RELATIONSHIPS BETWEEN LOBLOLLY PINE SMALL CLEAR SPECIMENS AND DIMENSION LUMBER TESTED IN STATIC BENDING

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Abstract. Prior to the 1980s, the allowable stresses for lumber in North America were derived from testing of small clear specimens. However, the procedures were changed because these models were found to be inaccurate. Nevertheless, small clear testing continues to be used around the world for allowable stress determinations and in studies that examine forest management impacts on wood quality. Using small clear and nondestructive technologies is advantageous because of the ease of obtaining and testing small clear specimens compared with lumber. The objective of this study was to compare mechanical properties in bending of small clear specimens with lumber specimens of loblolly pine. For this study, 841 pieces of lumber in the No. 1 to No. 3 grades and nominal 2 × 4 to 2 × 10 (38 × 89 to 38 × 235 mm) sizes were collected from a forest-through-mill study and tested in static bending. A small clear specimen (25 × 25 × 410 mm) was prepared from each piece of lumber and tested in static bending. The effect of growth ring orientation was explored, and overall, samples tested on the radial or rift face explained the variation in lumber more accurately than did samples tested on the tangential face. However, the relationships were generally poor for modulus of elasticity (MOE) ($R^2 = 0.22$) and modulus of rupture (MOR) ($R^2 = 0.11$) pooled data. A lumber-based multiple regression model explained 44% and 37% of the variability for MOE and MOR, respectively, whereas a stand-based multiple regression model explained 41% and 29% of the variability for MOE and MOR, respectively.

Keywords: Mechanical properties, modulus of elasticity, modulus of rupture, nondestructive testing, southern pine, wood quality.

INTRODUCTION

Loblolly pine (*Pinus taeda*), the predominant southern pine (SP) in terms of utilization, is widely planted in the southeastern United States and has been extensively improved through genetic selection (McKeand et al 2003). One of the most important products produced from loblolly pine timber is dimension lumber, which is typically made from chip-n-saw and sawtimber logs that have price premiums compared with pulpwood logs (Norris Foundation 2014). The design values for visually graded SP lumber were revised in 2013 with decreases in allowable properties for most grades and sizes after tests conducted by the Southern Pine Inspection Bureau (SPIB 2013). The design values for SP were revised in the 1980s, which was the first time that design values were determined from testing of lumber as opposed to small clear specimens (50 × 50 × 820 mm) scaled up to lumber sizes (Green et al 1989). In the 1960s and 1970s, research showed that the models used to scale up the small clear data were inaccurate and overstated property values up to 35% (Green et al 1989). These differences were principally caused by the presence of knots in lumber and their impact on wood failure; lumber tested in bending typically fails in tension (Madsen 1992; Butler et al 2016), whereas small clear specimens begin failure in compression. Also, as the neutral face is lowered, the specimen will then fail in tension (Madsen 1992).

Plantation growth rates of SP have accelerated during the past 30 yr because of improved genetics, mechanical and chemical site preparations, woody and herbaceous control, and the use of multiple fertilizer applications (Borders and Bailey 2001). These treatments have decreased the time it takes to grow loblolly pine sawtimber from 35-40 yr to 20-25 yr (Clark et al 2008) with merchantable size for the chip-n-saw being reached in as little as 16 yr (Clark et al 2008; Vance et al 2010). Higher productivity has increased both the sustainability of forest plantations in the south and their financial attractiveness (Munsell and Fox 2010). However, faster-grown trees will typically contain a high proportion of juvenile wood, which has low stiffness and strength (USDA Forest Service 1988; McAlister and Clark 1991; Larson et al 2001).

Small clear specimens have often been tested to directly measure modulus of elasticity (MOE) and modulus of rupture (MOR) for determining the effect of silvicultural treatment and genetic assessments simply because of the relative ease of obtaining and testing these samples. Clark et al (2008) evaluated the impact of planting density on small clear wood (25 × 25 × 410 mm) properties of loblolly pine and found that MOE and MOR increased with increasing planting density. Also working with loblolly pine, Antony et al (2011) modeled the regional variation in clear wood MOE and MOR. Researchers in New Zealand conducted extensive testing on 20- × 20- × 300-mm samples to quantify mechanical properties in radiata pine (Cown et al 1999; Jayawickrama 2001). Auty and Achim (2008) modeled how mechanical properties increased with age in scots pine using small clear specimens. Moya et al (2013) determined the mechanical properties of fast-grown loblolly pine and slash pine grown in Uruguay using small clear specimens.

In addition to small clear specimen testing, nondestructive testing (NDT) technologies, or indirect tests, have also emerged and have been used to rapidly quantify wood quality. The X-ray densitometer (Cown and Clement 1983) was developed to measure ring-by-ring variation in specific gravity (SG) of wood cores taken from standing trees or from wood disks. Densitometry of loblolly pine samples has been used to quantify regional variation in SG (Jordan et al 2008), the longitudinal variation within a tree in SG (Antony et al 2010), the impacts of midrotation fertilization (Antony et al 2009), and planting density (Clark et al 2008). The SilviScan suite of instruments, developed at Commonwealth Scientific and Industrial Research Organization, has used X-ray diffraction to rapidly assess microfibril angle (MFA) (Evans 1999). Using Silviscan, Clark et al (2006) determined the values of SG and MFA that define the transition in loblolly pine from juvenile to mature wood. Near-infrared spectroscopy (NIRS) has been used and models have been developed to relate the NIRS spectra to the MFA results from X-ray diffraction (Jones et al 2005; Schimleck et al 2005). The MOE and MOR of wood are reasonably well explained with SG and MFA (Evans 1999) for clear wood. Acoustics have been used to estimate dynamic MOE in standing trees and logs, and the results have been compared with small clear specimens of loblolly pine (Mora et al 2009) and radiata pine (Ivković et al 2009).

