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Determination of flexural strength of structural red and white oak and hardwood composite lumber

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In this research, flexural properties of mill-run, in-grade white oak and red oak lumber from a single mill and commercially available laminated hardwood composite were evaluated. Structurally graded green (wet) freshly sawn red oak 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.

DEDICATION

This thesis is dedicated to those who supported and guided me most through my life, my parents. You pushed me to always give my best efforts in any endeavor I pursue and you both never once stopped believing in me or my abilities. To them both I am forever thankful for all that they have done for me.

To my father, Alan. You have been a role model for me in every way a man should compose himself. You are a man of your word and the hardest worker I have ever met. You have taught me more than I can ever express. You were always there to pick me up when I was down, and to push me when I needed it. I cannot express the pride I have in being your son and how grateful I am for everything you have done for our family. Above all else you are a father, and the best one at that.

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INTRODUCTION

1.1 Research Summary

In this research, flexural properties of mill-run, in-grade white oak and red oak lumber from a single mill and commercially available laminated hardwood composite were evaluated. Structurally graded green (wet) freshly sawn red oak 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.

1.2 Materials Tested Background

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 structural 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 falcata* var. *pagodifolia*), northern red (*Quercus rubra*), southern red (*Quercus falcata*), 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 stellata*), 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.).

1.3 Research Objectives

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 white oak and red oak lumbers from a single mill and a laminated hardwood composite mill 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.

CHAPTER II

DETERMINATION OF FLEXURAL STRENGTH OF STRUCTURAL RED AND WHITE OAK AND HARDWOOD COMPOSITE LUMBER

2.1 Literature Review

2.1.1 The End of the Trade War? Effects of Tariff Exclusions on U.S. Forest Products in China

Forest product exports to the nation of China rose from $2 billion to $10 billion in the years of 2008-2018, as well as log exports rising from $5 billion to $11 billion. In 2019 lumber and log exports dropped 26% and 31% respectively, stemming from an international trade war centering around tariffs between China and the United States causing a value loss of $3 billion. This trade war works in a two-way variety stemming from the United States importing less of China's secondary wood products such as furniture, which has a negative demand effect for China's imports of American logs and lumber. The confidence interval used in this study suggests that with tariff elimination the United States imports to China of forest products could rise $1.06 billion in the long run, still leaving them far short of pre-trade war profits (Muhammad and Jones, 2021)

2.1.2 A Welfare Analysis of China's Tariffs on U.S. Hardwood Products

The United States has imposed tariffs on nearly half of all products imported from Chinese markets, and likewise China has imposed tariffs on nearly 70% of their exports to the United States. The forest products industry is a crucial part of the American economy as it accounts for nearly 4% of total manufacturing gross domestic product (GDP) with an annual production of nearly $210 billion. China plays a critical role in United States hardwood markets, because traditionally they have been the largest importer of hardwood lumber and logs. They experienced a yearly growth in imports until the trade war began. This article uses a EDM model as a means of comparative statistics to demonstrate the before and after change on markets stemming from the trade war. As China's import prices rise 23.5% their demand will drop by 11.51%. This affects United States hardwood producers by dropping lumber prices 1.5%, increasing domestic demand by .56%, and reducing production by .53%. This decrease in export demand will have a positive effect on the quality log supply available domestically to the consumer. This will have a negative effect on hardwood timberland owners and producers who will face significant losses. The expected loss to landowners and producers is negative $596.92 million as opposed to no tariffs on the logs (Zhang et al., 2020).

1.1.1 Timber Production, Timber Trade, and Tropical Deforestation

Tropical countries account for 15% of the total volume of global timber production and 11% of the value of global exports. The major tropical wood exporting countries are Malaysia, Ivory Coast, Brazil, Gabon and Congo. These countries all export forest products worth over $100 million annually. A study conducted in 1985 by (Poore et al.) found that less than 1 million ha. of 828 million ha. of tropical forest were practicing sustainable forest management and harvesting practices. This unsustainable harvesting and improper forest management have many negative consequences to indigenous folks living in these areas. Harvesting and hunting of natural wildlife are negatively affected as their ecosystem is damaged from improper harvesting techniques. Improper harvesting in these tropical lands often leads to irreparable damage to the forests because of improper use of equipment and inefficient logging practices (Burgess, 1993).

