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ORIGINAL

Bending strength and stiffness of loblolly pine lumber from intensively managed stands located on the Georgia Lower Coastal Plain

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Abstract Loblolly pine is increasingly grown on intensively managed plantation forests that yield excellent growth; however, lumber cut from these trees often contains a large percentage of juvenile wood which negatively impacts strength and stiffness. Because of changing forest management and mill practices the design values for visually graded southern pine were updated in 2013 to more accurately account for the material properties available in commerce. This study was undertaken to assess the bending strength and stiffness of loblolly pine lumber from intensively managed stands located on the Georgia Lower Coastal Plain. Eight hundred and forty-one pieces of lumber sawn from 93 trees age 24–33 years were tested in four-point bending according to ASTM International standards. The No. 1 grade MOE_{15} (11.9 GPa) was greater than the current (11.0 GPa) design value and comparable to the previous (11.7 GPa) design value. The No. 2 grade MOE_{15} (10.6 GPa) was greater than the current (9.7 GPa) design value but slightly less than the previous (11.0 GPa) design values. The No. 3 grade MOE_{15} (9.3 GPa) was between the current (9.0 GPa) design value and the previous (9.7 GPa) design value. Altogether, these results point to the MOE_{15} mean values being reasonably comparable to the previous design values and currently meeting or exceeding the current design values for visually graded southern pine lumber.

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1 Introduction

Loblolly pine (*Pinus taeda*), the most important southern pine 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 is dimension lumber. The majority of dimension lumber is graded visually in the United States according to ASTM D245 (ASTM International 2006). The National design specifications (NDS), or design values, for southern pine were revised in 2013 with most grades and sizes having reductions in allowable properties following testing conducted by the Southern Pine Inspection Bureau (SPIB) (ALSC 2013). Previously the design values for southern pine were revised after testing in the 1980s which was the first time that design values were based on actual lumber testing and not small scale testing scaled up to lumber sizes (Green et al. 1989).

Over the past 30 years, numerous changes have occurred in the standing timber used for southern pine lumber. One such change was the acceleration of the growth rate in plantations which increased both the sustainability of forest plantations in the South and their financial attractiveness (Munsell and Fox 2010). Plantation growth has accelerated because of improved genetics, intensive site preparations, weed control, and the use of multiple fertilizer applications (Borders and Bailey 2001). These treatments have combined to decrease the time it takes to grow loblolly pine sawtimber from 35–40 down to 20–25 years (Clark et al. 2008) with merchantable size for the chip-n-saw being reached in as little as 16 years (Clark et al. 2008; Vance et al. 2010). Faster grown trees will typically contain a high proportion of juvenile wood which has low stiffness and strength (USDA 1988; McAlister and Clark 1991; Larson et al. 2001).

Although it is widely accepted that loblolly pine juvenile wood has reduced mechanical properties compared to mature wood and that intensive management typically leads to trees with a large juvenile core upon reaching merchantable size (Clark et al. 2008), very few studies have specifically assessed the impact of intensive management on lumber properties [e.g., modulus of elasticity (MOE), a component of stiffness, and strength]. For example, Kretschmann and Bendtsen (1992) reported lower values for tension parallel to grain on fast-grown loblolly pine material from 100 trees felled from a 28-year-old plantation. Overall they found that much of the lumber would not meet the design values for visually-graded lumber and concluded that as more material was introduced into the lumber system with higher proportions of juvenile wood, the design values would need to be decreased. Biblis et al. (1993, 1995) found that by age 35 the lumber from loblolly pine plantations in West Central Alabama would meet the design values for bending stiffness but was still deficient for bending strength (F_b). Both the Kretschmann and Bendtsen (1992) and Biblis et al. (1995) studies obtained trees from sites with SI_{25} of 21 m. In a different study conducted in West Central Alabama, Biblis (2006) reported that at age 19 only 10 % of the lumber cut from a loblolly pine plantation would meet the design values for bending stiffness. Ledford et al. (2015) reported that lumber cut in 2001 from sites with a site index 21–24 m from the Lower Coastal Plain in South Carolina would meet the design values for bending stiffness only after attaining age 26.