Although small clear specimen testing and NDT have been widely used, it is important to understand the difference between the determined wood quality attributes and actual properties of lumber (Zhou and Smith 1991; Briggs 2010; Wessels et al 2011). Doyle and Markwardt (1966) cut clear bending specimens (25 × 25 × 410 mm) from 2 × 4 and 2 × 8 (38 × 184 mm) lumber and found subtle SG differences for lumber (0.52) and the small clear specimens (0.51), which they attributed to knots and other uniformity issues in the lumber. For these specimens, the relationship between lumber flatwise MOE and small clear MOE was 0.37 (R^2); MOR results were not reported. Besides the effect of knots, some of the variation between lumber and smaller specimens has been attributed to the variation that exists from stump to tip and pith to bark (Antony et al 2010, 2011). This variability is accounted for when dynamic MOE is measured on full-length lumber and compared with static bending MOE for Douglas-fir ($R^2 = 0.83$) (Vikram et al 2011) and southern pine ($R^2 = 0.86$) (Yang et al 2015). Limited studies have also linked wood properties to lumber properties. Specifically, Kretschmann and Bendtsen (1992) reported dynamic MOE and tensile strength values from loblolly pine 2 × 4 lumber cut from a 28-yr-old plantation. Samples that contained 100% juvenile wood (< 8-yr-old), as determined based on ring age, had 63% of the stiffness and 45% of the tensile values of wood that was 100% mature wood (≥ 8-yr-old). Also, Vikram et al (2011) found that disk density explained 25% of the variation in lumber MOE in Douglas-fir.

The research that showed differences in the design values derived from small clear specimens vs design values derived from lumber testing did not focus on correlating lumber data to small clear specimen data (Green et al 1989). To provide a context for small clear testing results, this study focused on the comparison between small clear samples and lumber cut from 93 loblolly pine trees from five mature stands

(24-33 yr old) that had received intensive management. Trees were felled and sawn into lumber, and the resulting lumber was dried, graded, and destructively tested in bending according to ASTM (2013, 2014c) standards. The objectives of this study were to 1) correlate small clear specimens with lumber as tested in bending using single and multiple linear regression models, 2) determine the impact that test face has on the relationships between small clear samples and lumber, and 3) calculate and compare the allowable stresses as derived from small clear specimens with the allowable stresses as derived from lumber specimens.

MATERIALS AND METHODS

Stands

Trees used in this study were harvested in 2013 within the lower coastal plain near Brunswick, GA. The stand and tree characteristics, including coordinates, are listed in Table 1. A total of 93 trees were felled from five stands with age ranging from 24 to 33 yr with site index of 25 yr (SI_{25}) from 25.3 to 27.4 m. Tree selection was conducted as a proportion of the board foot per acre per diameter class compared with total board foot per acre from the individual stand. Thus, sampling placed greater emphasis on larger trees than smaller trees. Trees with major defects such as cankers and forks were excluded. Felled trees were bucked into approximately three 5.2-m logs; log 1 was from stump to 5.2 m in height, log 2 was from 5.2 to 10.4 m in height, and log 3 was from 10.4 to 15.5 m in height. A total of 269 logs were transported to the participating mill where they were processed into 2 × 4, 2 × 6 (38 × 140 mm), 2 × 8, and 2 × 10 dimension lumber. The lumber was stickered, dried to less than 19% MC, planed, and graded into No. 1 and Btr (No. 1), No. 2, and No. 3 by certified graders from the mill. During processing, the location of the lumber within tree, log, and radial position was tracked. A total of 841 pieces of lumber were available after grading for testing with 120, 306, 347, and 68 samples sawn from the 2 × 4, 2 × 6, 2 × 8, and 2 × 10 sizes, respectively. A total of 158 pieces (19%) were No. 1 grade, 609 pieces (72%) were No. 2 grade, and 74 pieces (9%) were No. 3 grade. Sawn lumber was transported to the wood quality laboratory in Athens, GA, and stored indoors prior to testing.

Lumber Specimen Preparation and Edgewise Testing

The edgewise destructive bending test setup was performed according to ASTM (2014c) and ASTM (2013) via four-point bending setup in third-point loading (load heads positioned one-third of the span distance from the reactions) onan MTI 100-kN universal testing machine (Marietta, GA). The span-to-depth ratio was 17-1 (2 × 4: 1511-89 mm, 2 × 6: 2375-140 mm, 2 × 8: 3131-184 mm, and 2 × 10: 3994-235 mm). The tension (bottom) face of each specimen was randomly selected and the perceived worst defect was included in the test span region (ASTM 2013). Prior to testing, the lumber was trimmed to the test span; the test span included the predicted worst defect. A 0.5-m slab was cut next to the test span and was processed into a small clear specimen; whether the small clear specimen originated from the stump or tip side of the lumber piece depended on the availability

Table 1. Stand and felled tree characteristics.

