CASE STUDY OF 3-PLY COMMERCIAL SOUTHERN PINE CLT MECHANICAL PROPERTIES AND DESIGN VALUES

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(Received January 2022)

Abstract. This work elucidates on a case study of industrially manufactured cross-laminated timber (CLT). Two methods are used to calculate specimens section modulus: S_{gross} and $S_{effective}$. The first assumes that specimens behave as a continuous material, whereas the second considers the cross laminations (shear analogy method). Although the shear analogy method is indicated for construction purposes, applications, such as trench shoring, matting, and work platforms, could benefit from a simpler calculation method. Therefore, the objective of this work was to conduct a case study of Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) of southern pine CLT to compare the previously mentioned calculation methods. Both parametric and nonparametric fifth percentiles and associated F_b values are reported and were substantially higher than those of the constituent lumber. For MOE, empirical testing and calculation based on gross moment of inertia provided lower values as compared with the constituent lumber.

Keywords: Cross-laminated timber, bending design value, section modulus, strength, stiffness.

INTRODUCTION

The research reported herein provides a case study of industrially manufactured cross-laminated timber (CLT). Over the past decade, CLT has made significant advancement in the building construction sector. As a relatively new mass timber panel, CLT has demonstrated both potential and promise in various building construction applications. To enhance North American production and market acceptance, APA-The Engineered Wood Association (2018) has published a related product standard. Therein, among other items are minimum grade, strength, and stiffness, requirements for lumber to be used in layup laminations. It also contains information regarding moment capacity (strength) information ($F_b \cdot S$) as well as sectional stiffness, that is, the product of Modulus of Elasticity (MOE) times the moment of inertia ($E \cdot I$). These values are derived from the basic lumber lamination mechanical properties and effective section properties. Effective section properties are somewhat reduced from gross section properties to account for the cross lamination(s) in the inner ply or plies. The S_{gross} method assumes that the CLT panel behaves as a continuous composite material through its thickness, whereas the $S_{effective}$ method uses shear analogy applied to CLT. As such, the $S_{effective}$ is less than the S_{gross} because the rolling (across the grain) shear strength is taken as a fraction of parallel to grain shear. Although it's necessary to count for rolling shear strength for construction purposes, the shear analogy method can be seen as over conservative when applied to

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Wood and Fiber Science, 55(1), 2023, pp. 94-99
https://doi.org/10.22382/wfs-2023-09

other CLT uses. The shear analogy method not only requires more measurements, but also entails a more complex understanding of composite materials and strength calculations, which can act as a limitation to secondary CLT uses. Outside of the building construction industry, there are other opportunities for CLT use and adoption. Industrial applications, such as matting, trench shoring, other temporary shoring, and work platforms, are potential markets. In such cases, it is often helpful to have basic bending strength (Modulus of Rupture [MOR] and F_b) and stiffness, as MOE, properties of the manufactured panels. In such instances, the parameters calculation can still be seen as conservative, but will often be more easily assessed by quality control procedures already widely used by the wood products industry. Therefore, the objective of this work was to conduct a case study of MOR and MOE of southern pine CLT, along its major strength axis, to compare the previously mentioned calculation methods.

MATERIALS AND METHODS

In this case study, 24 2.44 m (8 ft) × 4.88 m (16 ft) 3-ply commercial CLT panels were acquired and defined as parent panels. Panels were made in accordance with PRG-320 (APA-The Engineered Wood Association 2018) from 5.08 × 20.3 cm (2 × 8 in.) nominal, 3.81 × 18.4 cm actual (1.50 × 7.25 in.) Number-2 southern yellow pine lumber and glued with polyurethane. According to PRG-320, this material is classified as V3 (Table 1). In addition, also in agreement with PRG-320, the basic bending design values for CLT are based directly on the material properties of the constituent lumber. In other words, PRG-320 uses basic, minimal lumber design values as the direct feedstock for CLT design value calculation. In that matter, one of the purposes of this study was to demonstrate that direct testing of CLT offers the possibility to derive or demonstrate superior properties. The process of lamination and development of a composite system routinely improves the allowable strength values.

Table 1. Design values (MPa) for laminations in longitudinal layers, per V3.

