ASSESSING SOUTHERN PINE 2 × 4 AND 2 × 6 LUMBER QUALITY: LONGITUDINAL AND TRANSVERSE VIBRATION

F. J. N. França†
Assistant Research Professor
E-mail: fn90@msstate.edu

R. D. Seale
Warren S. Thompson Professor
E-mail: rds9@msstate.edu

R. Shmulsky
Professor and Department Head
E-mail: rs26@msstate.edu

T. S. F. A. França†
Postdoctoral Associate
Department of Sustainable Bioproducts
Mississippi State University
Starkville, MS 39762-5724
E-mail: tsf97@msstate.edu

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Abstract. A primary goal of structural lumber grading is the identification of the strength-reducing characteristics that impact the MOE and the MOR. Nondestructive evaluation is a technique that can be used to identify material with greater stiffness. This study investigates the use of longitudinal and transverse vibration methods to evaluate the mechanical properties of No. 2 2 × 4 and 2 × 6 southern pine lumber, with varied length. A total of 1240 samples were conditioned to 12% EMC. All samples were first nondestructively tested using transverse vibration equipment (Metriguard E-computer) in the edgewise and flatwise directions and with three different longitudinal vibration devices (Fakopp Portable Lumber Grader, Director HM 200, and Falcon A-grader) and then destructively tested. The objective of this study was to analyze the effectiveness of nondestructive testing on southern pine lumber with several technologies used in the lumber industry. The results showed statistically significant correlations between static MOE and the dynamic MOE (dMOE) measured by nondestructive techniques. Weaker correlations were found between MOR and the dMOE values. This finding is likely because MOR is related to the ultimate strength of material, often associated with the existence of localized defects, such as knots. This study indicates that nondestructive techniques can potentially be used to evaluate 2 × 4 and 2 × 6 lumber stiffness to improve evaluation for end use.

Keywords: Stiffness, strength, stress wave, transverse vibration, nondestructive testing.

INTRODUCTION

Wood is a major construction material used in the United States. It has advantages when compared with other materials such as steel and concrete. It exhibits considerable mechanical resistance, and a favorable strength-to-weight ratio. The cost is competitive and the material is relatively easy to fasten, cut, and shape. In addition, wood is sustainable, renewable, and biodegradable; however, to use wood effectively as a structural material, a reliable strength evaluation via grading is required to optimize the strength and stiffness of the material for its end use (Frese 2008).

Wood has many features that directly influence its in-service performance. Nondestructive testing

* Corresponding author
† SWST member

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(NDT) methods provide ways to evaluate the physical and mechanical properties of the material without changing its characteristics (Ross et al 1991). Techniques such as ultrasound, transverse vibration, longitudinal vibration, and X-ray have been investigated and adopted by the industry because of their fast responses and high correlations with mechanical properties (Simpson and Wang 2001; Yang et al 2002; Brashaw et al 2009).

The MOE is one of the most important mechanical properties of wood because it is the most frequently used indicator of load resistance (Wang et al 1993; Nzokou et al 2006; Amishev and Murphy 2008). The dynamic methods to characterize wood and other materials calculate MOE through the natural frequency of the specimen's vibration and its geometric parameters. These methods have the advantage of being fast and repeatable (Esteban et al 2009; Cossolino and Pereira 2010). Since the 1960s, researchers from the forest products community have been developing NDT devices for evaluating the quality of lumber products, especially with regard to mechanical grading (Galligan and McDonald 2000; Divós and Tanaka 2005).

Lumber is more difficult to evaluate than small clear specimens because it is larger and has a multitude of interacting characteristics that could potentially reduce strength and stiffness. Predicting the MOE of lumber with longitudinal vibration has received considerable attention in recent years in terms of grading or presorting (Pellerin 1965; Kaiserlik and Pellerin 1977; Vogt 1985; Ross and Pellerin 1988; Wang 2013; Yang et al 2015; Aro et al 2016). The assessment of the quality of raw wood materials has become a crucial issue in the operational value chain, as the forestry and wood processing industries are increasingly under economic pressure to maximize its extracted value (Brashaw et al 2009).

High correlations between NDT and static bending MOE have been found. However, it is more difficult to predict the MOR. The relationship between MOE and MOR is not as statistically strong, and it often yields r^2 values from 0.47 to 0.6 (Green and Kretschmann 1991; Liliefna 2009; Ross 2015). The difficulty in predicting the MOR is due to the presence and location of wood-growth related characteristics, such as knots, and the slope of grain that have a significant effect on MOR (Falk et al 1990).

The quality of a strength-grading system is determined by the ability of the system to accurately predict the strength of each piece. The accuracy can be quantified by the coefficient of determination r^2, determined via regression analysis along with the coefficient of variation (Hanhijärvi et al 2005). In addition, a system is judged by the ability to sort-out pieces with different characteristics resulting in consistently low strength. If the regression analysis is based on measurements made under the same conditions and with the same apparatus that is used in the strength-grading machine, the effect of the measurement error and coefficient of variation is already included in the r^2 value directly. If the measurements are made under laboratory conditions, the effect of measurement error should be considered separately when evaluating the effectiveness of a certain strength-grading system (Bailleres et al 2009).