The differences found in the results from the above-mentioned mill studies could be attributed to numerous factors, one being the region from which the material was cut. Jordan et al. (2008) found significant differences in the specific gravity of loblolly pine grown across geographic regions with wood grown in the South Atlantic and Gulf regions having the greatest specific gravity while wood in the Hilly Coastal and Piedmont regions having the lowest specific gravity. Antony et al. (2011) found similar trends with stiffness and strength of short clear wood specimens. The regional differences are likely linked to the length of juvenile wood production which increases as planting moves north and west from the South Atlantic region; the prevalence of summer moisture in the South Atlantic region allows for greater production of latewood (Jordan et al. 2008). Similar trends are reported for microfibril angle (MFA) transition which is a critical factor in lumber stiffness (Clark et al. 2006). Other study differences could be the initial planting density, the age at which treatments were applied, or the age at which thinning occurred.

The recent change in the design values substantiates the need to evaluate the wood supply chain to better understand the quality of the timber currently being harvested. Likewise, there is a need to understand the effects of intensive silviculture on wood quality which could lead to better decisions regarding silvicultural regimes, manufacturing technologies, sourcing decisions, marketing approaches, and lumber grading methods (e.g., visual grading versus machine grading). To investigate the mechanical properties of intensively managed loblolly pine, 93 trees from five mature stands were felled and sawn into lumber. The resulting lumber was dried, graded, and destructively tested in bending according to ASTM D198 (ASTM International 2014a) standards. The objectives of the study were to (1) compare the mechanical properties of lumber sawn from intensively-managed loblolly pine stands located on the Georgia Lower Coastal Plain to the current and previous design values for MOE and F_b for visually graded southern pine lumber, and (2) calculate correlations between MOE and MOR for the lumber samples.

2 Materials and methods

2.1 Stands

Trees used in the present study were harvested in 2013 within the Lower Coastal Plain near Brunswick, Georgia. The stand and tree characteristics are listed in Table 1. A total of 93 trees were felled from five stands with ages ranging from 24 to 33 with SI_{25} from 25.3 to 27.4 m. These stands represent the current expectation of growth rates for stands in this region and have greater growth than prior published mill studies (Kretschmann and Bendtsen 1992; Biblis et al. 1995; Ledford et al. 2015). Tree selection was conducted as a proportion of the 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 not included in the sampling process.

Felled trees were bucked in the woods into approximately three 5.2-m logs. A total of 269 logs were transported to the participating mill where they were run through an optimized Chip-n-Saw headrig, gang saw, edger, and then sawn into 2 × 4, 2 × 6, 2 × 8, and 2 × 10 lumber. The lumber was not processed with an optimized trimmer in order to keep all the lumber at 4.9-m lengths to prevent warping due to uneven lengths within a package in the cooperating mills dry-kiln. Additionally, the sawing solution was forced into sawing nominal two-inch material (2 × 4 etc.,) and not any nominal one-inch material (1 × 4 etc.,) as the focus of the study was on the mechanical properties of dimension lumber. The lumber was stickered, dried to below 19 % moisture content, planed, and graded into No. 1 and better (No. 1), No. 2, and No. 3 by Timber Products Inspection, Inc. certified graders from the

Table 1 Stand and felled tree characteristics

Stand	Age	Stand				Felled tree		
		Site index (m)	Diameter at breast height (cm)	Trees per hectare (No)	Basal area (m^2/ha)	No. felled	Average height (m)	Diameter at breast height (cm)
S1	24	27.4	28.7	721	49	21	27.3	30.6
S2	25	27.1	29.5	415	30	20	27.3	30.9
S3	26	25.6	31.5	442	35	21	27.1	31.7
S4	27	26.2	29.7	442	32	21	25.7	30.9
S5	33	25.3	33.0	208	21	10	27.5	33.0

cooperating mill. A total of 841 pieces of lumber 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. No. 1 grade made up 158 pieces (19 %), No. 2 grade was 609 pieces (72 %), and No. 3 grade was 74 pieces (9 %).

2.2 Specimen preparation and testing

Sawn lumber was transported to the wood quality laboratory in Athens, GA where the sample dimensions, visual grade, moisture content, specific gravity and presence or absence of pith were recorded. The average moisture content of the lumber was 11.2 % with a range from 8.5 to 17.2 %. Prior to testing the lumber was trimmed to the test span with the predicted worst defect included randomly within the test span region (ASTM D4761).

