wave motion occurs in the same direction as the longitudinal vibration mode and the dMOE was calculated based on the information collected using the longitudinal vibration tools (Eq. 1).

$$E_L = \rho(L \times f)^2 = \rho \times v^2 \tag{1}$$

where E_L = dMOE (MPa), ρ = density (kg/m^3), L = length of the piece (m), f = first harmonic longitudinal vibration frequency (Hz), and v = wave velocity (m/s).

Transverse vibration

The transverse vibration data were collected in two orientations—flatwise (dMOE flat) and edgewise (dMOE edge)—using the Metriguard Model 340 Transverse Vibration E-Computer device. Through tapping the specimen near the center of the span, oscillation was generated. The frequency of vibration and weight was measured via a load cell, and the transverse vibration frequency for each piece was determined by the E-Computer software. From this information, the dMOE was calculated.

To capture the signal generated along the transverse direction, an impact was applied with a hammer per ASTM E1876 (ASTM International 2015a). The MOE was calculated using the first transverse vibration resonant frequency (Eq. 2):

$$E_T = \frac{f_r^2 \times W \times L^3}{2.46 \times I \times g} \tag{2}$$

where E_T = dMOE (GPa), f_r = resonant frequency (Hz), W = lumber piece weight (kg × g), L = beam span (m), I = moment of inertia (m^4), and g = acceleration of gravity (9.8 m/s^2).

The same procedure was applied to measure the dMOE in edgewise orientation. This action ensured that the vibration was vertical only because horizontal vibration, if present, has the potential to complicate or confuse the signal acquisition.

Static bending test

All specimens were destructively tested in static bending after the nondestructive measurements via four-point loading on an Instron Universal Testing Machine using Bluehill 3 software, with a depth/span ratio of 17 to 1 (ASTM D198; ASTM International 2015b). The distance between the load heads for 2 by 8 was 3.13 m and for 2 by 10 was 3.99 m.

Templates were cut to the length of the test span (one for each cross section/span length) and were used to mark the span and load head placement. The tension face and the strength-reducing characteristics were randomly selected without respect to their location between load heads. Figure 3 shows a sketch for the test setup. The rate of loading followed ASTM D4761 (ASTM International 2019). The deflection was measured by a deflectometer at midspan to determine MOE and a uniform deformation was assumed. MOR was calculated from the maximum load.

Statistical analysis

The statistical analyses and associated graphs were completed according to ASTM D2915 (ASTM International 2017) using SAS version 9.4 (SAS Institute 2013). Analysis of variance was performed to characterize the differences within the specimens sampled. For each specimen, individual models were developed using the combination of width and length, and for each relationship obtained, the coefficient of correlation (r) and coefficient of determination (r^2) were calculated.

Results and Discussion

Statistical analyses of the static bending MOR and MOE values are listed in Table 2. The difference between sizes (2 by 8 and 2 by 10) for MOE and MOR was not statistically significant ($\alpha = 0.05$).

The overall means found for 2 by 8 and 2 by 10 were 42.59 and 43.05 MPa, respectively. The MOR values found in this study showed a wide range, from 7.45 to 95.5 MPa. This range can largely be explained because samples were randomly placed on the testing machine. Some specimens had large knots placed between the load heads, which resulted in a reduction of the lumber strength. On the other hand, some specimens had knots or other strength-reducing characteristics such as slope of grain, compression wood, splits, and warp outside of the load span, which resulted in higher strength values.

For MOE, the overall means were 11.08 GPa for 2 by 8 and 11.11 GPa for 2 by 10. The minimum and maximum MOE values for 2 by 8 were 5.06 and 19.26 GPa, respectively, and for 2 by 10 were 4.60 and 18.99 GPa, respectively. Comparing the MOE values found in this research with the previous and current design values (11.00 and 9.70 GPa, respectively) published for southern yellow pine lumber, the results show that the MOE mean value exceeded the new published design value and also met the previous SPIB design values (American Forest and Paper Association 2005, ALSC 2013). The results in this study are also in accordance with the findings by Doyle and Markwardt (1966) when studying the strength for southern pine lumber. There the authors found MOE values ranging from 8.80 to 13.20 GPa.

