Flexural Properties of Visually Graded Southern Pine 2x4 and 2x6 Structural Lumber

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Flexural properties of visually graded southern pine structural lumber were evaluated. Several grade controlling characteristics were considered relative to bending properties and compared with current design values. A total of 751 southern pine lumber specimens were obtained from a broad spectrum of regions in the southeastern United States. Visually graded No. 2, nominally two inch thick specimens, in four and six inch widths, were obtained from commercial sawmills. All specimens were evaluated by a certified grader in the laboratory. Actual dimensions, weight, and moisture content (MC) were measured. Growth and manufacturing related characteristics were identified and classified into two categories: strength reducing characteristics (SRC) and grade reducing characteristics (GRC). Specific gravity (SG), bending modulus of elasticity (MOE), and modulus of rupture (MOR), were determined for each specimen. The presence of knots was identified as the most significant SRC; their presence had the most significant impact on SG, MOE and MOR. For GRC, specimens with knots, warp and specimens that fell into the category none, were significantly lower in SG, MOE and MOR. MOE and the allowable design bending strength values yielded in this study met the current design value criteria for both widths tested.

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Keywords: Grading lumber; Strength; Knots; Strength reducing characteristics

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INTRODUCTION

The southern U.S. has large scale timber and lumber production, which makes this region the most important domestic lumber producer. (Wear and Greis 2002; McKeand *et al.* 2003). Most of the southern pine wood is used for structural lumber. It is readily available, sustainable, strong, dries rapidly, and can be easily treated. Southern pine wood products have a significant contribution to economic and ecological values of the region (Jordan *et al.* 2008; AWC 2012; Coyle *et al.* 2015).

Because wood is a material with wide variability in mechanical properties, there are many challenges associated with visually grading lumber for structural purposes. Structural lumber production requires methods to establish allowed properties, and simple ways to minimize variability. Graded material is sorted into categories called stress grades. In the U.S., visual grading has historically been used to assign strength and stiffness properties to structural lumber (Ritter 1990; Kretschmann *et al.* 2010).

The demand for wood products has been increasing since the end of the 2008 housing recession; this growth is due to increase in population and disposable income (Oswalt *et al.* 2010). Grading of structural lumber has long been recognized as an essential marketing practice, both from the standpoint of promoting safety in design and improving efficiency of utilization (Doyle and Markwardt 1966). The profitability of a sawmill that produces visually graded lumber is influenced by many factors, including resource characteristics, lumber quality and size, and how well the raw material is processed (Brännström 2009). Finding new ways to improve the grading system is an ongoing challenge for wood industry (Doyle and Markwardt 1966).

Visually graded lumber is classified based growth and production characteristics known as Grading Rules. This method, along with one or more types of nondestructive evaluation, is the origin of stress grading of structural lumber. Visual grading accounts for the fact that mechanical properties of lumber differ from clear wood, *i.e.*, they are necessarily lesser, because of the effect of growth and production characteristics. Since these characteristics are macroscopic, it is possible to see it and judge them by eye. The macroscopic characteristics are the used to assign allowable strength class. The most common visual sorting criteria are knots, slope of grain, shake, checks and splits, density, decay, heartwood and sapwood, pitch pockets, wane, growth rate, and pith (Piazza and Riggio 2008; Kretschmann *et al.* 2010).

The objectives of this study were to (1) determine the strength and stiffness in the 2x4 and 2x6 lumber commercially produced across southern pine growth regions, (2) determine the influence of sawing orientation (flat *vs.* quarter) on specific gravity (SG), modulus of elasticity (MOE), modulus of rupture (MOR), and an allowable design bending strength (F_b); and (3) determine the effect of grade controlling characteristics on SG, MOE, and MOR.

EXPERIMENTAL

Materials

A production weighted sample of southern pine lumber specimens was obtained and used in this study. Table 1 summarizes the specific details of the sample. A total 751 lumber specimens were collected. The specimens were nominally two inches thick and either four or six inches wide (2x4 and 2x6).

Table 1. Summary of Sample Size and Testing Setup

Groups	2 x 4	2 x 6
Specimens procured	363	388
Lumber length (m)	2.4, 3.0, 3.7, 4.2, 4.9	3.0, 3.7, 4.2, 4.9, 7.3
Testing span (m)	1.51	2.38

All specimens were selected randomly from the various geographical regions spread across the southern U.S. (Fig. 1). All the specimens were visually graded as No. 2. This lumber size and grade combination was chosen because it represents the largest volume of southern pine lumber produced and used by size and grade (SFPA 2005). The specimens were transported to the testing laboratory of the Department of Sustainable Bioproducts, Mississippi State University, Starkville, MS. All specimens were evaluated by a certified grader, per the national grade rule (SPIB, 2010), in the laboratory to insure they met appropriate grade criteria.