				Stand				Felled tree		
Stand	Latitude	Longitude	Age	Site index (m)	Quadratic mean diameter (cm)	Trees per hectare	Basal area (m^2/ha)	Trees felled	Average height (m)	Diameter at breast height (cm)
S1	31.118729	−81.757379	24	27.4	29.2	721	49	21	27.3	30.6
S2	31.408185	−81.772966	25	27.1	30.1	415	30	20	27.3	30.9
S3	31.189826	−81.750544	26	25.6	31.9	442	35	21	27.1	31.7
S4	31.322529	−81.595399	27	26.2	30.4	442	32	21	25.7	30.9
S5	31.344459	−81.652424	33	25.3	33.0	208	18	10	27.5	33.0

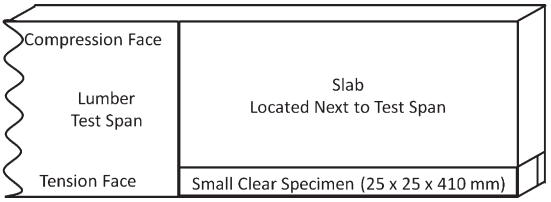

Figure 1. Example of lumber test span and small clear specimen preparation from slab cut from either the stump or tip side of original piece of lumber.

of clear wood (Fig 1). The source of the slab (stump or tip side) was recorded. In some cases, a clear wood specimen could not be obtained. Deflection was measured using a string-pot transducer and synchronized with load level in the elastic range to determine the MOE; MOR was calculated from the maximum load. For each piece of lumber, the sample dimensions, visual grade, MC, SG, and presence or absence of pith were recorded. The average MC of the lumber was 11.2% with a range from 8.5% to 17.2%.

A series of adjustments were made to the lumber (because of the standards, the adjustments were performed with customary US units) (Evans et al 2001; ASTM 2010, 2014a). Lumber design values are published at 15% MC, MOE is published at a 21-1 span-to-depth ratio with uniform loading and deflection measured at midspan, and bending strength (F_b) is published for SP lumber at 3.66-m length for 2 × 4 to 2 × 8 lumber and 6.1-m length for 2 × 10 lumber. The width of each piece was adjusted to 15% MC:

$$d_2 = d_1 \frac{1 - \dfrac{a - bM_2}{100}}{1 - \dfrac{a - bM_1}{100}} \tag{1}$$

where M_1 is the measured MC, M_2 is 15% MC, d_1 is the width at the measured MC (M_1), d_2 is the width at 15% MC (M_2), a is 6.031, and b is 0.215.

The MOE of each sample was adjusted to 15% MC, then to third-point uniform loading (MOE_{15}). The adjustment of MOE to 15% MC is

$$S_2 = S_1 + \left\{ \frac{(S_1 - \beta_1)}{(\beta_2 - M_1)} \right\} (M_1 - M_2) \tag{2}$$

where S_1 is the measured MOE at the tested MC (M_1), S_2 is the adjusted MOE at 15% MC, M_1 is the measured MC, M_2 is 15% MC, and β_1 and β_2 are parameters 1.857 and 0.0237, respectively, for MOE (ASTM 2014a). The adjustment from 17 to 1 span-to-depth ratio to uniform loading at a span-to-depth ratio of 21-1 is

$$E_{ai2} = \frac{1 + K_1 \left(\dfrac{h}{L_1}\right)^2 \left(\dfrac{E}{G}\right)}{1 + K_2 \left(\dfrac{h}{L_2}\right)^2 \left(\dfrac{E}{G}\right)} E_{ai} \tag{3}$$

where E_{ai2} is the adjusted MOE value as per design values (MOE_{15}), E_{ai} is the measured MOE value adjusted to 15% MC, K_1 is the factor for loading concentrated at third points with deflection measured at midspan ($K_1 = 0.939$), K_2 is the factor for uniform loading with deflection measured at midspan ($K_2 = 0.96$), h is the depth of the beam, L_1 is the total beam span between supports at 17-1 span-to-depth ratio, L_2 is the total beam span between supports at 21-1 span-to-depth ratio, E is the shear free MOE, G is the modulus of rigidity, with E/G being equal to 0.0625.

For each MOR > 16.6 MPa, the MOR was adjusted to 15% MC (MOR_{15}):

$$S_2 = S_1 + \left\{ \frac{(S_1 - \beta_1)}{(\beta_2 - M_1)} \right\} (M_1 - M_2) \tag{4}$$

where S_1 is the measured MOR at the tested MC (M_1), S_2 is the adjusted MOR at 15% MC, M_1 is the measured MC, M_2 is 15% MC, and β_1 and β_2 are parameters 2415 and 40, respectively, for MOR (ASTM 2014a).

To better facilitate comparisons of different size lumber because of the differences in tested and adjusted spans, the MOR_{15} values for each size were adjusted to the characteristic ($CMOR_{15}$) values:

$$F_2 = F_1 \left(\frac{W_1}{W_2}\right)^w \left(\frac{L_1}{L_2}\right)^l \tag{5}$$

where F_2 is MOR_{15} at volume 2, F_1 is MOR_{15} at volume 1, W_1 is width at F_1, W_2 is width at F_2,

L_1 is length at F_1, L_2 is length at F_2, w is 0.29, and l is 0.14; the width is the beam depth in this case. The $CMOR_{15}$ is defined as the 2 × 8 size (38 mm × 184 mm × 3.7 m). Therefore, W_2 is 184.15 mm and L_2 is 3.66 m. Bending strength (F_b) was calculated using the previous equation and adjusting the length of the 2 × 4 to 2 × 8 lumber to 3.7 m and the 2 × 10 lumber to 6.1 m and then dividing the adjusted values by 2.1 to account for safety, uncertainty, and differences in the testing time period and real-world structural uses (FPL 2011). The measured SG of each piece of lumber was adjusted to 15% MC (SG_L) using the measured SG, volumetric shrinkage value of loblolly pine of 12.3%, an FSP of 28.7%, and a scale factor to account for higher/lower shrinkage at higher/lower SG of each piece compared with the tabular values (Glass and Zelinka 2010; Kretschmann 2010).