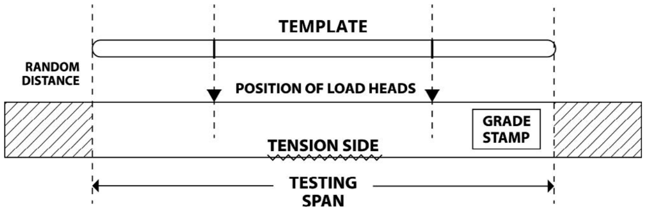


Figure 3.—Illustration of static bending test setup.

Table 2.—Static bending modulus of elasticity (MOE) and modulus of rupture (MOR) values of 2 by 8 and 2 by 10 southern pine dimensional lumber.

	Size	Mean	Median	Minimum	Maximum	SD	COV (%)[a]
MOE	2 × 8	11.08	11.14	5.06	19.26	2.43	21.95
(GPa)	2 × 10	11.11	10.96	4.60	18.99	2.57	23.12
MOR	2 × 8	42.59	41.07	8.43	95.54	15.71	36.89
(MPa)	2 × 10	43.05	42.67	7.45	89.49	16.37	38.02

[a] COV = coefficient of variation.

The overall MOR was 42.82 MPa, slightly higher than the values reported by Dahlen et al. (2014a; 40.7 MPa) for different southern pine No. 2 lumber sizes (2 by 4, 6, 8, 10, and 12) and by Yang et al. (2017; 38.26 MPa) for 2 by 4 southern pine No. 2 grade. However, the values were lower than the MOR value (48.3 MPa) reported in a prior test of southern pine 2 by 4 No. 2 grade (Dahlen et al. 2014b).

Longitudinal and transverse vibration

The dMOE mean values for longitudinal vibration collected with different tools are shown in Table 3. The overall dMOE mean value for both sizes tested with all three longitudinal vibration devices was 10.56 GPa, with a range from 4.03 to 20.71 GPa.

Table 4 summarizes the dMOE results for the transverse vibration test. When transverse vibration was applied, both dMOE flatwise and edgewise were slightly higher than the dMOE obtained from longitudinal vibration for 2 by 8 and 2 by 10 (11.01 and 10.98 GPa, respectively). The dMOE flatwise values ranged from 5.08 to 21.06 GPa, and dMOE edgewise values showed a range from 5.37 to 18.98 GPa. The dMOE edgewise was slightly lower than flatwise

Table 3.—Dynamic modulus of elasticity (dMOE) values obtained from longitudinal vibration technique on 2 by 8 and 2 by 10 southern pine dimensional lumber.

	Size	Mean	Median	Minimum	Maximum	SD	COV (%)[a]
dMOE_{FAK}[b]	2 × 8	10.59	10.43	4.78	20.12	2.69	25.40
(GPa)	2 × 10	10.59	10.32	4.06	20.22	2.84	26.82
dMOE_{DIR}[c]	2 × 8	10.66	10.52	4.95	19.39	2.72	25.52
(GPa)	2 × 10	10.62	10.22	4.14	20.71	2.83	26.65
dMOE_{FAL}[d]	2 × 8	10.44	10.31	4.75	19.89	2.65	25.38
(GPa)	2 × 10	10.44	10.14	4.03	19.98	2.79	26.72

[a] COV = coefficient of variation.

[b] Longitudinal vibration MOE value from the Fakopp lumber grader.

[c] Longitudinal vibration MOE value from the Director HM200.

[d] Longitudinal vibration MOE value from the Falcon A-Grader.

Table 4.—Dynamic modulus of elasticity (dMOE) values obtained from transverse vibration technique on 2 by 8 and 2 by 10 southern pine dimensional lumber.

	Size	Mean	Median	Minimum	Maximum	SD	COV (%)[a]
$\text{dMOE}_{\text{EDGE}}$[b]	2 × 8	10.93	10.93	5.37	18.98	2.31	21.13
(GPa)	2 × 10	11.00	10.68	4.63	18.78	2.51	22.82
$\text{dMOE}_{\text{FLAT}}$[c]	2 × 8	11.10	11.03	5.08	21.06	2.63	23.72
(GPa)	2 × 10	10.97	10.67	3.98	20.42	2.92	26.65

[a] COV = coefficient of variation.