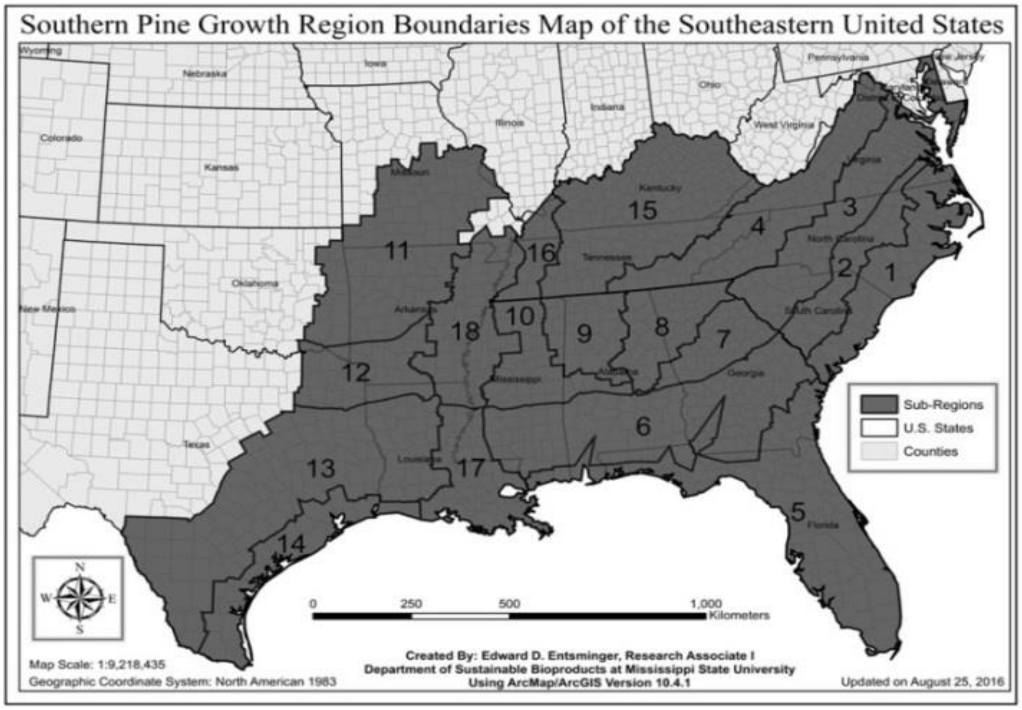


Fig. 1. Map of growth regions of southern pine. Adapted from Shelley (1989)

Methods

The following attributes were measured and determined for each specimen: cross sectional dimensions, weight, SG, and MC. All pieces were stored indoors in a humidity-controlled environment (conditioned to 12% equilibrium moisture content – temperature at 21.1 °C, and 65% relative humidity) during the evaluation process. Specific attention was placed on growth ring orientation within a specimen's cross section. It was noted whether the specimen was either flatsawn (growth rings tangent to the wide face of the specimen) or quartersawn (growth rings perpendicular to the wide face of the specimen). The certified grader identified grade and strength-controlling characteristics for each piece.

The edgewise bending test setup was conducted according to ASTM D198 (2015) via four-point loading and a span-to-depth ratio of 17 to 1 (Fig. 2). Both the tension face and the lengthwise positioning within the test fixture were randomly assigned (ASTM D4761, 2013). Load and displacement were continuously monitored using a calibrated load cell and displacement monitoring setup, and the rate of loading followed ASTM D4761 (ASTM 2012). MOE and MOR were determined for each specimen from their corresponding load versus deflection data.

A series of calculations was performed to adjust the measured MOE and MOR values for comparative purposes. Previous studies, and currently used design values, report values that are adjusted to a moisture content level of 15% (Evans *et al.* 2001; ASTM D1990 2016). The F_b yielded in this research was calculated using the nonparametric 5th percentile at 75% confidence and divided by 2.1 safety factor (ASTM D2915 2011; Evans *et al.* 2001). The SG of each piece was adjusted to MC 15%. The adjustments performed ensure the representativeness of the sample used in this work.

