Flexural Properties of Three-Ply Bolt-Laminated Pine Mats

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Abstract

In the current study, three-ply bolt-laminated southern pine (*Pinus* sp.) 244 by 427 cm (8 by 14 ft) mats were evaluated. Mats were destructively tested in ⅓-point bending on a universal testing machine according to ASTM International standards. Twenty-eight unique specimens were destructively tested, and mean modulus of rupture (MOR) and modulus of elasticity (MOE) were calculated. According to the results both MOR and MOE values for the specimens were highly uniform. The mean MOR was 11.74 MPa (1,704 psi) and the mean MOE was 1,144 MPa (0.166×10^6 psi). Additionally, the values of parametric and nonparametric F_b (design fiber stress in bending values) were reported as 4.05 MPa and 4.54 MPa (588 psi and 659 psi), respectively. The mechanical properties of these three-ply pine mats were also compared with other studies of mats from other species groups and design architectures.

Industrial access mats are widely used throughout the construction industry as they spread relatively heavy concentrated loads over large surface areas, thereby reducing ground pressure and soil compaction. These mats are particularly useful on soft and environmentally sensitive soils and are commonly used in the construction of roads, bridges, oil fields, pipe and transmission lines, wind and communication towers, crane and dragline operations, and others (Shmulsky et al. 2021b).

Whereas cranes, cables, shackles, straps, other rigging, and soils often have working load limits and stiffness ratings, the access mat layer between the soil and the equipment often does not have this load rating. This lack of information creates uncertainty and associated risk in the construction industries that use said mats. To begin to develop basic material properties of access mats, a series of evaluation tests has been conducted on mats from varying wood species and with varying architectures.

Shmulsky and Shi (2008) reported on the mechanical properties of laminated hardwood billets. In that case, low-grade glue-laminated hardwood lumber was tested in the laboratory and the laminated hardwood billets were drilled and bolted together, edge to edge, for commercial use as mats. Yang et al. (2015) reported on similar testing of glue-laminated southern pine that was manufactured with randomized butt joints. Three-layer cross-plied mats are another common variant for light-duty access. In that case, lumber is laminated together with bolts, nails, or other fasteners with the two surface plies oriented longitudinally and the inner ply oriented transversally with respect to the mat's long axis. Owens et al. (2020) reported on analogous testing of 20-cm (8 in.)-deep mixed hardwood timber mats. Shmulsky et al. (2021b) reported on testing of 20-cm and 30.5-cm (8-in. and 12-in.)-deep oak-bolted timber mats. Mechanically fastening timbers together, edge to edge, with through bolts is one of the most common forms of mat architecture. To diversify bioproducts that are used as matting, bamboo three-ply laminated mats have entered the market. Shmulsky et al. (2021a) reported on testing and evaluation of these bamboo mats. Snow et al. (2022) reported on testing of three-ply mixed oak and hardwood mats. In each of these cases, researchers have sampled and tested a sufficiently large sample (28-specimen minimum) to be able to develop nonparametric fifth percentiles (ASTM-D2915 2017a). These fifth percentiles are then used to develop allowable strength properties. Per ASTM-D2915 (2017a), allowable stiffness properties related to deflection under load are computed as the numerical mean of the sample. Additionally, glued cross-laminated timber

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Table 1.—Strength, stiffness, and allowable property results for various matting materials.

	Modulus of rupture		Modulus of elasticity		F_b (allowable bending strength; nonparametric)	
	MPa	psi	MPa	psi × 10^6	MPa	psi
20.32-cm (8-in.)-deep oak timber mats[a]	45.12	6,549	9,853	1.43	16.64	2,415
20.32-cm (8-in.) mixed hardwood timber mats[b]	45.20	6,560	7,648	1.11	15.98	2,319
30.48-cm (12-in.)-deep oak timber mats[a]	41.03	5,955	9,164	1.33	15.16	2,200
13.97-cm (5.5-in.)-deep glued hardwood billets[c]	49.66	7,208	10,687	1.55	21.19	3,075
18.41-cm (7.25-in.)-deep glued pine billets[d]	33.07	4,800	7,579	1.1	12.59	1,827
Three-ply waffle mixed hardwood, U.S. Upper Midwest[e]	15.16	2,200	1,171	0.17	7.26	1,053
Three-ply waffle mixed hardwood, U.S. South[e]	16.34	2,372	1,240	0.18	11.46	1,663
Three-ply solid mixed hardwood, U.S. Upper Midwest[e]	16.41	2,381	1,309	0.19	10.26	1,489
Three-ply solid mixed hardwood, U.S. South[e]	19.69	2,858	1,585	0.23	14.20	2,061
Three-ply bamboo[f]	25.83	3,749	1,929	0.28	8.09	1,174
Three-ply southern pine cross-laminated timber[g]	34.88	5,062	8,130	1.18	10.39	1,508