F_b[a]	Characteristic value[b]	F_b for #2 2x8 lumber[c]	MOE[c]
5.17	10.9	6.38	9650

[a] PRG-320, Table A1
[b] PRG-320, Table 1. (Note: F_b = Characteristic value/2.1)
[c] SPIB 2014

From each of 20 parent panels, one test specimen was ripped. From each of four parent panels, two test specimens were ripped. In sum, 28 unique test specimens were considered. This is the minimum number required, per American Society for Testing and Materials (ASTM) D2915 (2017a), for estimation of a nonparametric fifth percentile. In general, during the ripping process, the material from which any given specimen was ripped was not immediately adjacent to the material from which any other specimen was ripped. After ripping, some of the face lumber on the specimens was asymmetric, that is, it included two full 7.25-in. wide pieces, ripped strip to make up the full 18-in. wide test specimen. Test specimens were kept on an outside covered area previous to testing. Specimens presented an average density of 535.5 Kg/m^3 and average MC of 14%. As measured, each specimen was approximately 10.5-cm (4.13-in.) thick, 45.7-cm (18.0-in.) wide, and crosscut to 3.05-m (120-in.) long. The reason the specimens were 4.13-in. thick (rather than full 4.25-in.) is because each constituent piece was skim planed at the time of CLT manufacture.

The samples were destructive tested in the major direction (3.05-m), as arranged in a flatwise layup, via third-point bending over a 2.90-m (114-in.) span (Fig 1) and at a span to depth ratio of 27.6 according to a modified ASTM 5456 (2017b) and with consideration of PRG-320 "specimen width not less than 12 in. and the on-center span equal to approximately 30 times the specimen depth for the tests in the major strength direction. . . ." This relatively long specimen size minimizes the incidence of shear failure during the flexural test. The timber blocks between the machine fixture load heads and the specimen are approximately 6.5 × 10 × 60 cm (2.56 × 3.94 × 23.6 in.) in dimension. They are

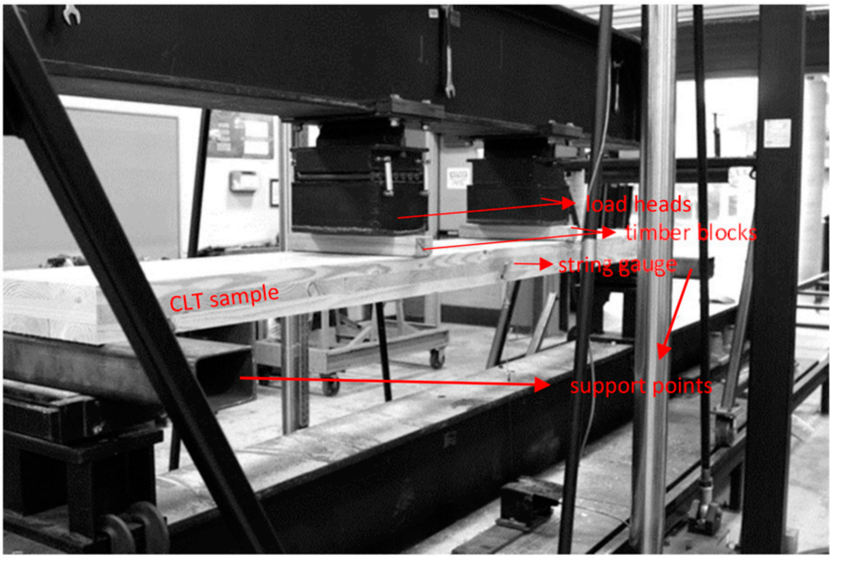

Figure 1. Test setup.

radiused per the standard at the points of specimen contact and provide line loads at the one-third points and are sufficiently wide to avoid indentation. A 600-kN capacity hydraulic universal test frame was used for testing. To record the deflection, a string gage deflectometer with the 0.001 ± 0.0005-in. accuracy was placed at midspan and at the panel's neutral axis. The test was displacement controlled with a rate of 0.0003 m/s (0.8 in./min). Load, deflection, testing rate, time to failure, and failure mode were recorded.