Continuous development and adoption of cost-efficient NDT technologies and tools is necessary to maintain a vibrant lumber industry. Additional information on NDT tool accuracy is beneficial for justifying the application of machine stress-grading in the southern pine lumber industry (Yang et al 2015).

The objectives of this study were: 1) to investigate the relationships between the dynamic MOE (dMOE) from longitudinal and transverse vibration and the mechanical properties (bending MOE and MOR) of No. 2 visually graded southern pine lumber using four commercially available NDT tools; 2) to evaluate the accuracy and reliability of the NDT tools that are widely used for grading and testing structural lumber; 3) to obtain a robust understanding of different NDT methods that are used to test full-size lumber.

MATERIALS AND METHODS

This study expands previous NDT work and provides additional estimates of grading accuracy.

Table 1. Dimensions of 2 × 4 and 2 × 6 southern pine dimensional lumber.

Size	Thickness (mm)	Width (mm)	Length (m)	Quantity by length
2 × 4	38	140	2.45 (96 in)	121
	—	—	3.06 (120 in)	151
	—	—	3.68 (144 in)	206
	—	—	4.26 (168 in)	48
	—	—	4.90 (193 in)	103
2 × 6	38	185	3.06 (120 in)	84
	—	—	3.68 (144 in)	262
	—	—	4.26 (168 in)	136
	—	—	4.90 (193 in)	98
	—	—	6.10 (240 in)	31

The description of the collection of the material and specimen preparation is described in França et al (2018). The presence of pith, number of rings per inch, and percentage of latewood are described in França et al (2018). The orientation of the board was also recorded.

To fully understand the relationships between dynamic and static lumber evaluation methods, experimental tests on 2 × 4 and 2 × 6 southern pine lumber were conducted with four commercially available NDT devices. A total of 1240 specimens of No. 2 southern pine lumber were obtained from retail lumber yards in the southeastern United States (Table 1). The lumber was divided into two groups according to the cross-section dimensions: 629 specimens of 2 × 4 (net 38 × 89 mm^2) and 611 specimens of 2 × 6 (net 38 × 140 mm^2). The average MC when tested was 11.4%, and the average air-dried density was 557 $kg \cdot m^{-3}$. Table 2 summarizes the general characteristics of the specimens (presence of pith, cut orientation, number of rings per inch, and percentage of latewood). Specimens were nondestructively evaluated with longitudinal vibration, and transverse vibration. The Fakopp,

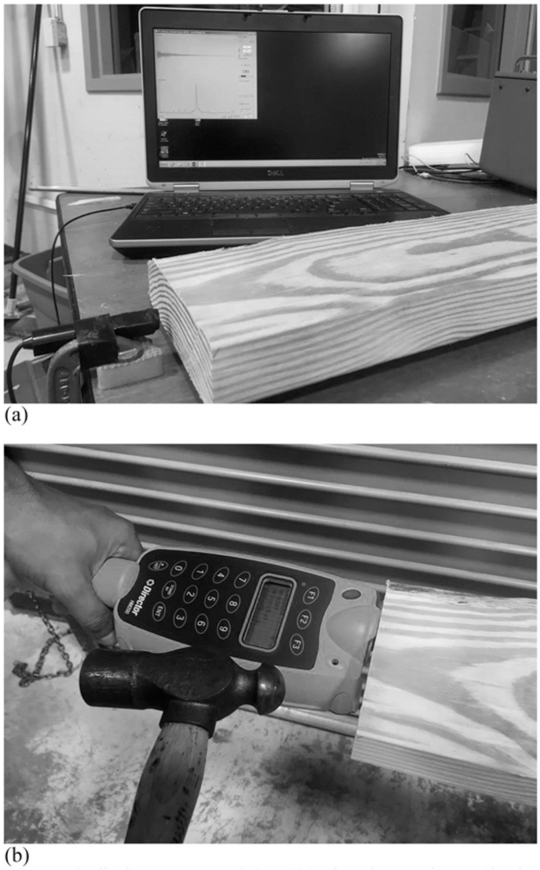


Figure 1. Longitudinal stress wave technique: (a) microphone: Fakopp and Falcon A-Grader; and (b) Director HM 200.

Falcon A-grader, and Director HM 200 were used to get the longitudinal vibration. For transverse vibration, the device used was the Metriguard Model 340 Transverse Vibration E-Computer (Metriguard Raute Group, Pullman, WA). The transverse vibration was captured in two orientations: flatwise and edgewise.

Table 2. Overall average information of No. 2 grade southern pine lumber by size.

Size	N	Pith (%)	Ring orientation (%)		Rings per inch	Latewood (%)
			Tangential	Radial		
2 × 4	629	25.0	86.0	14.0	4.9	43.4
2 × 6	611	30.7	85.8	14.2	4.8	44.7
Overall	1240	28.0	85.9	14.1	4.8	43.9

Longitudinal Vibration

Longitudinal vibration data were collected for each specimen using three commercially available testing devices: Fakopp Microsecond Timer (Fakopp Enterprise Bt, Ágfalva, Hungary), Falcon A-grader (Falcon Engineering Limited, Taranaki, New Zealand), and Director HM 200

Figure 2. Transverse vibration technique: Metriguard E-computer model 340 (edgewise–flatwise).

