Effect of Notching on Three-Ply Southern Pine Cross-Laminated Timber Panel Stiffness and Strength

Laurice Mara Spinelli Correa
Rubin Shmulsky
Robert J. Ross

Abstract

Considering the high demand for housing and the ongoing environmental issues our society faces, it's crucial to opt for more ecofriendly materials for building purposes. In that scenario, engineered wood products play an important role as they are not only based on a sustainable material but also can reduce the carbon footprint from construction. Cross-laminated timber (CLT) is one of the products that could expand wood products use while keeping up with low and mid-rise building needs. Although CLT use has been expanding in the United States for the last few years, there is still a high necessity for understanding this composite behavior. One of those needs is assessing the effect of notching on the panels and measuring strength reduction as well as possible reinforcement methods. The goal of this project was to evaluate the performance of CLT panels focusing on strength and stiffness properties. Mechanical bending testing of three-ply southern pine CLT samples was performed to evaluate the influence of notches and stitching reinforcement on panels. The strength reduction caused by notching was successfully measured. Control samples supported significantly higher loads than notched samples. However, it was found that the deeper the notch, the more effective the stitching can be regarding strength. Control samples presented cross-grain tension and splintering tension failure modes, whereas notched samples presented simple tension failure mode. The findings of this work are of great value toward updating manufacturing, design, and use criteria for notched CLT panels and can be potentially used in future building codes.

As the population grows so too does the demand for housing. Considering the need for sustainability, because of recurring environmental issues, renewable materials such as engineered wood products play an important role in future building structures. For the last few decades, the use of cross-laminated timber (CLT) in low to mid-rise construction has been expanded in Europe, and now, this product has been slowly incorporated in the United States. Engineered wood products as such CLT provide builders with a unique opportunity to renew the way we construct and see our everyday spaces. When compared with other common construction practices, in many instances building with prefabricated CLT is cleaner, faster, and requires less intensive labor. In addition, it has been noted that living/working in wood buildings can reduce stress levels and improve well-being (Rice et al. 2006). Regarding the high demand for carbon sequestration and sustainability, there aren't currently other materials that are as favorable as wood. Although many studies have been completed in support of CLT development and adoption, there are some current and pressing research needs.

Presently, the use of CLT in the United States is restricted by some recurring limitations. For instance, the price is yet not as competitive as desirable because of the current relatively small number of manufacturers in the country. In addition, CLT panels are still not comprehensively explored by building codes as other construction materials/methods; building processes are thus often more streamlined when designers choose more conventional building strategies. Moreover, as CLT are composite panels and therefore need more in-depth calculation methods for the design, adjust-

The authors are, respectively, Postdoctoral Associate (ls2090@msstate.edu [corresponding author]) and Head and Warren S. Thompson Professor of Wood Sci. & Technol. (rs26@msstate.edu), Dept. of Sustainable Bioproducts, Mississippi State Univ., Mississippi State, and Project Leader and Research Professor, Forest Service, Forest Products Lab. and Michigan Technol. Univ., Madison, Wisconsin (robert.j.ross@usda.gov). This paper was received for publication in December 2022. Article no. 22-00071.
©Forest Products Society 2023.
Forest Prod. J. 73(2):146–153.
doi:10.13073/FPJ-D-22-00071

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

ments due to notches have not yet been thoroughly explored, which increases the complexity of design calculations and limits panels' applications.

Notches are often used as construction details to facilitate mechanical interlocking and adjacent member placement, which can improve and facilitate building design and construction. However, notches influence the ultimate capacity of members, particularly in bending. As the moments of inertia and section moduli are reduced where notches are located, stresses concentrate in those areas. For instance, a high stress concentration in a notch could generate a localized brittle fracture in a member that is otherwise expected to have ductile behavior, which may lead to premature failure. The 2018 International Residential Code for one- and two-family dwellings (International Code Council 2017) restricts the use of notches on engineered wood products by requiring structural calculations rather than putting forth some of the ways notches might be used. The understanding and quantification of notched CLT floor panels' failure modes, ductility, and strength can allow the safe application of notches in building construction. With diligent and conservative research, architects and engineers will have access to better notch-related design information for CLT panels, which will most likely increase the use of relatively more sustainable products in the construction industry.

Many articles can be found regarding notched wood beams and glulam. The approaches for understanding the issue are vast and can be classified by groups such as experiments on modes I, II, and III failures (de Moura et al. 2006, 2018; Silva et al. 2006; Arrese et al. 2010; Dourado et al. 2015); fracture and crack propagation (Valentin and Adjanohoun 1992, Smith and Vasic 2003, Coureau et al. 2006, Sedighi-Gilani and Navi 2007, de Moura et al. 2010, Wang et al. 2012); notch design, shape, and position (Henrici 1976, Jockwer et al. 2014, Dewey et al. 2018); notched wood strength and stiffness (Jockwer et al. 2016, Dewey et al. 2019); and computer modeling (Toussaint et al. 2016, Tran et al. 2018).