[b] Edgewise transverse vibration MOE value.

[c] Flatwise transverse vibration MOE value.

orientation for 2 by 8 (1.5%), while this difference was higher for 2 by 10 (0.27%). Figures 4 and 5 show the relationships between dMOE obtained with longitudinal and transverse vibration and bending MOE and MOR for 2 by 8 southern pine specimens tested. The correlations between dMOE obtained with longitudinal and transverse vibration (edgewise and flatwise orientation) and bending MOE and MOR for 2 by 10 are shown in Figures 6 and 7, respectively.

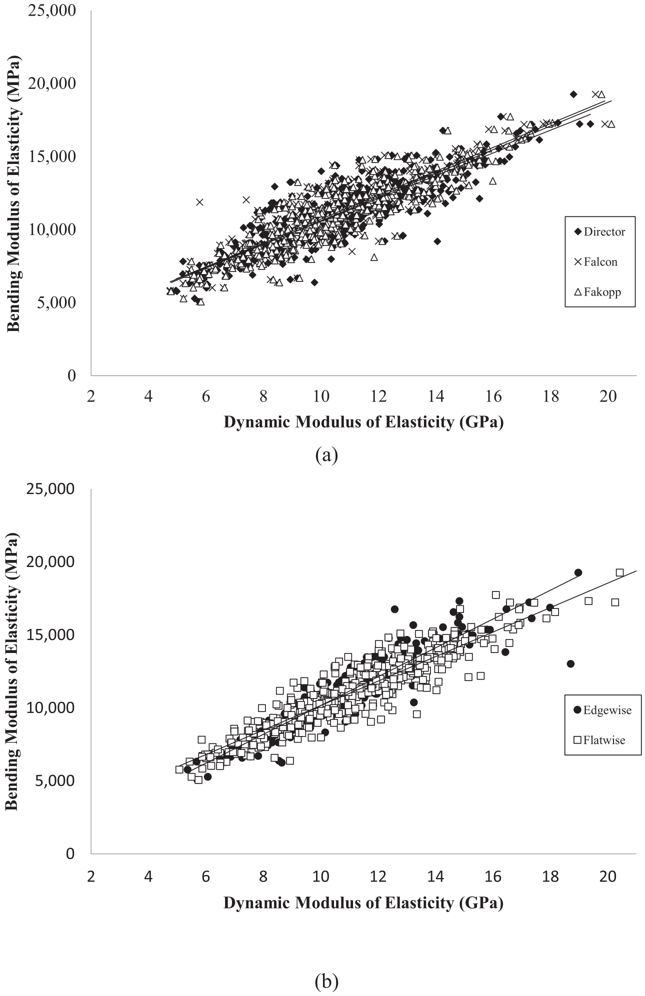


Figure 4.—Correlation between bending modulus of elasticity (MOE) versus dynamic MOE for 2 by 8 southern pine lumber: (a) Fakopp Lumber Grader, Director HM200, and Falcon A-Grader; and (b) edgewise and flatwise vibration.