Small Clear Specimen Preparation and Testing

From each slab, a small clear specimen (25 × 25 × 410 mm) was sawn from the bottom (tension) edge. Specimen dimensions and weight were recorded immediately prior to specimen testing. The small clear destructive bending test setup was conducted via third-point bending on a Tinius Olsen (Horsham, PA) 5000 universal testing machine with span-to-depth ratio of 14-1 (356-25 mm) (ASTM 2014b). The orientation of the growth rings was recorded into two groups, 90° and mixed orientation (rift-sawn). For samples with 90° orientation, the testing surface was sorted randomly into groups such that the load was applied on either the tangential or the radial surface. Different testing standards have different requirements for load orientation. ASTM (2014b) requires that the load be applied to the tangential face with the direction of the pith on the compression face, whereas other standards (BS 373, BS 1969; ISO 3349-1975, and DIN 52186-1992) require the load be applied to the radial face (BSI 1957; Adamopoulos 2002). As growth rate increases and specimen size is decreased, there are concerns regarding the influence that growth rings have on the testing results when applying loads to the tangential face. To this end, Grotta et al (2005) tested very small clear Douglas-fir samples (10 × 10 × 150 mm) on the radial face. MOE was calculated based on the specimen deflection and the corresponding proportional limit, and MOR was calculated from the maximum load. Following testing, the samples were oven-dried to determine the SG and the MC. The measured SG of each small clear sample was adjusted to 12% MC (SG_{SC}) (Glass and Zelinka 2010; Kretschmann 2010). The average MC of the small clear samples was 10% with a range from 5.2% to 17.7%. Unlike dimension lumber, there is no current ASTM standard for adjusting small clear samples to a uniform MC. Therefore, the framework developed by Kretschmann and Green (1996) was used in which they explained the mechanical properties of small clear SP based on MC and SG:

$$p_{\text{modeled}} = \left[I + a(\text{MC}) + b(\text{MC})^2 + c(\text{SG}) + d(\text{SG})^2 + e(\text{MC})(\text{SG})\right] \times f \quad (6)$$

where p_{modeled} is modeled MOE or MOR, MC is the MC expressed in percentage, SG is the SG at oven-dry weight and volume at 12% MC, I is 550 for MOE and 0.2134 for MOR, a is 102.0 for MOE and 0.63886 for MOR, b is −2.401 for MOE and −0.01469 for MOR, c is −517.1 for MOE and 23.092 for MOR, d is 5710.5 for MOE and 26.384 for MOR, e is −148.6 for MOE and −1.642 for MOR, and f is the adjustment from pounds per square inch ($\times 10^3$) to gigapascals for MOE and megapascals for MOR. The modeled property value at MC_X (p_{modeled}) was calculated and compared with the measured property at MC_X (p_{measured}). Then, the calculated expected property at 12% MC was calculated ($p_{\text{modeled12\%}}$) and the measured property at MC_X was adjusted by

$$P_{\text{adjusted12\%}} = p_{\text{measured}} + \frac{p_{\text{measured}}}{p_{\text{modeled}}} \times \left(p_{\text{modeled12\%}} - p_{\text{modeled}}\right) \quad (7)$$

where $p_{\text{adjusted12\%}}$ is MOE_{SC} and MOR_{SC} and p_{measured} is the measured MOE and MOR of the small clear specimens.

Comparison and Conversion of Small Clear Samples and Lumber

The assumed ratios between lumber strength and clear wood strength (strength ratios) for visually graded lumber are 55%, 45%, and 26% for the No. 1, No. 2, and No. 3 grades (ASTM 2011b). The actual strength ratio (S_{ratio}) of each piece was calculated by dividing the lumber MOR_L by the small clear MOR_{SC} (Doyle and Markwardt 1966):

$$S_{ratio} = \frac{MOR_L}{MOR_{SC}} \quad (8)$$

where S_{ratio} is the actual stress ratio, MOR_L is the MOR_{15} of the lumber, and MOR_{SC} is the MOR_{12} of the small clear specimens. The actual flexure ratio of each piece was calculated by dividing the lumber MOE_L by the small clear MOE_{SC}:

$$F_{ratio} = \frac{MOE_L}{MOE_{SC}} \quad (9)$$

where F_{ratio} is the actual stress ratio, MOE_L is the MOE_{15} of the lumber, and MOE_{SC} is the MOE_{12} of the small clear specimens.

The small clear specimens were scaled to allowable stress values for lumber (Madsen 1992; ASTM 2011a). However, specimens were tested dry. Thus, the moisture adjustment from green to dry conditions was not performed. The small clears were adjusted to full-sized lumber according to

$$F_b = (\bar{X} - 1.645S) \times F_{time} \times F_{depth} \times F_{grade} \times \frac{1}{F_{safety}} \quad (10)$$

where F_b is allowable bending stress in bending, $\bar{X}$ is the mean MOR_{SC} of the small clear specimens, S is the standard deviation of the small clear specimens, F_{time} is the adjustment factor for duration of load from minutes to 10 yr (0.62), F_{depth} is the depth adjustment for each size, F_{grade} is the stated strength ratio for each grade, and F_{safety} is the safety factor adjustment (1.3). F_{depth} is calculated as

$$F_{depth} = \left(\frac{SC_{depth}}{L_{depth}}^{d}\right) \quad (11)$$

where SC_{depth} is the depth of the small clear samples (eg 25 mm), L_{depth} is the depth of the lumber samples (eg 89 mm), and d is the depth adjustment exponent. The depth adjustment d is specified as 0.11. However, alternate values were also explored based on the results of the lumber testing. For lumber, the adjustment factor for depth is the same equation but d is 0.29 (ASTM 2014a), and thus, wider widths are penalized at a greater rate than in the original standard.

