COMPARISON OF NONDESTRUCTIVE TESTING METHODS FOR EVALUATING NO. 2 SOUTHERN PINE LUMBER: PART B, MODULUS OF RUPTURE

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Abstract. The identification of strength-reducing characteristics that impact modulus of rupture (MOR) is a key differentiation between lumber grades. Because global design values for MOR are at the fifth percentile level and in-grade lumber can be highly variable, it is important that nondestructive evaluation technology be used to better discern the potential wood strength. In that manner, higher-performance pieces could potentially be identified and their value captured accordingly. In this study, laboratory tests of three nondestructive testing (NDT) technologies and destructive four-point static bending were applied to 343 pieces of visually graded No. 2 southern pine lumber in the 38 × 140 mm^2 ($n = 86$), 38 × 186 mm^2 ($n = 112$), 38 × 236 mm^2 ($n = 91$), and 38 × 287 mm^2 ($n = 54$) sizes collected across the southeast region of the United States. The NDT tests included continuous lumber test in continuous proof bending (Metriguard Model 7200 High Capacity Lumber Tester), transverse vibration (Metriguard E-Computer), and two longitudinal stress wave tools (Falcon A-Grader and Fiber-gen Director HM200). Following nondestructive tests, the specimens were destructively tested in four-point static bending. Single-predictor linear correlations were observed between static bending MOE and MOR value; and NDT outputs and bending MOR value. The regression results showed that the average

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NDT outputs ($r^2 = 0.23$-0.28) had lower performance than static bending MOE ($r^2 = 0.39$), for predicting the bending MOR of sawn lumber.

Keywords: Nondestructive evaluation, transverse vibration evaluation, longitudinal stress wave evaluation, high capacity lumber tester, modulus of rupture, lumber grades.

INTRODUCTION

Because a single piece of lumber cannot be broken in more than one failure mode, and given that the single test itself is destructive, prediction of lumber strength properties is a critical need during lumber grading. The relationships between lumber properties have been used in deriving allowable strength properties for lumber (ASTM 2016). Modulus of elasticity (MOE), which is a component of the stiffness of the material within the elastic deformation range, has been found to be a good indicator of MOR. The coefficient of determination (r^2) for the relationships between MOR and MOE is the basis for machine stress–rated (MSR) grading (Hoyle 1961; Kramer 1964; Sunley and Hudson 1964). In practice, the relationship between MOR and MOE forms the basis for sorting most MSR lumber sold in the United States (Galligan et al 1979; Galligan et al 2015).

To establish a thorough evaluation system in relating MOR to MOE, it is important to investigate the relationships between MOR and the MOE values of in-grade lumber. Green and Kretschmann (1991) conducted in-grade testing for visually graded dimension lumber and the data were used to identify lumber property relationships for engineering design standards. Similarly, Liliefna (2009) conducted a study on the structural property relationships for southern pine (SP), Douglas-fir and Hem-fir lumber. For all studies, the general relationships between static bending MOR and MOE were defined by single-variable linear regression models with coefficients of determination (r^2) found as 0.52 and 0.60 for SP, 0.54 and 0.58 for Douglas-fir, and 0.52 and 0.47 for Hem-fir. Similarly, according to the previous in-grade testing results, the coefficients of determination (r^2) ranged from 0.47 to 0.60 for the tested in-grade species (Green and Kretschmann 1991; Liliefna 2009).

Nondestructive techniques (NDT) that are applied during the lumber grading process results in improved grading accuracy and have been used extensively to sort lumber in North America since the 1960s and around the world (Murphy and Cown 2015; Ross 2015). NDT techniques have been proven to provide reliable prediction performance with regard to MOE. To assign a grade to a given lumber piece, the MSR grading process conducts NDT on the lumber and then a visual oversight of the lumber is carried out to check characteristics such as knots that the machines cannot or may not properly evaluate (Galligan and McDonald 2000; Kretschmann 2010). As a result, the volume of mechanically graded lumber has increased during the past few decades (Galligan and McDonald 2000; Kretschmann 2010).