(Fibre-gen, Christchurch, New Zealand). During the testing, two rigid sawhorses, positioned at ¼ and ¾ the length, supported the specimens, and foam was used at the contact surfaces between the sawhorses and specimen as a way to reduce damping and increase accuracy. To generate the specimen vibration a hammer was used (Fig 1). To collect the longitudinal frequencies, the Fakopp device was used. The device has a microphone that was used to capture the vibration. A computer with the fast Fourier vibration analyzer (Fakopp Enterprise Bt 2005) and Falcon A-grader software was used to read the natural frequency of each piece. The Director HM 200 is a portable device that measures the vibration velocity and was also used to collect data.

Each test was initiated with the impact of a hammer to produce the longitudinal vibration in each test specimen according to ASTM E 1876 (ASTM 2015a). dMOE was calculated from the data collected with the three longitudinal vibration devices as per Eq 1, where E_L = dMOE (MPa), ρ = density ($kg \cdot m^{-3}$), L = length of the piece (m), f = first harmonic longitudinal vibration frequency (Hz), and v = wave velocity ($m \cdot s^{-1}$).

$$E_L = \rho \cdot (L \times f)^2 = \rho \cdot v^2 \qquad (1)$$

Each piece was oriented flatwise, supported on one end by a knife-edge support and at the opposite end by a point support. As such, each piece was permitted to vibrate in an unrestrained manner.

Transverse Vibration

Each piece was nondestructively examined using transverse vibration equipment (Metriguard Model 340 Transverse Vibration E-Computer) in both orientations: flatwise and edgewise (Fig 2). Oscillation was initiated by gently tapping the specimen near the center of the span. A load cell measured the frequency of vibration and weight, and the E-Computer determined the transverse vibration frequency for each piece and calculated its dMOE.

The impact was applied with a hammer, and the signal captured along the transverse direction per ASTM E 1876 (2015a). The calculation of the MOE by the first transverse vibration resonant frequency is shown in Eq 2, where E_T = dMOE (GPa), F_r = resonant frequency (Hz), W = lumber piece weight ($kg \cdot g$), L = beam span (m), I = moment of inertia (m^4), and g = acceleration of gravity (9.8 $m \cdot s^{-2}$).

$$E_T = \frac{f_r^2 \cdot W \cdot L^3}{2.46 \cdot I \cdot g} \qquad (2)$$

A similar procedure was used in the measurement of dMOE in the edgewise orientation (dMOE

Table 3. Static bending MOE and MOR values of 2 × 4 and 2 × 6 southern pine structural lumber.

	N	Size	Mean	Median	Minimum	Maximum	STD	COV (%)
MOE (GPa)	629	2 × 4	10.86	10.75	3616	19.14	2.80	25.8
		2 × 6	10.41	10.25	3650	18.27	2.40	23.0
MOR (MPa)	611	2 × 4	55.39	53.76	10.89	121.35	20.76	37.5
		2 × 6	45.88	44.66	7.70	99.25	17.93	39.1

SD, standard deviation; COV, coefficient of variation.

edge). Special care was taken to ensure that the vibration was vertical because horizontal vibration has the potential to vibrate in an additional mode, which can complicate or confuse the machine-determined frequency.

Static Bending Test

Following the nondestructive measurements, all specimens were destructively tested in static bending on an Instron Universal Testing Machine using Bluehill 3 software (Instron, Norwood, MA) to obtain the MOE and MOR. The edgewise static bending tests were conducted using a four-point bending setup, and the span-to-depth ratio was 17 to 1 (ASTM D198 2014b), and the rate of loading followed ASTM D4761 (2014c). The load–deflection data were recorded and the flexural MOE was calculated using Eq 3, where MOE = static bending MOE (MPa), P = force (N), L = distance between load points (m), δ = midspan deflection (m), and I = moment of inertia (m^4). The tension face and the grade characteristics were placed randomly, selected without respect to positioning.

$$\mathrm{MOE} = \frac{P \times (3L^2 - 4a^2)}{48 \times \delta \times I} \tag{3}$$

MOR was calculated based on Eq 4, where P = maximum transverse load (N), L = specimen span (m), b = specimen thickness (m), and h = specimen depth (m).

$$\mathrm{MOR} = \frac{P \times L}{b \times h^2} \tag{4}$$

Statistical Analysis

All statistical analyses of static bending MOE and strength (MOE and MOR) and dMOE values were conducted using SAS 9.4 (SAS Institute 2013). Single-variable linear regression analysis (α = 0.05) techniques were used to develop models relating dMOE from the devices to static bending MOE and MOR. Individual models were developed for each lumber width and length combination. The coefficient of correlation (r) and coefficient of determination (r^2) were noted for each relationship.

RESULTS

The results of the statistical analyses of the static bending MOR and MOE values are listed in Table 3. There is a statistically significant difference ($\alpha = 0.05$) between groups 2 × 4 and 2 × 6 only for MOR. This difference could be explained by the knot size and knot position on each specimen. Knot type in a specimen depends on the inherent log, and the sawmill yield decision during breakdown.