Fig. 2. Static bending test setup

The controlling characteristics were divided into two categories, strength reducing characteristics (SRC) and grade reducing characteristic (GRC). These characteristics can be knots or other types of defects that are presented in ASTM D4761 (ASTM 2014b). The grader specified the SRC and GRC and subsequently assigned a grade to each piece. Before the analysis, controlling characteristics that had a sample size less than 10 were grouped into a group called "other" for statistics and graphing purposes. For SRC, the controlling characteristics were divided into the following categories: (1) specimens with knots; (2) none, specimens that presented no controlling characteristics; (3) other, specimens containing: compression wood, handling damage, decay, sawcut, split, undersize, and worm pitch; (4) specimens with excessive slope of grain; and (5) specimens with wane. Meanwhile, controlling characteristic on GRC were divided into: (1) specimens with knots; (2) none, specimens that presented any type of the controlling characteristics; (3) other; (4) shake; (5) skip; (6) slope of grain; (7) wane; and (8) warp.

The statistical analyses and associated graphics were done in SAS 9.4 (2013) according to ASTM D2915 (2011). The mean, median, and coefficient of variation (COV) were calculated for SG, MOE, and MOR. The distributions that best fit SG, MOE and MOR data using normal, lognormal and Weibull distributions were selected using PROC UNIVARIATE and the histogram option of SAS.

RESULTS AND DISCUSSION

The MC of the specimens averaged 11.1% and ranged from 6.0 to 17.0%. Results obtained from static bending tests performed on the specimens are summarized in Table 2. The sample had an average specific gravity of 0.54. Note that there was no significant difference in the average SG (p = 0.5640) values observed for the two widths of lumber used. The lumber from this study had an average SG value that was greater than that reported by Dahlen *et al.* (2014a). It should be noted that the cited work only utilized 2x4 material. The mean SG value observed had similar characteristics of mature wood reported by Larson *et al.* 2001, and it was found to be slightly greater than that published for clear specimens of loblolly pine wood (FPL 2010).

Table 2. Summary Statistics for Specific Gravity (SG), Modulus of Elasticity (MOE), Modulus of Rupture (MOR) and Bending Strength (F_b) for No. 2 Grade, from 2x4 and 2x6 Southern Pine Lumber by Size

Size	Specific Gravity			MOE (GPa)			MOR (MPa)			F_b (MPa)
	Mean	Median	COV (%)	Mean	Median	COV (%)	Mean	Median	COV (%)	
2x4	0.55[ns]	0.54	11.4	10.2	10.2	23.9	51.1	49.7	34.3	11.2[a]
2x6	0.54	0.53	10.9	9.7	9.3	22.7	41.6	40.4	37.8	9.2[a]
Overall	0.54	0.53	11.2	9.9	9.7	23.5	46.1	44.4	37.4	–

[*]ns indicates no statistical difference at α = 0.05 within sizes
[a]Indicates F_b value met 2011 design value (8.6 MPa) after rounding to nearest 0.3 MPa, ASTM D1990 (2016).

The overall mean MOE was found to be 9.9 GPa. The mean values of MOE by size were 10.2 GPa for the 2x4 specimens and 9.7 GPa for 2x6 specimens. The mean MOR value for the entire sample was 46.1 MPa. A MOR mean value of 51.1 MPa was found for the 2x4 specimens. The average MOR value for the 2x6 specimens was 41.6 MPa. There was significant difference between sizes for MOE (p = 0.0020) and MOR ($p < 0.0001$) mean values. As expected, the COV for MOR (37.4%) was found to be greater than MOE (23.5 %). The F_b value ranged from 11.2 MPa to 9.2 MPa for 2x4 and 2x6, respectively.

For 2x4 samples, the MOE mean value met the previous design value (11.0 GPa), and it was similar to the previous study on southern pine 2x4 lumber (11.0 GPa) (Dahlen et al. 2014a). The 2x6 samples exceeded the current design value (9.7 GPa) (AFPA 2005, ALSC 2013) after rounding according to ASTM D1990 (2016).

For MOR, the overall mean value was lower than the overall mean value MOR (48.3 MPa) found in a prior test of southern pine 2x4 lumber (Dahlen *et al.* 2014a). The F_b value for both sizes are higher than previous and current design values. The F_b value for the 2x4 specimens was higher than the value found by Dahlen *et al.* (2014a) (9.1 MPa).