Previous research of conducting longitudinal stress wave analysis on different wood species indicated that this method has potential in sorting logs for the production of high MOE products such as veneer or dimension lumber (Halabe et al 1997; Rippy et al 2000; Wang et al 2002; Wang 2004; Achim et al 2011; Wang et al 2013). Stress wave vibration methods were conducted (Byeon et al 2005) to evaluate the strength performance for finger-jointed wood. Magnetic driver (both ends free condition) and a tapping hammer were used to measure dynamic MOE. As to the magnetic driver, vibration was induced via a small steel plate attached to the bottom end of the finger-jointed wood specimens and suspended by two threads at the magnetic driver. The results obtained from magnetic driver show that the coefficient of determination values for dynamic MOE vs MOR (Sitka spruce: $r^2 = 0.33$; red pine: $r^2 = 0.50$) were close to those for static MOE vs MOR (Sitka spruce: $r^2 = 0.37$; red pine: $r^2 = 0.50$). The results obtained from tapping hammer show that the coefficient of determination values for MOR vs dynamic MOE (Sitka spruce: $r^2 = 0.29$; red pine: $r^2 = 0.47$) were lower than but close to those for MOR vs static MOE (Sitka spruce: $r^2 = 0.37$; red pine: $r^2 = 0.50$). In this study, both dynamic MOE methods were considered as very useful to predict the MOR of finger-jointed wood specimens. In another study, longitudinal stress wave velocity was also considered a predictor of both stiffness and strength in 13-cm dowels (Shmulsky et al 2006).

The northwest and southeast regions of the United States accounts for 94% of the softwood lumber production (Howard 2007), of which SP accounts for half of the production (US Census Bureau 2012) with 2015 production totaling 16.7 billion board feet (SFPA 2016a). The United States imported 13.6 billion board feet of lumber in 2015 and SP exports totaled 0.6 billion board feet (SFPA 2016b, c). The No. 2 visual grade accounts for the largest proportion of SP production (SFPA 2005). The NDT grading technique has not replaced visual grading due to the familiarity the market has with the specific visual grades (ie No. 1, No. 2) vs the machine grades (2400f-2.0E) and the overwhelming majority of structural lumber in North America is still visually graded (US Census Bureau 2012). A limitation in visual grading lumber became apparent when in 2013 the design values for visually graded SP lumber were reduced following a large reevaluation of the lumber resource (ALSC 2013). This causes many mills to add MSR lumber capability; however, visual grading still dominates and in 2015 there were approximately 50 mills that sell MSR lumber products in the United States. Among all lumber mills registered with the Southern Pine Inspection Bureau, only 27 out of 278 (9.7%) sell MSR lumber products. Additional up-front investment in stress rating machinery is needed compared with visual grading and it appears that more marketing is needed to promote the advantages of the machine grades.

The objectives in this study are to investigate the linear relationships between MOR and dynamic MOE, and compare the results to that of static bending MOR and MOE. To obtain a wide understanding of the expression of the MOR value that can be predicted by different NDT methods, experimental tests on full-size, in-grade lumber specimens were conducted with four commercially available stress grading tools.

MATERIALS

Visual grade No. 2 SP lumber was selected for this study as it accounts for the largest percentage of SP market share by grade (SFPA 2005). Four hundred and ninety pieces of lumber with a No. 2 grade stamp was sourced randomly from 31 different mills throughout the southeastern United States to mimic the sampling procedures of in-grade testing (Yang et al 2015). The lumber was purchased in lots of 10 pieces per mill per size from 31 mills located in Alabama (5 mills), Arkansas (6 mills), Florida (1 mill), Georgia (4 mills), Louisiana (5 mills), Mississippi (5 mills), North Carolina (1 mill), South Carolina (2 mills), and Texas (2 mills). The lumber was transported to the testing laboratory at Mississippi State University, and then regraded by a certified SP lumber grader. Finally, only the lumber that was confirmed as on-grade No. 2 was evaluated in this study.

A total of 343 pieces of on-grade No. 2 SP lumber were obtained from the regrade process. The lumber was divided into four groups according to the cross-section dimensions: 86 pieces of 2 × 6 (38×140 mm^2), 112 pieces of 2 × 8 (38×186 mm^2), 91 pieces of 2 × 10 (38×236 mm^2), and 54 pieces of 2 × 12 (38×287 mm^2). The average MC when tested was 11.4%, and the average air-dried density was 556.7 kg/m^3. Not all pieces were available to be tested with all NDT tools, thus, the sample sizes for each NDT method were different.

TEST METHODS

Specimens were evaluated nondestructively with continuous proof bending, transverse vibration, and longitudinal stress wave methods in sequence. The specimens were then destructively evaluated by four-point static bending tests following the instruction of ASTM D198-15 (ASTM 2015) to obtain the static MOE and MOR values. Although variable lengths were recorded within each size group, the testing span was fixed as 17 times the depth for each cross section. Thus, the influence of length on the ultimate bending stress value was not considered in the results from static bending tests.