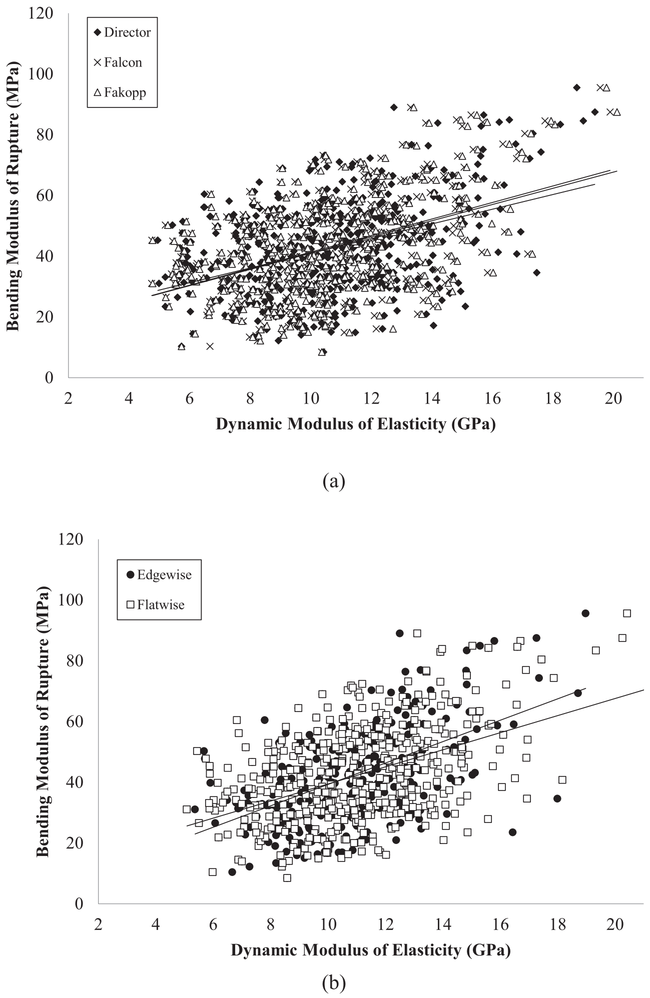
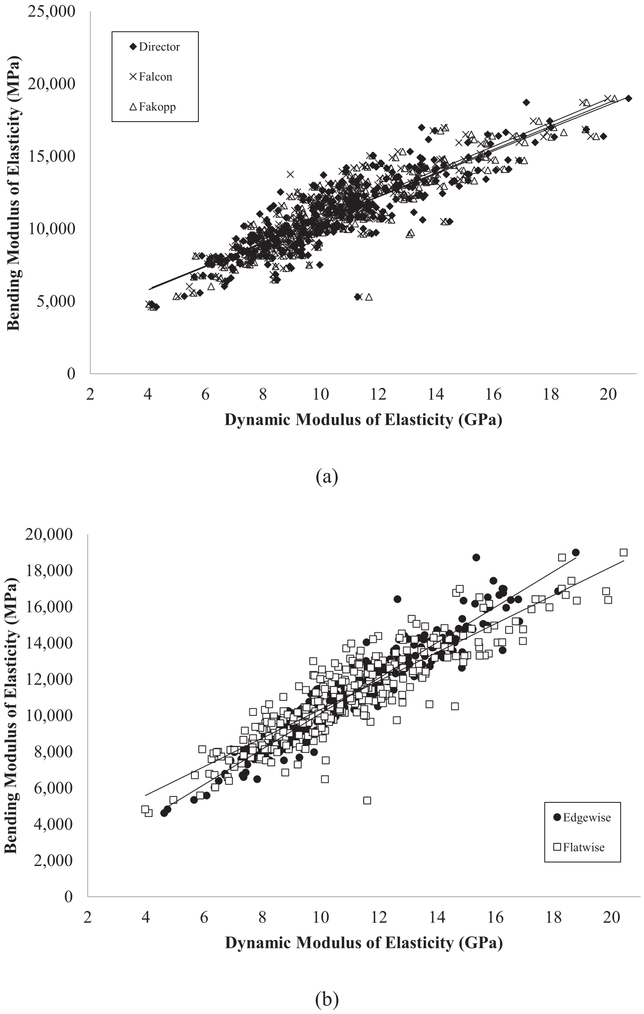


Figure 5.—Correlation between bending of modulus of rupture versus dynamic modulus of elasticity for 2 by 8 southern pine lumber: (a) Fakopp Lumber Grader, Director HM200, and Falcon A-Grader; and (b) edgewise and flatwise vibration.

Linear regression analysis performed in this study

Table 5 summarizes the results of the linear regression analyses relating static bending MOE with the dMOE obtained with longitudinal vibration from different devices for 2 by 8 and 2 by 10 southern pine dimensional lumber. The coefficients β_0 and β_1 are used in the generalized model where the static property = $\beta_0 + \beta_1 \times$ dMOE.