Overall, the majority (86.7 %) of the specimens were flatsawn (growth rings tangential to the wide face) (Table 3), and as previously noted, most of the specimens were tangentially sawn (2x4 specimens 87.3%, 2x6 specimens 86.1%). Flatsawn is often the most common breakdown method used for 2x4 and 2x6's lumber production because it is the most inexpensive way to manufacture logs into lumber and has a faster drying rate (Knight 1961; Wengert and Meyer 1993; Denig *et al.* 2000). That said, contemporary pine sawmills scan and cut for volume. Therein, logs may yield jacket boards as well as multiples or cants that will be resawn into lumber. In this case, the goal is maximum and rapid production rather than flat *vs.* quarter sawing, *per se*.

Table 3. Percentage and Number of Samples for Sawing Orientation of No. 2 Grade, from 2x4 and 2x6 Southern Pine Lumber

Size	Tangential	Radial
2x4	87.3 (n = 317)	12.7 (*n* = 46)
2x6	86.1 (n = 334)	14.0 (*n* = 54)
Overall	86.7 (n = 651)	13.3 (*n* = 100)

The sample size and percentage of SRC and GRC for overall samples and each size are shown in Table 4. The most abundant controlling characteristic in SRC was knot, representing 86%, followed by wane (6.0%) and slope of grain (4.8%). Only 1.5% of the specimens fell into the category none, which means that these specimens did not present any SRC, followed by the category other (1.7%). There was not much difference between 2x4 and 2x6 in percentage of knots (85.7% and 86.3%, respectively) and slope (4.1% and 5.4%, respectively); however, slope of grain as a GRC was much higher in 2x4's than in 2x6's (7.2% and 4.9%, respectively).

Table 4. Percentage and Number of Samples (*n*) for Strength Reducing Characteristic and Grade Reducing Characteristic of No. 2 grade, from 2x4 and 2x6 Southern Pine Lumber

Strength Reducing Characteristic			
Characteristic	2x4	2x6	Overall
Knot	85.7 (*n* = 311)	86.3 (*n* = 335)	86.0 (*n* = 646)
None	0.6 (*n* = 2)	2.3 (*n* = 9)	1.5 (*n* = 11)
Other	2.5 (*n* = 9)	1.0 (*n* = 4)	1.7 (*n* = 13)
Slope	4.1 (*n* = 15)	5.4 (*n* = 21)	4.8 (*n* = 36)
Wane	7.2 (*n* = 26)	4.9 (*n* = 19)	6.0 (*n* = 45)
Grade Reducing Characteristic			
Characteristic	2x4	2x6	Overall
Knot	10.5 (*n* = 38)	22.2 (*n* = 86)	16.5 (*n* = 124)
None	41.9 (*n* = 152)	31.5 (*n* = 122)	36.5 (*n* = 274)
Other	0.8 (*n* = 3)	4.5 (*n* = 18)	2.8 (*n* = 21)
Shake	0.8 (*n* = 3)	1.6 (*n* = 6)	1.2 (*n* = 9)
Skip	3.9 (*n* = 14)	5.7 (*n* = 22)	4.8 (*n* = 36)
Slope	1.4 (*n* = 5)	0.5 (*n* = 2)	1.0 (*n* = 7)
Wane	27.0 (*n* = 98)	23.2 (*n* = 90)	25.0 (*n* = 188)
Warp	13.8 (*n* = 50)	10.8 (*n* = 42)	12.3 (*n* = 92)

*In some cases, the grade reducing characteristic is the strength reducing characteristic. In other case it is not. Due to randomized lengthwise positions, the grade reducing characteristic was not always positioned between the load heads.

For GRC, it is important to emphasize that in some cases, the GRC is the SRC and because of that for GRC, most pieces (36.5%) were grouped in the category "none". Wane (25.0%) and warp (12.3%) were most prominent defects causing lumber downgrades. The findings in this study are in accordance with Shmulsky *et al.* (2005), who stated that the main degrading characteristics for southern pine lumber, especially for 2x4's are knots, wane and warp.

The effect of growth ring orientation (flatsawn and quartersawn) on the SG, MOE and MOR of southern pine lumber was examined on each dimension size (Table 5).