Continuous Proof Bending Evaluation

To conduct the continuous proof bending evaluation, a mobile High Capacity Lumber Tester Model 7200 (HCLT; Metriguard Inc., Pullman, WA) was set up in the Mississippi State University laboratory. The setup of this tester is shown in Fig 1 (Yang et al 2015). The HCLT testing was performed in a continuous manner by subjecting each test specimen to a series of rollers. The rollers deflected each specimen over two bending spans (1.22 m each in length), whereas the first roller bends up and the second bends down. Deflections at the points of each roller were measured continuously as the lumber passed over the rollers. To compensate for bow in the lumber, two measurement data were averaged to calculate the local MOE values. Average MOE and low-point MOE values were recorded in this study. A total of 134 pieces of on-grade No. 2 SP lumber was evaluated flatwise along the longitudinal direction. Because MOR is highly related to the localized defect (such as knot), assumption was made that the lowest NDT MOE (E_{LHCLT}) could be the more reliable information for this study. Thus, the lowest NDT MOE (E_{LHCLT}) and average NDT MOE (E_{HCLT}) of each lumber were obtained and reported from this testing tool. For the HCLT tool, a total of 134 pieces were tested with 19 pieces 2 × 6, 33 pieces 2 × 8, 54 pieces 2 × 10, and 28 pieces 2 × 12.

Figure 1. Continuous proof bending evaluation: Mobile High Capacity Lumber Tester Model 7200.

Transverse Vibration Evaluation

An E-computer Model 340 (Metriguard Inc.) was used as the transverse vibration testing tool. The setup of this testing tool is shown in Fig 2 (Yang et al 2015). The test was set up edgewise in a simply supported beam configuration. Member vibration was induced in the middle of the lumber by a hammer and the impact detected with an accelerometer fixed to a support. Member weight and dimensions (length, width, and thickness) were also recorded as input. The dynamic MOE (E_{TV}) values were obtained directly from this tool.

Longitudinal Stress Wave Evaluation

To conduct the longitudinal stress wave evaluation, both A-Grader (Falcon Engineering Ltd., Inglewood, New Zealand) and Director HM200 (Fiber-gen, Inc., Christchurch, New Zealand) were used as the testing tools. The setup of the testing tools are shown in Fig 3 (Yang et al 2015). These two stress wave devices operate under the same principle of determining the stress wave velocity by detecting the resonant frequencies of an imparted stress wave. During testing, a mechanical stress wave was induced at one end of the specimen by a hammer impact and detected at the same end with an accelerometer (Director HM200) or a microspeaker receiver (A-Grader). Member weight and dimensions (length, width, and thickness) were recorded as input for the Falcon. The devices recorded the velocity of the stress wave and the estimated dynamic MOE (E_{SW1}) value was obtained directly from Falcon. Stress wave velocity (V_{SW2}) was the output of Director HM200, whereas dynamic MOE (E_{SW2}) was then calculated based on the V_{SW2} and the density values given the following equation (Ross and Pellerin 1994):

$$E_d = \rho V^2 \tag{1}$$

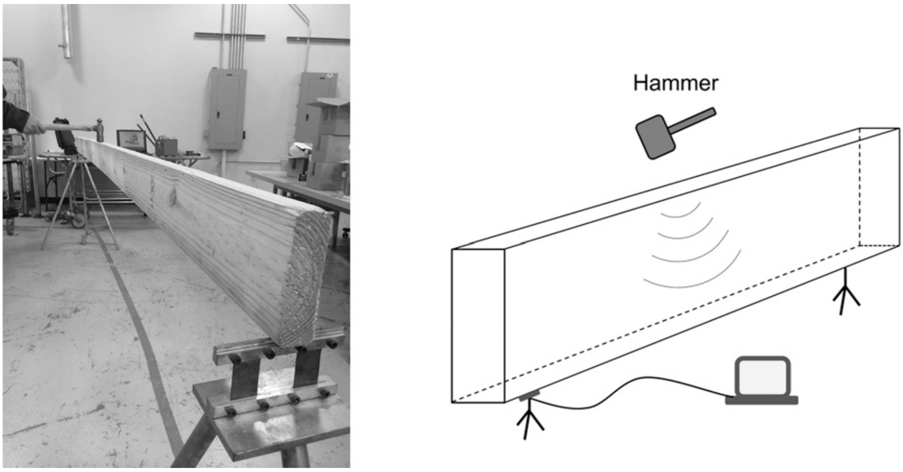


Figure 2. Transverse vibration evaluation: E-computer Model 340.

where E_d is dynamic modulus of elasticity, $\rho =$ density of the material, and V is the propagation speed.