1.1.2 Deforestation in the Tropics

Tropical deforestation has numerous negative side effects for our planet and the local environment. Tropical deforestation at the present rate is expected to account for 15-30% of global carbon dioxide emissions contributing to the buildup of greenhouse gasses. Global efforts to limit greenhouse gas emission has been a primary effort by our society over the past few decades. According to this study 1/10th of 1% of remaining tropical forests are being managed properly for sustained productivity. This inefficient management practice not only affects our planet's carbon crisis, but also affects local environments in numerous ways. The ecosystems of tropical forests are home to half of the global species of wildlife. Conserving these tropical forests is vital in ensuring these species do not become endangered or extinct. Aside from wildlife, the poor management practices have a negative effect on indigenous people of the lands in which these forests grow. These people rely on these forests for hunting, fruits and nuts, and medicinal compounds. Poor management practices are draining these forests of resources available to the people who rely on them in their daily lives. These inefficient practices that cause such great damage include neglecting to use proper logging trails, which play a vital role in causing minimal damage to surrounding forest and wildlife (Repetto, 1990).

2.1.3 Grading and Properties of Hardwood Structural Lumber

Structural markets have traditionally been dominated by softwood lumber species. Hardwood species have been used for structural applications in the form of timbers for highway bridges and railways, railroad ties, pallets, and containers. The lack of 2 in. thick hardwood structural application stems from a low market acceptance and low profit margins in these applications. In order for 2 in. thick hardwood structural lumber to be a viable building material the price points must be competitive with that of softwood species used in these applications, specifically southern pine. To maximize profits on hardwood lumber it is necessary to have an efficient means of sorting hardwood logs during the milling process. Upon sorting the next necessary step in producing hardwood structural lumber will be establishing a relationship between consumers of structural lumber with proof of success in the necessary applications. (Green, 1990).

2.1.4 Mechanical Properties of Sapwood versus Heartwood in Three Different Oak Species

This research sought to explore the mechanical properties of sapwood and heartwood of white and red oak. The investigation found that there were no significant differences in mechanical properties between heartwood and sapwood, but found significant statistical differences between white and red oaks. This research sought to disprove the notion that sapwood has lower mechanical properties than that of heartwood, which is a commonly held belief throughout the wood science community. Red oak and white oak timbers were randomly collected from a lumber yard to determine their density and mechanical properties on a per species basis and on the basis of heartwood vs. sapwood. Following ANOVA, white oak sapwood was found to have the lowest density, while red oak sapwood was found to have the highest. This was followed by findings that within species groups of red oak and white oak a difference in density between sapwood and heartwood was not statistically significant. The authors of this article concluded that the hypothesis of sapwood being inferior to heartwood in mechanical properties was an incorrect assumption. They found these results through various calculations such as density, bending strength, MOE, compression strength, and hardness (Merela and Cufar, 2013).

2.1.5 Nondestructive evaluation of Red Oak and White Oak Species

This research sought to investigate the relationship between dynamic Modulus of Elasticity (MOE) calculated through acoustic based nondestructive testing (NDT) and static bending properties of red oak and white oak. Testing was conducted according to ASTM D143. In this research they sought to use the dynamic MOE as a predictor for MOE and MOR. 48 specimens of red oak were gathered along with 44 specimens of white oak from the Stair Builders and Manufacturers Association to be able to accurately represent the boards in supply of the staircase industry. Boards were evaluated in NDT through longitudinal wave vibration followed by static bending test. The results of this study found that the MOE for red oak was higher in the tangential direction than the radial. Also the MOE values for white oak were similar in the radial and tangential directions, however white oak had a higher MOR in the tangential direction. In regard to the accuracy of the evaluation tools as predictors of MOE and MOR, it was found that the Smarthumper and Fakkop NDT were more effective at predicting MOE and MOR, when compared to the Falcon Tool and density as the single predictors. Also, it was found that the radial MOE prediction was more effective in all three evaluations than that of tangential (Turkot et al., 2020).