Static bending MOR values ranged from 7.7 to 121.5 MPa. The mean MOR is 55.4 MPa for 2 × 4 and 45.9 MPa for 2 × 6 (Table 3). Strength is greatly affected by the position of knots during destructive testing because specimens were positioned randomly on the testing machine. The placement of the specimen on the load head was carried out randomly. Thus, in some cases, large-sized knots were placed between the load heads, reducing strength. In other cases, knots were outside of the load span, increasing strength.

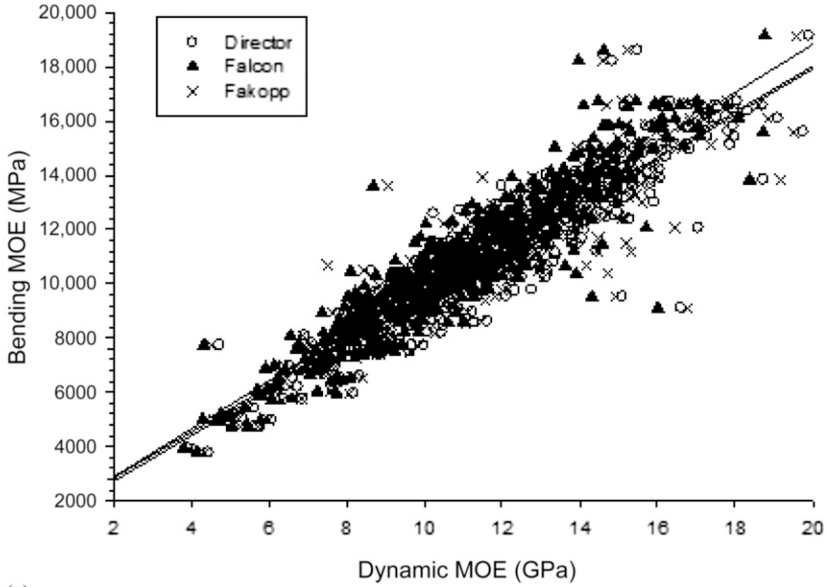
Table 4. Dynamic MOE (dMOE) values obtained from longitudinal vibration technique on 2 × 4 and 2 × 6 southern pine structural lumber.

	Size	Mean	Median	Minimum	Maximum	STD	COV (%)
$dMOE_{FAK}$[a] (GPa)	2 × 4	11.51	11.49	3.95	21.42	3.03	26.3
	2 × 6	11.16	10.82	3.82	20.77	2.89	25.9
$dMOE_{DIR}$[b] (GPa)	2 × 4	11.65	11.54	3.93	21.59	3.05	26.2
	2 × 6	11.25	10.93	4.08	21.05	2.88	25.6
$dMOE_{FAL}$[c] (GPa)	2 × 4	11.02	10.97	3.81	20.46	2.89	26.2
	2 × 6	11.95	11.53	4.11	26.31	3.14	26.3

SD, standard deviation; COV, coefficient of variation.
[a] Longitudinal vibration MOE value from the Fakopp lumber grader.
[b] Longitudinal vibration MOE value from the Director HM 200.
[c] Longitudinal vibration MOE value from the Falcon A-Grader.

The mean MOE for 2 × 4 and 2 × 6 are 10.9 GPa and 10.4 GPa, respectively.

For 2 × 4, the minimum, mean, and maximum MOE values are 3.62, 10.86, and 19.14 GPa, respectively. For 2 × 6, the minimum, mean, and maximum MOE values are 3.65, 10.41, and 18.27 GPa, respectively. The MOE mean value found in this research exceeded the new published design value (9.7 GPa) and also met the previous SPIB design values (11.0 GPa) (AFPA 2005; ALSC 2013). Doyle and Markwardt (1966) studying southern pine dimensional



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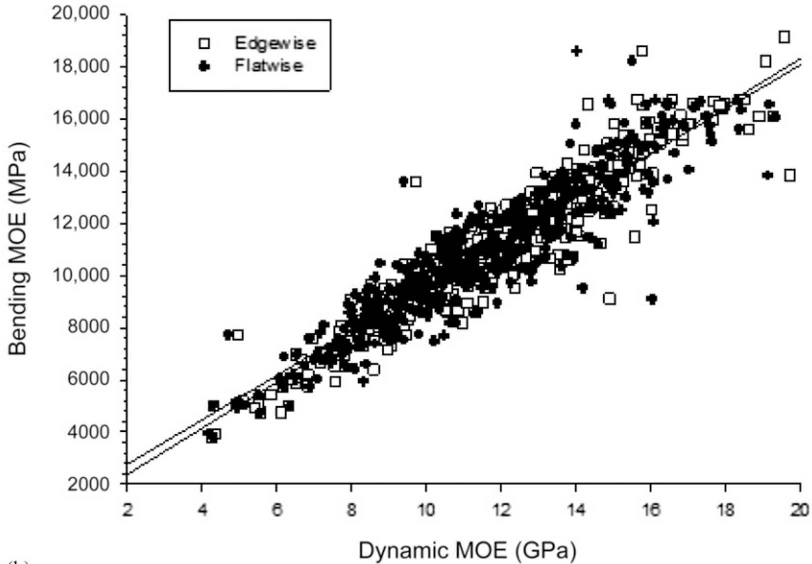