Table 5. Effect of Sawing Orientation on SG, MOE, MOR, and F_b in No. 2 Grade 2x4 and 2x6 Southern Pine Lumber

Size	SG		MOE (GPa)		MOR (MPa)	
	Tangential	Radial	Tangential	Radial	Tangential	Radial
2x4	0.55	0.51	10.5	8.4	52.7	40.4
2x6	0.55	0.53	9.8	9.0	42.1	37.2
Overall	0.55	0.52	10.1	8.7	47.2	38.6

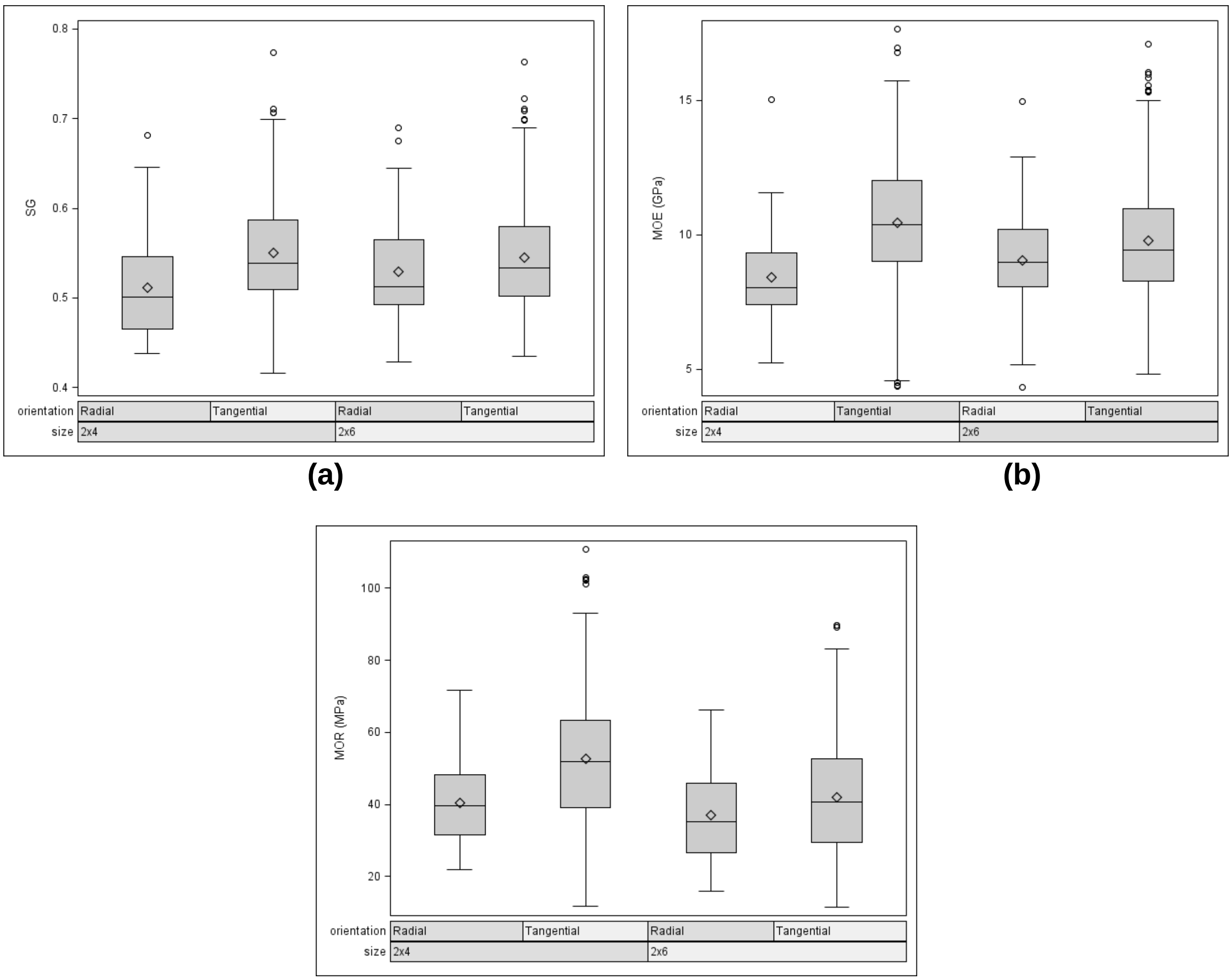


Fig. 3. Boxplot of (a) SG; (b) MOE; and (c) MOR of 2x4 and 2x6 No. 2 grade southern pine lumber by grain orientation. Boxplots: circles indicate outlies; diamonds indicate mean values, colored boxes indicate lower quartile, median and upper quartile; upper and lower bars indicate minimum and maximum values