Considering notched wood beams, Murphy (1979) used fracture mechanics to predict failure and observed that wide-notched beams fail under higher loads more often than narrow-notched beams. His study showed that fracture mechanics is an effective way of quantifying the influence of notch depth on bending strength. Gustafsson (1988) studied the strength of notched beams by taking into account the code design formulas, the influence of size of fracture region, and the initial cracks on notched beams, concluding that failure typically starts at the notched area, and it is not increased by beam volume. Therefore, the fracture in the notch area is not necessarily proportional to beam size. He also concluded that the fracture energy and material properties can be of big importance to notch strength; the failure can be analyzed by fracture mechanics; and that strength of the notch does not correlate with tensile strength perpendicular to grain. Zalph and McLain (1992) used a critical fillet hoop stress model to predict tension-side notched beam failure loads by considering the effects of notch location, loading condition, shear/moment ratio, notch depth, beam depth, and fillet radius. The finalized model was able to well predict critical loads and the authors concluded that the first major load drop can be used as a conservative estimation of beam ultimate capacity. Moreover, Aicher et al. (2002) published a compilation of articles surrounding strength analysis of holed and notched timber beams based on fracture mechanics models.

Regarding notched glulam beams, as cited in Rammer (personal communication, 2019), researchers have tested glulam beams comparing numerous notch geometries, notch depths, and reinforcing technics aiming to reinforce notched glulam beam capacity. Murphy (1986) performed a study that tested beams with notches and slits. This research was done by focusing on changing slits/notch position and geometry to compare the results with proposed fracture methodology. The fracture approach was able to predict the critical crack propagation load. Moreover, Smith et al. (2015) explain CSA Standard 086-141 design provisions for tension-side notched glulam beams, concluding that relatively small notches in small glulam members usually increase load capacities, whereas considerable large notches in large glulam beams under high shear forces ultimately reduce load capacities.

Flaig (2014) tested CLT beams to determine the load-carrying capacity of beams with notches and holes. He observed that the shear stresses in the crossing areas resulted in failure of the beams and developed an accurate design method for not continuous CLT beams. However, there is still a need for a better understanding of notched CLT panels' strength, stiffness, failure pattern, crack propagation, and stress distribution.

The objective of this study was to evaluate the performance of CLT panels focusing on strength and stiffness properties. To accomplish this goal, mechanical testing of commercially produced three-ply CLT samples was performed to evaluate the influence of notches and stitching reinforcement on panels.

Materials and Methods

A pilot-scale experiment was designed to address the stress concentration caused by the notches as well as the possibility of increasing the ductile behavior of CLT. A total of twenty 2.44 by 4.88-m (8 by 16-foot) three-ply commercial cross-laminated timber panels was used in this study. Each of 20 three-ply commercial CLT panels was defined as a parent panel. Each parent panel was then ripped lengthwise into five strips. Each strip was then cut into two sections, one approximately 3.05-m (120-inches) long and one approximately 1.68-m (66-inches) long. In sum, 200 specimens were generated: 100 long-span (3.05-m) specimens and 100 short-span (1.68-m) specimens. This manuscript deals only with the long-span specimens. The intent of this schema was to investigate the flexure behavior of the CLT wherein bending and not shear would be the primary failure mode. Each long-span specimen was approximately 0.105 by 0.457 by 3.05 m (4.125 by 18 by 120 inches). The long-span specimens are shown on the left side of the master cut-up schematic of Figure 1. Small-dimensional fluctuations were observed among the parent panels. As such, treatments were randomly assigned to each of the five specimens from each parent panel. The treatments were (1) control; (2) notch to 33 percent of first-layer depth; (3) notch to 33 percent of first-layer depth with stitches; (4) notch to 66 percent of first-layer depth; and (5) notch to 66 percent of first-layer depth with stitches (Table 1). Each treatment group contained 20 specimens, that is, one specimen from each of the parent panels. Stitching consisted of installing four 8.89-cm (3.5-inch)-

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

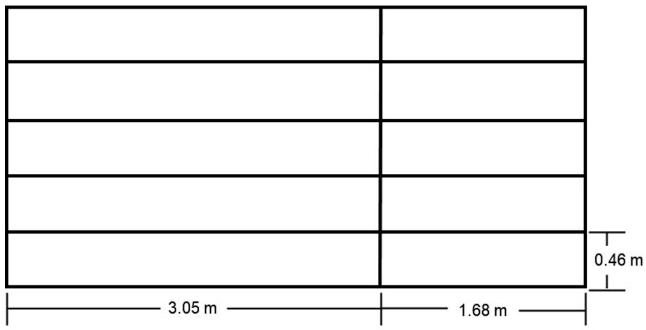

Figure 1.—Panel's cutting layout.

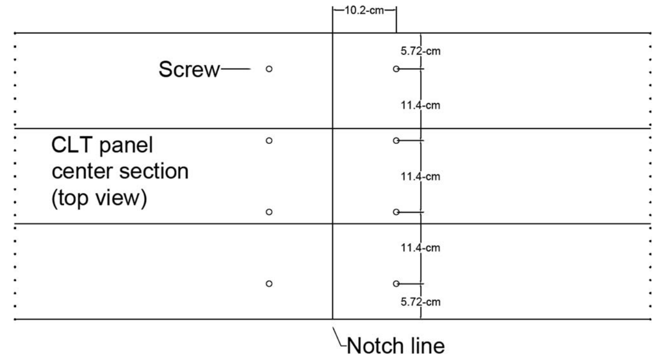

Figure 2.—Screw arrangement for stitched treatments—cross-laminated timber (CLT) panel center section, top view.

long construction screws in an evenly spaced row along each edge of each notch as described below.