2.1.6 The Wood Handbook- Wood-Based Composite Materials Panel Products, Glued-Laminated Timber, Structural Composite Lumber, and Wood-Nonwood Composite Materials

Structural glulam timber is one of the most historically used engineered wood products. Glulam consists of two or more layers of lumber glued together, with all of the grain oriented parallel to the length of the product. The laminations can be a maximum of 2 in. thickness and it is required that glulam be produced in an approved manufacturing plant. The size of the glulam is only limited by the manufacturing capabilities of the facility where it is produced. Often times these glulam members can be between 100-140 ft. long. The advantages of glulam are numerous as a building material. It has a great size capability, meaning it can be made larger than the trees it was harvested from. This is especially valuable in today's forest products industry because of the smaller stems that are being used in modern plants. Glulam also has the capability of being manufactured into a curved member, an advantage many of its substitute materials do not have. Another major advantage of glulam is the ability to use lower grade wood products and still produce a member with a high strength value. This is done by using higher grade lumber on the outside edges, which experience greater amounts of stress, and using lower grade lumber in the center of the member. The manufacturing of glulam can be broken down into four main phases. First, the materials need to be dried and graded. Second, the lumber must be end jointed, most commonly using a finger jointing method. Afterward, it is necessary to face bond, which involves planing the wide faces of the material followed by using an adhesive for gluing. Phenol resorcinol is the most commonly used adhesive in the face gluing process. Lastly, finishing and fabrication of the material occurs. This involves planning the outside edges of the glulam to ensure leftover adhesive is discarded. Finishing practices are dictated by appearance requirements for the three classifications of glulam timber: industrial, architectural, and premium. Industrial application has the lowest appearance requirements, while architectural the appearance of the member plays a big role. The highest grade appearance glulam members will be those classified as premium. After finishing, the fabrication of the material involves final cuts, and if necessary drilling holes required for the specific end use. Glulam that is used in high moisture content applications will be required to undergo a fifth step in the process of pressure treating with a preservative to be able to ensure performance in high moisture areas (Stark et al., 2010).

2.1.7 The Wood Handbook- Characteristics and Availability of Commercially Important Woods

Red oak predominantly grows in the eastern United States. Species that are included in the red oak species group are: northern red (*Quercus rubra*), scarlet (*Quercus coccinea*), Shumard (*Quercus shumardii*), pin (*Quercus palustris*), Nuttall (*Quercus nuttallii*), black (*Quercus velutina*), southern red *(Quercus falcata*), cherrybark *(Quercus falcata var.pagodifolia*) water (*Quercus nigra*), laurel (*Quercus laurifolia*), and willow (*Quercus phellos*). The red oak species group is indistinguishable from one another once sawn based on their characteristics. It must be distinguished in the standing tree form. Red oak products are easily distinguished from white oak, however, based on the size of latewood pores and the lack of tyloses. Due to the large latewood pores in red oak, it is very permeable to liquids, making it unsuitable for applications needed to contain liquids such as barrels. This can be altered with the use of sealants, but naturally red oak is not a suitable material for these applications. Red oak is primarily used in applications such as lumber, railroad cross-ties, mine timbers, fence posts, veneer, pulpwood, and fuelwood. Often the lumber produced from red oak is then used in applications such as flooring, pallets, furniture, and caskets.

White oak predominately grows within the southeastern United States. However, it can also be found naturally growing in the Central states, and throughout the Appalachian range. Species that are included in the white oak species group are: white (*Quercus alba*), chestnut (*Quercus prinus*), post (*Quercus stellata*), overcup (*Quercus lyrata*), swamp chestnut (*Quercus michauxii*), bur (*Quercus macrocarpa*), chinkapin (*Quercus muehlenbergii*) and swamp white (*Quercus bicolor*). Pores within white oak tend to be clogged with tyloses, which allow for distinction from red oak, and also make them suitable for end applications where it is necessary to be impenetrable to liquids. White oak wood is typically heavier than red oak. White oak is also known to be strong in decay resistance. End applications for white oak include lumber, railroad crossties, cooperage, mine timbers, fence posts, veneer, and fuelwood. A crucial application of white oak is in boat building where the heartwood is often requested for use because of its natural decay resistance.