It was found that growth ring orientation had a significant impact on SG, MOE, and MOR. The boxplots of SG, MOE and MOR by grain orientation are presented in Fig. 3. Specimens tangentially sawn were greater ($p < 0.0001$) in SG (0.55 *vs.* 0.52), MOE (10.1 *vs.* 8.7 GPa) and MOR (47.2 *vs.* 38.6 MPa). For 2x4 tangentially sawn had greater SG (0.55 *vs.* 0.51), MOE (10.5 *vs.* 8.4 GPa), and MOR (52.7 *vs.* 40.4 MPa). The same trend was found for 2x6 lumber, where tangentially sawn samples had significantly greater SG (0.55 *vs.* 0.53), MOE (9.8 *vs.* 9.0 GPa), and MOR (42.1 *vs.* 37.2 MPa). Similar results were found by Sarkhad *et al.* (2020) when studying bending properties of *Pinus sylvestris* and *Larix sibirica* dimension lumber. This pattern has been reported by other authors for southern pine, this type of lumber has a higher portion of mature wood than juvenile wood compared to lumber cut into quartersawn (Dahlen *et al*. 2014a,b).

The impact of SRC was statistically significant for SG ($p < 0.0001$), MOE ($p < 0.0001$), and MOR ($p < 0.0001$). Specimens that received knot as the SRC were significantly lower in all variables tested (SG 0.54; MOE 9.7 GPa; and MOR 43.8 MPa), which are in accordance with the findings in the literature. Koman *et al.* (2013) emphasized that the utilization of wood as a building material due to the characteristics that are inherent to wood, and knots are considered to be the most limiting characteristic and having the highest impact on overall properties of wood. Pieces that fell into the category "none" had the highest mean value for SG (0.59), MOE (12.7 GPa), and MOR (61.2 MPa) (Table 6). The boxplots for SG, MOE, and MOR versus GRC are shown in Fig. 4.