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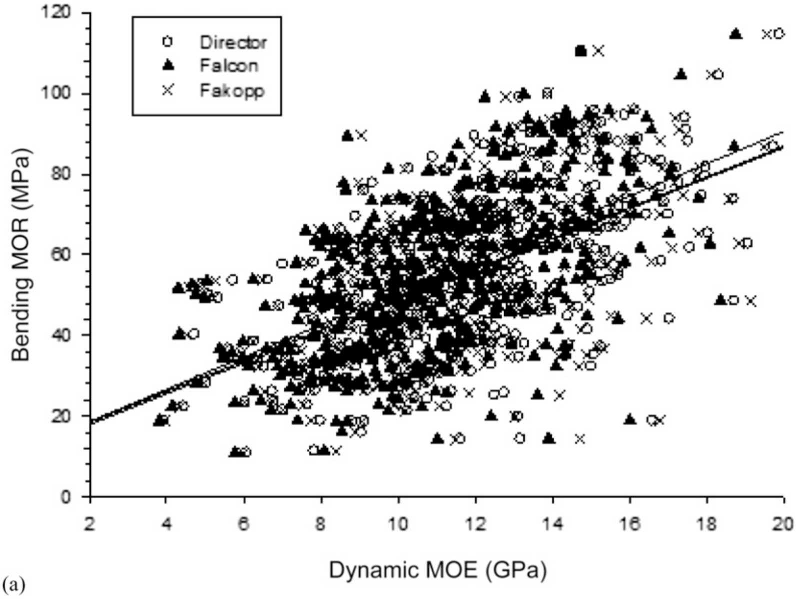
Figure 3. Linear regression plots for 2 × 4 southern pine lumber showing bending MOE vs dynamic MOE from (a) Fakopp Lumber Grader, Director HM 200, and Falcon A-Grader, and (b) edgewise and flatwise vibration.

lumber, found MOE values ranging from 8.8 to 13.2 GPa.

Longitudinal and Transverse Vibration

Table 4 summarizes the dMOE mean values for the longitudinal vibration with different tools. The dMOE obtained with longitudinal vibration ranged between 3.81 and 21.60 GPa, with the average around 11.5 GPa for all three longitudinal vibration devices. The Falcon device detected a wider range of stiffness values associated with the same lumber. The relationship between



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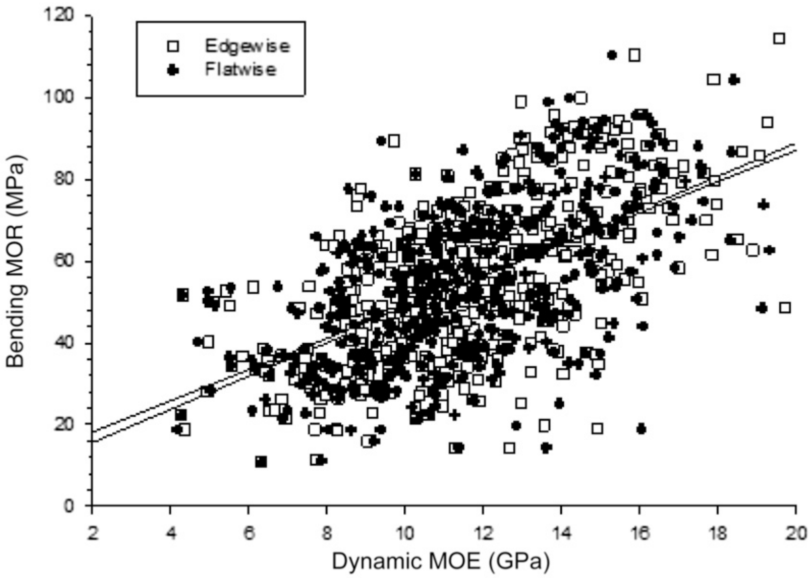


(b)

Figure 4. Linear regression plots for 2 × 4 southern pine lumber showing bending MOR vs dynamic MOE from (a) Fakopp Lumber Grader, Director HM 200, and Falcon A-Grader, and (b) edgewise and flatwise vibration.

dMOE and bending MOE for 2 × 4 for longitudinal and transverse vibration are shown in Figs 3 and 4. Applying transverse vibration techniques, the dMOE values for the flatwise orientation ranged from 3.8 to 21.6 GPa, with the average being 11.4 GPa, and those for the edgewise orientation ranged from 2.7 to 20.8 GPa, with the average being 11.4 GPa. Overall, flatwise dMOE values were slightly higher if compared with edgewise dMOEs (Table 5). The relationship between dMOE and bending MOR for 2 × 6 are shown in Figs 5 and 6, edgewise transverse vibration and flatwise transverse vibration, respectively.