Statistical Analyses

The statistical analyses and associated graphics were completed in R 3.1.1 statistical software (R Core Team 2014) with RStudio 0.98.932 interface (RStudio 2014) and the packages agricolae (de Mendiburu 2014), extrafont (Chang 2014), and lawstat (Gastwirth et al 2015).

RESULTS AND DISCUSSION

Small Clear Results

Based on the availability of clear material, a total of 743 small clear specimens were prepared and tested from the 841 pieces of lumber. There were no significant differences ($p = 0.11$) in SG_{SC} among the different test faces using analysis of variance (ANOVA) (Table 2). The test face was found to be significantly different for both MOE_{SC} and MOR_{SC} ($p < 0.001$) using ANOVA with the tangential face being significantly lower for MOE_{SC} and the radial face being significantly higher for MOR_{SC}. These results are similar to those found by Biblis (1971) in which specimens loaded on the tangential face had MOR_{SC} values approximately 10% lower than samples loaded on the radial face. Biblis (1971) did not find significant differences in mechanical properties of small clear specimens from the loading face. However, the lack of statistical significance was probably caused by the relatively small number of samples tested ($n = 22$) compared with this study ($n = 743$). The data for the paired relationship using linear regressions between MOR_{SC}, MOE_{SC}, and SG_{SC} are shown in Table 3. Generally, the

Table 2. Summary on the effect of testing face on specific gravity (SG_{SC}), modulus of elasticity (MOE_{SC}), and modulus of rupture (MOR_{SC}) for small clear samples.

		SG_{SC}		MOE_{SC}		MOR_{SC}	
Sample face	*N*	Mean	SD	Mean	SD	Mean	SD
Tangential	152	0.53	0.06	10.6 b	2.0	97.8 b	18.8
Radial	163	0.54	0.06	11.5 a	2.1	108.5 a	19.1
Rift	428	0.54	0.06	11.2 a	2.1	100.4 b	17.2
Overall	743	0.54	0.06	11.2	2.1	101.6	17.9

radial and rift faces had stronger models than the tangential face. Modeling only within a single lumber size generally results in the model performance decreasing as lumber size increases. Based on the results, MOE_{SC} and MOR_{SC} were moderately correlated and surprisingly, the results as found in the small clear samples were not much better than those found between MOE and MOR in SP lumber in the No. 2 2 × 4 grade and size ($R^2 = 0.52$) (Butler et al 2016). For the tangential face, the model performance of the small clear samples was worse than the coefficient of determination as found in the lumber models. These results point to erratic effects that tangential growth ring orientations can have on the samples tested on the tangential face. Specifically, the presence of earlywood or latewood on the surface of the tension face can impact the bending performance of these small clear samples.

Relationship Between Small Clear Specimens and Lumber

The linear regression relationship between SG_L and SG_{SC} was moderate (intercept = 0.20, coefficient = 0.58, $R^2 = 0.50$). The linear regression relationships between MOE_L and MOE_{SC} ($R^2 = 0.20$) and MOR_L and MOR_{SC} ($R^2 = 0.11$) were poor (Table 4). The poor relationship for MOR was expected given the differences between clear wood and lumber that contains knots. However, the relationship for MOE was worse than expected, particularly when given the moderate relationship for SG. For MOE, with the load applied to the radial or rift face, the model was better than with the load applied to the tangential face. For MOR, there were no large differences in performance of the model when applying loads to different faces. Running separate models for each lumber size resulted in similar results for the MOE model. The MOR model had an improved linear relationship ($R^2 = 0.29$) for the 2 × 4 size compared with that for the other sizes, the latter being more variable. Another method to determine if the test face influences the performance of the model is by Levene's statistical test. The null hypothesis in this test assumes equal variance for two or more groups. When predicting the MOE and MOR of the full-sized lumber, the smaller the residuals or differences between the actual value and the predicted value, the better the model. The null hypothesis here is to assume that all three testing faces perform equally in the context of the

Table 3. Linear models ($y = a + bx$) on the relationships between specific gravity (SG_{SC}), modulus of elasticity (MOE_{SC}), and modulus of rupture (MOR_{SC}) for small clear samples.

	MOE_{SC} (y) vs SG_{SC} (x)			MOR_{SC} (y) vs SG_{SC} (x)			MOR_{SC} (y) vs MOE_{SC} (x)		
Sample face	Coefficient *a*	Coefficient *b*	R^2	Coefficient *a*	Coefficient *b*	R^2	Coefficient *a*	Coefficient *b*	R^2
Tangential	2.06	16.16	0.29	−10.37	204.68	0.49	32.77	6.13	0.40
Radial	2.71	16.17	0.21	−18.47	233.90	0.54	31.23	6.73	0.56
Rift	0.34	20.32	0.34	−15.26	215.93	0.60	35.84	5.76	0.52
Overall	1.11	18.75	0.30	−16.29	220.12	0.55	33.38	6.12	0.50
2 × 4	2.09	16.68	0.26	−23.36	234.00	0.58	19.45	7.34	0.61
2 × 6	−0.79	22.73	0.42	−10.02	209.45	0.61	40.06	5.40	0.50
2 × 8	2.10	16.52	0.24	−21.23	227.75	0.55	31.46	6.38	0.48
2 × 10	1.92	17.45	0.22	−7.20	205.70	0.33	31.92	6.50	0.47

Table 4. Linear models ($y = a + bx$) on the relationships between lumber modulus of elasticity (MOE_L) and modulus of rupture (MOR_L) with small clear modulus of elasticity (MOE_{SC}) and modulus of rupture (MOR_{SC}).