The edgewise destructive bending test setup was done according to ASTM D198 (ASTM International 2014a) and ASTM D4761 (ASTM International 2013) via four-point bending setup in third-point loading (load heads positioned one-third of the span distance from the reactions) on a universal testing machine. The span to depth ratio was 17 to 1 (2 × 4: 1511–89 mm, 2 × 6: 2375–140 mm, 2 × 8: 3131–184 mm, 2 × 10: 3994–235 mm). The tension (bottom) face of each sample was randomly selected (ASTM D4761). Deflection was measured using a string pot transducer. The deflection was synchronized with load-level in the elastic range and used to determine the MOE; MOR was calculated from the maximum load.

A series of adjustments [refer to Dahlen et al. (2013, 2014b) for calculations] with the data were done in order to compare the results to the design values which are published at 15 % moisture content (ASTM D1990). MOE is published at 21–1 span to depth ratio with uniform loading and deflection measured at midspan (ASTM D1990; ASTM D2915). The MOE of each sample was adjusted according to 15 % MC and third point uniform loading in 21–1 loading conditions (MOE_{15}) (ASTM D1990, ASTM D2915, Dahlen et al. 2013, 2014b). The mean values are reported as well as the values after rounding to the nearest 100,000 psi (0.7 GPa) (ASTM D1990). The MOR of each sample was adjusted to 15 % MC (ASTM D1990, Dahlen et al. 2013, 2014b). To calculate F_b, the dimensions of each piece were adjusted to 15 % MC (MOR_{15}) then to a characteristic length of 3.66 m for 2 × 4, 2 × 6 and 2 × 8 material and to 6.1 m in length for 2 × 10 material and divided by a 2.1 safety factor (ASTM D1990, Dahlen et al. 2013, 2014b; Evans et al. 2001). F_b is the nonparametric 5th percentile at 75 % confidence (ASTM D2915; FPL 2011); however given the limited sample size in some combinations of grade and size this value could not be calculated. The characteristic MOR ($CMOR_{15}$) was calculated for each piece to allow for better comparisons between sizes for MOR; the $CMOR_{15}$ is defined as the 2 × 8 size (38 mm × 184 mm × 3.66 m). The characteristic bending strength (CF_b) was calculated by dividing the $CMOR_{15}$ by 2.1. The measured specific gravity of each piece was adjusted to 15 % moisture content (SG_{15}) using the measured specific gravity, volumetric shrinkage value of loblolly pine of 12.3 %, a fiber saturation point of 28.7 %, and a scale factor to account for higher/lower shrinkage at higher/lower specific gravity of each piece compared to the tabular values (Glass and Zelinka 2010; Kretschmann 2010).

2.3 Statistical analysis

The statistical analysis and associated graphics were done 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), car (Fox and Weisberg 2011), and multcompView (Graves et al. 2012). The mean, median, standard deviation and coefficient of variation (COV) was calculated for MOE_{15}, MOR_{15}, $CMOR_{15}$, and SG_{15} with guidance from ASTM D2915 (ASTM International 2010). The F_b strength value was calculated using the non-parametric 5th percentile at 75 % confidence (FPL 2011). Because some samples did not have enough observations to adequately describe the bending strength values using the nonparametric approach, the value was estimated using the parametric 4th percentile value. The

4th percentile values provided similar results as the non-parametric 5th percentile value at 75 % confidence for groups that had a relatively high number of samples (Nos. 2 2 × 6 and 2 2 × 8). The estimated 4th quantile was calculated for MOE_{15}, MOR_{15}, $CMOR_{15}$, and SG_{15}. The MOE_{15}, F_b, and CF_b values were compared to the current and previous design values (AFPA 2005; ALSC 2013). Analysis of variance at the 0.05 significance level was used to determine significant differences in MOE_{15}, MOR_{15}, and SG_{15} by failure type (tension, compression, combined tension and compression, shear). A *t* test was run to determine significant differences in lumber properties for lumber that failed directly at a knot compared to failing at clear wood. To determine the effect of pith a *t* test was conducted overall on each grade and overall on each size. The coefficient of determination (R^2) was determined between MOE_{15} and $CMOR_{15}$ with a linear model.