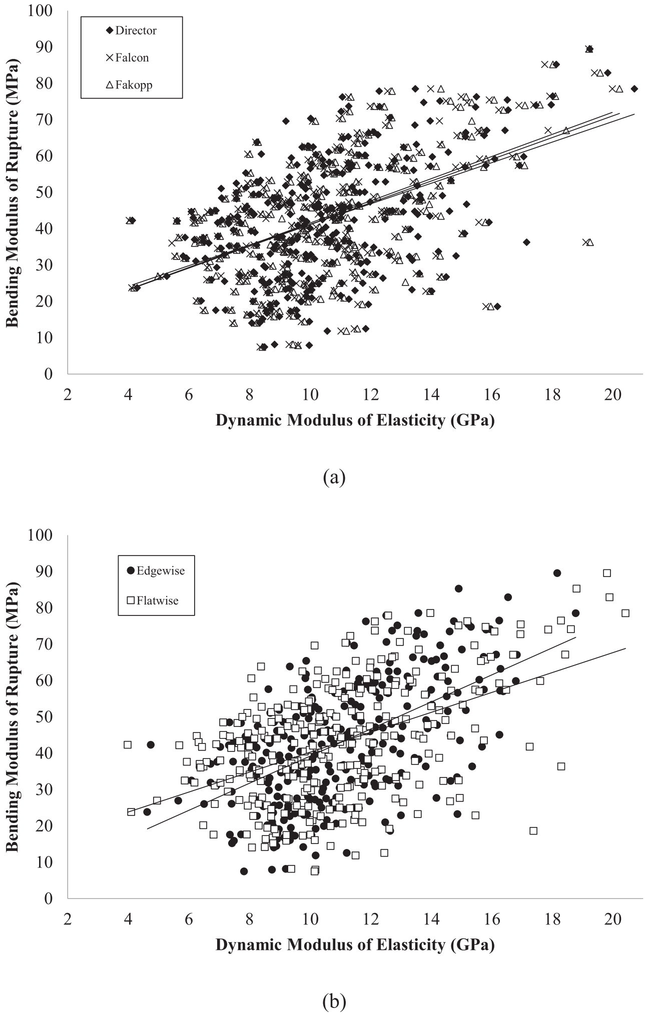
The overall average for r^2 values obtained from longitudinal vibration for both sizes tested was 0.79, where Fakopp had the highest r^2 values for 2 by 8 (0.80), the Falcon device showed the highest r^2 for 2 by 10 specimens (0.81), and the Director HM200 showed the lowest r^2 for both sizes (2 by 8 = 0.76; 2 by 10 = 0.77). The results for the relationship between static MOE and transverse vibration showed that r^2 values from edge orientation were higher than flatwise orientation for both 2 by 8 and 2 by 10 (0.80 and 0.92, respectively). The results found in this study emphasize the potential of NDT methods to estimate MOE, and they are in accordance with other previous studies (Ross et al. 1991, Divós and Tanaka 1997, Yang et al. 2015).



(a)

(b)

Figure 6.—Correlation between bending modulus of elasticity (MOE) versus dynamic MOE for 2 by 10 southern pine lumber: (a) Fakopp Lumber Grader, Director HM200, and Falcon A-Grader; and (b) edgewise and flatwise vibration.



(a)

(b)

Figure 7.—Correlation between bending modulus of rupture versus dynamic modulus of elasticity for 2 by 10 southern pine lumber: (a) Fakopp Lumber Grader, Director HM200, and Falcon A-Grader; and (b) edgewise and flatwise vibration.

Table 6 summarizes the results of the linear regression analyses relating static bending MOR with dMOE from different devices for 2 by 8 and 2 by 10 lumber. The r^2 for 2 by 8 ranged from 0.17 to 0.27, where the E-computer edgewise direction had the highest r^2 value and the Director HM200 tool presented the lowest r^2 value; these results were similar to the ones obtained for dynamic MOE. For 2 by 10, r^2 ranged from 0.24 to 0.32, and again the E-computer in edgewise direction showed the highest r^2 value. However, the E-computer flatwise and Director HM200 showed the lowest r^2 values.

The results show a weak but statistically significant ($P < 0.0001$) relationship between dMOE and MOR. This low correlation can perhaps be explained by the presence of knots and other wood defects (checks, splits, and grain deviations) present in specimens tested. In addition, the static bending was performed over a 17:1 span-to-depth ratio wherein each specimen was randomly positioned in the testing machine, while the NDT analysis was performed over the entire length of each piece. Also, all specimens tested were classified in the same grade. These correlations

Table 5.—Results of linear regression analyses relating static bending modulus of elasticity (MOE) and dynamic MOE (dMOE) from different devices for 2 by 8 and 2 by 10 southern pine dimensional lumber.