Apitong, also known as keruing, is a tropical species naturally growing throughout Indonesia to Malaysia. There are more than 70 species that fall into the genus of *Dipterocarpus*, which are all sold under the name keruing. Typically, the name apitong is reserved for wood in this genus coming from the Philippines. Physical characteristics of keruing include the fact that the heartwood of this species group rangesfrom light to dark red brown and sometimes contains a purple hue. There is a high amount of resin ducts present in this species group making it a tough wood to treat with preservatives. Keruing is known as a moderately durable material. Common applications for material made of keruing are construction, framing for boats, flooring, pallets, veneer and plywood, railroad crossties, and truck flooring (Wiemann, 2010).

2.1.8 Physical and Mechanical Properties of Clear Wood from Red Oak and White Oak

The natural growth distribution of red oak spans from the eastern United States to the Central states. White oak is known to grow within the southern United States, the South Atlantic States, and Central states. Previous studies evaluating red and white oak species groups have found that they are strong performers in hardness, bending, and compressions strength. red oak and white oak are ring porous species that have high densities specifically within their latewood regions. Red oak and white oak have many common applications such as furniture, stairways, railroad ties, fence posts, and marine timbers. This research conducted testing to evaluate specific gravity, static bending strength, compression parallel and perpendicular to grain, and

Janka hardness. The results of this research found red oak to be higher in MOE and MOR values than white oak. MOE values found in this research were found to be comparable to that of the previous publication Newlin and Wilson (1917), but higher than those of Markwardt and Wilson (1935) and the Wood Handbook (Kretschmann 2010). MOR values of red oak were found to be higher than those of all three previous publications researching these topics. MOE values of white oak were found to be slightly lower than all three previous publications, while MOR values of white oak were found to be slightly higher than all three previous studies. This paper concludes that the mechanical properties of red oak and white oak have not experienced a significant change from the previous publications within the last 100 years. However, they did find that growth rings for both species had decreased when compared to past studies. The paper also concluded that red oak MOE and MOR were higher than that of white oak therefore showing a significant difference in mechanical properties between the two species groups (Carmona et al., 2020).

2.1.9 Advanced Wood Engineering: Glulam Beams

Glulam also known as glue laminated timber is a material that's origins can be dated back to the late 19th century in Europe. Glulam uses sawn lumber laminations that are bonded together with the use of adhesives to create the final product. Common applications for glulam include beams, truss members, joists, pedestrian bridges, and headers. Glulam beams have multiple advantages over alternative materials commonly used in these applications. One of their major advantages is the ability to use lower grade material, therefore decreasing the costs of the product. Higher grade and therefore higher strength wood is used on the outer edges that experience the most stress in flexural members, and lower grades are used within the core of glulam. Another distinct advantage of glulam is the ability to decrease the effect of natural growth characteristics, such as knots, by distributing them throughout the material. Glulam also offers the advantage of being used in applications where sawn lumber is not available in the size requirements for the necessary end use. Another major advantage of using glulam as a structural member is that it typically has a higher strength value than that of sawn lumber. The final distinct advantage of glulam beams is their ability to be homogenous based on a controlled and precise manufacturing process.

This research sought to investigate the flexural properties of reinforced and unreinforced glue laminated beams. The research team used six reinforced beams and three unreinforced beams in this study. Test of static bending, compression parallel to grain, shear parallel to grain and tension parallel to grain were all conducted according to ASTM D198-94. This research concluded that a larger scale test should be conducted to accurately measure the strength of reinforced and unreinforced glulam beams. A sample size of 200 specimens was suggested as opposed to the tested sample size of 9 specimens. The conclusions of the research suggested that the use of reinforced glulam beams have various benefits such as the ability to use lower grade and therefore lower cost material while maintaining a higher strength value. They also found the reinforced beams to have a lower variability in the material's strength and faced a less significant influence by natural growth characteristics. (Issa and Kmeid, 2004).