To calculate flexural stress (MOR), one must first calculate the section modulus of the panel. For CLT, calculation of section modulus for uniform rectangular sections is done in two ways and thus, yields two different MOR, and subsequently, F_b values. Either method might be acceptable, depending on the final use of the panel, as they ultimately equate to the same moment capacity. The S_{gross} method assumes that the CLT panel behaves as a continuous composite material, whereas the $S_{effective}$ method uses shear analogy applied to CLT, considering the orientation of the laminations. In the case of industrial applications, such as matting, it is often more practical to use gross section modulus (S_{gross}) for determination of F_b as it is readily calculable.

$$S_{gross} = \frac{b \cdot h^2}{6}$$

Where:

b = width; h = thickness.

$$S_{eff} = \frac{2EI_{eff}}{E_1 \cdot h}$$

Where:

EI_{eff} = Effective bending stiffness; E_1 = MOE of outermost layer (Characteristic value of 9.65×10^3 MPa [1.4×10^6 psi per SPIB 2014]); and h = Entire thickness of the panel (Karacabeyli and Douglas 2013).

$$EI_{eff} = \sum \left(E_i \cdot b_i \cdot \frac{{h_i}^3}{12} \right) + \sum \left(E_i \cdot A_i \cdot {z_i}^2 \right)$$

Where:

E_i = "i" layer's design value MOE (9.65×10^3 MPa [1.4×10^6 psi per SPIB 2014]); b_i = "i" layer's width; h_i = "i" layer's thickness; and

Table 2. Summary statistics for the flexural testing.

	Load (kN)	MOR gross (MPa)	MOR effective (MPa)	MOE gross (MPa)
N (number of specimens)	28	28	28	28
Average	65.4	34.9	35.9	8142
Maximum	81.6	44.9	45.9	10,469
Minimum	42.2	23.1	23.9	5755
Standard deviation	9.58	4.9	5.09	1068
Coefficient of variation	14.7%	14.1%	14.2%	13.1%
K factor*	1.88	1.88	1.88	1.88
Parametric fifth percentile	47.4	25.7	26.4	—
Order statistic	1	1	1	—
Non parametric 5th percentile	42.2	23.1	23.9	—
Factor for conservatism (NDS 2015)	—	0.85	0.85	—
Combined load duration and safety factor (ASTM 2017b)	—	2.1	2.1	—
F_b (parametric)	—	10.4	10.7	—
F_b (nonparametric)	—	9.34	9.67	—

*Estimated K factor for one sided tolerance limit, for $n = 28$, at 75% confidence per Table 3, (ASTM 2017a).

A_i = "A" layer's section area; z_i = distance from the neutral axis of the panel to the center of respective layer.

These two section moduli were then used to calculate panel stress values. With these two section moduli, two sets of stress values were calculated. F_b gross was calculated as maximum moment divided by S_{gross}. F_b effective was calculated as maximum moment divided by $S_{effective}$. Per associated guidance from PRG-320, effective moment capacities must be multiplied by a factor of 0.85 for conservatism. As such, one can either multiply the 0.85 factor times the F_b value, the section modulus value, or their product ($F_b \cdot S$). To calculate the stiffness of the panel, the traditional calculation method for lumber was applied (ASTM 2022).

$$E_{app\ (gross)} = \frac{23P \cdot l^3}{108b \cdot d^3 \cdot \Delta}$$

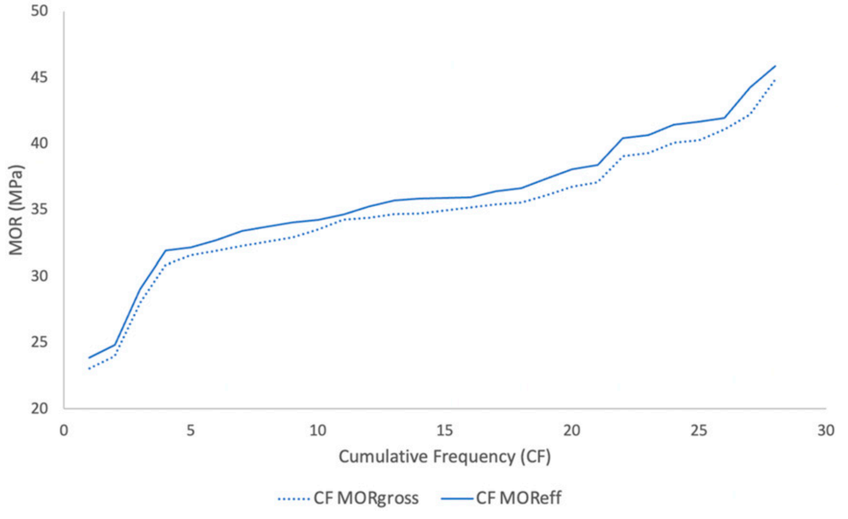

Figure 2. Cumulative frequency distribution of MOR values.