	MOE_L (y) vs MOE_{SC} (x)			MOR_L (y) vs MOR_{SC} (x)		
Sample face	Coefficient a	Coefficient b	R^2	Coefficient a	Coefficient b	R^2
Tangential	6.68	0.33	0.09	12.5	0.24	0.13
Radial	4.24	0.54	0.25	12.43	0.24	0.09
Rift	5.23	0.50	0.22	12.86	0.28	0.12
Overall	5.26	0.48	0.20	14.03	0.25	0.11
2 × 4	2.25	0.80	0.30	−10.52	0.61	0.29
2 × 6	4.20	0.54	0.29	10.52	0.28	0.14
2 × 8	6.87	0.35	0.11	18.18	0.18	0.09
2 × 10	5.54	0.55	0.25	18.89	0.19	0.11

one-way ANOVA. For both MOE ($p = 0.92$) and MOR ($p = 0.345$), there were no significant differences among these three testing faces. These results suggest that the wood test face does not impact the model. However, given the influence that a growth ring can have on a small clear sample and to ensure more consistency across global testing standards, it may still be more appropriate to test samples on the radial face. The results also indicate that it may be more appropriate to test larger small clear specimens when assessing the forest resource. When starting with trees, a 50.8- × 50.8-mm sample would contain more growth rings per sample than the 25.4- × 25.4-mm samples. For linking lumber properties, a 38.1- × 38.1-mm sample may yield better results given the initial constraints with the material size.

The MOE model performance was much lower than that found by Doyle and Markwardt (1966) who observed an R^2 of 0.37 between lumber MOE tested in the flatwise direction and small clear specimen MOE. The relationship between lumber MOR and small clear specimen MOR was not reported in that study. The weaker relationship for MOE in this study could be attributed to the difference in the timber resource from 1966 to today. The intensively managed timber used in this study had high within-tree variability because of the relatively rapid early growth, which led to a large juvenile core, but because these trees were mature, they still contained a large volume of mature wood. Other evidence that may support this is that Doyle and Markwardt (1966) found that the SG of the lumber (0.52) was slightly greater than the SG of the small clear samples (0.51). They attributed the higher SG of the lumber to the presence of knots. We found the SG of the small clear samples (0.54) was significantly greater ($p < 0.0001$) than the SG of the lumber (0.51). We attributed this to the fact that the small clear sample was cut from the tension edge in which there was a higher prevalence of mature wood than juvenile wood, which occurred in the middle of each piece of lumber. Some lumber pieces failed directly at a knot, whereas other pieces did not. Whether the lumber failed directly at a knot did not affect the model results. Other differences between lumber and the small clear results may also be attributed to the four-point bending test setup conducted on the lumber and the three-point bending setup conducted on the small clear specimens.

A multiple regression model was explored to determine the small clear specimen factors that impact the lumber properties. Two approaches were used. The first was from the perspective of explaining the lumber properties, and the model variables tested included the small clear results, the size and grade of the lumber, the log position from which the lumber came (1, 2, or 3), the relative radial position within the log from which the lumber was sawn (expressed as a percentage), and the relative vertical location within the log from which the small clear sample was obtained (stump side or tip side) (Table 5). Samples from the stump side of log 1 would be expected to have low MOE because of their high MFA (Jordan et al 2006). The second approach was from the

Table 5. Multiple regression model for lumber modulus of elasticity (MOE_L) and modulus of rupture (MOR_L) based on lumber properties.

Variable		Dummy variable	Coefficient
Lumber perspective–MOE_L, $Y = \beta_0 + \beta_1 + \beta_2 + \beta_3 + \beta_4 + \beta_5 + \beta_6 + \beta_7 + \beta_8$			$R^2 = 0.44$
Intercept	β_0		1.42
Short clear MOE	β_1		0.21
Short clear specific gravity	β_2		14.55
Testface (rift)	β_3	X	
Tangential			−0.55
Radial			−0.44
Lumber grade (No. 1)	β_4		
No. 2		X	0.29
No. 3			−1.35
Lumber size (2 × 4)	β_5		
2 × 6		X	−0.78
2 × 8			−0.52
2 × 10			0.15
Log (1,2,3)	β_6		−0.30
Lumber radial position within log (%)	β_7		1.39
Small clear vertical position within log (stump side)	β_8	X	
Tip side			0.68
Lumber perspective–MOR_L, $Y = \beta_0 + \beta_1 + \beta_2 + \beta_3 + \beta_4 + \beta_5 + \beta_6 + \beta_7 + \beta_8$			$R^2 = 0.37$
Intercept	β_0		23.25
Short clear specific gravity	β_1		51.74
Short clear MOR	β_2		0.068
Testface (Rift)	β_3	X	
Tangential			−2.77
Radial			−2.00
Grade (No. 1)	β_4		
No. 2			−3.00
No. 3			−8.72
Size (2 × 4)	β_5	X	
2 × 6			−10.52
2 × 8			−14.34
2 × 10			−15.93
Log (1,2,3)	β_6		−3.87
Lumber radial position within log (%)	β_7		8.79
Small clear vertical position within log (stump side)	β_8	X	
Tip side			3.59

