Determination of Flexural Strength of Structural Red and White Oak and Hardwood Composite Lumber

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Abstract

In this research, flexural properties of mill-run, in-grade red and white oak lumber from a single mill and commercially available laminated hardwood composite were evaluated. Structurally graded green (wet) freshly sawn red and white oak 5 by 10-cm (2 by 4-in) nominal lumber as well as glue-laminated hardwood composite billets were tested in bending and their modulus of rupture (MOR) and modulus of elasticity (MOE) properties were developed. It is well documented that MOR and MOE are two major indicators to evaluate flexural strength of wood lumbers. From these data, summary statistics, design values, and mean separations were calculated and reported. Overall, the red and white oak lumber performed similarly to structural No. 2 grade material. The hardwood composite billets were highly uniform. Each of the three materials demonstrated a reasonably good relationship between MOE and MOR, thereby suggesting that MOE could be used as a selection criterion for strength in a commercial use situation.

In recent decades, the North American trailer flooring industry has been incorporating new technologies. Trailer and truck decking materials, which were originally virtually all lumber and steel, have grown to include laminated wood, aluminum, fiberglass-reinforced wood, and fiberglass-reinforced plastics (Lu et al. 2009). Wood-based trailer decking is renewable and recyclable, thus, it is an ecofriendly product. For manufacture, wood-based decking is higher in energy efficiency and lower in carbon emission than steel, aluminum, and plastics. In addition, using more wood-based trailer flooring promotes both sustainable forestry and carbon sequestration, which decreases global warming. Solid sawn lumber has been used as truck and trailer decking for as long as trucks and trailers have been in service. It is recommended that trailer and truck decking should comprise suitable levels of flexural strength, stiffness, compression strength, abrasion resistance, and biological durability. In comparison to the original generation of flooring materials, contemporary production flooring materials for truck trailers have shown the enhanced mechanical properties, lighter weight, and higher service durability (Bumgardner 2007). In the United States, trailer and truck flooring has been produced using tropical hardwoods such as apitong for military trailers for several decades. Apitong is categorized as a crucial species for flooring material due to its remarkable characteristics, including appropriate strength, resistance to abrasion and decay, heavy thicknesses, and particularly clear pieces. In any application wherein long service life is required, apitong is an outstanding wood (Freeland 1938, Gerry 1952). Apitong is also a durable flooring material as a moderately resistant tropical hardwood. It has been reported that untreated apitong can last about 5 years for use as railway ties (Gerry 1952, Kukachka 1970). However, use of tropical hardwoods now has greater liability and less sustainability; apitong is classified as endangered. As such there is a current and pressing need to evaluate sustainable US hardwoods, particularly oak, for use in this application due to promising results of oak species as structural

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materials and vast growth distribution throughout the United States (Carmona et al. 2020). Additionally, laminated hardwoods, particularly oaks, have been used in domestic truck and trailer flooring applications. Thus, it seems appropriate to investigate newly developed hardwood composites for potential use in this application.

The research described herein is part of a larger program aimed at assessing the suitability of oak or hardwood composites for use in this application. Red and white oak have published design values associated with structurally graded material (Northeastern Lumber Manufactures Association [NeLMA] 2017). Per the NeLMA (2017) standard, the red oak group includes the following species: black (*Quercus velutina*), cherrybark (*Quercus falcate* var. *pagodaefolia*), northern red (*Quercus rubra*), southern red (*Quercus falcate*), laurel (*Quercus laurifolia*), pin (*Quercus palustris*), water (*Quercus nigra*), and willow (*Quercus phellos*) oak while the white oak group includes chestnut (*Quercus prinus*), live (*Quercus virginiana*), post (*Quercus stellate*), swamp chestnut (*Quercus michauxii*), white (*Quercus alba*), bur (*Quercus macrocarpa*), overcup (*Quercus lyrata*), and swamp white (*Quercus bicolor*) oak. As tested, the specifications for the glue-laminated hardwood composites permit any combination of American beech (*Fagus grandifolia*), ash (*Fraxinus* spp.), maple (*Acer* spp.), gum (*Liquidambar* spp.), birch (*Betula* spp. excluding paper birch [*Betula papyrifera*]), hickory (*Carya* spp.), oak (*Quercus* spp.), sycamore (*Platanus* spp.), tupelo (*Nyssa* spp.), honeylocust (*Gleditsia* spp.), and elm (*Ulmus* spp.)