3 Results and discussion

3.1 Overall grade distribution

The overall mean MOE_{15} and MOR_{15}, $CMOR_{15}$ values by grade are presented in Table 2. Significant differences in MOE_{15}, MOR_{15}, $CMOR_{15}$ and SG_{15} were found due to lumber grade (Nos. 1, 2, and 3) and size (2 × 4, 2 × 6, 2 × 8, and 2 × 10) at the 0.05 significance level using Tukey's test. There were significant differences in the mechanical properties by grade (all *p* values <0.0001) with the No. 1 grade having significantly higher values than the other. The MOE_{15} and the characteristic $CMOR_{15}$ values follow a similar trend of increasing values with better grade for the Nos. 1–3 grades (Fig. 1). While the results are not surprising that better grades have better properties because they carry different design values, the results differ from those found by Madsen and Nielsen (1992) on testing in the Hem-Fir species group where the No. 2 grade was stronger and stiffer than the No. 1 grade. Madsen and Nielsen (1992) also found in testing on Douglas-fir and Spruce-Pine-Fir that the No. 1 grade was only marginally better than the No. 2 grade. For southern pine, Green and Evans (1988) report marginally better No. 1 values than No. 2 values from testing from the 1980s in-grade test. No. 1 material was not tested in the recent re-evaluation of southern pine because the ASTM D1990 (ASTM International 2014b) standards states that design values can be derived from testing the select structural and No. 2 grades in the 2 × 4, 2 × 8, and 2 × 10 sizes. The COV values for the No. 2 grade material bending stiffness and bending strength (21 and 34 %, respectively) are less than what Dahlen et al. (2012) report for 2 × 4 material (31 and 42 %, respectively). This likely resulted from the stands

Table 2 Overall results by grade

Grade	*N*	MOE_{15} (GPa)				MOR_{15} (MPa)				Characteristic MOR_{15} (MPa)				SG_{15}			
		Mean	Median	COV (%)	4th	Mean	Median	COV (%)	4th	Mean	Median	COV (%)	4th	Mean	Median	COV (%)	4th
No. 1	158	11.9a	11.7	18	8.5	46.5a	45.1	31	25.9	42.5a	42.5	25	24.5	0.53a	0.53	9	0.45
No. 2	609	10.6b	10.4	21	7.3	39.1b	37.4	34	20.3	35.4b	34.3	32	18.4	0.50b	0.50	10	0.43
No. 3	74	9.3c	9.3	23	6.5	33.3c	31.7	43	12.8	28.6c	27.5	41	11.1	0.50b	0.49	9	0.44
Overall	841	10.7	10.5	22	7.3	40.0	38.3	35	20.0	36.1	35.4	33	17.8	0.51	0.51	10	0.43