Static Four-point Bending Test

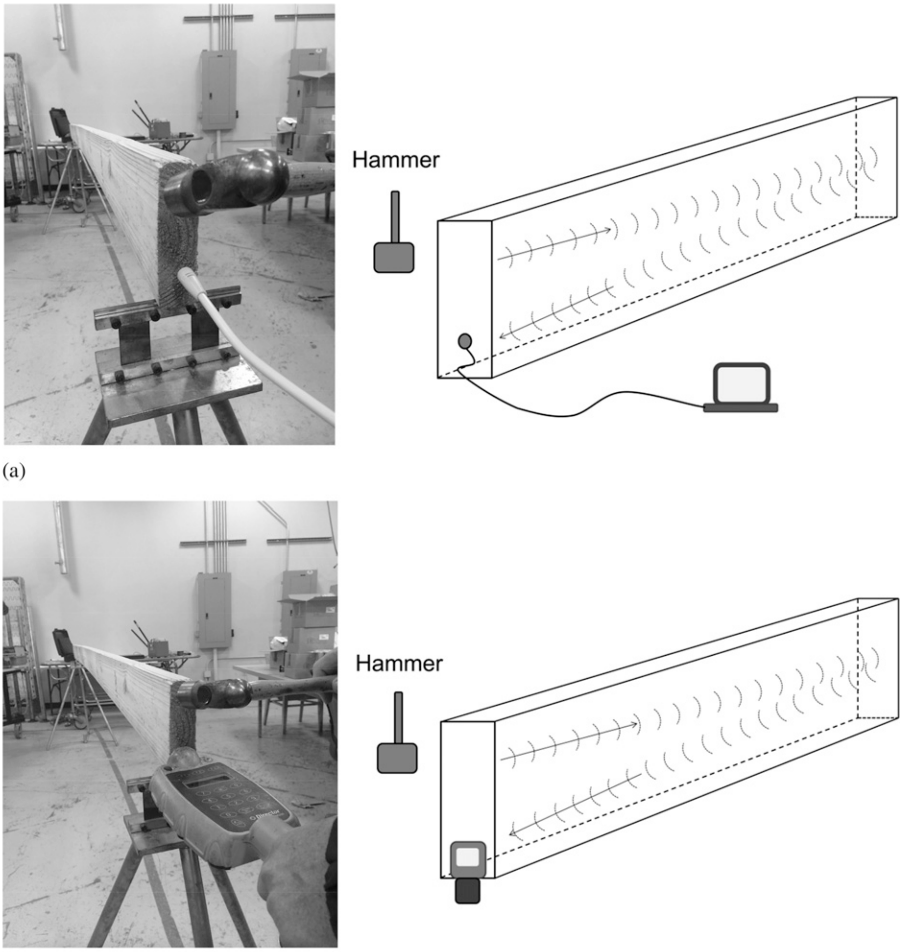
Following the NDT tests, the specimens were destructively evaluated by four-point static bending tests following ASTM D198-14 to obtain the static bending MOE value. The test support spans were fixed with a span to depth ratio of 17:1 (2380-140 mm, 3145-185 mm, 4012-236 mm, and 4879-287 mm). The test support spans were fixed in different cross-section lumber specimens, herein, this fact excluded differences in the varying lengths within each group of lumber.

RESULTS

All statistical analysis was conducted using SAS 9.4 (SAS Institute, Cary, NC). Statistical analysis of the static bending MOR and MOE values, and the dynamic MOE values obtained from NDT techniques are listed in Table 1. Analysis of variance (ANOVA) at the fifth level of significance ($\alpha = 0.05$) was performed to characterize the differences within the specimens sampled by cross sections. Mean separation for the four groups of specimens were then checked using Tukey's method. As to static bending MOR values (38.26-44.14 MPa), there is no significant difference ($\alpha = 0.05$) between groups. The average MOR value of all specimens among groups is 40.4 MPa. Plots were constructed in the R statistical programing environment (R Core Team 2016) with RStudio interface (RStudio 2016).

Because MOR relates to the ultimate strength of material, it is often associated with the existence of localized defect (such as a knot) of each lumber piece. Thus, among numerous test specimens, the variation of MOR value is often relatively high. On the other hand, as a global property, MOE describes a function of all the wood in a piece—which tends be related to the overall quality of the piece, its variation is typically lower. For the No. 2 SP lumber evaluated in this study, higher coefficient of variance (COV) of MOR values (35.3-40.3%) were observed, compared with those of static bending MOE values (17.4-25.8%) and dynamic MOE values (16.9-29.2%). In previous study on this results (Yang et al 2015), traditional single-linear regression analyses were conducted and the results showed that the MOE value of the tested samples can be readily predicted by the NDT techniques.

