Bending Strength and Stiffness of Three-ply Bolt-Laminated Mixed Oak and Hardwood Industrial Mats

Dusty Snow,* Rubin Shmulsky, Gabrielly S. Bobadilha, and Dercilio Junior Verly Lopes

Crane mats provide safe, stable, and flat work surfaces for heavy equipment and provide environmental protection. In this manuscript, two types of three-ply mats from two geographic regions were evaluated for stiffness and strength. Mats were sourced from the Southern USA and Midwestern USA in both solid configurations where the boards in all plies are touching and waffle configurations where gaps of approximately 1.8 inches were left between boards. Both types were mechanically fastened with regularly scheduled 3/8th inch diameter carriage bolts. The mats consisted of 1.5-inch-thick mixed oak and hardwood lumber oriented in a similar manner to plywood to form 4.5-inch-thick panels, each of which is 8 ft x 14 ft. Mats were prepped for testing by being ripped into strips 24 ± 4 inches wide. In this manner, 28 test specimens were developed from 7 parent mats. Mats were subjected to three-point bending tests. In both types of mats, the Southern-sourced specimens were statistically stronger and stiffer than those from the Midwest. Modulus of rupture (MOR) results showed that solid mats from the South were stiffer compared to waffle configurations produced in either location. The regression analysis indicated that modulus of elasticity could potentially estimate MOR.

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Contact information: Department of Sustainable Bioproducts, Forest and Wildlife Research Center (FWRC), Mississippi State University, Mississippi State, MS, USA;
** Corresponding author: rds45@msstate.edu*

INTRODUCTION

Industrial mats are an integral part of construction activity. These relatively large panelized products are placed directly on the ground. Then, people, materials, and supplies, and heavy equipment operate on top of the mats. Given their relatively large surface areas and load-spreading characteristics, they convert relatively heavy and concentrated loads into relatively low ground pressures (particularly on wet, unstable, or otherwise sensitive soils). These mats form temporary roads and work platforms and are particularly critical in pipeline, transmission line, road, bridge, and other forms of heavy construction. When construction is finished, the industrial mats are picked up, cleaned, and may be reused elsewhere. The construction site then is able to return to its undisturbed preconstruction state.

Timber and lumber are the most common types of matting materials. Additionally, polymers and metals are entering the market, and their adoption is growing in certain applications. While most materials (cranes and other equipment, nuts and bolts, shackles, cables, trusses, spreader bars, *etc.*) at construction jobsites currently have load ratings, industrial mats do not. The work reported herein addresses the mechanical property evaluation of three-ply mats made from mixed oak and hardwood lumber. The primary mechanical properties of interest are stiffness as modulus of elasticity (MOE) and strength as modulus of rupture (MOR) and allowable fiber stress in bending (Fb).

The three-ply mats consist primarily of sawn lumber that is mechanically fastened. They are similar to plywood or three-ply cross-laminated timber in that the middle ply is oriented perpendicular to the surface plies. The mechanical fastening between and among the plies is provided by nails (clinched or not clinched), screws, lag bolts or screws, carriage bolts, or some combination thereof. This hardware holds the individual planks together such that they behave as a mechanically-fastened composite. Adhesive is not typically incorporated in three-ply mats as the timbers are rough, may vary in thickness, and are green (that is not dried).

Many species or species groups of graded timber have associated design values. The Northeastern Lumber Manufacturers Association (NELMA) puts forth grading specifications and allowable design values for mixed oak lumber and timbers (NELMA 2017). These design values appear in the *National Design Specification for Wood Construction* (National Design Specification 2018). However, these design values are for single or redundant members and do not necessarily lend themselves to the construction of three-ply mats. Shmulsky and Shi (2008) reported on the development of glue laminated billets for use as a timber replacement in bolt-laminated mats. Shmulsky *et al.* (2008) reported on the composite effect of bolt lamination in a multi-member mat. Additional and related work regarding the use of strain gauges to monitor the behavior of composite mats under flexural loading was reported by Stroble *et al.* (2012). As part of graduate research, Herberg (2018) reported on the bending performance of nail-laminated crane mats. Others have reported on the mechanical properties of mixed hardwood bolt-laminated 8-inch deep mats (Owens *et al.* 2020) and mixed oak bolt laminated 8- and 12-inch deep mats (Shmulsky *et al.* 2021). While these research findings detail varying aspects of the flexural behavior of mats or mat components, none speaks to the behavior or design properties of three-ply, mechanically fastened, hardwood mats.