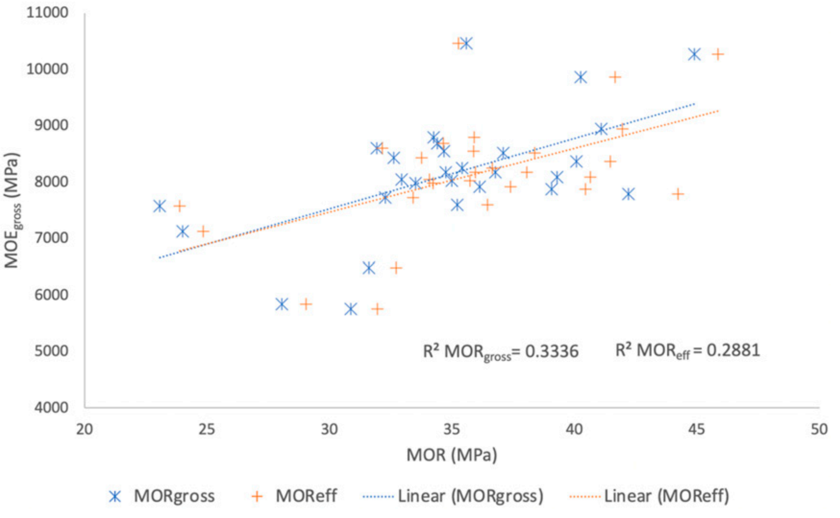

Figure 3. Relationship between MOE and MOR for the 28 specimens.

Where:

$E_{app\ (gross)}$ = Apparent MOE; P = load; l = span; b = width; d = panel thickness; and Δ = increment of deflection.

RESULTS AND DISCUSSION

From the test data, MOR was calculated by both gross and effective section moduli. For each of these methods, both parametric and nonparametric fifth percentiles (ASTM 2017a) and associated F_b values are reported. MOE was calculated based on the gross moment of inertia. The summary statistics are presented in Table 2. Both parametric and nonparametric F_b values (9.34 and 10.4 MPa, respectively) were substantially higher than those of the constituent lumber (6.38 MPa).

MOE gross is included because it can be readily calculated based on the direct physical measurements of the panel along with its observed deflection in response to a given load. MOE effective is not considered herein because it is generally calculated based on the published design value MOE of the constituent lumber rather than on the empirical observations. Figure 2 illustrates the cumulative frequency distribution of MOR values. Figure 3 illustrates the relationship between MOE and MOR. The MOR_{gross} R^2 value for this relationship is 0.33. This finding indicates that 33% of the variation in MOR_{gross} is explained by MOE.

CONCLUSIONS

- For MOR_{gross}, empirical testing provided favorable results as compared with currently assigned values derived as defined in PRG-320 based on the published values for the constituent lumber. This finding suggests that it is likely in a manufacturer or user's best interest to evaluate their specific material's flexural strength. In this manner, a manufacture can most accurately market their material based on its inherent properties and a user can derive the maximum possible potential utility and engineering value from said materials.
- For MOE, empirical testing and calculation based on gross moment of inertia provided lower values as compared with the constituent lumber. This result is likely due to the fact that the center ply was oriented perpendicular to the facial plies and as such, displayed predictably lower stiffness. This finding suggests that it is likely in a user's best interest to evaluate their specific material's flexural stiffness if deflection under load is an important use criteria.
- The relationship between MOR_{gross} and MOE was relatively weak. This finding indicates

that nondestructive evaluation based on MOE, for this material, may not be a particularly useful tool for evaluating ultimate or allowable strength characteristics.

- In the case of matting, heavier loads applied over softer soils require increasingly predicable strength and stiffness. Reliable strength values prevent mat breakage, potential equipment loss, and unsafe working conditions. Reliable stiffness values minimize rutting, enhance environmental protection, and increase safety particularly with respect to crane and other lifting operations. The information developed and reported herein can be useful for those who employ CLT mats in heavy construction, road building, powerline and pipeline operations, and so on.

ACKNOWLEDGMENTS

This publication is a contribution of the Forest and Wildlife Research Center, Mississippi State University. The authors wish to acknowledge the support of U.S. Department of Agriculture (USDA), Research, Education, and Economics (REE), Agriculture Research Service (ARS), Administrative and Financial Management (AFM), Financial Management and Accounting Division (FMAD), and Grants and Agreements Management Branch (GAMB), under Agreement No. 58-0204-6-001. Any opinions, findings, conclusion, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the U.S. Department of Agriculture.

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