Strength and Stiffness of 8-Inch Deep Mixed Hardwood Composite Timber Mats

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There is a current and pressing need to develop engineering standards for timber- and other wood-based mats. In 2018 a group of mat producers and users began discussing a potential grading specification standard specific to mats. There are large gaps in the literature regarding the performance of the available raw materials as well as bolt-laminated mat systems. This work represents a novel attempt to begin to assess the mechanical properties of timber mats. Eight-inch deep mixed hardwood timbers were graded according to an experimental specification standard. Then, they were drilled and bolt laminated into 28 three-timber composite mats that were 24 inches (60.96 cm) in width. The bending stiffness (modulus of elasticity [MOE]) and strength (modulus of rupture [MOR]) performance were evaluated with a static bending test. The 5th percentile nonparametric tolerance limit (5% NTL) and design value for fiber stress in bending (F_b) were calculated. The nonparametric design value compared favorably with that of graded timbers, as described in the 2018 National Design Specification (NDS) for wood.

Keywords: Crane mat; Construction mat; Timber mat; Mixed hardwood; Modulus of elasticity; MOE; Modulus of rupture; MOR; Strength; Stiffness

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INTRODUCTION

Throughout North America and around the world, timber- and wood-based access mats are used in heavy construction. Cranes, draglines, and pipe layers are a few examples of equipment that benefit from access mats, as they spread relatively large and concentrated loads over large areas to reduce ground pressure. This action decreases rutting and soil disturbances and protects plant and biotic communities. Mats facilitate both rapid site access before construction and thorough clean up and removal upon completion of the job. With increasing crane sizes and loads—as well as pressure on forest and environmental resources, safety standards, and construction costs—there is a current and pressing need to develop engineering standards associated with timber- and other wood-based mats.

Historically, the lumber and timbers used in mats have not been structurally graded. At best, specifications have related to wood species and restrictions on wane and decay. In the case of timber mats, individual timbers are typically drilled and bolted together tightly with redundant steel rods. Often, these bolted timber mats are on the order of 4 feet (121.92 cm) wide. Timber mats typically range from approximately 14 to 24 feet (4.27 to 7.32 m) in length. However, based on resource availability and production equipment, the length may go up to 40 feet (12.19 m) long.

Related to mat materials and mechanical property development, researchers have evaluated the performance of laminated hardwood billets. Shmulsky and Shi (2008) prepared and glued low-grade sweetgum (*Liquidambar styraciflua*) lumber. Then, they tested the lumber in bending to determine bending strength and stiffness properties. The laminated billets were intended for use as components in bolt-laminated access mats. The laminated billets were an engineered substitute for solid timber in mat applications. Similarly, researchers have evaluated the performance of laminated pine lumber billets. Yang *et al.* (2015) prepared and glued No. 3 grade pine structural dimension lumber. Then, they tested the lumber in bending to determine bending strength and stiffness properties for potential use in access matting. Shmulsky *et al.* (2008) evaluated the composite effect, also known as load sharing, between and among hardwood billets that were bolt-laminated together. Also, research has been conducted that relates load and instrumentation-based strain deformation for hardwood mats that were tested in bending (Stroble *et al.* 2012). These findings are particularly useful in beginning to describe the performance of wood-based materials used in structural matting applications. However, there are large gaps in the information related to the performance of the available raw materials as well as bolt-laminated mat systems.

A commercially available form of grading for hardwood timbers is promulgated by the Northeastern Lumber Manufacturers Association (NELMA) (2017). NELMA (2017) provides grade rules for structural timbers, such as those used in mat construction. Their species or species groups of interest include: red maple (*Acer rubrum*); mixed maple (*Acer* spp.); beech (*Fagus grandifolia*), birch (*Betula* spp.), and hickory (*Carya* spp.); mixed oak (*Quercus* spp.); red oak (*Quercus* spp.); and white oak (*Quercus* spp.). These NELMA specifications and design values are cited in the National Design Specification (NDS) for wood (2018).

To date, mat producers, in general, have not graded their timbers to a standardized guideline or rule. Rather, producers typically develop their own “in house” quality guideline(s) or grade rule(s), and these vary greatly among producers. In 2018, a group of mat producers and users began discussing a potential grading specification standard specific to mats. The research described herein evaluates the mechanical bending properties of bolt-laminated 8-inch deep mats from mixed hardwoods that were graded per an experimental specification standard.

The objective of this study was to mechanically evaluate the bending stiffness (modulus of elasticity [MOE]) and strength (modulus of rupture [MOR]) performance of 8-inch deep composite timber mats and statistically calculate the 5th percentile nonparametric tolerance limit (5% NTL) and design value for fiber stress in bending (F_b) of the experimental timber mats. These objectives are in support of the development of a broader quality and performance standard to timber mats.