All *p* values <0.0001

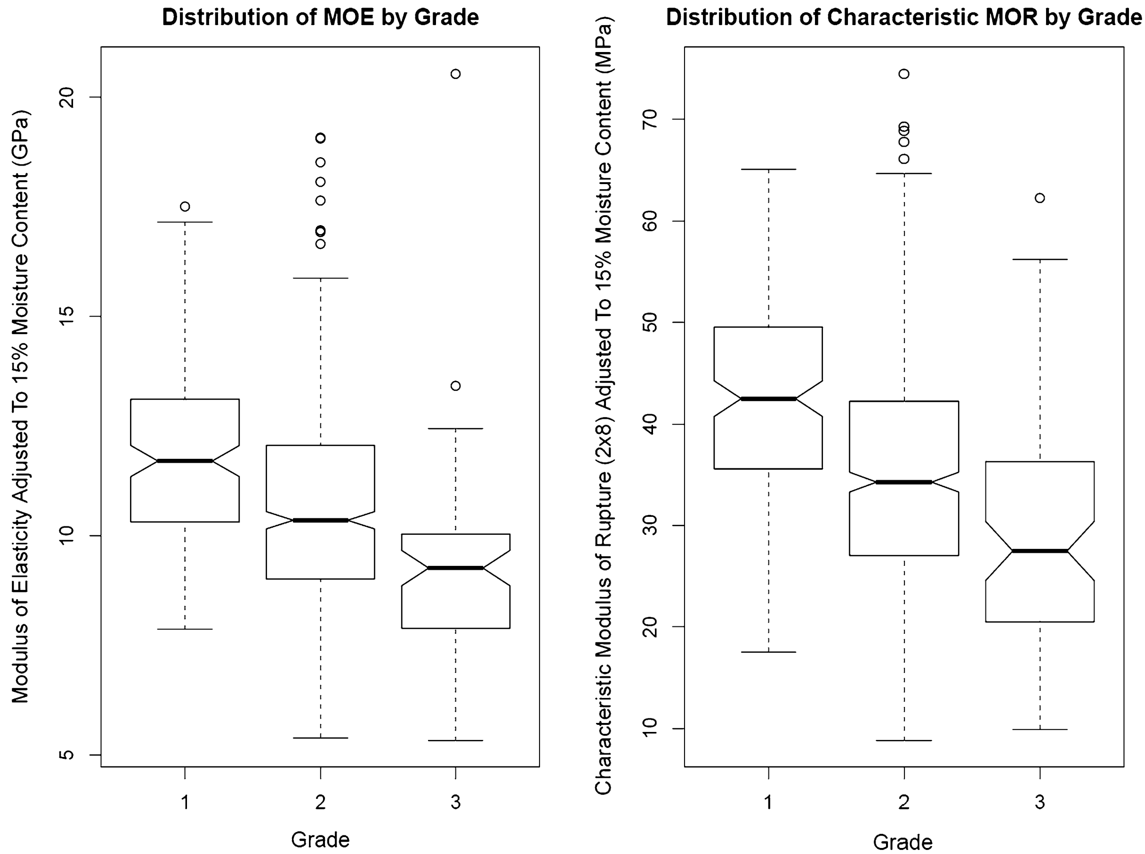

Fig. 1 *Boxplot* of modulus of elasticity (*left*) and characteristic modulus of rupture (*right*) (2 × 8) by lumber grade. The *boxplots* show outliers as dots, the minimum value except outliers, 1st quartile (25 %), median, 3rd quartile (75 %), and maximum value except outliers

being of similar age compared to the normal variability in age associated with the raw material normally sawn by a mill.

Comparisons to the current and previous design values for bending stiffness (MOE_{15}) and characteristic bending strength (CF_b) by grade for grades Nos. 1, 2 and 3 are shown in Table 3. The No. 1 grade MOE_{15} (11.9 GPa) was greater than the current (11.0 GPa) design value and comparable to the previous (11.7 GPa) design values. The No. 2 grade MOE_{15} (10.6 GPa) was greater than the current (9.7 GPa) design value but slightly less than the previous (11.0 GPa) design values. The published design values are rounded to the nearest 100,000 psi (0.7 GPa) and thus the results are very similar to the non-rounded value (10.8 GPa) found in the bending dataset from the 1980s in-grade testing program (Green and Evans 1988). The No. 3 grade MOE_{15} (9.3 GPa) was greater than the current (9.0 GPa) design value and comparable to the previous (9.7 GPa) design value after rounding (9.7 GPa) according to ASTM D1990. These results point to the MOE_{15} mean values being reasonably comparable to the previous design values and they currently exceed the current design values for visually graded southern pine lumber. The characteristic bending strength values for all grades were comparable to the previous design values and greater than the current design values. While these results represent a small proportion of the trees, stands, and lumber grown and cut from the Coastal Plain in Georgia, they do indicate that lumber cut from stands with similar characteristics such as planting density, age, and current trees per acre within the Coastal Plain should meet the current design value specifications for visually graded lumber. Based on the results further studies in different regions seem appropriate given the differences in the age of transition from juvenile to mature wood that occur between the regions (Jordan et al. 2008).

3.2 Size and grade distribution

The breakdown of property values by size and grade combination is shown in Table 4. For MOE_{15} the values were relatively comparable to the previous design values with some grade and size combinations being greater than the previous design values while other combinations being less than the previous design values. Most importantly, each size and grade combination met or exceeded the current design

Table 3 Comparison of modulus of elasticity (MOE_{15}) and characteristic bending strength (CF_b) (2 × 8) adjusted to15 % MC versus the current and previous design values

Grade	*N*	MOE	MOE after rounding	Current design value	Previous design value	Order statistic[a]	Characteristic F_b	4th Quantile	Current design value[b]	Previous design value[c]
No. 1	158	11.9	11.7	11.0	11.7	6	10.4	11.7	8.6	10.3
No. 2	609	10.6	10.3	9.7	11.0	27	8.5	8.8	6.4	8.3
No. 3	74	9.3	9.7	9.0	9.7	2	5.0	5.3	3.6	4.8

[a] The order statistic is the Xth lowest piece which is used to determine the bending strength (F_b)

[b] American Lumber Standards Committee (2013)