Test specimens were kept on an outside covered area until testing. Specimens presented an average density of 538.1 kg/m^3 and average moisture content of 14 percent. In addition, panels were glued with polyurethane. Each specimen was labeled according to parent panel, testing type, position in the parent panel, and treatment assigned. For instance, a long-span sample located in the third line of panel 18 assigned to treatment 4 would have the label P18-L3-T4. Treatments 2 through 5 were cross-cut, with a shallow dado-type cut, at mid-length, conferring with the notch specification for the respective treatment. The overall width of the cut was approximately 0.508 cm (0.20 inch). For treatments 2 and 3 the notch depth was approximately 1.19 cm (0.47 inch)—33 percent of the outer layer's depth. For treatments 4 and 5 the notch depth was approximately 2.39 cm (0.94 inch)—66 percent of the outer layer's depth. Specimens in treatments 3 and 5 were stitched with premium exterior wood screws (no. 10, 3 ½ inches). Each screw was installed perpendicularly to the CLT length, 10.16 cm (4 inches) away from the notch line and 11.43 cm (4½ inches) apart from each other. The outermost screws in the stitch line were installed 5.72 cm (2¼ inches) from the edges (Fig. 2). Panels were made per PRG-320 (APA—The Engineered Wood Association 2018) from 2 by 8 (nominal) No. 2 southern yellow pine lumber. Per PRG this material is classified as V3. Table 2 illustrates the allowable design properties for this raw material.

All specimens were destructively tested in third-point bending (Fig. 3) according to ASTM D198 and in compliance with PRG-320. The span for testing was 2.90 m (1.14 inches). This span-to-depth ratio (approximately 26.8) was chosen to facilitate bending, rather than rolling shear failure. To record the deflection, a string gauge-type deflectometer with 0.001 ± 0.0005 inch accuracy was placed at midspan on the center of a panel's neutral axis. The test was displacement controlled with a rate of 0.0003 m/s (0.65 inch/min). During the test, notches were located on the tension side (bottom) of each specimen. Load, deflection, testing rate, and failure mode were recorded so further analysis could be developed. The load vs. displacement curves obtained during the test for treatments 1 through 5 can be seen in Figure 4. To assess the influence of notches on three-ply CLT panels, calculations of modulus of elasticity (MOE), modulus of rupture (MOR), and work were applied. Failure mode was also observed.

Table 1.—Treatment groups.

Treatment identification	Notch condition	Stitch condition
1	Nonnotched (control)	Nonstitched (control)
2	Notched 33 percent of first layer depth	Nonstitched
3	Notched 33 percent of first layer depth	Stitched
4	Notched 66 percent of first layer depth	Nonstitched
5	Notched 66 percent of first layer depth	Stitched

To calculate CLT section modulus, two calculation methods were applied. As both methods ultimately equate to the same moment capacity, either technique might be used, depending on the panel's final application. The first, named here as S_{gross} method, considers the CLT panel as one continuous noncomposite material, whereas the second, generally known as $S_{\text{effective}}$, accounts for CLT laminations and applies the shear analogy method into its calculation. The first method might not be recommended for building construction applications. However, it is routinely applied to industrial applications as such as matting. The calculations for each method are as follows.

$$S_{\text{gross}} = \frac{bh^2}{6}$$

where S_{gross} = gross section modulus; b = width; h = thickness.

$$S_{\text{effective}} = \frac{2EI_{\text{eff}}}{E1h}$$

where $S_{\text{effective}}$ = effective section modulus; EI_{eff} ($EI_{\text{effective}}$) = effective bending stiffness; $E1$ = MOE of outermost layer (1.4 by 106 psi per Southern Pine Inspection Bureau [SPIB 2014]); h = entire thickness of the panel.

Table 2.—Design values (MPa) for laminations in longitudinal layers, per V3.

F_b[a]	Characteristic value[b]	F_b for #2 2 × 8 lumber[c]	Modulus of elasticity (MOE)[c]
5.17	10.9	6.38	9,650

[a] PRG-320, Table A1.
[b] PRG-320, Table 1. (Note: F_b = characteristic value/2.1).
[c] Southern Pine Inspection Bureau 2014.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