EXPERIMENTAL

Materials

Four species groups were identified as candidates for evaluation in the potential mat grading standard. These were oak (*Quercus* spp.), mixed hardwoods, pine (*Pinus* spp.), and “unclassified.” This research tested mats from mixed hardwoods. The mixed hardwood group includes any combination of the following: ash (*Fraxinus* spp.), beech (*Fagus grandifolia*), hickory (*Carya* spp.), red oak (*Quercus* spp.), sweetgum (*Liquidambar* *styraciflua*), and white oak (*Quercus* spp.). As tested, the mats contained ash, hickory, oak, and sweetgum. An experimental two-tier grading system was documented based on the resources that are generally consumed in mat construction. The grading system specifies limits on bark pockets/seams, decay, holes, knots, slope of grain, size tolerances, splits, stain, and wane. In the case of this research, only timber components that graded as Tier 1 were used. The Tier 1 grading standard is described in Table 1.

Table 1. Tier 1 Grading Specifications for Individual Timber Components

Characteristic	Allowable Description
Bark pockets/seams	Maximum depth from surface: 20% of timber thickness Maximum length: 10 inches
Decay	Not permitted in any form
Holes	Maximum: 1 hole, up to 1-inch diameter, 3 inches deep, on any single mat surface
Knots	Sound knots only. Maximum knot diameter must not exceed ¼ of the timber thickness. Sum diameter of knots in combination must not exceed ¼ of the timber thickness
Slope of grain	1 in 15
Timber thickness tolerance	± 3%
Mat thickness tolerance	± 6%
Mat width tolerance	± 2%
Mat length tolerance	± 1%
Splits	Maximum length: 12 inches from the end. Maximum of two split timbers in any single mat end
Stain	Permissible as long as it is not of any strength- or stiffness-reducing type
Wane	Not more than 10% of the overall surface area of the mat

Once a sufficient number (84) of on-grade timbers were selected from a random pool, the timbers were bolted together to form 8-inch (20.32 cm) deep by 24-inch (60.96 cm) wide mats. In total, 28 mats were produced and tested. In this case, each mat was comprised of three timbers. Each timber was drilled with a 1-inch diameter hole every 2 feet along its 12-foot length. Then, ¾-inch (1.91 cm) diameter steel tension rods were inserted into the holes. The ends of the rods were threaded, and nuts were installed and tightened on the rods to approximately 200-pound feet (271.16 N·m) of torque. This level of torque tightened the individual timbers together such that they behaved as a composite panel. All timbers and mats were manufactured and tested in the green condition, that is, above 30% moisture content. This moisture content level is consistent with timber mats in service and represents that which corresponds to the lowest strength and stiffness values.

Methods

The mats were flexurally tested per ASTM D5456-17 (2017) and D198-15 (2015) at a 17:1 span-to-depth ratio (Fig. 1). In addition to the composite action created by the tension rods, the test fixture applied the loads across the width of the mat. In this manner, only the performance of the multi-timber composite, not that of the individual timber components, was considered. The order statistic for the 5% NTL was determined per ASTM D2915-17 (2017). In this case, the 5^{th} percentile is taken as the lowest observation among a minimum of 28 observations ranked lowest to highest. The design value for F_b

was calculated by dividing the 5% NTL value by a safety and load duration actor of 2.1 as per ASTM D5456-17 (2017). It should be noted that while this load duration factor assumes a load duration of 10 years, the typical life of a construction mat in service is only about 3 to 5 years. Thus, the F_b value could be considered conservative. The design value was not adjusted for uniform loading.

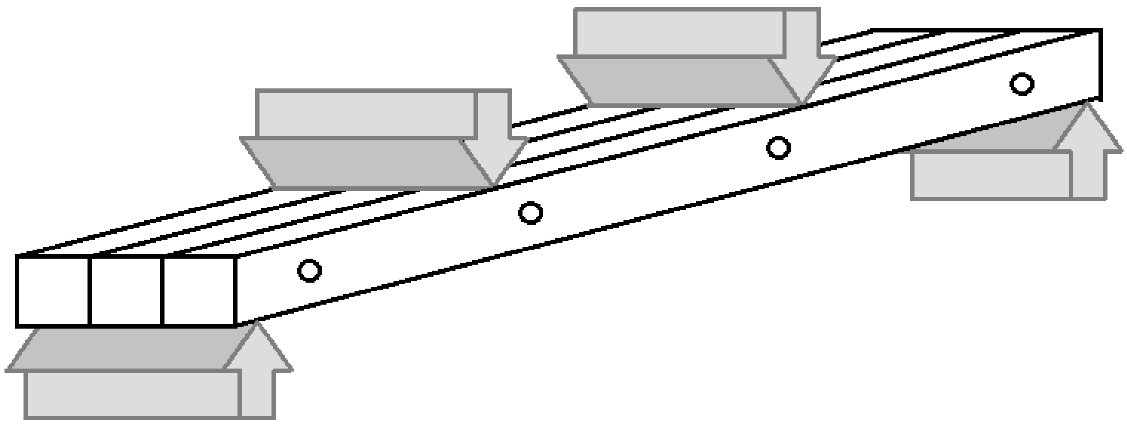

Fig. 1. Third point flexural loading configuration for 8-inch deep, 24-inch wide 3-timber bolt laminated mats