Linear Regressions Analysis

The coefficients β_0 and β_1 are used in the generalized model where the static property = $\beta_0 + \beta_1 \cdot \text{dMOE}$. The results of the linear regression analyses relating static bending MOE with the dMOE from different devices for 2 × 4 and 2 × 6 southern pine dimensional lumber are listed in Table 6.

The results indicate significant correlations between the properties determined by nondestructive techniques and static MOE. For 2 × 4, the r^2 ranged from 0.89 to 0.85, where the E-computer in the edgewise direction showed the highest r^2 value and the E-computer in the flatwise direction showed the lowest r^2 value. For 2 × 6, the r^2 for the E-computer ranged from 0.81 to 0.85, and the edgewise orientation showed the highest r^2 value, whereas the Falcon showed the lowest r^2. Many studies on other softwood species and grades have demonstrated the potential of these methods to estimate MOE (Ross et al 1991; Divós and Tanaka 1997).

The results of the linear regression analyses relating static bending MOR with dMOE from different devices for 2 × 4 and 2 × 6 southern pine dimensional lumber are listed in Table 7. For 2 × 4, the r^2 ranged from 0.38 to 0.41, and similar to the dMOE, the E-computer edgewise direction had the highest r^2 value, whereas Falcon showed the lowest r^2 value. The r^2 for 2 × 6 ranged from 0.38 to 0.45, where the Director HM 200 showed the highest r^2 value, whereas Fakopp showed the lowest r^2 value.

Linear relationships between dMOE and MOR were, in general, weak (Table 7). The low correlations are largely explained by 1) the presence of knots and other wood defects such as checks, splits, and grain deviations present in southern pine dimension lumber and by the fact that all lumber were in the same grade, and 2) the NDT analysis was performed over the entire length of each piece, but the static bending was performed over a 17:1 span-to-depth ratio that was randomly positioned in the testing machine. Inclusion of multiple grades would have provided specimens of both greater and lesser quality which would have most likely improved these correlations.

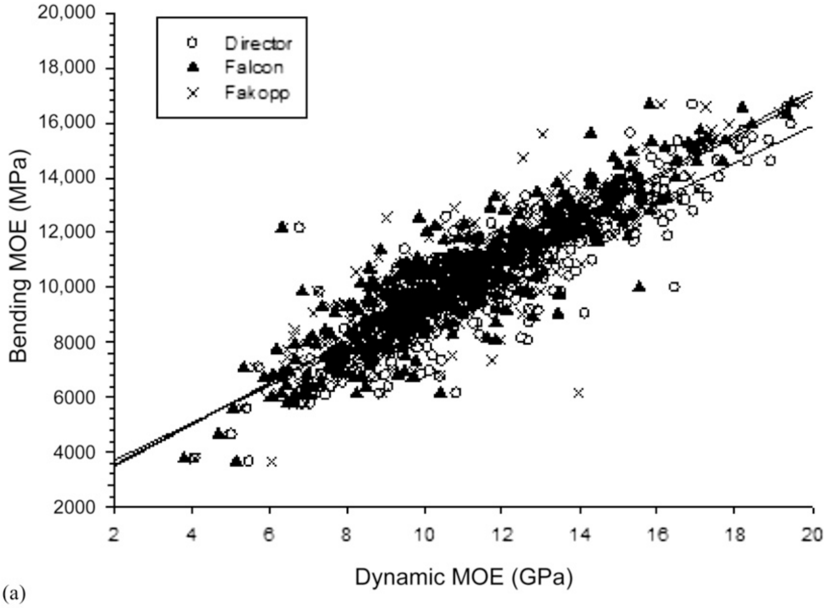
DISCUSSION

Table 8 summarizes research conducted to examine the relationship between the longitudinal vibration MOE and static bending (MOE and MOR) of southern pine structural lumber. The correlations found in this study were comparable with those reported in previous literature. Pellerin (1965), using free transverse vibration on the flatwise orientation of Douglas-fir dimensional lumber, found correlations between 0.67 and 0.93 for various lumber grades. In his study of lodgepole pine dimensional lumber using the transverse vibration technique, O'Halloran

Table 5. Dynamic MOE (dMOE) values obtained from transverse vibration technique on 2 × 4 and 2 × 6 southern pine structural lumber.

	Size	Mean	Median	Minimum	Maximum	STD	COV (%)
$\text{dMOE}_{\text{EDGE}}$[a] (GPa)	2 × 4	11.61	11.50	4.26	20.80	2.93	25.2
	2 × 6	11.19	10.90	4.17	20.30	2.67	23.9
$\text{dMOE}_{\text{FLAT}}$[b] (GPa)	2 × 4	11.51	11.41	4.16	20.50	3.00	26.1
	2 × 6	11.31	11.07	3.93	21.60	2.86	25.3

SD, standard deviation; COV, coefficient of variation.
[a] Edgewise transverse vibration MOE value.
[b] Flatwise transverse vibration MOE value.