		Modulus of elasticity (MOE)[a]					
Size	Test method	Device[b]	β_0	β_1	r^*	r^2	SE (u)
2 × 8	Longitudinal	FAK	2,504	810	0.90	0.80	18.47
		DIR	2,769	779	0.87	0.76	20.11
		FAL	2,550	817	0.89	0.79	19.18
	Transverse	EDGE	310	986	0.94	0.88	16.85
		FLAT	1,758	840	0.91	0.83	17.64
2 × 10	Longitudinal	FAK	2,523	811	0.90	0.80	22.99
		DIR	2,667	795	0.88	0.77	24.95
		FAL	2,471	827	0.90	0.81	23.18
	Transverse	EDGE	313	981	0.96	0.92	16.79
		FLAT	2,450	790	0.90	0.81	22.13

[a] β_0 and β_1 are used in the generalized model static bending MOE (MPa) = $\beta_0 + \beta_1$·[nondestructive parameter(GPa)]. * = All correlations were significant (P value < 0.05).

[b] FAK = Fakopp; DIR = Director HM200; FAL = Falcon A-grader; EDGE = Metriguard E-Computer Edgewise; FLAT = Metriguard Vibration E-Computer Flatwise.

Table 6.—Results of linear regression analyses relating static bending modulus of rupture (MOR) and dynamic modulus of elasticity (dMOE) from different devices for 2 by 8 and 2 by 10 southern pine structural lumber.

	Modulus of rupture (MOR)[a]					
Size	Device[b]	β_0	β_1	r^*	r^2	SE (u)
2 × 8	FAK	14.32	2.67	0.46	0.21	0.24
	DIR	16.86	2.41	0.42	0.17	0.24
	FAL	14.18	2.72	0.46	0.21	0.24
	EDGE	4.15	3.52	0.52	0.27	0.27
	FLAT	11.47	2.80	0.47	0.22	0.24
2 × 10	FAK	11.46	2.98	0.52	0.27	0.28
	DIR	13.16	2.82	0.49	0.24	0.29
	FAL	11.30	3.04	0.52	0.27	0.29
	EDGE	2.31	3.70	0.57	0.32	0.31
	FLAT	13.18	2.72	0.49	0.24	0.28

[a] β_0 and β_1 are used in the generalized model static bending MOR (MPa) = $\beta_0 + \beta_1 \cdot$[nondestructive parameter (GPa)]. * = All correlations were significant (P value < 0.05).

[b] FAK = Fakopp; DIR = Director HM200; FAL = Falcon A-grader; EDGE = Metriguard E-Computer Edgewise; FLAT = Metriguard Vibration E-Computer Flatwise.

would very likely be improved if multiple grades were included (lumber with higher and lower quality).

Linear regression analysis performed in previous studies

Other studies have examined the relationship between longitudinal vibration MOE and static bending (MOE and MOR) of southern pine and other species. Correlations found herein are comparable to those reported in the previous literature (Table 7).

Transverse vibration in flatwise orientation was used to predict strength properties of Douglas-fir (*Pseudotsuga menziesii*) dimension lumber by Pellerin (1965), and the author found correlations between 0.67 and 0.93 for various lumber grades. O'Halloran (1972) found a correlation of 0.89 for lodgepole pine (*Pinus contorta*) dimensional lumber using the transverse vibration technique. The relationship between stress wave, transverse vibration, and ultrasonic test on green and dry southern pine dimensional lumber was studied by Halabe et al. (1995), and the results showed that dry static bending MOE was able to be predicted using the relationship between dry static MOE and stress wave velocity directly. Green and McDonald (1993) found a correlation of 0.58 for northern red oak (*Quercus rubra*) lumber using transverse vibration in a flatwise orientation. However, when the authors used ultrasonic waves, low coefficients of determination were found for grading long-dimension lumber. A more narrowly focused study by Yang et al. (2015) to predict E and bending MOE of southern pine dimensional lumber using transverse vibration and stress waves found r^2 values ranging from 0.77 to 0.86, which is similar to the results found in this study.