2.1.10 Trends in Flatbed Flooring

Flatbed flooring manufacturers have used a number of materials in their production process. In the 1960's a variety of domestic hardwoods were used in this application such as oak, beech, hickory, and hard maple. However, these domestically grown woods brought with them concerns over natural growth defects. Tropical hardwoodsexperience a much more consistent growing season and therefore have fewer natural growth defects, as opposed to domestics which grow in temperate climates, became a suitable alternative. Present day materials such as wood products, synthetic flooring, and metallic flooring are all used in this application. In the past decade there has been a push in the flatbed flooring industry to begin using aluminum flooring as the primary material, accounting for 55-60% of the flooring that is produced. This shift stems from the light weight nature of aluminum and the low costs of the material. Aluminum has begun to be the primary component of flatbed flooring as opposed to the historically used apitong hardwood flooring. Many factors such as weight, costs, durability and availability come into play when determining which material has the largest grasp on the market. In regards to price, the customer is consistently monitoring the market prices for both aluminum and wood materials such as apitong and when one materials price rises, the demand for the alternative rises as well. In regards to weight, the consumer prefers aluminum because of its ability to haul the most amount of product. However, this is not a universal statement because many specialized haulers are still preferring to use the traditional wood material. With respect to durability, wood flatbed flooring still seems to be the superior alternative. Wood experiences much less impact damage than the alternative of aluminum. When aluminum is damaged it must be repaired through cutting and welding processes. Availability is the final factor affecting the material of choice to be used in the flatbed flooring industry. Rising global demand for wood products has helped to shift the industry toward aluminum flooring. Aside from rising global demand, a limited production season due to monsoons in tropical regions has also limited the amount of tropical hardwoods that can be imported into the United States. These two factors combined have opened the door for aluminum in recent years to take a strong grasp of the flatbed flooring market. However, wood based flatbed flooring has still held strong value specifically in the drop-deck trailer flooring markets (Bumgardner, 2007).

2.1.11 The Commercial Exploitation of Philippine Hardwoods

The forest products industry is one of the key elements of the Philippine economy. One of the major woods exported yearly from the Philippines is apitong. Apitong that originates within the Philippines contains 15-17 different species of trees. This species group of wood is one that is hard and heavy and weighs an average of 45.9 lbs. per cubic foot. Apitong is known to be a strong performer in end applications that require high strength values. It also is useful when a material is needed to be abrasive resistant, long lengths, and clear wood is required. Apitong is known to have a long service life therefore requiring less common repairs as opposed to other materials. Its recommended uses include boat decks, warehouse floors, and heavy duty timbers. This material is less likely to warp and check than many other tropical hardwoods found throughout the world (Freeland, 1938).

2.1.12 Sustainable Trailer Flooring

The trailer flooring industry is undergoing a change in how they manufacture and market their products. In the past, many materials have been used for this application such as wood materials, aluminum, plastics, and steel. The desire for sustainability has taken hold of our society in recent decades. A desire to fight the carbon crisis and with it global warming has become at the front of many producer's minds when manufacturing their materials. By marketing a material as "green," manufacturers are able to persuade the consumer into the belief that they are helping the environment by choosing their product over an alternative. This paper seeks to explore the new materials that are commonly being used in trailer flooring applications and their true environmental impact. This paper first assesses durability as a measure of environmental impact. When comparing durability of steel, aluminum, E-glass, plastics and wood (red oak, white oak, hard maple, keruing). This research finds oak and hard maple to be the most durable when comparing domestic species, while also finding apitong to be a very durable species as well. This research also explores the carbon emissions that are released in the life cycle of the materials used in trailer flooring. Wood is a carbon storing material and therefore has the lowest carbon emission when compared to the other materials' manufacturing processes. The next measurement of environmental impact researched by this paper is embodied energy. Embodied energy can be defined as the amount of energy needed by the various stages of production of a material. When examining wood materials compared to the alternatives used in trailer flooring applications, wood is again found to be the most efficient in the goals of sustainability. The research continues to point out wood as a sustainable material by demonstrating that wood is a renewable resource. With proper silvicultural practices the material is able to be replenished faster than it is harvested. By replenishing this material, we are also able to offset the carbon impact of production of trailer flooring because of the carbon capturing nature of trees. The article concludes that using wood is the most sustainable practice when compared to its alternatives in the production of trailer flooring systems. Wood's ability to be renewable, carbon neutral, and recyclable all have positive environmental implications that make it the ideal material for this use (Lu et al., 2009).