With respect to the oak lumber, when compared to the softwood industry very few hardwood mills cut and grade species for structural applications. Thus, in order to develop a snapshot of contemporary oak properties, a single mill was selected as a source. Additionally, the existing design values for these species are based on adjusted small clear wood properties. During the 1980s and early 1990s a change in property assessment occurred wherein full-size in-grade specimens were tested. As such, it was appropriate to use full-size in-grade specimens in this research. This study did not aim to fully assess current design value properties and as such, multiple mills (sources) from multiple geographical ranges or areas were not considered. Similarly, material from a mill that produces commercial-scale glue-laminated hardwood billets, for use as access mats, was selected for consideration. In support of developing domestic sources for military truck and trailer decking, a snapshot of the flexural properties of mill-run, in-grade red and white oak lumbers from a single mill and a laminated hardwood composite were assessed. Therefore, the objective of this study was investigation of flexural properties of structurally graded red and white oak lumber as well as structural laminated hardwood composites for potential truck and trailer flooring applications.

Materials and Methods

Approximately 1,900 board feet (4.52 m^3, converting as 1 $m^3 = 35\ ft^3 = 420$ board feet) of white oak lumber and 1,900 board feet (4.52 m^3) of red oak lumber were ordered as 4.5 cm by 20 cm (1.75 in by 8 in) cross-sectional sizes (mat/board road, sound). Lumber was sawn at a mill in Attala County, Mississippi. Lumber was received at Mississippi State University in November 2020. Both species groups were received rough green. The laminated hardwood composite billets were ordered from a mill in central Arkansas. They were received as blanks approximately 6.98 cm (2.75 in) thick, 30.5 cm (12 in) wide, and 305 cm (10 ft) long. The adhesive used for the laminated hardwood composite was commercially available polyurethane. These were crosscut at midlength and thus each parent billet yielded two test specimens. Because the billets are comprised of random-length, butt-jointed hardwood lumber, there was no reason to consider the end matching of the billets in the statistical analysis. Through each billet's width, 1.9-cm (0.75-in)-diameter holes were drilled on 61-cm (24-in) center spacing. These repetitive holes were used to facilitate billet assembly into mats. Because this material is drilled as a part of the manufacturing process, it seemed appropriate to test billets with holes. Because the holes were located at middepth, that is, the neutral axis, their influence on strength was minimized. As a target volume, approximately 200 specimens each of white oak, red oak, and laminated hardwood composites were prepared.

Lumber was crosscut to approximate test specimen lengths of 203 cm (80 in); that is, specimens were of sufficient length to account for both the clear span plus a small amount of length to rest on the reaction blocks of the testing machine. Lumber was then rip-sawn on a bandsaw mill to an approximate 10.2 cm (4 in) width. As such, in that size (4.44 by 10.16 by 203 cm [1.75 by 4 by 80 in]) and condition, specimens were machined for testing (rough and green). Lumber was then stored under a water sprinkler to maintain its green/wet moisture condition prior to grading and testing. Lumber was stored for approximately 4 to 5 weeks under the sprinkler, solid packed, and at approximately 4°C to 10°C (40°F to 50°F) to minimize drying while awaiting testing. Lumber was then graded per the national grade rule (NeLMA 2017) and a breakdown of grade proportions was tabulated. These grade distributions are shown in Table 1.