Furthermore, the aim of this study was to evaluate the strength and stiffness of crane mats of different origins and structural design. The overall goal was to develop design values that will provide crucial information for mat users, developers, and distributors on product performance under heavy load. The specific goals were to investigate the modulus of elasticity (MOE) and modulus of rupture (MOR) and predict their relationship. The MOE is important for predicting mat deflection under load. This property is important for estimating the extent to which cranes and pipelayers will tip during operation, which is an important life-safety issue. The MOE, along with intended loading and subsoil characteristics, is also needed to predict rutting and environmental impacts. The MOR is necessary in the derivation of allowable bending strength (Fb), which is needed for safety, mat performance, and economics as prematurely broken mats are a loss. It was hypothesized that solid mats would be stiffer and stronger than waffle mats. It was also hypothesized that strength and stiffness of like mats (*i.e.* solid *vs.* solid and waffle *vs.* waffle) would not differ between regional (*i.e.* South *vs.* Midwest) sources.

EXPERIMENTAL

Specimen Description and Preparation

For this research, the authors sourced commercial three-ply mats of two different types (solid and waffle faces) from two different manufacturers in two different geographic locations (USA South (Alabama) and USA Midwest (Indiana)). Each mat was composed of three plies or layers. Each layer was 1.5-inch-thick rough sawn mixed oak and other hardwood lumber. The mats from Alabama were composed solely of mixed oak. The mats from Indiana contained a species mix of mixed oak, hickory, pecan, beech, ash, honey locust, and sycamore. Each finished mat was approximately 4.5-inches thick. Each mat was manufactured at 8-feet wide and 14 feet long. Figure 1 presents a schematic of the mat's architecture.

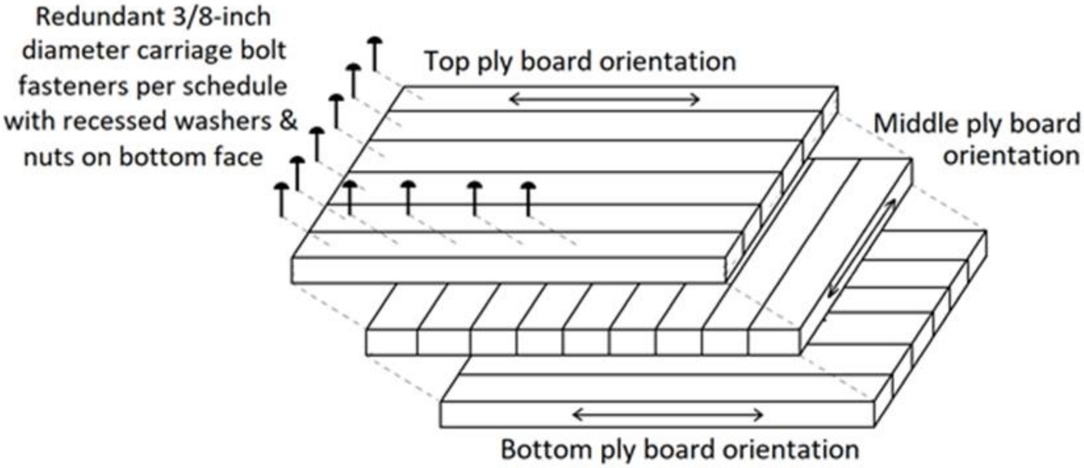

Fig. 1. Schematic of a three-ply mat

The lumber quality was specified as free of any defects that may impair its intended use and performance. The excluded defects were decay, large splits or shakes, severe grain run out, large or numerous holes, and large or numerous knots. Thus, the wood quality was somewhat analogous to Number 3 utility boards as per the National Hardwood Lumber Association (1994).