2.2 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 1.75 inch by 8 inch (4.5 by 20 cm) 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 mid-length 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 mid-depth, 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 four to five 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 2.1

Table 1.1 Grade distribution, number of specimens (and associated %) in each grade by species

Grade	Red Oak: n pieces (%)	White Oak: n 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)

2.2.1 Test Method

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. 2.1 and 2.2). 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 four and five 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 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 in different ways such that a distribution-independent fifth percentile can be developed. From each of these, the design fiber stress in bending values (Fb) is calculated by dividing the fifth percentile (either parametric or nonparametric) by 2.3 for hardwoods, per ASTM D245 (ASTM 2019).

Figure 2.1 Hardwood composite billets on Tinius Olsen machine before (upper panel) and after (lower panel) failure

(ASTM D143-14 [ASTM 2017a]).

Figure 2.2 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]).

2.2.2 Moisture Content and Specific Gravity Measurement

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 G_b (basic 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, ρ_{12} (apparent density) was measured and reported instead of specific gravity (Table 2.2).

Table 2.1 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	
	G_b	MC (%)	G_b	MC (%)	ρ_{12} (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

2.3 Statistical Analysis

The experimental design was a completely randomized design, and data for the MOR and MOE results were analyzed using 1-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 oak and white oak were considered in their entirety (204 specimens each) and not separated 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.

2.4 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 2.2. Table 2.2 also illustrates the moisture content (dry basis) at the time of testing. Table 2.3 illustrates the summary statistics for MOR and MOE as well as the parametric and nonparametric fifth percentiles and Fb for MOR, as per ASTM D2915-10 (ASTM 2017d). The design value for MOE is equivalent to the mean MOE. Table 2.4 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.

Table 2.2 Summary statistics for modulus of rupture (MOR) and modulus of elasticity (MOE) along with parametric and nonparametric fifth percentiles and Fb 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*	1.723		1.723		1.723	
Parametric 5%	44.2		21.8		24.7	
Parametric F_b	19.2		9.5		10.7	
Order statistic	8		8		8	
Non-parametric 5%	43.1		20.3		20.2	
Non-parametric F_b	18.8		8.8		8.8	

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

Grade	MOR (MPa)		MOE (GPa)	
	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

The results of the ANOVA and mean separations are shown in Table 2.5. 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 Figures 2.3-2.5.

Table 2.4 Mean modulus of rupture (MOR) and modulus of elasticity (MOE) values along with P value levels of significance as well mean separations.

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	

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.