Liliefna (Liliefna 2009) conducted in-grade studies on SP lumber and compared a variety number of regression models, the results showed that the traditional linear relationship is a good model for the mean trend or general relationship between MOE and MOR ($r^2 = 0.60$). Thus,



(a)

(b)

Figure 3. Longitudinal stress wave evaluation: (a) A-Grader and (b) Director HM200.

single-variable linear regression model was adopted in this study. Single-variable linear regression models ($\alpha = 0.05$) were built for each lumber group, to correlate the static bending MOE values and NDT outputs to MOR values. The linear regressions were conducted given the independent variables (x, which can be represented by E_{SB}, E_{LHCLT}, E_{HCLT}, E_{TV}, E_{SW1}, E_{SW2}, and V_{SW2}) and the dependent variable (y, MOR). Coefficient of determination (r^2), which measures how well the regression line approximates the real data points, was the main focus. The regression parameters for samples at all sizes are listed in Table 2. The regression parameters for samples at each individual size are listed in Table 3.

DISCUSSIONS

Relations between Static Bending MOE and MOR Values

Linear regression analyses were conducted for static bending MOR and MOE values. The coefficients of determination (r^2) were in the range of 0.30-0.46 for the four lumber size groups, separately. The results agree with several previous NDT studies on similar lumber materials (Byeon et al 2005: $r^2 = 0.37$ on Sitka spruce lumber, $r^2 = 0.50$ on Red pine lumber; Shmulsky et al 2006: $r^2 = 0.42$ on 13-cm diameter SP dowels; Baillères et al 2012: $r^2 = 0.28$ on radiata pine lumber). Mean trends in the

Table 1. MOR values of tested No. 2 SP lumber.

	Size	Tukey[a]	*N*	Mean	Median	SD	COV (%)
MOR[b] (MPa)	2 × 6	A	85	39.24	37.01	13.53	34.48
	2 × 8	A	111	39.98	38.41	14.11	35.29
	2 × 10	A	85	38.26	39.49	15.40	40.25
	2 × 12	A	52	44.14	45.80	15.96	36.16
E_{SB}[c] (GPa)	2 × 6	A	78	10.07	9.93	2.21	21.94
	2 × 8	A	112	10.29	10.37	2.64	25.66
	2 × 10	AB	87	10.99	10.90	2.84	25.84
	2 × 12	B	52	11.73	11.99	2.04	17.39
E_{LHCLT}[d] (GPa)	2 × 6	A	19	6.81	6.83	1.87	27.53
	2 × 8	AB	33	7.64	7.41	2.36	30.95
	2 × 10	AB	54	8.38	8.00	2.53	30.15
	2 × 12	B	28	8.52	8.48	2.05	24.03
E_{HCLT}[e] (GPa)	2 × 6	A	19	9.12	9.10	2.11	23.13
	2 × 8	AB	34	9.91	9.65	2.73	27.55
	2 × 10	AB	53	10.53	10.48	2.39	22.69
	2 × 12	B	28	10.94	10.79	2.12	19.38
E_{TV}[f] (GPa)	2 × 6	AB	69	9.99	9.79	2.13	21.32
	2 × 8	B	111	9.54	9.45	2.18	22.85
	2 × 10	AB	87	9.93	9.86	2.49	25.08
	2 × 12	A	53	10.74	10.69	1.81	16.85
E_{SW1}[g] (GPa)	2 × 6	A	75	12.22	12.41	2.93	23.98
	2 × 8	A	86	12.10	11.58	2.92	24.13
	2 × 10	A	79	12.23	12.13	3.39	27.72
	2 × 12	A	51	13.29	13.65	2.78	20.92
E_{SW2}[h] (GPa)	2 × 6	AB	83	11.30	10.83	3.15	27.88
	2 × 8	B	111	10.51	10.26	3.07	29.21
	2 × 10	AB	84	11.17	11.06	3.19	28.56
	2 × 12	A	51	12.44	12.83	2.50	20.10

COV, coefficient of variance; SP, southern pine.

[a] Tukey's test was conducted with $\alpha = 0.05$.

[b] MOR.

[c] Static bending MOE value.

[d] Continuous proof bending lowest MOE value.

[e] Continuous proof bending average MOE value.

[f] Transverse vibration MOE value.

[g] Longitudinal stress wave MOE value from Falcon A-grader.

[h] Longitudinal stress wave MOE value from Director HM200.

relationship between static bending MOE and MOR for the No. 2 in-grade SP lumber are shown in Fig 4.