The solid face mats had lumber oriented edge-to-edge along the full width of each mat face. In this manner, each face was composed of approximately 12 pieces of 1.5- × 8-inch oak lumber. Some of the lumber in some of the mats, however, had variable width ranging from 8 up to 12 inches (actual). This variation in lumber width occurs when hardwood logs are sawn into lumber with a goal of maximizing yield. The middle or core ply, which was oriented perpendicular to the external lumber pieces' faces, also consisted of lumber placed edge-to-edge, thus making a solid core. With respect to lumber volume, each layer contained 168 board feet and each mat contained 504 board feet. Each mat was held together by 180 3/8-inch diameter carriage bolts. This fastening schedule amounted to 1 bolt per 2.8 board-foot-volume and 1.61 bolts per square foot of mat surface area. On the top face of each mat, each bolt head was pressed snuggly into the face of the mat. On the bottom face of each mat, the bolt holes were recessed and an integrated nut/washer was installed and torqued onto the carriage bolt shaft. In this manner, the bolts and nuts did not protrude below the bottom face of the mat. Figure 2 shows a stack of three-ply solid mat specimens cut and prepared for testing.

The waffle face mats had lumber arranged with gaps between each of the facial planks and core planks. The face consisted of 10 pieces of 1.5- × 8-inch oak lumber spread evenly across the mat's 96-inch width. In this manner, each gap was approximately 1.8 inches wide., their grip improves into soft ground due to the gaps between face boards.

Fig. 2. Stack of three-ply solid mat flexural specimens cut and prepared for testing

Fig. 3. Three-ply waffle parent mat after ripping into four, 2-foot wide, flexural test specimens

Similar spacing was developed in the core layer. With respect to lumber volume, each layer contained 140 board feet and each mat thus contained 420 board feet. Each of the waffle face mats was held together by 152 3/8-inch diameter carriage bolts. This fastening schedule amounted to 1 bolt per 2.9 board-foot-volume and 1.36 bolts per square foot of mat surface area. These bolts were installed in the same manner as those on the solid face mats. Figure 3 shows a three-ply waffle mat cut into four, 2-foot-wide, flexural test specimens. These mats are lighter and less costly than solid mats. Additionally, their grip improves into soft ground due to the gaps between face boards.

Prior to testing, parent mats were ripped with a chainsaw into strips that were approximately 20 to 28 (24 ± 4) inches wide and 14 feet long. The solid face mats were ripped along the joint of adjacent face boards. Each test specimen was approximately 3 facial boards wide. The waffle face mats were also ripped at their respective joints, or gaps, in the facial boards. Because each mat had 10 boards on each face layer, half of the test specimens were 3-boards wide, and half of the specimens were 2-boards wide. These differences in specimen width were taken in to account during the calculations of section modulus, moment of inertia, MOR, and MOE of each specimen.

Performance Evaluation

The actual maximum width of each specimen was measured at the time of testing and used for the calculation of section modulus and subsequent MOR. Additionally, the actual thickness, 4.5 inches, was used in the calculation of section modulus and moment of inertia. In this manner, the MOR values were considered conservative. Seven parent mats were considered for each mat type. Once ripped, these seven parents yielded 28 test specimens for each mat type. The 28 specimens were chosen because that is the minimum required number for development of a non-parametric 5th percentile per ASTM D2915 (2017). For flexural evaluation, mats were tested in third-point bending per ASTM D5456-17 (2017).

Fig. 4. Three-ply solid flexural specimen in the universal testing machine while being destructively evaluated

Because the mats were three-ply, with the middle lamina running perpendicular to the long axis of the mat (and the long axis of the test specimen) and rolling shear was known to be a factor, ASTM D5456-17 (2017) was modified. The span to depth ratio was increased to 28:1 pursuant to the guidance of PRG 320 (2019). In this manner, the potential for shear failure during the flexural test was minimized. It was noted that the MOE appeared low and the deflection appeared high during the testing of the Midwestern mats.