Following grading of the oak, specimens were tested in third point bending per ASTM D198 (ASTM 2017b) on a 13,600-kg (30,000-lb.)-capacity screw-actuated Instron universal testing machine (Figs. 1 and 2). The span was set at 173 cm (68 in) thereby yielding a span-to-depth ratio of 17:1, for the 10.2-cm (4-in)-wide lumber. The rate of loading was controlled such that average time to failure was between approximately 4 and 5 minutes. Specimens were randomly positioned in the test fixture with respect to which edge was oriented up (in compression) as well as lengthwise across the 173 cm (68 in) long span. At the time of specimen placement in the fixture, at least 5.08 cm (2 in) of overhang was maintained at either end on the reaction supports. Center point deflection was measured with a deflectometer. The composite specimens were also tested per ASTM D198 (ASTM 2017b). The 6.98 cm (2.75 in) thick composites were tested over a 137 cm (54 in) span. This span created a 19.6:1 span-to-depth ratio. This span-to-depth ratio is slightly larger than that used for the oak lumber. This

Table 1.—Grade distribution; number of specimens (and associated percentage) in each grade by species.

Grade	Red oak: no. of pieces (%)	White oak: no. of pieces (%)
1	107 (52.5)	109 (53.4)
2	64 (31.4)	58 (28.4)
3	19 (9.3)	27 (13.2)
4	14 (6.9)	10 (4.9)

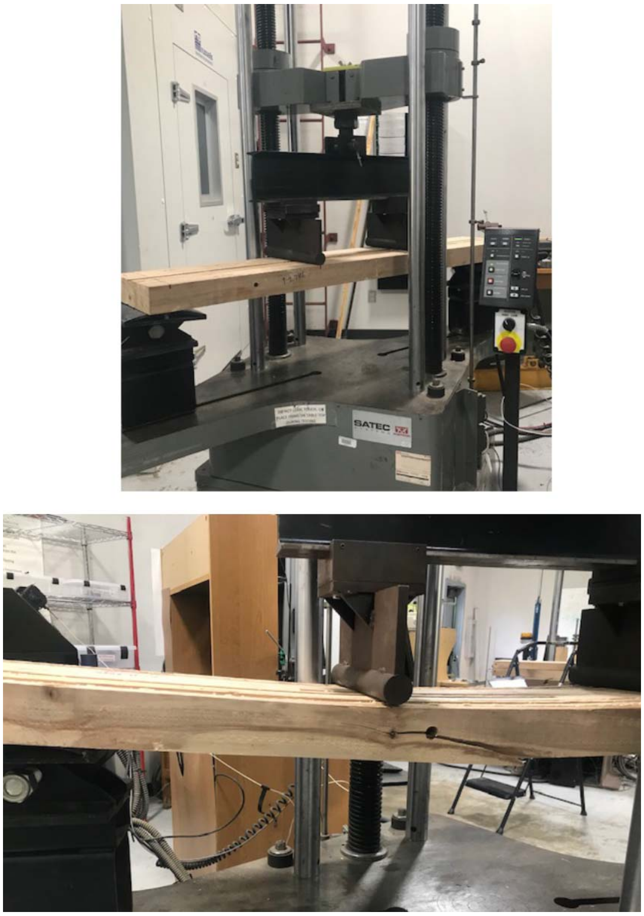


Figure 1.—Hardwood composite billets on Tinius Olsen machine before (upper panel) and after (lower panel) failure (ASTM D143-14 [ASTM 2017a]).

Figure 2.—Red oak lumber on Tinius Olsen machine before (upper panel) and after failure (lower panel) with the type of failure in static bending cross-grain tension (ASTM D143-14 [ASTM 2017a]).

larger ratio was chosen in order to increase the likelihood of locating one of the billet's drilled holes within the middle third (maximum moment zone) of the specimen. Both ratios (17:1 for lumber and 19.6:1 for composites) are within the permissible range, i.e., 17:1 to 21:1 in ASTM D-198, and the formulae for MOR and MOE take these into account. During each test, maximum load and load-deflection curves were captured. From these, MOR and MOE were calculated, respectively. Additionally, from the MOR data, fifth percentiles were calculated both parametrically and nonparametrically, per ASTM D2915 (ASTM 2017d). That standard allows for calculation by in different ways such that a distribution-independent fifth percentile can be developed. From each of these, the design fiber stress in bending values (F_b) is calculated by dividing the fifth percentile (either parametric or nonparametric) by 2.3 for hardwoods, per ASTM D245 (ASTM 2019).