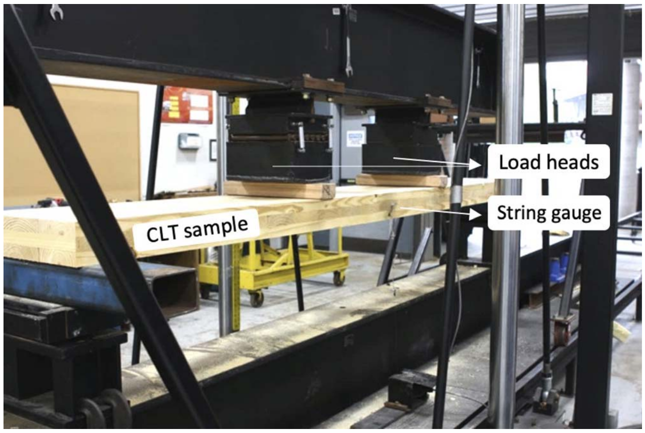

Figure 3.—Test setup—third-point bending test, in accordance with ASTM D198 and PRG320 (2.90-m span and span-to-depth ratio of approximately 26.8). A string gauge-type deflectometer was placed on the center of panel's neutral axis to measure panel's deflection.

$$EI_{\text{eff}} = \sum E_i \times b_i \times \frac{h_i^3}{12} + \sum E_i \times A_i \times z_i^2$$

where E_i = layer's MOE (1.4 by 106 psi per SPIB [2014]); b_i = layer width; h_i = layer thickness; A_i = layer's section area; z_i = distance from neutral axis of panel to center of respective layer (Equation per CLT handbook; Karacabeyli and Douglas 2013).

To calculate the stiffness of the panel, the same concept may be applied. However, as many testing facilities might only use a string gauge-type deflectometer to register panel deflection (as in this testing setup), an apparent bending stiffness (E_{app}) might be calculated to account for shear deformation. In that way, the gross E_{app} might be calculated as per ASTM D198. In addition, total work was calculated by summing the area under the load vs. displacement graph.

$$E_{\text{app}}(\text{gross}) = \frac{23Pl^3}{108bd^3\Delta}$$

where E_{app} = apparent elasticity; P = load; l = span; b = width; d = panel thickness; Δ = increment of deflection.

Results and Discussion

The control group was expected to be significantly better (higher MOR and MOE) than notched groups. Moreover, reinforcement provided by the screws on treatments 3 and 5 was expected to contain the crack propagation to a certain extent, thereby improving the ductile behavior of the panel. Although it seems intuitive that the presence of notches would negatively influence panels' behavior, it is also necessary to quantify the extent of damage and strength decrease on CLT panels, as notches are often used for diverse design functions. The strength reduction as well as the descriptive statistics can be seen in Table 3. Therefore, the information collected in this project might serve as data for the International Building Code and consequently, the expansion of CLT use in the United States.

A statistical analysis using one-way analysis of variance (ANOVA) was applied to compare the data sets for MOR, MOE, and work. The output indicates that there was a significant difference between groups for MOR (both S_{gross} and $S_{\text{effective}}$), MOE, and work (Table 4). Thus, a Tukey honestly significant difference (HSD) test was used to identify the significance between groups.

On the basis of the Tukey HSD test, MOR (on the basis of both S_{gross} and $S_{\text{effective}}$) and work can be divided into three statistical groups: (1) treatment 1 (control), (2) treatments 2 and 3, and (3) treatments 4 and 5. This group separation indicates that when all of the specimens in the study are analyzed together, there is a statistically significant difference in MOR and work with respect to notch depth. However, no statistically significant difference was detected on the basis of stitching condition (Table 5). With respect to MOE, the differences among treatments did not appear as straightforward as treatments 4, 5, and 2; 5, 2 and 1 and 2, 1,

Table 3.—Descriptive statistics.

	Treatment	N	Mean	SD	SE	Minimum	Maximum	Strength reduction (%)[a]
Modulus of elasticity (MOE; MPa)	1	20	8,044.6	1,055.6	236.0	5,755.2	10,277.2	—
	2	20	7,782.5	1,082.5	242.1	6,000.2	9,873.1	—
	3	20	8,300.0	880.4	196.9	6,934.5	10,499.8	—
	4	20	7,164.3	1,002.0	224.0	5,305.1	9,138.0	—
	5	20	7,339.4	597.4	133.6	6,273.5	8,297.4	—
Modulus of rupture (MOR; MPa) S_{gross}	1	20	34.7	5.5	1.2	23.1	44.9	—
	2	20	26.7	5.1	1.1	17.4	35.9	23
	3	20	28.3	5.6	1.2	20.7	46.0	19
	4	20	13.9	2.4	0.5	9.9	20.0	60
	5	20	15.6	2.6	0.6	11.6	20.8	55
MOR (MPa) $S_{\text{effective}}$	1	20	36.0	5.7	1.3	23.9	45.9	—
	2	20	27.5	5.3	1.2	18.0	37.1	23
	3	20	29.1	5.7	1.3	21.4	47.0	19
	4	20	14.3	2.5	0.6	10.1	20.4	60
	5	20	16.0	2.7	0.6	12.0	21.2	56
Work (N/m)	1	20	5,099.3	2,952.7	660.2	1,490.8	12,032.6	—
	2	20	2,472.4	1,221.9	273.2	657.0	5,760.6	—
	3	20	2,823.1	1,614.5	361.0	1,170.8	6,965.9	—
	4	20	852.3	330.8	74.0	400.8	1,899.5	—
	5	20	959.3	361.5	80.8	437.4	1,667.2	—

[a] Strength reduction percentage for each treatment is based on the control group.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