[a] Shmulsky et al. (2021b).
[b] Owens et al. (2020).
[c] Shmulsky and Shi (2008).
[d] Yang et al. (2015).
[e] Snow et al. (2022).
[f] Shmulsky et al. (2021a).
[g] Spinelli (2022).

(CLT) has also been evaluated and is used commercially as matting. A standard specification for CLT manufacturing has been developed (APA 2018). Also, commercially available CLT matting specimens have been evaluated for their strength and stiffness performance (Spinelli 2022). Three-ply southern pine, No. 2 grade on faces and at least No. 3 grade in the core (SPIB 2014), was evaluated. Strength, stiffness, and allowable property results for all these material evaluations are presented in Table 1. This type of bolt-laminated mat architecture and construction is used commercially throughout the United States. However, to the authors' knowledge, no research with respect to the mechanical properties of these composites has been put forth. In this study, 61-cm (2-ft)-wide specimens were specified and ASTM-D5456 (2017b) was used as the test method. Therefore, the objective of this study was to evaluate the mechanical performance of three-ply bolt-laminated southern pine mats. In this case, plies are oriented perpendicular to each other, that is, the two face plies are oriented longitudinally and the middle ply is oriented perpendicularly. No adhesive is used. From this evaluation, allowable design strength and stiffness were determined. This information is directly and immediately applicable to the industrial access mat community. It was hypothesized that these pine mats would perform similarly to the hardwood mats previously investigated by Snow et al. (2022). It was also hypothesized that these bolt-laminated pine mats would not be as stiff as the southern pine CLT as reported by Spinelli (2022).

Figure 1.—Chainsaw ripping of each 243.84 by 426.72-cm (8 by 14-ft) parent mat into four test specimens, each approximately 60.96 cm (2 ft) wide.

Materials and Methods

In this research, seven mats, each three ply and 244 by 427 cm (8 by 14 ft) were procured. All mats were manufactured from No. 2-grade commodity southern pine (*Pinus* sp.), 5 by 20-cm (2 by 8-in.) nominal-dimension lumber. Each mat contained approximately 1.6 m^3 (672 board ft) of lumber. Lumber was kiln dried; however, mats were permitted to sit in the outside weather before testing. In this manner, moisture content (MC) was not controlled and mats were considered wet, that is, at or above 19 percent MC at the time of testing. Each mat was specified to contain at least 180 through bolts. Bolts were carriage-head type, 0.953-cm (⅜-in.) diameter. Bolt length was approximately 11.4 cm (4.5 in.). Nuts were countersunk and the bolt shaft was flush with the bottom face of the mat. The bolt spacing and schedule was determined by the commercial specifier and was more or less uniform about the face. Given the mat area of 10.4 m^2 (112 ft^2), there were approximately 17 bolts per m^2 (1.61 bolts per ft^2). Bolts were torqued to their specified rating on the basis of their grade, diameter, and pitch. The bolts were carriage type with the carriage head on the top face and a recessed and integrated nut and washer on the bottom face. For testing, each mat was ripped with a chainsaw into four equivalent test specimens (Fig. 1). In this manner, from seven parent mats, a total of 28 unique test

Figure 2.—Examples of grade stamps that were visible on one of the surfaces of one of the parent mats.

Figure 3.—One of the test specimens in the universal testing machine while being destructively evaluated in ⅓-point bending.

specimens was generated. Figure 2 illustrates examples of grade stamps that were visible on the surface of the mats.