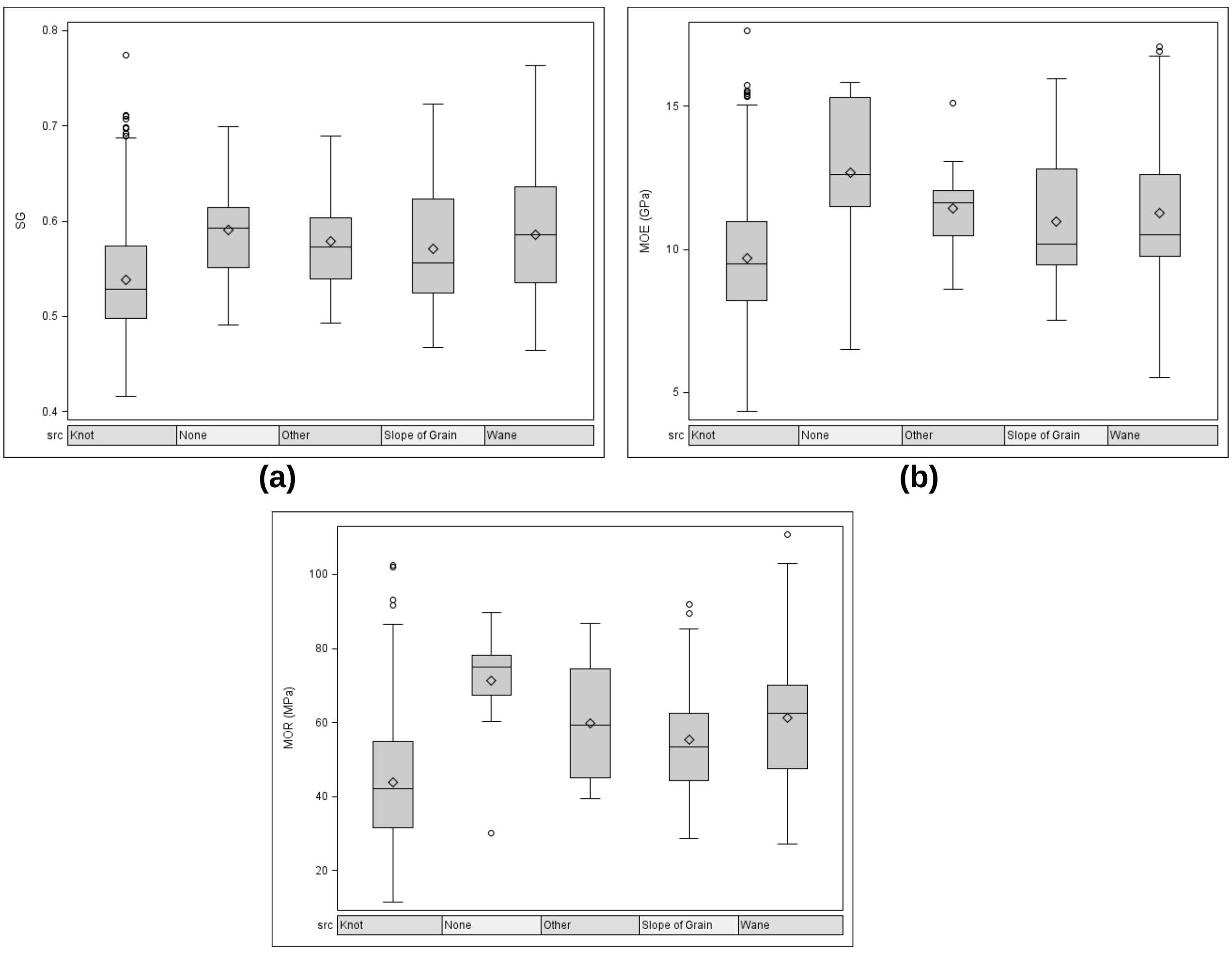
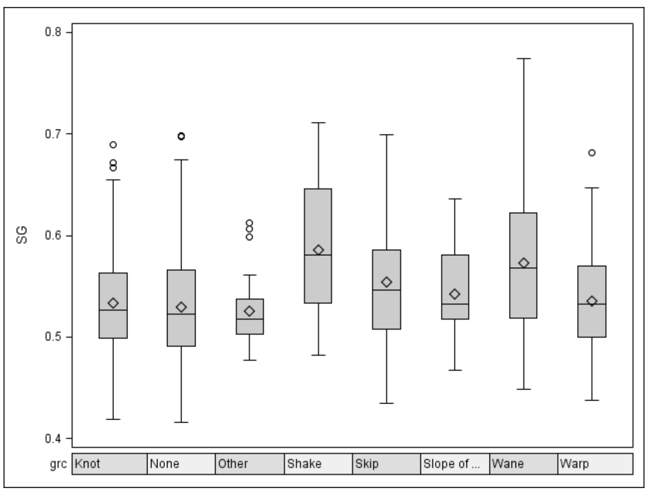
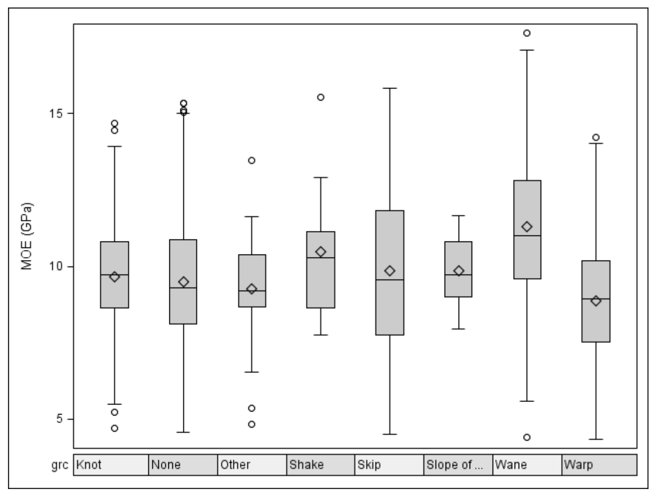


Fig. 4. Boxplot of (a) SG; (b) MOE; and (c) MOR of 2x4 and 2x6 No. 2 grade southern pine lumber by strength reducing characteristic (SRC). Boxplots: circles indicate outlies; diamonds indicate mean values, colored boxes indicate lower quartile, median and upper quartile; upper and lower bars indicate minimum and maximum values

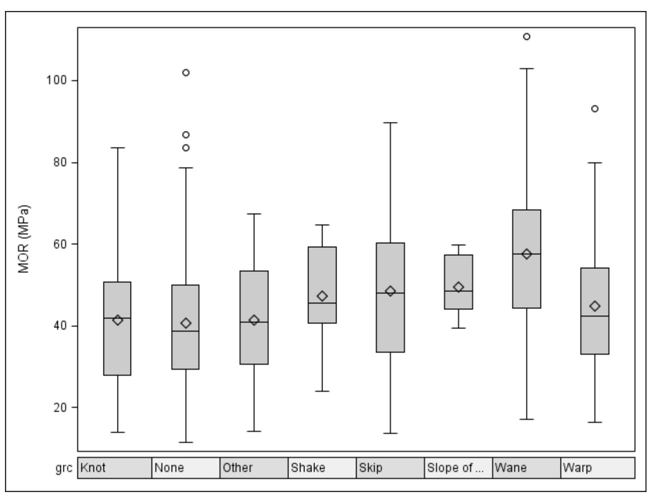
Table 6. Effect of Strength Reducing Characteristic (SRC) on SG, MOE, and MOR of No. 2 Grade 2x4 and 2x6 Southern Pine Lumber