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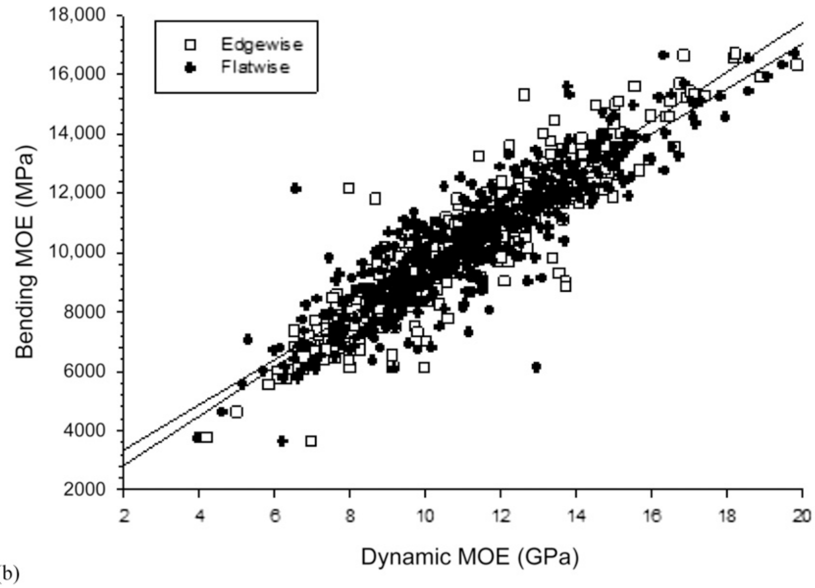
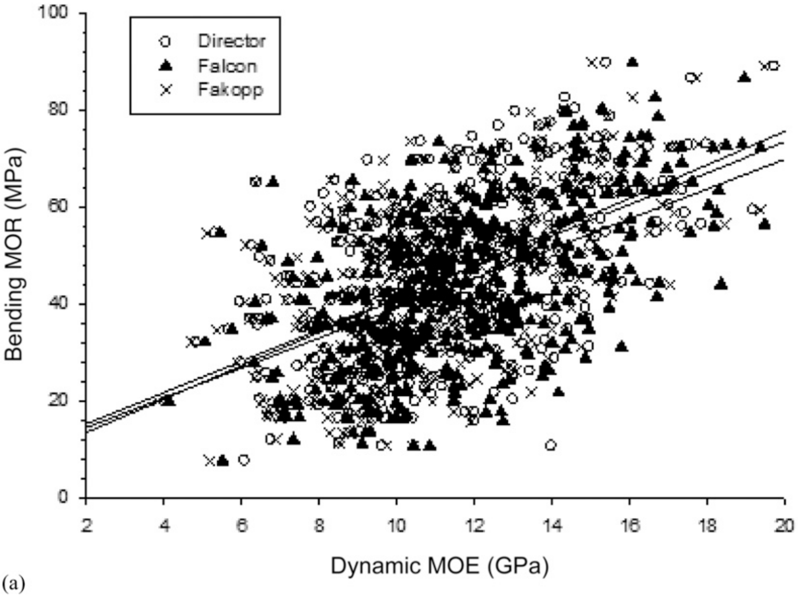


(b)

Figure 5. Linear regression plots for 2 × 6 southern pine lumber showing bending MOE vs dynamic MOE from (a) Fakopp Lumber Grader, Director HM 200, and Falcon A-Grader, and (b) edgewise and flatwise vibration.

(1972) found a correlation of 0.89. Green and McDonald (1993), using transverse vibration in a flatwise orientation, found a correlation of 0.58 for northern red oak lumber. Halabe et al (1995) studied the relationship between stress wave, transverse vibration, and ultrasonic tests on green and dry southern pine dimensional lumber. The results showed that the relationship between dry static bending MOE vs stress wave velocity can directly be used to predict the dry static bending MOE. However, the relationships for MOR were low. In addition, there were low coefficients of determination



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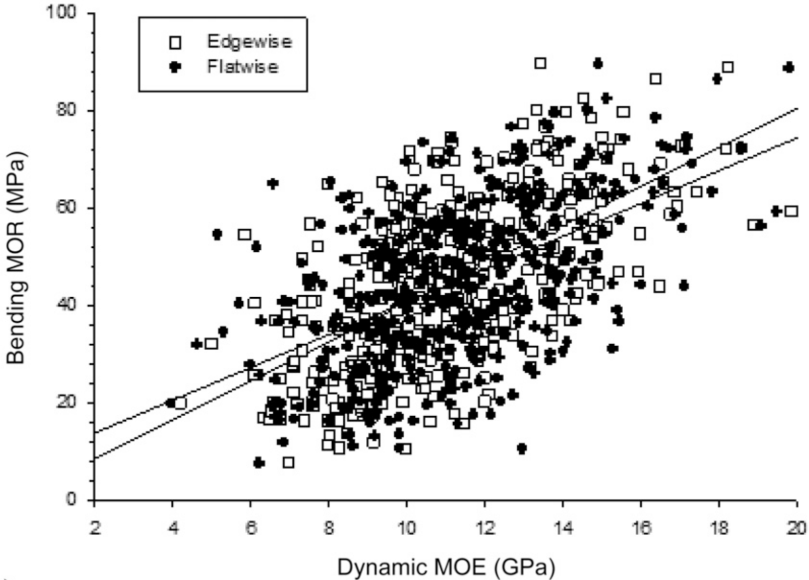

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Figure 6. Linear regression plots for 2 × 6 southern pine lumber showing bending MOR vs dynamic MOE from (a) Fakopp Lumber Grader, Director HM 200, and Falcon A-Grader, and (b) edgewise and flatwise vibration.

for ultrasonic testing, showing that this test is not suitable for the grading of long-dimension lumber.