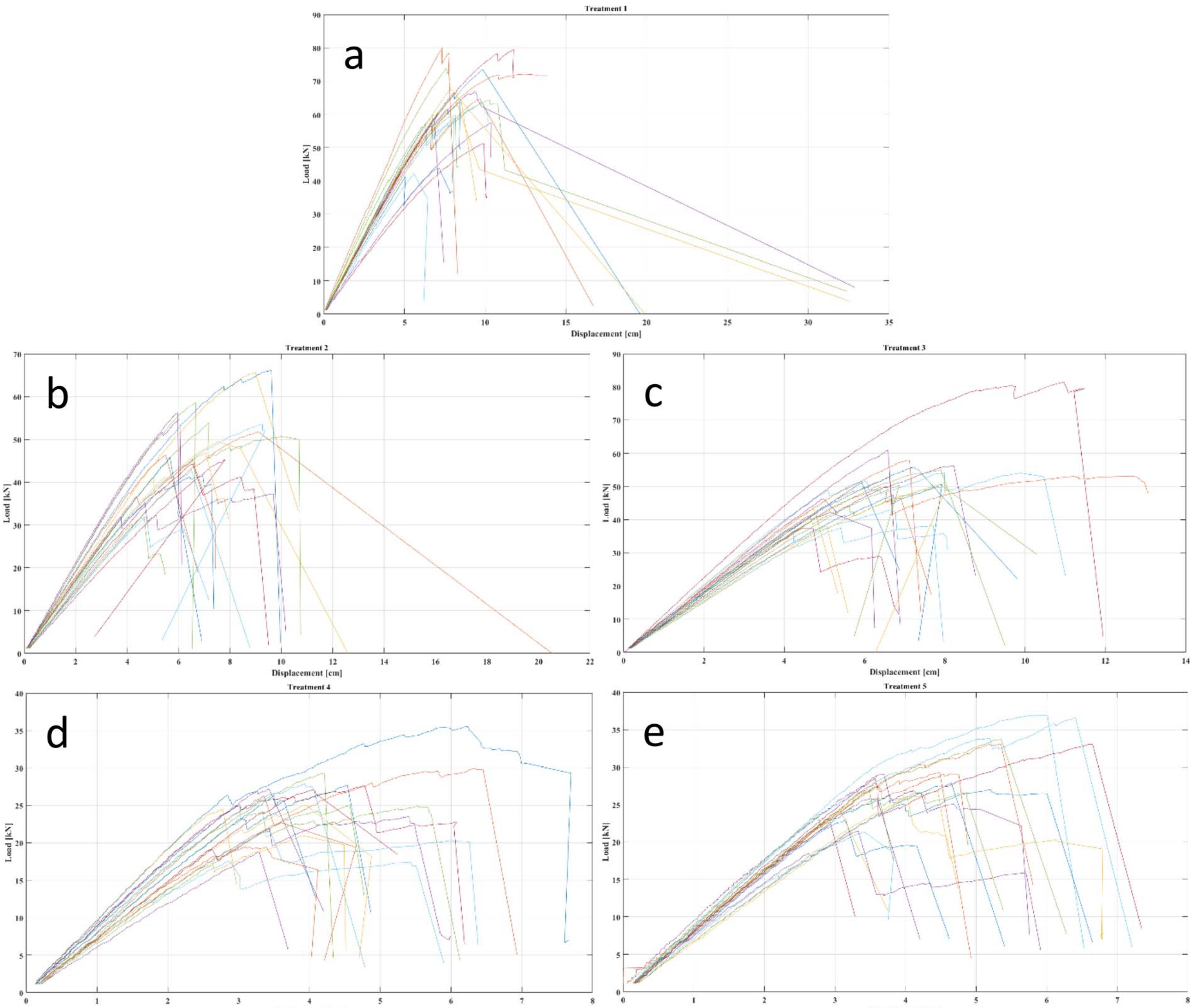

Figure 4.—Load vs. displacement curves. (a) Treatment 1, (b) treatment 2, (c) treatment 3, (d) treatment 4, and (e) treatment 5.

Table 4.—Mean comparison of treatment groups 1 through 5—analysis of variance (ANOVA).

	Sum of squares	df	Mean square	*F*	Significance (*P*)
Modulus of elasticity (MOE; MPa)					
Between groups	17,981,680.5	4	4,495,420.13	5.083	<0.001
Within groups	84,019,843.8	95	884,419.409		
Total	102,001,524	99			
Modulus of rupture $(MOR)_{gross}$ (MPa)					
Between groups	6,290.525	4	1,572.631	78.714	<0.001
Within groups	1,898	95	19.979		
Total	8,188.525	99			
MOR_{eff} (MPa)					
Between groups	6,761.714	4	1,690.429	80.178	<0.001
Within groups	2,002.921	95	21.083		
Total	8,764.635	99			
Work (N/m)					
Between groups	238,655,613	4	59,663,903.3	22.846	<0.001
Within groups	248,101,107	95	2,611,590.6		
Total	486,756,720	99			

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

Table 5.—Tukey honestly significant difference (HSD) test for modulus of rupture (MOR)$_{gross}$, MOR$_{eff}$, and work—subset for alpha = 0.05.