SRC	N	SG			MOE (GPa)			MOR (MPa)		
		Mean	Median	COV	Mean	Median	COV	Mean	Median	COV
Knot	646	0.54b	0.53	10.8	9.7c	9.5	22.8	43.8c	42.3	36.6
None	11	0.59a	0.59	21.1	12.7a	12.6	21.1	61.2a	75.0	22.0
Other	13	0.58a	0.57	10.0	11.4ab	11.6	14.8	59.8ab	59.2	26.9
Slope	36	0.57a	0.56	11.5	11.0b	10.2	21.8	55.4b	53.4	27.8
Wane	45	0.59a	0.59	11.6	11.3ab	10.5	24.6	61.2ab	62.6	32.0
SRC with the same letters are not significantly different at α =0.05. Values with different letters are significantly different at α =0.05.										





(a) (b)



(c)

Fig. 5. Boxplot of (a) SG; (b) MOE; and (c) MOR of 2x4 and 2x6 No. 2 grade southern pine lumber by grade reducing characteristic (GRC). Boxplots: circles indicate outlies; diamonds indicate mean values, colored boxes indicate lower quartile, median and upper quartile; upper and lower bars indicate minimum and maximum values.

The overall results for GRC are shown in Table 7. For GRC, there was a significant impact of GRC in SG ($p < 0.0001$), MOE ($p < 0.0001$), and MOR ($p < 0.0001$). Pieces that fell into "other" category had the lowest SG (0.52), while pieces with warp showed the lowest mean value for MOE (8.9 GPa), and pieces in none the category had the lowest mean value for MOR (40.6 MPa). Pieces that contained shake had the highest mean value for SG (0.59), and pieces with wane had the highest mean value in MOE (11.3 GPa) and MOR (57.6 MPa). The boxplots for SG, MOE, and MOR versus GRC are shown in Fig. 5.

Table 7. Effect of Grade Reducing Characteristic (GRC) on SG, MOE, and MOR of No. 2 Grade 2x4 and 2x6 Southern Pine Lumber

GRC	N	SG			MOE (GPa)			MOR (MPa)		
		Mean	Median	COV (%)	Mean	Median	COV (%)	Mean	Median	COV (%)
Knot	124	0.53b	0.52	10.1	9.7bc	9.7	19.8	41.5b	42.0	37.0
None	274	0.53b	0.52	10.3	9.5bc	9.3	22.7	40.6b	38.8	36.6
Other	21	0.52b	0.52	7.7	9.3bc	9.2	22.2	41.5b	41.0	36.2
Shake	9	0.59a	0.58	13.8	10.5ab	10.3	23.8	47.3ab	45.6	30.3
Skip	36	0.55ab	0.55	11.9	9.9ab	9.6	26.5	48.6ab	48.1	41.1
Slope	7	0.54ab	0.53	9.8	9.9abc	9.7	12.2	49.5ab	48.5	15.3
Wane	188	0.57a	0.57	11.7	11.3a	11.0	21.0	57.6a	57.6	30.0
Warp	92	0.54b	0.53	9.6	8.9c	9.0	23.3	44.8b	42.3	33.7

Significant difference grade reducing characteristic indicated by different letters at $\alpha = 0.05$

CONCLUSIONS

1. The results of this research present an overall characterization of commercially produced of No. 2 grade, 2x4 and 2x6 southern pine lumber sampled from throughout its geographic distribution in the US.
2. The specific gravity (SG) was not statistically different between sizes. That finding suggested that both sizes routinely come from the same or similar timber resources.
3. The overall modulus of elasticity (MOE) met or exceeded the new design value. A statistically significant difference was present between sizes for MOE and modulus of rupture (MOR). The F_b for both sizes met or exceeded the previous and current design values.
4. A significant effect on southern pine properties was found due to sawing pattern, where flatsawn lumber had higher mean values than quartersawn lumber for all the tested properties.
5. The grade reducing characteristics (GRC) also had a significant effect on southern pine lumber, where warp was the main grader reducer for MOE, and the lowest MOR was found in specimens with no GRC.
6. For strength reducing characteristics (SRC), presence of knots was the main characteristic that reduced the strength of the material.

7. On the other hand, for GRC, lumber with shake presented the highest significant values in SG and lumber with wane had the highest mean values of MOE and MOR.

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