Immediately following testing, moisture content and density specimens were cut from the ends of the lumber specimens. Moisture content was calculated per ASTM D4442-16 (ASTM 2017e), and specific gravity was calculated per ASTM D143-14 (ASTM 2017a). The authors acknowledge that an alternate, and more rapid, means of assessing specific gravity, that associated with ASTM D2395 (ASTM 2017c), could have been used. The authors chose ASTM D143 (ASTM 2017a) as a means of measuring specific gravity due to its accurate and reliable empirical nature as compared to the ASTM D2395 method, which is based on modeling. For the composite billets, because each of these was dry and was comprised of multiple species, basic density was measured and reported instead of specific gravity (Table 2).

Statistical Analysis

The experimental design was a completely randomized design, and data for the MOR and MOE results were analyzed using one-way analysis of variance (ANOVA). ANOVA was computed on the three material types. The statistical analysis was performed with SAS 9.4 (SAS Institute Inc., Cary, North Carolina), SAS (2013) to generate the linear mixed models (PROC GLIMMIX). For this analysis, the data sets for red and white oak were considered in their entirety (204 specimens each) and not separated out by grade. The *P* values for MOR and MOE were calculated and a statistical general linear mixed model was used for mean separations. Differences were considered significant with a *P* value less than or equal to 0.05.

Results

The summary statistics for the red and white oak specific gravity and the basic density of the hardwood composite billets are shown in Table 2. Table 2 also illustrates the moisture content (dry basis) at the time of testing. Table 3 illustrates the summary statistics for MOR and MOE as well as the parametric and nonparametric fifth percentiles and F_b for MOR, as per ASTM D2915-10 (ASTM 2017d). The design value for MOE is equivalent to the mean MOE.

Table 2.—Red and white oak green specific gravity, and composite hardwood billet density and moisture content (MC; percent dry basis) of all at the time of testing.

	Red oak		White oak		Composite	
	Specific gravity	MC (%)	Specific gravity	MC (%)	Density (kg/m^3)	MC (%)
Mean	0.58	80.7	0.64	63.8	613.51	13
Median	0.58	81.7	0.63	64	615.11	12.7
Min	0.54	60.7	0.53	46.9	565.45	9.5
Max	0.66	95	0.97	100.3	667.97	19.4

Table 4 illustrates the mean MOR and MOE for the red and white oak lumbers by grade. These results revealed that in all grades, both MOR and MOE of white oak lumbers were higher than MOR and MOE of red oak lumbers except for Grade 3.

The results of the ANOVA and mean separations are shown in Table 5. According to the results, there was significant interaction in both MOR ($P < 0.0001$) and MOE ($P = 0.0001$) among red and white oak lumbers as well as hardwood composite billets. Also of importance is the relationship between MOR and MOE. In the case of contemporary structural applications, MOE is often used as a predictor for MOR and truck and trailer decking would seemingly be no different. For each of the three materials—red oak, white oak, and composites—the relationships between MOR and MOE are shown in Figure 3 (Figs. 3a, 3b, and 3c, respectively).

Discussion

In this study, there were significant differences in both MOR and MOE properties between red and white oak lumber. In research by Merela and Cufar (2013) mechanical properties of sapwood and heartwood in red and white oak were investigated. The results revealed that there were no significant differences between sapwood and heartwood properties, but statistically significant differences were found between the bending strength and MOE properties of white and red oak. It is possible that the difference between white and red oaks can be, in part, based on their wood anatomy (Richter and Dallwitz 2000).