After ripping, each of the 28 test specimens was tested in ⅓-point bending per ASTM-D5456 (2017b). Figure 3 illustrates one of the test specimens in the universal testing machine during mechanical testing. Loads were applied as line loads across the full width of each specimen at the ⅓-span points. Deflection was measured by a string encoder affixed to each specimen's neutral axis at midspan. After testing, the modulus of rupture (MOR) and modulus of elasticity (MOE) were calculated (Eqs. 1 and 2) and the data were evaluated such that allowable design properties could be developed.

$$\mathrm{MOR} = 1.5PL/bh^2 \tag{1}$$

where P is the breaking load (maximum load, N), L is the distance between supports (m), b is the width of the beam (m), and h is the depth of the beam (m).

$$\mathrm{MOE} = PL^3/48ID \tag{2}$$

where P is the concentrated center load (N), L is the span (m), D is the deflection at midspan (m), and I is moment of interia (m^4).

Results and Discussion

The descriptive statistical results are shown in Table 2. The order statistic for the 28 specimens is 1 and that value is used as the nonparametric fifth percentile. The k factor for the 28 specimens is 1.88. The F_b value is calculated as the fifth percentile divided by 2.1.

Both MOR and the MOE values for the specimens were highly uniform, with coefficient of variation (COV) values of 14.7 percent and 9 percent, respectively. These COV values are much less, indicating much greater uniformity, as compared with the variation among southern pine graded dimension lumber. The mean strength of the mats as shown in Table 2 is higher than that of pine 5 by 20-cm (2 by 8-in.) No. 2 grade dimension lumber (SPIB 2014). This finding indicates that the composite action developed in the mat is effective. The nonparametric F_b value, approximately 4.54 MPa (659 psi), is slightly less than half of the value of three-ply mixed hardwood mats and of three-ply southern pine CLT (Shmulsky and Shi 2008; Owens et al., 2020; Spinelli

Table 2.—Mechanical strength and stiffness summary statistics for three-ply bolt-laminated mats.

	Modulus of rupture		Modulus of elasticity	
	MPa	psi	MPa	psi $\times 10^6$
Mean	11.74	1,704	1,144	0.166
Standard deviation	1.72	250	1,027	0.149
Coefficient of variation (%)	14.70	14.70	9	9
Minimum	9.53	1,383	971	0.141
Maximum	15.77	2,289	1,350	0.196
N	28	28	28	28
k factor (ASTM D2915-10 2017a)	1.88	1.88	Not applicable	Not applicable
Nonparametric fifth percentile	9.53	1,383		
Parametric fifth percentile	8.50	1,234		
F_b nonparametric[a]	4.54	659		
F_b parametric	4.05	588		

[a] F_b = design fiber stress in bending value.

2022). This finding suggests that the three-ply hardwood mats likely have inherently stronger raw materials (Snow et al. 2022). This finding also suggests that the adhesive action in the CLT helps the mat behave as a stiffer and stronger composite as compared with the bolt laminations. The average MOE, approximately 1,144 MPa (0.166×10^6 psi), is comparable with the mean value seen in three-ply mixed hardwood mats with waffle-type construction. Bolt laminating allows greater deflections in three-ply mats as compared with adhesively bonded CLT. This action allows mats to deflect over and conform to uneven terrain and thereby resist breaking. As a basic failure mode, in general, tension face planks failed in simple tension typically initiating at obvious knots. Also, the individual plies exhibited shear during testing that was easily noted at the ends of the specimens while under loading.

Conclusion

The evaluation of the mechanical performance of three-ply bolt-laminated southern pine mats was performed in this research. The results showed that the values for MOR and MOE were uniform. The mean strength was higher in three-ply bolt-laminated southern pine mats in comparison with southern pine No. 2-grade dimension lumber. The results of nonparametric F_b values indicated that three-ply hardwood mats performed better and had inherently stronger raw materials in comparison with three-ply bolt-laminated southern pine mats with manufacturing from No. 2-grade southern pine. As such, three-ply pine mats have a niche in the access mat industry. Therefore, the bolt-lamination process for the graded dimension pine lumber reported herein does not develop allowable bending strength as compared with similarly constructed hardwood mats.

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