[c] American Forest & Paper Association (2005)

values for southern pine. Then it was determined if MOE varied by size for each grade combination. For the No. 1 grade there was a significant difference in MOE_{15} by size (*p* value <0.0001) with the 2 × 4 size being significantly greater than the 2 × 6 and 2 × 8 size. For the No. 2 grade, there was a significant difference in MOE_{15} by size (*p* value <0.0001) with the 2 × 10 size being significantly greater than the 2 × 6 and 2 × 8 size and the 2 × 4 size being significantly different from the 2 × 6 size. These results are somewhat similar to results found by Dahlen et al. (2014b) where larger lumber sizes (2 × 10) had significantly higher MOE_{15} values than the 2 × 6 and 2 × 8 sizes. For the No. 3 grade, there was no significant difference in MOE_{15} by size (*p* value = 0.81). The bending strength (F_b) values are more variable which could be attributed to the relatively small sample size of some grade and size combinations; the ASTM D1990 standard recommends that at least 360 samples be tested in order to generate design values. While the purpose of this work was not to develop design values it would be ideal if a greater number of samples was available for a more accurate comparison to the design values. In the No. 2 grade and 2 × 6 and 2 × 8 sizes, which have a higher sample size, the bending strength values exceed the previous design values.

These results suggest that when grown to maturity (i.e., 25 years) intensively managed loblolly pine can produce acceptable lumber and thus intensive management may not be the sole reason why the design values were lowered for southern pine. Another possible explanation for the decrease in design values is due to the recent economic downturn in the United States which caused lumber production to fall and thus sawlog prices significantly declined (Norris Foundation 2005–2014). This decline in sawlog prices may have caused many landowners to stop clear-cutting mature stands which would have caused more of the lumber to be produced from forest thinning's on younger stands compared to mature clear-cuts. These factors would result in a greater percentage of lower stiffness and strength juvenile wood being available in commerce. In 2014 the SPIB conducted follow-up testing on 362 samples of No. 2 2 × 4 (SPIB 2014). From this testing the SPIB report MOE_{15} and F_b values of 10.3 GPa and 9.3 MPa, respectively. This new testing revealed

Table 4 Comparison of modulus of elasticity (MOE_{15}) and bending strength (F_b) adjusted to15 % MC versus the current and previous design values

Grade	Size	*n*	MOE_{15}	MOE_{15} COV (%)	MOE_{15} current	MOE_{15} previous	Order statistic	F_b nonparametric	F_b 4th	F_b current	F_b previous
No. 1	2 × 4	25	13.2	17	11.0	11.7	1	10.4	12.8	10.3	12.8
No. 1	2 × 6	36	11.8	16	11.0	11.7	1	12.7	13.1	9.3	11.4
No. 1	2 × 8	71	11.3	17	11.0	11.7	2	10.0	10.6	8.6	10.3
No. 1	2 × 10	26	12.3	16	11.0	11.7	1	11.5	12.1	7.2	9.0
No. 2	2 × 4	77	11.1	27	9.7	11.0	3	8.5	9.9	7.6	10.3
No. 2	2 × 6	238	10.2	20	9.7	11.0	10	9.4	9.4	6.9	8.6
No. 2	2 × 8	255	10.7	20	9.7	11.0	10	9.2	9.2	6.4	8.3
No. 2	2 × 10	39	11.9	18	9.7	11.0	1	4.6	9.1	5.5	7.2
No. 3	2 × 4	18	9.1	20	9.0	9.7	–	–	7.0	4.5	5.9
No. 3	2 × 6	32	9.2	19	9.0	9.7	1	5.4	7.2	4.0	5.2
No. 3	2 × 8	21	9.5	31	9.0	9.7	–	–	5.3	3.6	4.8
No. 3	2 × 10	3	10.2	20	9.0	9.7	–		11.3	3.3	4.1

MOE_{15} and F_b values lower than the 1991 design values (11.0 GPa and 10.3 MPa) but greater than the current design values (9.7 GPa and 7.6 MPa). The increase in the results from the 2011 to 2014 testing could be because of the reduced number of combination knots in the 2014 sample (5 %) as opposed to (22 %) in the 2011 sample. An increase in the amount of combination knots would support the view that a higher percentage of younger material was being cut into lumber when the design values were updated because of the increase prevalence of branch whorls in a particular piece of lumber.

3.3 Failure type and effect of knots

The lumber that failed in tension or combined tension and compression had significantly lower MOE_{15} and $CMOR_{15}$ (p values <0.0001) than lumber that failed in compression (Table 5). For lumber that failed in shear the MOE_{15} values were not different from lumber that failed in compression but the $CMOR_{15}$ values were different. Since the 4th quantile of $CMOR_{15}$ for the pieces that failed in compression is approximately double those with the other failure types, it appears that compression face failures happened at relatively high loads. Bending strength values would likely be higher if the tension face had been selected based on defects and not randomly. Overall, 56 % ($n = 475$) pieces failed directly at a knot while 44 % ($n = 366$) pieces had failures not directly associated with a knot and 74 % of the samples failed at a location within the span under or between the two load heads. There was a significant difference in the mechanical properties with the lumber that failed at a knot compared to lumber that did not fail at a knot (p values <0.0001).