Yang et al (2015) tested the relationship between the predicted E and bending MOE, and found r^2 values ranging from 0.77 to 0.86, which are similar to the results found in this study. The r^2 values found by Yang et al (2017) for dMOE and bending MOR that ranged from 0.23 to 0.28 were lower than the bending MOR r^2 predicted in this study. Vega et al's (2011) investigation of chestnut timber found r^2 to be between 0.10 and

Table 6. Results of linear regression analyses relating static bending MOE and dynamic MOE (dMOE) from different devices for 2 × 4 and 2 × 6 southern pine structural lumber.

	MOE (GPa)					
Size	Device	β_0	β_1	r*	r^2	Standard error (u)
2 × 4	Fakopp	0.6191	0.0010	0.9270	0.8593	1.1368
	Director	0.6271	0.0010	0.9325	0.8695	1.1011
	Falcon	0.5744	0.0001	0.9304	0.8657	1.0615
	Edgewise	0.8718	0.0001	0.9439	0.8909	0.9694
	Flatwise	0.7220	0.0001	0.9265	0.8584	1.2781
2 × 6	Fakopp	−0.3599	0.0011	0.9173	0.8415	1.1511
	Director	−0.1130	0.0011	0.9075	0.8236	1.2101
	Falcon	−0.3987	0.0012	0.9047	0.8185	1.3384
	Edgewise	0.4563	0.0010	0.9243	0.8543	1.0202
	Flatwise	0.0363	0.0011	0.9081	0.8246	1.1968

β_0 and β_1 are used in the generalized model static bending = $\beta_0 + \beta_1 \cdot$(nondestructive parameter).
* All correlations were significant (p-value < 0.0001).

0.17 using three different NDT methods (ultrasound, impact waves, and longitudinal waves), concluding that dynamic variables by themselves are not adequate to estimate bending strength.

The different r^2 values among the devices were small and not considered as an indication of superiority of a certain method compared with another because of the reasons explained above. Furthermore, when considering the suitability of a strength grading system to a certain application, the evaluation of the prediction accuracy in terms of r^2 and the coefficient of variation alone is not adequate. Obviously, the price of the system, its suitability for the production line, and target strength classes are other important factors.

CONCLUSIONS

This study investigated the accuracy of four commercial NDT tools for predicting MOE and MOR of No. 2 southern pine structural lumber. The devices were divided into two groups, longitudinal vibration (Fkopp, Falcon, and Director HM 200) and transverse vibration (Metriguard Model 340 Transverse Vibration E-Computer) in flatwise and edgewise orientation. The results of this study show that:

1. All the devices tested were able to predict MOE. The differences between the devices were small.
2. Transverse edgewise vibration showed higher correlations with static MOE compared with

Table 7. Results of linear regression analyses relating static bending MOR and dynamic MOE from different devices for 2 × 4 and 2 × 6 southern pine structural lumber.

	MOR (MPa)					
Size	Device	β_0	β_1	r*	r^2	Standard error (u)
2 × 4	Fakopp	6.4932	0.0906	0.6209	0.3855	2.3761
	Director	6.5668	0.0917	0.6290	0.3905	2.3798
	Falcon	6.2118	0.0868	0.6227	0.3878	2.2663
	Edgewise	6.5815	0.0908	0.6425	0.4128	2.2487
	Flatwise	6.5631	0.0894	0.6179	0.3818	2.3626
2 × 6	Fakopp	6.4187	0.1034	0.6418	0.4119	2.2172
	Director	6.6862	0.0994	0.6191	0.3833	2.2625
	Falcon	6.8646	0.1108	0.6325	0.4001	2.4319
	Edgewise	6.5997	0.1001	0.6717	0.4512	1.9802
	Flatwise	6.6986	0.1006	0.6314	0.3987	2.2163

β_0 and β_1 are used in the generalized model static bending = $\beta_0 + \beta_1 \cdot$(nondestructive parameter).
* All correlations were significant (p-value < 0.0001).

Table 8. Summary of research conducted to examine the relationship between longitudinal vibration MOE and static bending (MOE and MOR) of structural lumber.

Reference	Material	Correlation coefficient
Pellerim (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 = 0.92

the MOE of transverse flatwise vibration and longitudinal vibration.

3. The NDT methods and tools tested in this study were statistically significant predictors of MOR. However, the tools were less accurate predictors of MOR compared with MOE.
4. Potentially, this study could have been improved by testing lumber specimens in both higher and lower grades and by testing the entire span of each piece consistent with the NDT analysis.
5. Better correlations would be possible if additional grades were included, rather than No. 2 graded lumber only, a greater range of stiffer/stronger specimens and less stiff/weaker specimens.

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