Treatment	*N*	MOR$_{gross}$ (MPa)	MOR$_{eff}$ (Mpa)	Work (N/m)
4	20	13.89 A[a]	14.31 A	852.28 A
5	20	15.56 A	16.00 A	959.32 A
2	20	26.74 B	27.54 B	2,472.37 B
3	20	28.29 B	29.10 B	2,823.08 B
1	20	34.74 C	35.97 C	5,099.27 C

[a] Letters A–C indicate the statistical grouping. Averages with the same letter are not significantly different. Averages not sharing a letter differ significantly at alpha = 0.05 as indicated by Tukey's HSD.

and 3 were not statistically different (Table 6). Therefore, on the basis of the Tukey HSD test, no separation can be done considering notch size or presence of reinforcement method for MOE.

To further investigate, independent-samples *t* tests were applied to compare treatments 2 and 3 and treatments 4 and 5, as both groups present the same notch depth with stitched vs. nonstitched conditions. For the comparison between treatments 2 and 3 (Table 7), the *t* test indicated that there is no statistically significant difference for panels notched to 33 percent of the depth of the outermost layer either with or without stitches. Therefore, on the basis of the *t* test, treatments 2 and 3 were not statistically different for MOE, MOR, and work.

Considering the *t* test comparison between treatments 4 and 5 (Table 8), the data indicate that there is a statistically significant difference for MOR (both S_{gross} and $S_{effective}$) for stitched vs. nonstitched panels notched to 66 percent depth of their outermost layer. However, in the case of MOE and work, no statistically significant difference was detected between these two treatments. Therefore, treatments 4 and 5 were found to be statistically different with respect to strength, but not stiffness and work, meaning that the deeper the notch, the more effective stitching can be with regard to strength.

As expected, when the controls were compared with all the treatments, the control group was significantly stronger (MOR) and developed significantly higher work than all notched groups. However, MOE for the controls was neither statistically different from either of the 33 percent depth notched panels (i.e., stitched and nonstitched) nor statistically different from the 66 percent notch depth stitched panels. When comparing means for all treatments, treatment 4 (panels with 66% of the first layer notched and nonstitched) developed the lowest stiffness. The result indicated that stitching can improve stiffness to a certain extent, but its effectiveness might be affected by other factors as such as screw length, diameter, and number.

Table 6.—Tukey honestly significant difference (HSD) test for modulus of elasticity (MOE)—subset for alpha = 0.05.

Treatment	*N*	MOE (MPa)
4	20	7,164.32 A[a]
5	20	7,339.44 AB
2	20	7,782.47 ABC
1	20	8,044.60 BC
3	20	8,300.00 C

[a] Letters A–C indicate the statistical grouping. Averages with the same letter are not significantly different. Averages not sharing a letter differ significantly at alpha = 0.05 as indicated by Tukey's HSD.

Table 7.—Independent-samples t *test comparing means for treatments 2 and 3.*

	Levene's test for equality of variances		*t* Test for equality of means		
	F	Significance (*P*)	*t*	df	Significance (2-tailed)
Modulus of elasticity (MOE; MPa)					
Equal variances assumed	0.656	0.423	−1.66	38	0.105
Equal variances not assumed			−1.66	36.5	0.106
Modulus of rupture (MOR) S_{gross} (MPa)					
Equal variances assumed	0.062	0.804	−0.916	38	0.366
Equal variances not assumed			−0.916	37.7	0.366
MOR S_{eff} (MPa)					
Equal variances assumed	0.085	0.773	−0.905	38	0.371
Equal variances not assumed			−0.905	37.8	0.371
Work (N/m)					
Equal variances assumed	0.832	0.368	−0.775	38	0.443
Equal variances not assumed			−0.775	35.4	0.444

Regarding failure behavior, most panels presented an expected brittle failure inherent to wood panels. However, the stitched panels (treatments 3 and 5) did present a higher number of ductile failures than the nonstitched panels. In

Table 8.—Independent-samples t *test comparing means for treatments 4 and 5.*

	Levene's test for equality of variances		*t* Test for equality of means		
	F	Significance (*P*)	*t*	df	Significance (2-tailed)
Modulus of elasticity (MPa)					
Equal variances assumed	5.92	0.020	−0.671	38	0.506
Equal variances not assumed			−0.671	31	0.507
Modulus of rupture (MOR) S_{gross} (MPa)					
Equal variances assumed	0.171	0.682	−2.08	38	0.044
Equal variances not assumed			−2.08	37.8	0.044
MOR S_{eff} (MPa)					
Equal variances assumed	0.203	0.655	−2.09	38	0.044
Equal variances not assumed			−2.09	37.8	0.044
Work (N/m)					
Equal variances assumed	0.950	0.336	−0.977	38	0.335
Equal variances not assumed			−0.977	37.7	0.335

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

Table 9.—Failure behavior.