RESULTS AND DISCUSSION

The detailed performance of the 8-inch deep mixed hardwood mats is shown in Table 2. The design value for F_b was 2319 psi (15.99 MPa), and the average MOE was 1.11 million psi (7.65 GPa).

Table 2. Mechanical Strength and Stiffness Summary Statistics for 8-Inch Deep Tier 1 Mixed Hardwood Mats

	MOR	MOE
Number	28	28
Average	6560 psi (45.23 MPa)	1.11 psi × 10^6 (7.65 GPa)
Maximum	8460 psi (58.33 MPa)	2.08 psi × 10^6 (14.34 GPa)
Minimum	4870 psi (33.58 MPa)	0.52 psi × 10^6 (3.59 GPa)
Coefficient of Variation	16.5%	30.5%
5% NTL (95% content, 75% confidence)	4870 psi (33.58 MPa)	Not applicable
F_b	2319 psi (15.99 MPa)	Not applicable

This work represents a novel attempt to begin to assess the mechanical properties of timber mats. The nonparametric design value compared favorably with that of graded timbers as described in the NDS for wood (2018). As a comparison, per NELMA (2017), the F_b for No. 1 red oak (*Quercus* spp.) in the post and timber size (5 inch × 5 inch [12.7 × 12.7 cm] and greater) is 1000 psi (6.90 MPa). Adjusted for redundant members ($F_b' = F_b$

× C_r, where C_r [repetitive member factor] = 1.15) (NDS 2018), the F_b' is 1150 psi (7.93 MPa). The MOE per NELMA (2017) for No. 1 red oak is 1.2 million psi (8.27 GPa). Per the NDS (2018), the wet service factor is 0.9. Thus, the MOE for No. 1 red oak, above 19% moisture content (MC), is 1.1 million psi (7.58 GPa) – parity for timber composites tested herein.

There are several key differences between this work and the existing published hardwood timber design values by NELMA (2017). Firstly, the existing hardwood timber design values are meant for individual timbers that are graded per a different standard, *i.e.*, based on the NELMA (2017) grade rules. The values determined herein are empirical and for composite mats comprised of timbers that were graded to a novel and experimental standard. The composite action elevates the strength values by load sharing, wherein stronger and weaker pieces often occur in the same mat, thereby limiting variability. Lower variability increases the 5th percentile, which ultimately increases the F_b in design. The work described herein includes a species mix that is commonly used in mat construction but is not described by NELMA (2017). Also, the NELMA (2017) design values for timbers are based on small, clear bending specimen values that have been adjusted for a series of factors, such as size, grade, moisture content, *etc*. The values determined herein were based on actual testing of full-scale timber mats.

It is anticipated that future research work will include mats made from other species, such as oak, and other sizes up to 12 inches (30.48 cm) deep. Because the grading system used herein was developed by producers, this information could be potentially useful to describe the mechanical properties of timber mats as produced.

CONCLUSIONS

1. The nonparametric design value F_b of the mats tested (2319 psi [15.99 MPa]) compared favorably with that of graded timbers as described in the NDS for wood (2018). As a comparison, per NELMA (2017), the F_b for No. 1 red oak (*Quercus* spp.) in the post and timber size (5 inch × 5 inch [12.7 × 12.7 cm] and greater) is 1000 psi (6.90 MPa). Adjusted for redundant members ($F_b' = F_b \times C_r$, where C_r [repetitive member factor] = 1.15), the F_b was 1150 psi (7.93 MPa). If adjusted for wet service, the NDS (2018) values would be lower.
2. The average MOE (1.1 million psi [7.58 GPa]) of the mats tested compared favorably. The MOE per NELMA (2017) for No. 1 red oak, adjusted for wet service (above 19% MC), is also 1.1 million psi (7.58 GPa).
3. The composite action of the mats elevates the strength values by load sharing, wherein stronger and weaker pieces often occur in the same mat, thereby limiting variability. Lower variability increases the 5th percentile, which ultimately increases the F_b in design.
4. The findings detailed herein are successful to the extent that they begin to fill the void of quantitative strength and stiffness data for hardwood timber mats. Additional data for other species groups, thicknesses, and grades is however necessary for full implementation of a production and quality standard.

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