This research puts forth a snapshot of mechanical properties for structurally graded oak. For the red oak grade mix as tested, F_b and MOE were 23.13 MPa (3,355 psi) and 9.61 GPa (1.39 million psi), respectively. For red oak, as a comparison from NeLMA (2017), the F_b (800 psi [base] adjusted for 2 in by 4 in size [1.5], green moisture content [0.85], and 10-minute load duration [1.6]) and MOE values for the No. 2 grade 2 in by 4 in size are 1,632 and 1.2 million psi, respectively. For the white oak grade mix as tested, F_b and MOE were 25.35 MPa (3677 psi) and 10.28 GPa (1.49 million psi), respectively. For white oak, as a comparison from NeLMA (2017), the F_b (850 psi [base] adjusted for 2 in by 4 in size [1.5], green moisture content [0.85], and 10-minute load duration [1.6]) and MOE values for the No. 2 grade 2 in by 4 in size are 1,734 and 900,000 psi, respectively. These findings suggest that the grade mixes, as tested, demonstrated mechanical properties similar to those of No. 2 grade lumber. It should be noted that the nonparametric fifth percentiles were considerably lower than the parametric fifth percentiles. This finding suggests that there were a few pieces that were much weaker than predicted and that the MOR distributions were likely skewed to the left (low) tail. It is anticipated that these lower tails would shrink if the No. 4 grade lumber were culled from use. Results showed that, as tested, MOE could be used to predict MOR. In that case, automated nondestructive evaluation system(s) could potentially be used to classify and sort lumber. This action is favorable because lumber graders require extensive training, and they are not always readily available.

For the composite billets, the design values as tested, $F_b = 36.29$ MPa (5,263 psi) and MOE = 10.04 GPa (1.46 million psi), were highly uniform and predictable with coefficients of variation equaling 10.8% and 8.4% respectively. Given their structural properties, it seems that any of these three materials would be suitable for use as truck and trailer decking. The white oak would likely exhibit the greatest durability and biological resistance. The composite decking was the most uniform with respect to mechanical properties but because it permits less-dense species such as honey

Table 3.—Summary statistics for modulus of rupture (MOR) and modulus of elasticity (MOE) along with parametric and nonparametric fifth percentiles and F_b values.

	Hardwood composite billets		Red oak		White oak	
	MOR (MPa)	MOE (GPa)	MOR (MPa)	MOE (GPa)	MOR (MPa)	MOE (GPa)
Mean	54.31	10.04	43.36	9.61	46.53	10.28
Median	54.04	10.04	42.95	9.47	48.66	10.28
SD	5.87	0.85	12.48	2.17	12.69	1.82
Coefficient of variation	10.80%	8.40%	28.90%	22.60%	27.30%	17.70%
Minimum	38.66	7.76	9.96	3.99	5.49	5.26
Maximum	67.78	12.05	76.9	14.58	82.43	14.54
n	200	200	204	204	204	204
K factor[a]	1.723		1.723		1.723	
Parametric 5%	83.46		53.21		58.31	
Parametric F_b	36.29		23.13		25.35	
Order statistic	8		8		8	
Nonparametric 5%	46.7		25.66		31.36	
Nonparametric F_b	20.3		11.15		13.63	

[a] K factor = Once sided tolerance limit, for normal distribution, based on sample size and confidence interval. In this case, 95% tolerance limit at the 75% confidence level. ASTM D2915 (2017d).

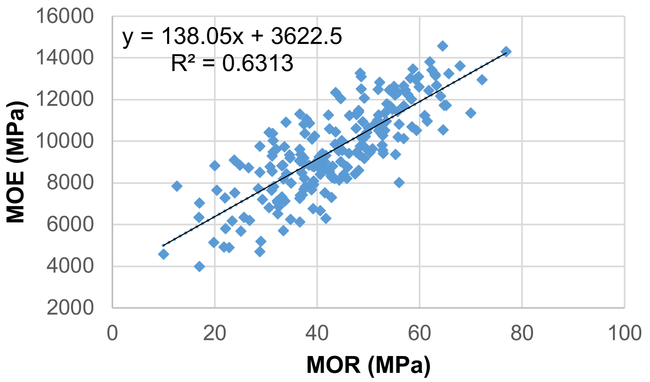
Table 4.—Mean modulus of rupture (MOR; MPa) and modulus of elasticity (MOE; GPa), by lumber grade, for the red and white oak specimens.