3.4 Mechanical properties in lumber containing pith

Lumber that contains pith originate from the center of the log and thus can contain a large percentage of juvenile wood. Overall 57 % of the samples contained pith ($n = 483$) (Tables 6 and 7). As lumber size increased the percentage of lumber pieces that contained pith increased. Overall, lumber that contained pith had significantly lower MOE_{15} (10.2 GPa) than lumber that did not contain pith (11.5 GPa), significantly lower MOR_{15} (35.5 MPa) than lumber that did not contain pith (46.1 MPa), and significantly lower SG_{15} (0.49) than lumber that did not contain pith (0.53) (all p values <0.0001). There was significant variation for all sizes except in the 2 × 10 size for MOR_{15}. Lumber with pith has a similar effect by grade as it does by size except for the No. 3 grade where there was no significant difference in MOE_{15} or $CMOR_{15}$. Lumber without pith would meet or exceed the previous design values for MOE_{15} in the Nos. 1 and 2 grades and lumber with pith would meet or exceed the current design values for MOE_{15} in these grades. These results follow a similar trend as reported by Dahlen et al. (2014a) where No. 2 2 × 4 material with pith had significantly lower mechanical properties than lumber without pith. However the results vary compared to results reported in Dahlen et al. (2014b) where there were no significant differences between lumber with and without pith in the larger sizes. The difference between the two findings can likely be tied to the lumber from this study coming from relatively even age stands whereas lumber in the Dahlen et al. (2014b) study was collected from multiple mills across the growing region and likely contained lumber from trees from a variety of ages. One key difference compared to the Dahlen et al. (2014b) study was that the samples that contained pith (0.49) had a SG_{15} equal to the samples with no pith (0.49) found in that study.

3.5 Relationship between characteristic modulus of rupture and modulus of elasticity

The data for the paired relationship between $CMOR_{15}$ and MOE_{15} are shown in Fig. 2 (Table 8). The coefficient of determination was 0.56 for the combined model and the 3.8 coefficient found was similar to the 4.4 coefficient found by

Table 5 Summary statistics for modulus of elasticity and characteristic modulus of rupture (2 × 8) adjusted to15 % MC by failure type and whether the specimen failed at a knot

Failure type	N	MOE_{15} (GPa)				$CMOR_{15}$ (MPa)			
		Mean	Median	COV (%)	4th	Mean	Median	COV (%)	4th
Tension	651	10.4b	10.1	21	7.2	34.2b	32.8	33	17.0
Compression	113	12.5a	12.4	16	9.2	46.7a	45.1	19	33.7
Tension and compression	59	10.4b	10.3	20	7.3	36.7b	36.2	33	18.9
Shear	18	11.9a	11.6	25	8.2	37.6b	38.4	28	22.9
Not at knot	366	11.5a	11.4	20	7.9	41.8a	40.8	27	24.4
At knot	475	10.2b	10.0	21	7.0	31.7b	31.0	33	15.3

Significant difference ($\alpha = 0.05$) indicated by (letters)

Table 6 The effect of pith on modulus of elasticity, modulus of rupture, and specific gravity in southern pine lumber adjusted to 15 % moisture content by size

Size	Pith (%)	Modulus of elasticity (15 %) (GPa)			Modulus of rupture (15 %) (MPa)			Specific gravity (15 %)		
		p value	No pith	Pith	*p* value	No pith	Pith	*p* value	No pith	Pith
2 × 4	26	<0.0001	12.0	9.2	<0.0001	55.8	38.6	<0.0001	0.54	0.47
2 × 6	47	<0.0001	11.0	9.5	<0.0001	42.9	34.4	<0.0001	0.53	0.49
2 × 8	71	<0.0001	11.7	10.3	<0.0001	42.9	35.0	<0.0001	0.53	0.50
2 × 10	90	0.02	13.8	11.8	0.17	44.0	38.3	0.03	0.54	0.51
Overall	56	<0.0001	11.5	10.2	<0.0001	46.1	35.5	<0.0001	0.53	0.49