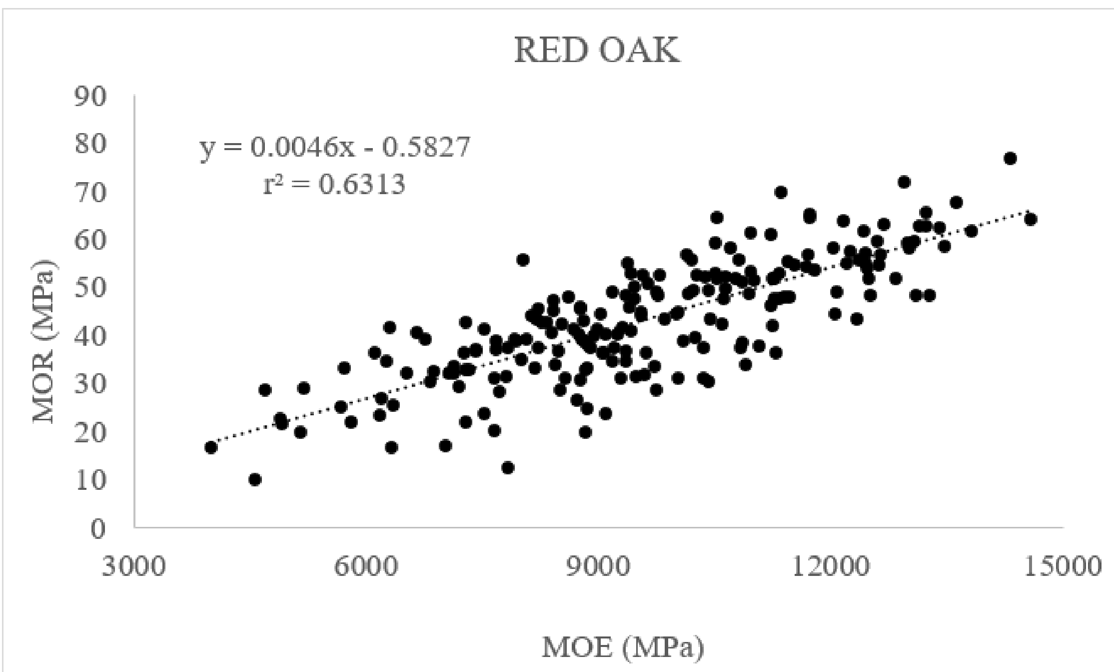

Figure 2.3 Relationship between modulus of elasticity (MOE) and modulus of rupture (MOR) for red oak

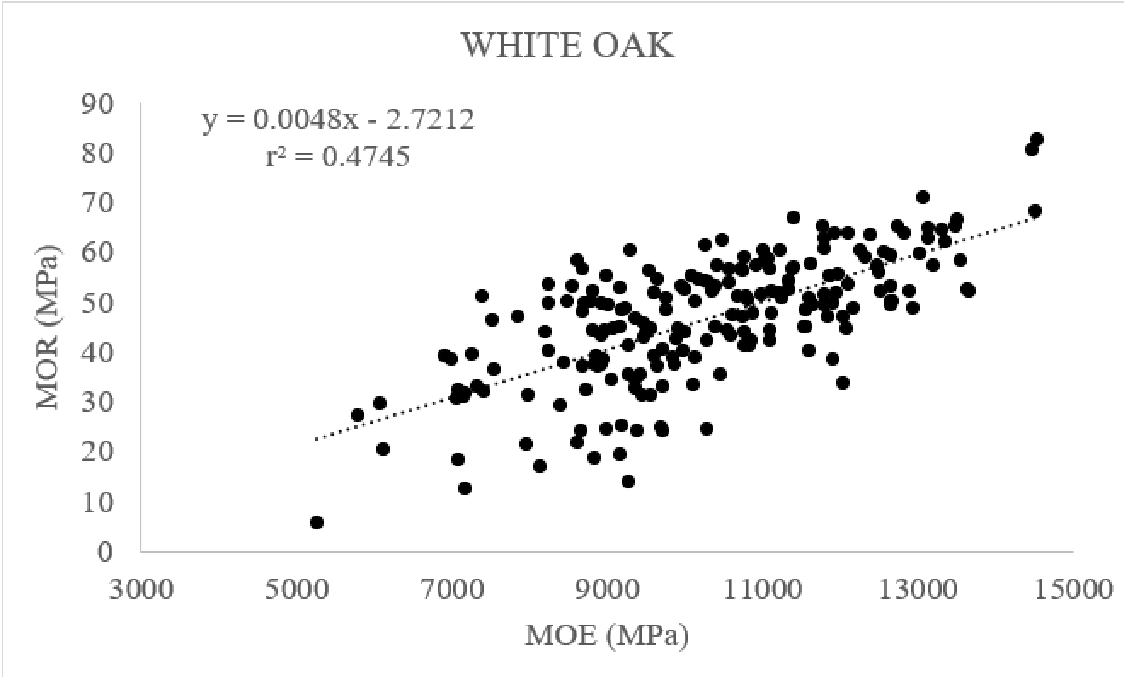

Figure 2.4 Relationship between modulus of elasticity (MOE) and modulus of rupture (MOR) for white oak