Relations between Dynamic MOE and Static Bending MOR Values

Linear regression analyses were conducted for static bending MOR and five dynamic MOE values. For each NDT techniques, the analyses were also conducted for each lumber size, separately (Table 3). Mean trends in the relationship between dynamic MOE and MOR for the No. 2 in-grade SP lumber are shown in Fig 5a-f.

Overall, coefficient of determination of dynamic MOE and MOR results were compared with those of static bending MOE and MOR regressions. The coefficient of determination obtained from the group of 2 × 12 lumber were less reliable than other groups while using continuous proof bending technique ($r^2 = 0.03$), transverse vibration technique ($r^2 = 0.16$), and longitudinal stress wave technique A-Grader ($r^2 = 0.19$). This may be because 2 × 12 lumber group potentially contains the largest localized strength-reducing defects, such as knots. The increasing defects increased the COV of MOR, thus decreased the regression prediction between MOR and static

Table 2. Linear regression relationship for dynamic MOE and MOR values (four sizes in total).

y	x	β_0	β_1	r^2	RMSE[i]	F value	N
MOR[a]	E_{SB}[b]	−2.14	4.06	0.39	13.02	209.11	328
MOR	E_{LHCLT}[c]	17.07	3.67	0.23	15.66	39.84	133
MOR	E_{HCLT}[d]	11.03	3.40	0.23	15.21	39.17	133
MOR	E_{TV}[e]	2.75	3.86	0.26	14.65	109.36	319
MOR	E_{SW1}[f]	5.11	2.97	0.27	14.87	106.14	290
MOR	E_{SW2}[g]	8.82	2.89	0.28	14.40	125.52	328
MOR	V_{SW2}[h]	−18.90	0.01	0.15	15.61	58.29	328

[a] MOR.
[b] Static bending MOE value.
[c] Continuous proof bending lowest MOE value.
[d] Continuous proof bending average MOE value.
[e] Transverse vibration MOE value.
[f] Longitudinal stress wave MOE value from Falcon A-grader.
[g] Longitudinal stress wave MOE value from Director HM200.
[h] Longitudinal stress wave velocity from Director HM200.
[i] Root-mean-square error.

MOE. Thus, the results from groups of 2 × 6, 2 × 8, and 2 × 10 were further discussed as follows: As to the continuous proof bending technique, while looking into the results from all sample sizes, r^2 obtained for the NDT MOE vs MOR were the same for both the lowest and average NDT MOE values ($r^2 = 0.23$). Although considering the sample sizes separately, the average NDT MOE value (E_{HCLT} vs MOR, r^2 = 0.19-0.29) showed lower prediction performance compared with the lowest NDT MOE value (E_{LHCLT} vs MOR, r^2 = 0.17-0.43). It is shown that this technique provides lower r^2 value compared with that of static bending MOE vs MOR (r^2 = 0.30-0.46).

Table 3. Linear regression relationship for dynamic MOE and MOR values (individual size group).

Size	y	x	β_0	β_1	r^2	RMSE	F value	N
2 × 6	MOR[a]	E_{SB}[b]	5.32	3.38	0.30	11.40	33.12	79
2 × 8			8.34	3.08	0.33	11.58	54.32	111
2 × 10			−3.72	3.87	0.46	11.32	72.38	85
2 × 12			−8.21	4.47	0.31	13.62	22.9	52
2 × 6	MOR	E_{LHCLT}[c]	4.34	5.03	0.43	11.15	12.89	19
2 × 8			24.99	2.23	0.17	12.08	6.07	32
2 × 10			18.82	2.82	0.21	12.50	13.37	52
2 × 12			37.90	1.44	0.04	15.42	0.98	28
2 × 6	MOR	E_{HCLT}[d]	11.69	2.95	0.19	13.32	3.96	19
2 × 8			19.81	2.26	0.23	11.41	9.49	33
2 × 10			7.53	3.27	0.29	11.94	20.68	52
2 × 12			36.41	1.24	0.03	15.48	0.78	28
2 × 6	MOR	E_{TV}[e]	10.55	2.74	0.19	12.05	15.99	69
2 × 8			11.08	2.99	0.23	12.05	32.13	110
2 × 10			0.06	3.91	0.35	12.50	44.48	85
2 × 12			5.41	3.68	0.16	15.67	9.42	53
2 × 6	MOR	E_{SW1}[f]	11.41	2.24	0.23	12.22	21.29	75
2 × 8			10.47	2.50	0.27	12.25	29.97	85
2 × 10			4.34	2.87	0.34	12.79	38.92	77
2 × 12			10.42	2.64	0.19	15.40	11.33	51
2 × 6	MOR	E_{SW2}[g]	15.61	2.10	0.21	12.11	21.18	82
2 × 8			17.32	2.17	0.22	12.52	31.05	110
2 × 10			6.85	2.84	0.31	12.96	35.72	82
2 × 12			−3.83	3.93	0.35	13.70	25.76	51
2 × 6	MOR	V_{SW2}[h]	0.41	0.01	0.08	13.05	11.21	82
2 × 8			3.79	0.01	0.10	13.47	12.08	110
2 × 10			−27.40	0.01	0.22	13.81	21.95	82
2 × 12			−66.21	0.02	0.26	14.61	16.78	51