prediction of lumber properties based on stand attributes, and the model variables tested included the small clear results, the log position from which the lumber came, the relative radial position within the log from which the lumber was sawn (expressed as a percentage), and the relative vertical location within the log from which the small clear sample was obtained (stump side or tip side), height of the tree, height to the live crown, crown ratio, diameter at breast height (DBH), crown width, height of the largest branch, and diameter of the largest branch. Only the stand attributes model is provided herein (Table 6). For MOE, the lumber model (R^2 = 0.44) and the stand model (R^2 = 0.41) had better performance than the MOE_{SC} only model (R^2 = 0.20). For MOR, the lumber model (R^2 = 0.37) and the stand model (R^2 = 0.29) had better performance than the MOR_{SC} only model (R^2 = 0.11). Overall, the models indicate that some of the variability in lumber properties can be explained by small clear samples when stand attributes are accounted for.

For all the results, only a single small clear sample was tested per lumber piece. The relationship between small clear samples and lumber

Table 6. Multiple regression model for lumber modulus of elasticity (MOE_L) and modulus of rupture (MOR_L) based on stand attributes.

Variable		Dummy variable	Coefficient
Stand perspective–MOE_L, $Y = \beta_0 + \beta_1 + \beta_2 + \beta_3 + \beta_4 + \beta_5 + \beta_6$			$R^2 = 0.44$
Intercept	β_0		0.92
Short clear MOE	β_1		0.20
Short clear specific gravity	β_2		14.51
Testface (rift)	β_3	X	
Tangential			−0.32
Radial			−0.42
Log (1,2,3)	β_4		−0.46
Lumber radial position within log (%)	β_5		1.38
Small clear vertical position within log (stump or tip side)	β_6	X	
Tip side			0.79
Stand perspective–MOR_L, $Y = \beta_0 + \beta_1 + \beta_2 + \beta_3 + \beta_4 + \beta_5 + \beta_6 + \beta_7 + \beta_8$			$R^2 = 0.37$
Intercept	β_0		18.74
Short clear specific gravity	β_1		36.98
Short clear MOR	β_2		0.09
Log (1,2,3)	β_3		−3.50
Crown width (m)	β_4		0.91
DBH (cm)	β_5		−2.13
Height to largest branch (m)	β_6		0.69
Lumber radial position within log (%)	β_7		20.59
Small clear vertical position within log (stump or tip side)	β_8	X	
Tip side			2.80

may improve if multiple samples are obtained from each lumber piece. In addition, it may be appropriate to test larger small clear samples, in this case 38.1-mm samples. To better mimic the traditional small clear testing method, preparing all possible small clear samples from a piece of lumber in the center of the log should be tested to determine if this is more effective than the method used in this study. Testing multiple samples from a piece of lumber cut from the center of the log would also allow for comparisons to typical small clear sampling procedures where wood properties are measured from pith to bark (Clark et al 2006). To this end, the small clear samples were able to discern differences using ANOVA because of log position in the tree for both MOE_{SC} ($p < 0.0001$) and MOR_{SC} ($p < 0.0001$). Small clear samples cut from lumber originating in logs 1 (11.53 GPa) and 2 (11.42 GPa) had significantly greater MOE_{SC} than small clear samples from log 3 (10.2 GPa). Small clear samples cut from lumber originating in log 1 (109.8 MPa) had significantly greater MOR_{SC} than samples from log 2 (100.9 MPa), which were significantly greater than those from log 3 (90.9 MPa).

Comparison and Conversion of Small Clear Samples and Lumber

The assumed ratios between lumber strength and clear wood strength (strength ratios) for visually graded lumber are 55%, 45%, and 26% for No. 1, No. 2, and No. 3 grades, respectively (ASTM 2011b). The actual strength ratio was determined for each piece, and the average values were found to be 42%, 39%, and 34% for No. 1, No. 2, and No. 3 grades, respectively (Fig 2). The No. 1 and No. 2 grade actual strength ratios were lower than the visual strength ratios, whereas for No. 3 grade, the actual strength ratio was greater than the visual strength ratio. Most sizes within each grade followed this trend. Actual strength ratios may be lower than visual strength ratios because each small clear sample was collected from the tension edge of each piece of lumber. This resulted in the small clear sample being from the outer portion of the log instead of the middle of