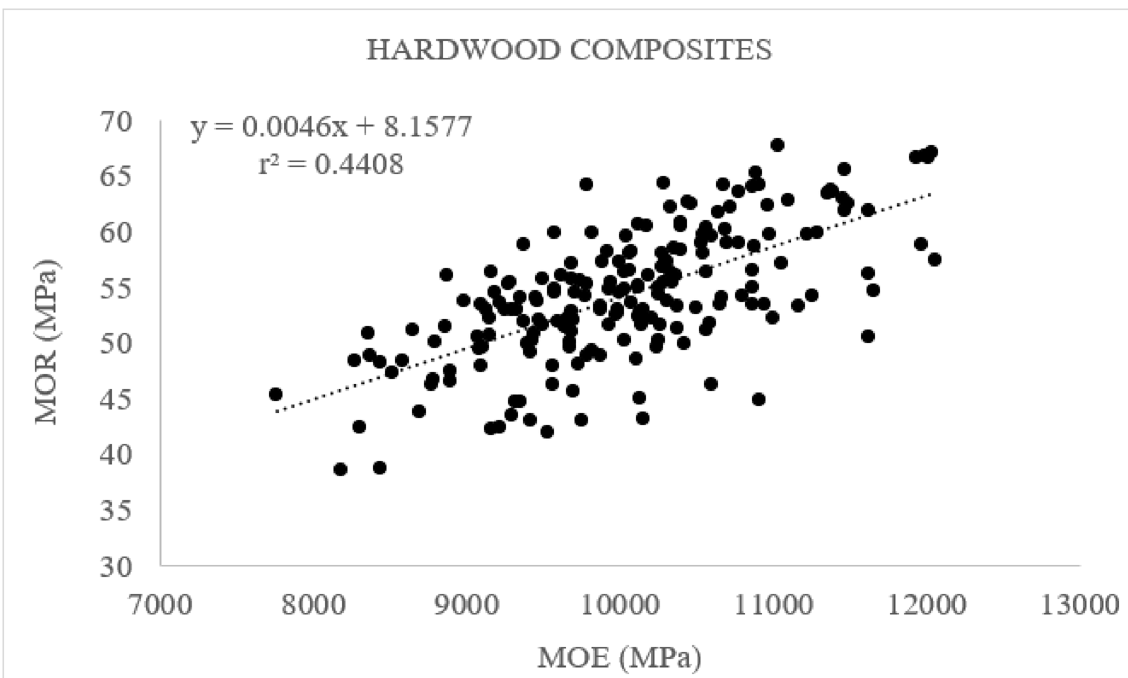

Figure 2.5 Relationship between modulus of elasticity (MOE) and modulus of rupture (MOR) for hardwood composites

2.5 Discussion

In this study, there were significant differences in both MOR and MOE properties between red oak 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).

2.5.1 Red and White Oak

This research puts forth a snapshot of mechanical properties for structurally graded oak. For the red oak grade mix as tested, Fb and MOE were 9.5 MPa (1,377 psi) and 9.61 GPa (1.39 million psi), respectively. For red oak, as a comparison from NeLMA (2017), the Fb (800 psi [base] adjusted for 2 by 4 inch size [1.5], green moisture content [0.85], and 10-minute load duration [1.6]) and MOE values for the No. 2 grade 2 by 4 size are 1,632 and 1.2 million psi, respectively. For the white oak grade mix as tested, Fb and MOE were 10.7 MPa (1,551 psi) and 10.28 GPa (1.49 million psi), respectively. For white oak, as a comparison from NeLMA (2017), the Fb (850 psi [base] adjusted for 2 by 4 size [1.5], green moisture content [0.85], and 10-minute load duration [1.6]) and MOE values for the No. 2 grade 2 by 4 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 however 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 systems 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.

2.5.2 Hardwood Composites

For the composite billets, the design values as tested, Fb = 19.2 MPa (2.784 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 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 r2 values ranging from 0.44 to 0.63. The hardwood composite billets showed the lowest r2 value and this is not surprising as that was the most uniform and least variable material.

2.6 Conclusion

The aim of the 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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