[a] MOR.
[b] Static bending MOE value.
[c] Continuous proof bending lowest MOE value.
[d] Continuous proof bending average MOE value.
[e] Transverse vibration MOE value.
[f] Longitudinal stress wave MOE value from Falcon A-grader.
[g] Longitudinal stress wave MOE value from Director HM200.
[h] Longitudinal stress wave velocity from Director HM200.

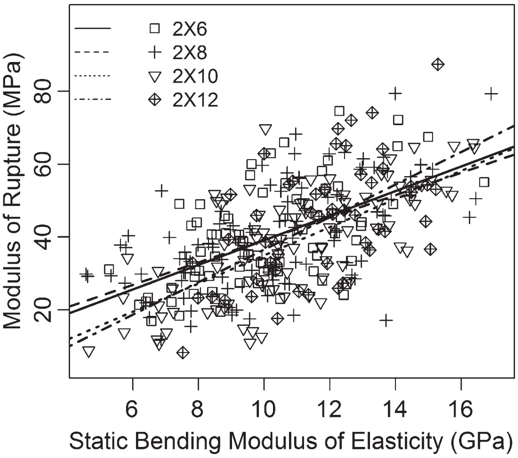


Figure 4. Linear regression plot of static MOE (E_{SB}) and MOR, each lumber size.

Similarly, the r^2 obtained from transverse vibration technique (E_{TV} vs MOR) are 0.19-0.35. The r^2 obtained from longitudinal stress wave technique with Falcon A-Grader tool (E_{SW1} vs MOR) are 0.23-0.34, whereas with Director HM200 tool (E_{SW2} vs MOR) are 0.21-0.31. Overall, compared with that of static bending MOE to MOR ($r^2 =$ 0.30-0.46), lower r^2 were obtained given the NDT MOE as independent variables.

The direct output from longitudinal stress wave technique with Director HM200 tool was stress wave velocity (V_{SW2}). The velocity value obtained for each specimen was then converted to dynamic MOE value (E_{SW2}) using Eq 1. The r^2 of E_{SW2} vs MOR are from 0.21 to 0.34, for each of the four groups of samples. However, on the other hand, the r^2 of V_{SW2} vs MOR varied from 0.08 to 0.26. The results indicated that by converting the velocity outputs to dynamic MOE values, Director HM200 produced potentially useful results when predicting lumber bending strength.

CONCLUSIONS

This study investigated the reliability of four commercial NDT techniques in predicting the static bending MOR value on on-grade No. 2 SP lumber. A mobile Metriguard Model 7200 HCLT was set up in the laboratory to conduct the continuous bending evaluation, Metriguard Model 340 Transverse Vibration E-computer was used to conduct the transverse vibration evaluation, and Falcon Engineering A-Grader and Fiber-gen Director HM200 were adopted as testing tools to conduct the longitudinal stress wave evaluations. The results of this study suggest that:

1. Static bending MOE can be used to predict MOR value of No. 2 grade SP lumber. The coefficient of determination (r^2) ranged from 0.30 to 0.46 for the group sizes of 2 × 6, 2 × 8, 2 × 10, and 2 × 12.
2. By predicting MOR value with the given outputs, NDT tools have great potential to be implemented as a quality control tool through the operation value chain. Besides the group of 2 × 12, the r^2 ranged from 0.17 to 0.43 with MOE values obtained by continuous proof bending technique (Metriguard Model 7200 HCLT), from 0.19 to 0.35 with MOE values obtained by transverse vibration technique (Metriguard Model 340 Transverse Vibration E-computer); and from 0.23 to 0.34 with MOE values obtained by longitudinal stress wave technique (Falcon Engineering A-Grader).
3. Dynamic MOE value obtained from Fiber-gen Director HM200 was considered as the most reliable predictor among all tests results in this study. The r^2 ranged from 0.23 to 0.34.
4. Longitudinal stress wave velocity is not recommended to be used directly for the purpose of predicting MOR value of SP lumber.
5. Predicting MOR value of larger dimension lumber received less accurate results. Further experimental study considering the quality and quantity of lumber defects as independent variables is recommended.