As such, the span to depth ratio was adjusted to 26:1 during that testing in an effort to facilitate bending failure. This minor adjustment of span to depth ratio was recorded in the data and it was taken into consideration for calculation of bending moment, MOR, and MOE. This adjustment facilitated subsequent comparable analysis. Figure 4 illustrates a solid three-ply test specimen in the universal testing machine (Satec series 600KN; Instron, Norwood, MA, USA) while undergoing a third-point destructive bending test.

Statistical Analysis

Statistical analysis of variance (ANOVA) was performed for each response variable. The MOE and MOR were analyzed as completely randomized factorial designs with subsamples. When the interaction between factors origin (A) and type (B) was not significant, each factor was analyzed in isolation. A 5% level of significance was used to detect differences, and when a significant difference was found, Tukey test was performed. Analyses were performed using Statistical Analysis System (SAS, SAS Institute Inc., version 9.4, Cary, NC, USA). Regression analysis was performed on Excel (Microsoft Corp., version 1908, Redmond, WA, USA), with the Data Analysis extension.

RESULTS AND DISCUSSION

Following testing, for each mat type and origin, summary and design value statistics, per ASTM D2915 (2017) were generated (see Tables 1 and 2).

Table 1. Summary and Design Value Statistics, for MOE, Along with Mean Separation at the α = 0.05 Level of Significance, for Each Mat Type and Origin

	Solid Construction, U.S. South	**Solid Construction, U.S. Upper Midwest**	**Waffle Construction, U.S. South**	**Waffle Construction, U.S. Upper Midwest**
n	28	28	28	28
Average (psi) (Design Value MOE)	228,268	191,854	181,874	165,865
Median (psi)	224,881	195,209	173,843	171,240
Standard Deviation (psi)	24,478	26,471	36,949	26,276
Coef. of Variation (%)	11	14	20	16
Maximum (psi)	277,450	245,134	309,462	197,342
Minimum (psi)	190,850	149,837	136,553	94,663

The interaction between source and origin was not significant at α = 0.05 for MOE values (p = 0.4647). For this reason, each factor was analyzed in isolation.

Table 2. Means Comparisons of MOE of Mats by Origin and Type

	Origin		Type	
	South	**Midwest**	**Solid**	**Waffle**
Average MOE (psi)	205,070 A*	178,860 B	210,061 A	173,869 B

*Results followed by the same letter per type and origin are not significantly different by Tukey test at α = 0.05

Independently of type, samples from the South generated higher MOE values. Additionally, when comparing by type, solid mats were significantly more elastic than waffle-type mats disregarding their origin. The p-value for differences in MOR was 0.0487, *i.e.*, the interaction between type and origin was significant (Table 3).

Table 3. Summary and Design Value Statistics, for MOR, Along with Mean Separation at the α = 0.05 Level of Significance, for Each Mat Type and Origin

	Solid Construction, U.S. South	**Solid Construction, U.S. Upper Midwest**	**Waffle Construction, U.S. South**	**Waffle Construction, U.S. Upper Midwest**
n	28	28	28	28
Average (psi)	2,858	2,381	2,372	2,200
Median (psi)	2,779	2,398	2,368	2,246
Standard Deviation (psi)	347	332	525	417
Coefficient of Variation (%)	12	14	22	19
Maximum (psi)	3,674	3,068	4,173	2,835
Minimum (psi)	2,061	1,489	1,663	1,053
Mean Separation *	2,857.96 A*	2,380.79 B	2,371.96 B	2,200.07 B
Parametric 5th Percentile (psi)	2,208	1,758	1,387	1,418
Parametric Fb (psi)	1,051	837	661	675
Non Parametric 5th Percentile (psi)	2,061	1,489	1,663	1053
Non Parametric Fb (psi)	981	709	792	501

* Values that are not significantly different at the α = 0.05 level are denoted with the same letter as analyzed by Tukey test for mean separation.

In use, mats are often deployed based on type and material, but they are rarely deployed by geographic origin. As such, the allowable Fb and MOE are shown below, in Table 4, based on data pooled by type (solid vs. waffle).