Table 7 The effect of pith on modulus of elasticity, characteristic modulus of rupture (2 × 8), and specific gravity in southern pine lumber adjusted to 15 % moisture content by grade

Grade	Pith (%)	Modulus of elasticity (15 %) (GPa)			Characteristic modulus of rupture (15 %) (MPa)			Specific gravity (15 %)		
		p value	No pith	Pith	*p* value	No pith	Pith	*p* value	No pith	Pith
No. 1	58	<0.0001	12.6	11.3	0.0006	45.9	40.1	<0.0001	0.56	0.51
No. 2	59	<0.0001	11.5	10.0	<0.0001	39.5	32.5	<0.0001	0.53	0.49
No. 3	46	0.64	9.2	9.5	0.24	30.1	26.8	0.01	0.51	0.49
Overall	56	<0.0001	11.5	10.2	<0.0001	39.6	33.6	<0.0001	0.53	0.49

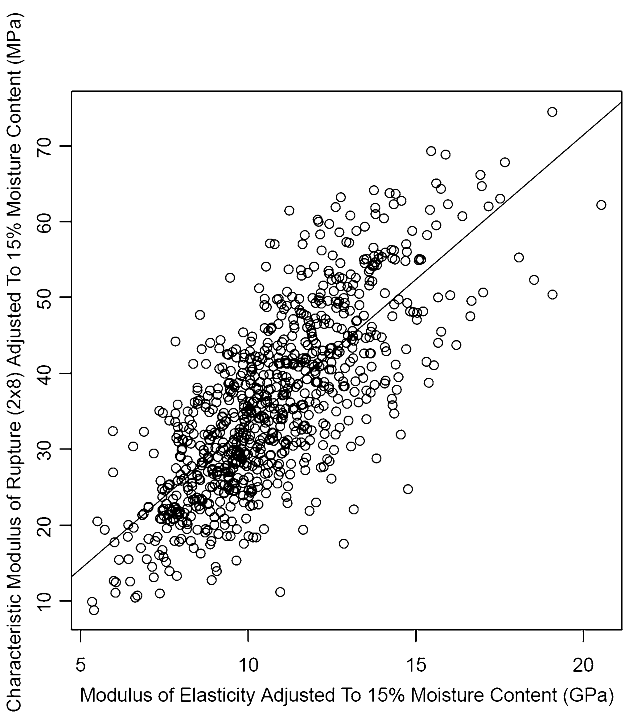

Fig. 2 Overall plot of characteristic modulus of rupture (2 × 8) vs modulus of elasticity adjusted to 15 % MC ($CMOR_{15}$ vs. MOE_{15})

Dahlen et al. (2012). Based on the results it appears that MOE and MOR are moderately correlated. The No. 2 grade material was similar to the overall results while the Nos. 1 and 3 had slightly lower coefficient of determination. These results are interesting and follow the logical trend for No. 3 material being lower given the larger knots but it was unexpected that the No. 1 grade material model would have a poorer fit than the No. 2 material. Perhaps with a larger sample size the relationship for the No. 1 material would be comparable to that for the No. 2 grade material. Overall while the coefficient of determination was not very strong the relationship still indicates that on average MOE can predict bending strength reasonably well.

Table 8 Coefficients of determination (R^2) values among modulus of elasticity and characteristic modulus of rupture (2 × 8) adjusted to 15 % moisture content (MOE_{15} and $CMOR_{15}$)

$CMOR_{15}$ versus MOE_{15}				
Grade	*N*	R^2	Intercept	Coefficient
No. 1	158	0.39	4.7	3.2
No. 2	609	0.56	−4.3	3.7
No. 3	74	0.50	−5.8	3.6
Overall	841	0.56	−4.8	3.8

p values of the regression models are all <0.0001

4 Conclusion

Due to the recent decline in southern pine design values it is imperative that industry determines the specific causes for the reductions in design values such that adjustments could be made throughout the supply chain. For this study lumber was cut from intensively managed stands sawn from stands located in the Coastal Plain in Georgia. Overall lumber quality was similar to the previous design values for southern pine and exceeded the current design values. The results suggest that intensively managed stands in the Coastal Plain of Georgia can produce acceptable quality structural lumber if given time to mature. This study did not address lumber sawn from intensively managed stands located in different physiographical regions or at a variety of ages. Due to the relative difficulty in converting logs into lumber it is important that models be developed to allow for prediction of lumber properties based on stand attributes.

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