	MOR (MPa)		MOE (GPa)	
Grade	Red oak	White oak	Red oak	White oak
1	43.41	48.1	9.56	10.56
2	43.27	45.79	9.55	10.03
3	43.2	41.32	9.65	9.51
4	43.55	47.86	10.18	10.7

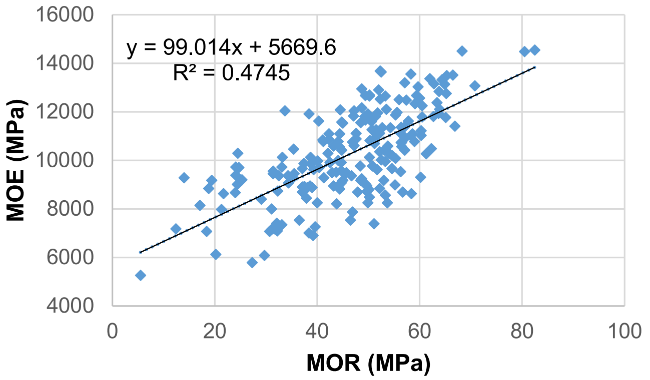
Table 5.—Mean modulus of rupture (MOR) and modulus of elasticity (MOE)values along with P *value levels of significance as well mean separations. Materials with the same letter were not statistically different from each other at the* $\alpha = 0.05$ *level of significance. Red oak and white oak include all specimens across all grades.*

Material	MOR (MPa)	MOR mean separation	MOE (GPa)	MOE mean separation
Composite billets	54.3	A	10.04	A
Red oak	43.35	B	9.61	B
White oak	46.53	C	10.28	A
SEM	1.0793		0.1703	
P value	<0.0001		0.0001	

(a) Red oak



(b) White oak



(c) Hardwood composites

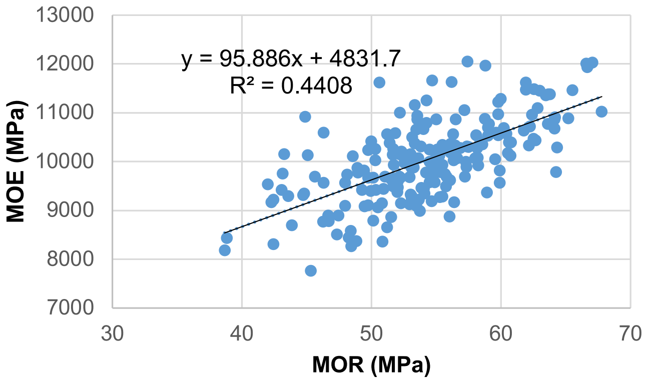


Figure 3.—Relationship between modulus of rupture (MOR) and modulus of elasticity (MOE) for (a) red oak, (b) white oak, and (c) hardwood composite billets.

locust, sweetgum, and sycamore its abrasion resistance would not likely match that of red or white oak. Additionally, because the composite billets contain lumber from nondurable species, the billets would need to be treated with preservative before potential use.

The relationships between MOR and MOE are reasonably good with r^2 values ranging from 0.44 to 0.63 (Figure 3). The hardwood composite billets showed the lowest r^2 value and this is not surprising as that was the most uniform and least variable material.

Conclusion

The aim of current study was to determine the flexural strength of structural red and white oak and hardwood composite lumber. Each of the three materials showed a significant interaction between MOE and MOR. Current findings revealed that the mechanical properties of the grade mixes, as tested, resembled that of No. 2 grade lumber. Nevertheless, each of the three materials could be suitable candidates for using in truck and trailer decking, while the highest durability and biological resistance was in white oak.

In order to increase the reliability of current research, further research is needed to determine flexural properties of red and white oak and hardwood composites that have been collected from multiple industrial units.

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