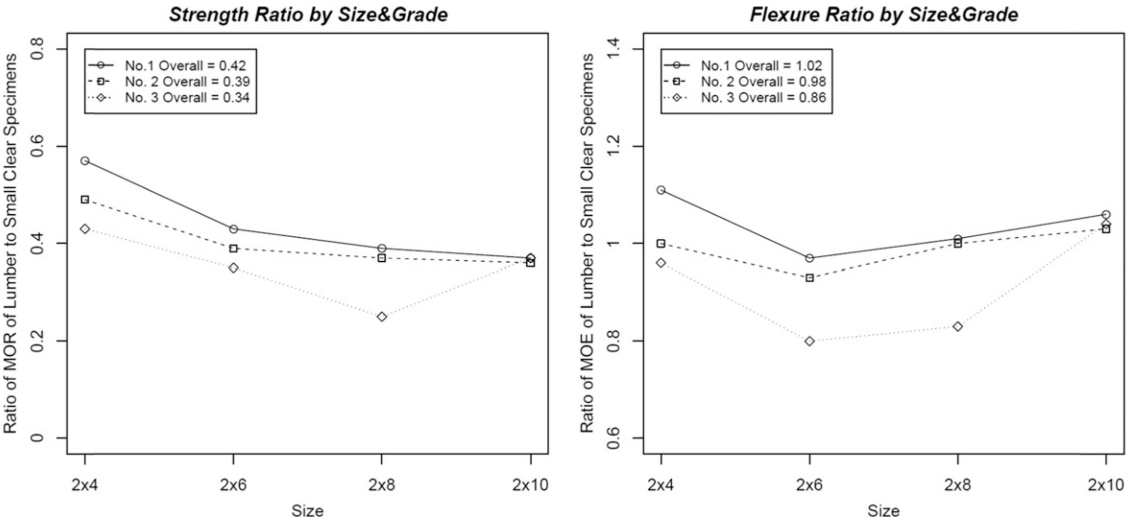

Figure 2. Relationship of the ratio of MOR and MOE of full-sized dimension lumber specimens and small clear matching specimens to depth of beam.

the log. Thus, the mechanical properties of the samples would be greater. Flexural ratios were determined for each piece, and average values were found to be 102%, 98%, and 86% for No. 1, No. 2, and No. 3 grades, respectively. Based on the flexural ratios, No. 1 and No. 2 grades had similar MOE values for both lumber and small clear samples, whereas the No. 3 grade flexural ratio was lower. The flexure ratios being lower for the No. 3 grade is logical given the larger knots that are present in the lower grades and given the fact that knotty wood has lower MOE than clear wood.

The adjustments as outlined in ASTM (2011a) were followed and compared with the lumber (Table 7). It is evident that the values derived from small clear samples with a depth factor of 0.11 were very different from those of the lumber. Substituting the lumber depth factor of 0.29 from ASTM (2014a) resulted in a model that had reasonable performance compared with the lumber properties. One interesting point is that for lumber, there is both a depth adjustment (0.29) and a length adjustment (0.13), but if both adjustments are used, the values generated are too conservative. Likewise, if the actual strength ratio of the material is used, the values are also too conservative. The location from which the small clear sample was cut from each piece of lumber may be the reason for this.

CONCLUSIONS

Wood quality is impacted by the environment, stand dynamics, silvicultural treatments, and genetics, as well as inherent within-tree, within-stand, and within-region wood variability. Small clear testing and NDT have been extensively conducted to evaluate these factors. However, few studies tie the specific tests to lumber quality. This study provides context to 25- × 25- × 410-mm small clear samples for loblolly pine. Overall, the results showed that only poor-to-moderate relationships can be obtained from small clear samples for predicting lumber properties, and thus, they are not a dependable method to determine actual values in lumber. Simple linear models for MOE ($R^2 = 0.20$) and MOR ($R^2 = 0.11$) were found between lumber and small clear samples. The poor relationships were probably caused by numerous factors including differences in failure mode for small clears and lumber and the amount of variability that exists within a given piece of lumber, which is not reflected within a small clear sample. When a multiple regression model was constructed that accounted

Table 7. Comparison between average MOE values for lumber and small clears and adjustment of small clear MOR values to working stress and comparison with bending strength (F_b) values as determined from lumber testing.

				F_b lumber		F_b derived from small clears	
Grade No.	Size	MOE lumber	MOE small clear	Nonparametric	4th Quantile	Depth factor, $d = 0.11$	Depth factor, $d = 0.29$
1	2 × 4	13.2	11.3	10.4	12.8	16.5	13.2
1	2 × 6	11.8	12.2	12.7	13.1	15.7	11.6
1	2 × 8	11.3	11.5	10.0	10.6	15.2	10.7
1	2 × 10	12.3	11.8	11.5	12.1	14.8	9.9
1	Adjusted[a]	11.9	11.7	10.4	11.7	15.2	10.7
2	2 × 4	11.1	10.9	8.5	9.9	13.5	10.8
2	2 × 6	10.2	11.1	9.4	9.4	12.8	9.5
2	2 × 8	10.7	10.8	9.2	9.2	12.5	8.7
2	2 × 10	11.9	11.7	4.6	9.1	12.1	8.1
2	Adjusted[a]	10.6	11.0	8.5	8.8	12.5	8.7
3	2 × 4	9.1	9.8	—	7.0	7.8	6.2
3	2 × 6	9.2	12.0	5.4	7.2	7.4	5.5
3	2 × 8	9.5	11.7	—	5.3	7.2	5.0
3	2 × 10	10.2	10.2		11.3	7.0	4.7
3	Adjusted[a]	9.3	11.3	5.0	5.3	7.2	5.0
All	All	10.7	11.2	—	—	—	

[a] Adjusted to 2 × 8 size.

for more of the variation, including SG, location within a tree based on log number, and location from pith to bark, model performance increased to $R^2 = 0.44$ for MOE and $R^2 = 0.37$ for MOR for the stand-based models. It was found that the previous models used to develop allowable stresses from small clear specimens were not accurate. However, changing the depth effect from 0.11 to 0.29, as indicated in the current lumber model (ASTM 2014a), allows for numbers that are somewhat similar to F_b values found from lumber testing. Further study is warranted to link wood properties at different scales to lumber quality, and performance may be increased if both larger small clear samples are tested as well as multiple small clear samples from each piece of lumber.

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