Treatment	Brittle	Ductile
1	18	2
2	15	5
3	14	6
4	15	5
5	12	8

addition, in agreement with what was found for strength values, treatment 5 performed better than treatment 3 regarding ductility increase. This find also suggests that the deeper the notch, the more effective the stitching can be to increase ductile behavior of panels. Table 9 presents the number of brittle and ductile failures for treatments 1 through 5. In addition, the overall failure behavior of panels can be seen in Figure 4. Considering failure mode, the control panels tended to fail under splintering tension and cross-grain tension, followed by rolling shear. Meanwhile, notched panels failed under simple tension, also followed by rolling shear. Typical failure modes for treatments 1 through 5 can be seen in Figure 5.

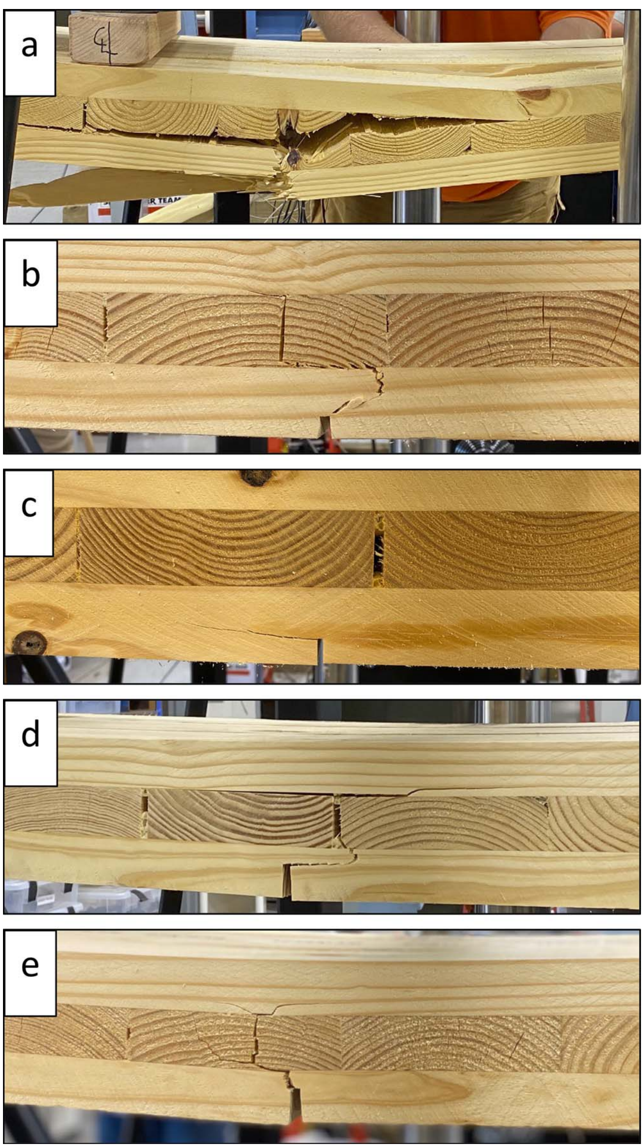

Figure 5.—Typical failure modes. (a) Treatment 1, (b) treatment 2, (c) treatment 3, (d) treatment 4, and (e) treatment 5).

Conclusions

This study was successful in quantifying the extent of strength decrease caused by notching three-ply CLT panels. The study also addressed changes in MOE and work caused by said notches. This type of information is potentially of great value toward updating manufacturing, design, and use criteria for notched CLT panels. Before it can be used in support of potential building code criteria, further investigation is likely necessary to better define notched CLT reinforcement possibilities and limitations.

Acknowledgments

This research was funded by a grant from USDA Forest Service. This publication is a contribution and is approved as journal article SB 1055 of the Forest and Wildlife Research Center, Mississippi State University.

Literature Cited

Aicher, S., P. J. Gustafsson, P. Haller, and H. Petersson. 2002. Fracture mechanics models for strength analysis of timber beams with a hole or a notch—A report of rilem tc-133. Lund Univerity, Lund, Sweden. 118 pp.

Arrese, A., N. Carbajal, G. Vargas, and F. Mujika. 2010. A new method for determining mode II R-curve by the end-notched flexure test. Eng. Fract. Mech. 77:51–70. https://doi.org/10.1016/j.engfracmech.2009.09.008

APA—The Engineered Wood Association. 2018. PRG 320-2018. Standard for performance-rated cross-laminated Timber. Tacoma, Washington.

ASTM International. 2015. D198: Standard test methods of static tests of lumber in structural sizes. American Society for Testing and Materials, Conshohocken, Pennsylvania.

Coureau, J. L., P. J. Gustafsson, and K. Persson. 2006. Elastic layer model for application to crack propagation problems in timber engineering. Wood Sci. Technol. 40:275–290. https://doi.org/10.1007/s00226-005-0033-x

de Moura, M. F. S. F., N. Dourado, and J. Morais. 2010. Crack equivalent based method applied to wood fracture characterization using the single edge notched-three point bending test. Eng. Fract. Mech. 77:510–520. https://doi.org/10.1016/j.engfracmech.2009.10.008

de Moura, M. F. S. F., M. A. L. Silva, A. B. de Morais, and J. J. L. Morais. 2006. Equivalent crack based mode II fracture characterization of wood. Eng. Fract. Mech. 73:978–993. https://doi.org/10.1016/j.engfracmech.2006.01.004