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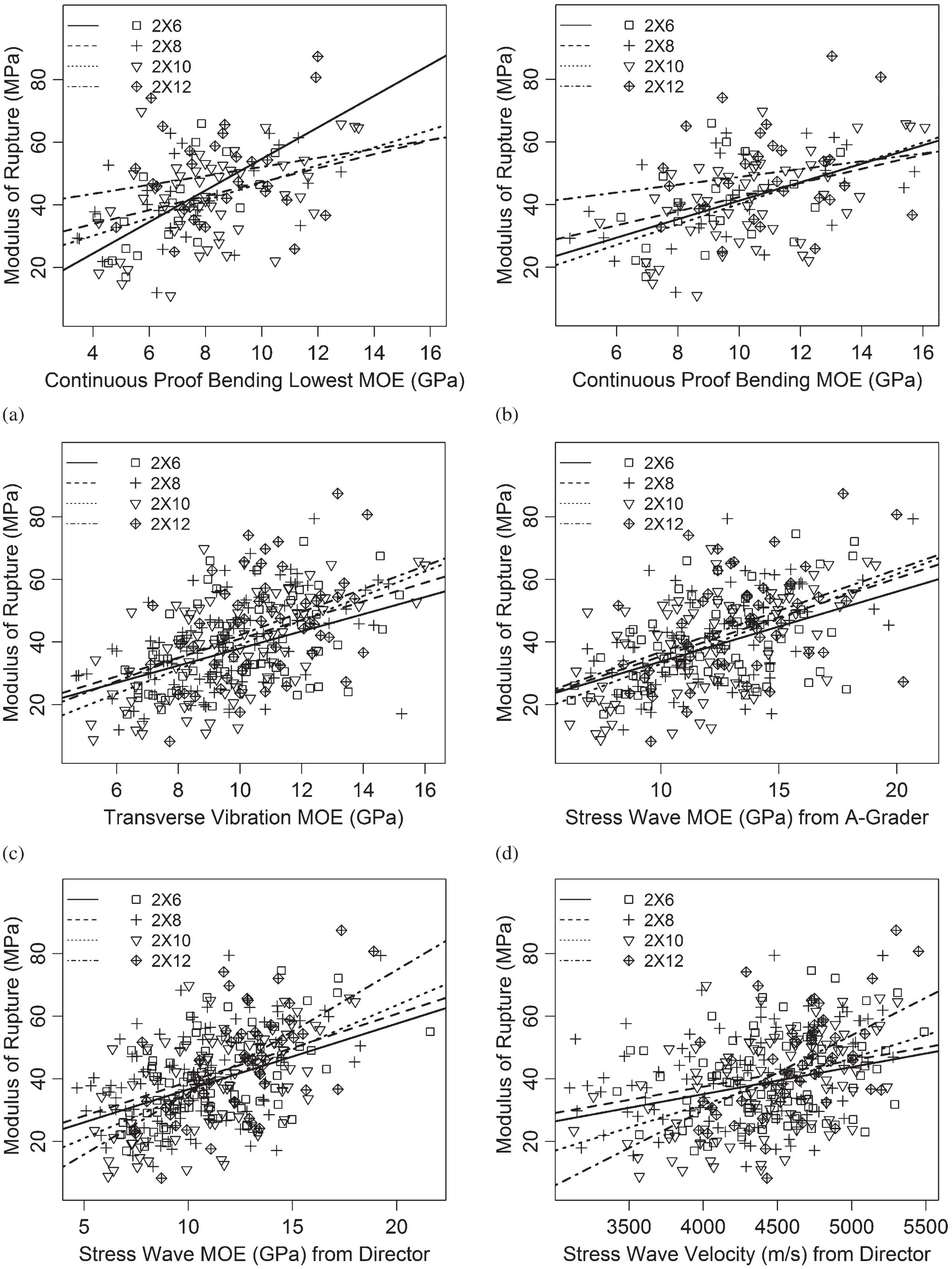

(a) (b) (c) (d) (e) (f)

Figure 5. Linear regression plots for each lumber size: MOE vs MOR: (a) E_{LHCLT} and MOR, (b) E_{HCLT} and MOR, (c) E_{TV} and MOR, (d) E_{SW1} and MOR, (e) E_{SW2} and MOR, and (f) V_{SW2} and MOR.

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