Table 4. Allowable Properties, Fb and MOE (psi), for Solid and Waffle Mats, Pooled by Region

	Solid	**Waffle**
n	56	56
Fb Parametric	893	679
Fb Non-parametric	878	598
MOE	210,000	174,000

Solid mats produced in the South were significantly stiffer than those produced in Upper Midwest. The MOE is often used as a nondestructive predictor of MOR. In cases where MOE correlates well with MOR, then stiffness/deflection is a robust predictor of strength. The relationship of MOE to MOR for all the three-ply mats as tested is shown in Fig. 5. In this case, MOE accounted for 64.81% of the variance in MOR.

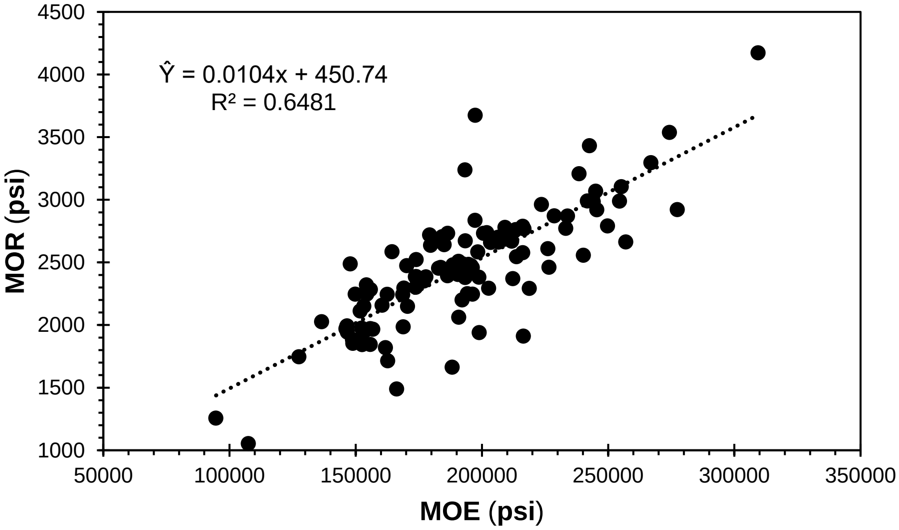

Fig. 5. Relationship between MOE and MOR

Discussion

For both the solid and waffle construction, the Southern-sourced mats were stronger and stiffer than those from the Midwest. In each case, the solid mats contained approximately 20% more board-foot volume than the waffle construction type. The MOR values for the solid mats were 10 to 20% higher than those for the same source waffle construction. The MOE values for the solid mats were 15 to 25% higher than those for the same source waffle construction. The p-levels of significance for MOE and MOR among these four mat types, were 0.4746 and 0.0487, respectively. The mean separations are shown in Tables 2 and 3.

With respect to Fb values, in some cases the parametric-based values were higher and, in some cases, the non-parametric based values were higher. This finding suggests that the statistical distributions of MOR values among mat types may not have been exactly alike. Among all mat types, MOE appeared to be a reasonably good predictor of MOR ($R^2 = 0.65$). This relationship might be further explored as a means of nondestructively testing mats after varying degrees of field service. It is known that Southern forests grow faster than those in colder Northern and upper Midwestern climates. When diffuse porous woods grow faster, they become denser, as their low density annual early wood band remains approximately the same while their higher density latewood band become wider. As such the southern red oak is generally denser (and subsequently stiffer and stronger) than that from the north.

CONCLUSIONS

1. In this study, two types of mats sourced from two different geographic locations in the U.S. were assessed with respect to their modulus of elasticity and rupture. Results indicated that solid mat type processed in the Southern U.S. was statistically stronger than its counterparts manufactured in the Midwest region.
2. In terms of mats' stiffness, statistical analyses revealed that the U.S. Southern and solid-type mats produced stiffer products, with wood characteristics likely playing a key role in performance. Lastly, the regression analysis indicated that MOE could potentially estimate MOR.
3. In general, as hypothesized, solid mats were stiffer and stronger than waffle mats. Contrary to the hypothesis, strength and stiffness varied by region, that is, mats from the U.S. South were stiffer and stronger.

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