Dewey, J., R. Tuladhar, and N. Sivakugan. 2018. Review of design methods for round notched timber sections subjected to flexure and shear. J. Build. Eng. 18:130–141. https://doi.org/10.1016/j.jobe.2018.03.002

Dewey, J., R. Tuladhar, and N. Sivakugan. 2019. Experimental study on the performance of notched round timber sections. J. Build. Eng. 25:100840. https://doi.org/10.1016/j.jobe.2019.100840

Dourado, N., M. F. S. F. de Moura, S. Morel, and J. Morais. 2015. Wood fracture characterization under mode I loading using the three-point-bending test. Experimental investigation of Picea abies L. Int. J. Fract. 194:1–9. https://doi.org/10.1007/s10704-015-0029-y

Flaig, M. 2014. Design of CLT beams with rectangular holes or notches. Karlsruhe Institute of Technology, Karlsruhe, Germany. 13 pp.

Gustafsson, P. J. 1988. A study of strength of notched wood beams. International Council for Building Research Studies and Documentation. CIB-W18A/21-10-1.

Henrici, D. 1976. Spannungsoptische Untersuchung rechtwinkelig ausgeklinkter sowie lochbelasteter Biegeträger. Holz als Roh- und Werkst. Eur. J. Wood Wood Ind. 34:91–100. https://doi.org/10.1007/BF02612799

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

International Code Council. 2017. IRC: International residential code for one- and two-family dwellings. Country Club Hills, Illinois. 962 pp.

Jockwer, R., R. Steiger, and A. Frangi. 2014. State-of-the-art review of approaches for the design of timber beams with notches. J. Struct. Eng. 140(3): 04013068–1–04013068-13. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000838

Jockwer, R., R. Steiger, A. Frangi, and E. Serrano. 2016. Load-carrying capacity and failure modes of glulam beams with reinforced notches. Eur. J. Wood Wood Prod. 74:481–482. https://doi.org/10.1007/s00107-015-0959-0

Karacabeyli, E. and B. Douglas. 2013. CLT handbook: Cross-laminated timber. FPInnovations, Pointe-Claire, Québec.

Murphy, J. F. 1979. Using fracture mechanics to predict failure in notched wood beams. Reprints. US Forest Service 159–173.

Murphy, J. F. 1986 Strength and stiffness reduction of large notched beams. J. Struct. Eng. 112:1989–2000.

Rice, J., R. A. Kozak, M. J. Meitner, and D. H. Cohen. 2006. Appearance wood products and psychological well-being. Wood Fiber Sci. 38:644–659

Sedighi-Gilani, M. and P. Navi. 2007. Micromechanical approach to wood fracture by three-dimensional mixed lattice-continuum model at fiber level. Wood Sci. Technol. 41:619–634. https://doi.org/10.1007/s00226-007-0133-x

Silva, M. A. L., M. F. S. F. de Moura, and J. J. L. Morais. 2006. Numerical analysis of the ENF test for mode II wood fracture. Compos. Part A Appl. Sci. Manuf. 37:1334–1344. https://doi.org/10.1016/j.compositesa.2005.08.014

Smith, I., Kiwelu Meleki, and H. J. Weckendorf. 2015. Explanation of tension-side notch design provisions for glulam in CSA standard 086-141. Can. J. Civ. Eng. 42:787–796. https://doi.org/10.1139/cjce-2015-0088

Smith, I. and S. Vasic. 2003. Fracture behaviour of softwood. Mech. Mater. 35:803–815. https://doi.org/10.1016/S0167-6636(02)00208-9

Southern Pine Inspection Bureau (SPIB). 2014. Standard grading rules for southern pine lumber. Table 1c. Structural light framing, structural joists and planks, and studs—2″ to 4″ thick (8″ wide only). Southern Pine Inspection Bureau, Pensacola, Florida.

Toussaint, E., E. Fournely, Moutou Pitti, and R. M. Grédiac. 2016. Studying the mechanical behavior of notched wood beams using full-field measurements. Eng. Struct. 113:277–286. https://doi.org/10.1016/j.engstruct.2016.01.052

Tran, T. B., E. Bastidas-Arteaga, Y. Aoues, C. F. Pambou Nziengui, S. E. Hamdi, R. Moutou Pitti, E. Fournely, F. Schoefs, and A. Chateauneuf. 2018. Reliability assessment and updating of notched timber components subjected to environmental and mechanical loading. Eng. Struct. 166:107–116. https://doi.org/10.1016/j.engstruct.2018.03.053

Valentin, G. and G. Adjanohoun. 1992. Applicability of classical isotropic fracture mechanics specimens to wood crack propagation studies. Mater. Struct. 25:3–13.

Wang, V. Z., J. D. Ginger, and K. Narayan. 2012. Intralaminar and interlaminar fracture characterization in glued-laminated timber members using image analysis. Eng. Fract. Mech. 82:73–84. https://doi.org/10.1016/j.engfracmech.2011.11.024

Zalph, B. L. and T. E. McLain. 1992. Strength of wood beams with filleted interior notches: A new model. Wood Fiber Sci. 24(2):204–215.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26