Table 7.—Summary of research conducted to examine the relationship between longitudinal vibration modulus of elasticity (MOE) and static bending (MOE and modulus of rupture [MOR]) of structural lumber.

Reference	Material	Correlation coefficient
Pellerin (1965)	Douglas-fir	dMOE × MOE = 0.98 dMOE × MOR = 0.67–0.93
O'Halloran (1969)	Lodgepole pine	dMOE × MOE = 0.98 dMOE × MOR = 0.89
Gerhards (1982)	Southern pine	
	Knotty lumber	dMOE × MOE = 0.87
	Clear lumber	dMOE × MOE = 0.95
Porter et al. (1972)	Clear lumber	dMOE × MOE = 0.90–0.92
Shmulsky et al. (2006)	Southern pine dowels	dMOE × MOE = 0.81 dMOE × MOR = 0.42
Yang et al. (2015)	Southern pine dimensional lumber	dMOE × MOE = 0.71–0.97
Yang et al. (2017)	Southern pine dimensional lumber	dMOE × MOR = 0.43–0.66
França et al. (2019)	Southern pine dimensional lumber 2×4 and 2×6	dMOE × MOE = 0.90–0.94 dMOE × MOR = 0.62–0.67

Although the results for predicting static MOE are favorable and accurate, the relationships for MOR are still limited. Yang et al. (2017) found r^2 values for dMOE and bending MOR ranging from 0.23 to 0.28. Those results were lower than the bending MOR r^2 values found herein. For chestnut timber, Vega et al. (2011) found r^2 values between 0.10 and 0.17 using ultrasound, impact wave, and longitudinal waves. These results showed that the dynamic variables used by these authors were not adequate to estimate bending strength. França et al. (2019), studying the prediction of static MOE and MOR for 2 by 4 and 2 by 6 southern pine lumber using different NDT equipment, found r^2 between 0.81 and 0.88 for dMOE versus MOE. However, lower r^2 values were found for dMOE versus MOR (0.38 and 0.45).

When comparing the r^2 values among different equipment used in this study, the results show that the differences were small, and no single type of equipment or technology was superior. Results also show that using the accuracy of r^2 and the coefficient of variation alone is not sufficient to evaluate equipment accuracy. Other variables such as price of the system, its suitability for the production line, and target strength classes are also important to consider when choosing the best NDT tool for a given operation. Ultimately, however, these technologies are critically important toward increasing the value of the solid sawn resource.

Conclusions

This study evaluated the mechanical properties of 2 by 8 and 2 by 10 No. 2 visually graded southern pine lumber using NDT tools by evaluating the relationships between the dMOE and bending MOE and MOR obtained from longitudinal and transverse vibration. Through this research it was possible to obtain more information on the variability of mechanical properties of pine lumber using different NDT techniques available on the market. It is economically important for the southern pine lumber industry to improve the accuracy and reliability of NDT tools. Such improvements will result in a higher utility value of sawn lumber.

Herein, the devices were divided into two groups, longitudinal vibration (Fakopp, Falcon, and Director HM200), and transverse vibration (Metriguard Model 340 Transverse Vibration E-Computer) in flatwise and edgewise orientation. The results of this study show the following:

- The NDT tools used were able to predict the MOE value of 2 by 8 and 2 by 10 No. 2 visually graded southern pine lumber.
- The dMOE value obtained from the E-Computer in edgewise orientation showed the highest r^2 values for 2 by 8 and 2 by 10 (0.88 and 0.92, respectively), while the Director HM200 had the lowest r^2 values (076 and 0.77, respectively).
- The results of linear regression analyses relating static bending MOR and dMOE obtained from different devices showed that for 2 by 8, the E-Computer in edgewise orientation also had the highest r^2 values (0.27 and 0.32, respectively); and for 2 by 8, the Director HM200 showed the lowest r^2 value (0.17). For 2 by 10, the Director HM200 and the E-Computer in flatwise orientation showed the lowest r^2 values (0.27 for both devices).
- The increase of the cross-section of pieces (2 by 10 vs. 2 by 8) was inversely related to NDT accuracy. The study recommends that further investigation, including a greater range of grades, should be included to increase the prediction of mechanical properties of full-sized lumber.

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