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Cross-laminated timber (CLT) mechanical properties evaluation.

By

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Approved by:

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Robert Ross
L. Wes Burger (Dean, College of Forest Resources)

A Dissertation
Submitted to the Faculty of
Mississippi State University
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for the Degree of Doctor of Philosophy
in Forest Resources
in the Department of Sustainable Bioproducts

Mississippi State, Mississippi

May 2022
As the use of engineered wood products as such as cross-laminated timber (CLT) evolves in United States, it’s imperative to understand its behavior under different circumstances as well as to explore new possible streams for product’s application. In that matter, it was proposed that a research study would be developed to evaluate the performance of CLT panels focusing on strength and stiffness properties. To accomplish this goal, three main objectives were traced: 1) To complete preliminary test on traditional lumber in order to observe notched wood failure behavior focusing on strength, ductility, and failure mode; 2) To perform mechanical testing and non-destructive evaluation on 3-ply CLT control panels in order to compare design calculation methods and efficiency of NDE on CLT; and 3) To perform mechanical testing on notched 3-ply CLT samples to evaluate the influence of notches and stitching reinforcement on panels. Based on these objectives, this dissertation features five main sections: 1) General Introduction, 2) Technical note: Ductility and brittleness in small clear notched S-P-F beams, 3) Evaluation of the modulus of elasticity and modulus of rupture of cross-laminated timber with longitudinal vibration NDE techniques, 4) Case study of 3-ply commercial southern pine CLT mechanical
properties and design values, and 5) Effect of notching on 3-ply southern pine cross-laminated timber panels stiffness and strength.
DEDICATION

To God, who has given me strength and courage throughout so many years of studying. To Him is all the Glory, for He kept breath in my lungs and gave me a new chance to succeed every morning. I am truly blessed.

To my mom and dad, who have always loved and supported me in every step of the way and who have made so many sacrifices to make sure I would make it. I wouldn’t be where I am if it wasn’t for you, this degree is more yours than mine.

To my family, friends, and all of those who have been cheering for my success, who have many times taken care of me or given me a piece of advice. To all of you, who have helped me stay sane through difficult times, I will be forever grateful.
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Thank you, Dr. Seale, Dr. Ross, and Dr. Lopes, for taking on the challenges of this project with me. Thank you for keeping the doors open to help solve whatever problem I had at the time. And most importantly, thank you for always being kind and encouraging. You have no idea of how many times your words of wisdom have kept me going. I will be forever grateful.

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Thank you to the office staff: Jeanie McNeel, Kay Davidson, Marica McGinnis, Shawna Johnson, and Karen Williams. Thank you for keeping track of all documents, forms, and everything else we need to do. You are all so efficient and make our lives so much easier. Jeanie, thank you for bringing me the word of God in the worse moments. I can’t tell how many times your faith and your motherly advice brought me to the light. May God bless you all.
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CHAPTER I
GENERAL INTRODUCTION

As the demand for housing and sustainable construction materials increases, the use of engineered wood products as such CLT has brought a variety of new opportunities in building construction. However, the behavior of CLT under specific circumstances as such as notches and different testing approaches as such non-destructive evaluation (NDE) of panels, are still to be explored. In addition, the construction market is not the only one where CLT panels use could be beneficial. The matting industry might also take advantage of CLT panels expansion, especially when it comes to lower grade lumber usage. Therefore, it is of interest of the wood products community to address said topics in order to expand United States’ CLT fabrication and growth as a construction and matting material.

In that matter, it was proposed that a research study would be developed to evaluate the performance of CLT panels focusing on strength and stiffness properties. To accomplish this goal, three main objectives were traced: 1) To complete preliminary test on traditional lumber in order to observe notched wood failure behavior focusing on strength, ductility, and failure mode; 2) To perform mechanical testing and non-destructive evaluation on 3-ply CLT control panels in order to compare design calculation methods and efficiency of NDE on CLT; and 3) To perform mechanical testing on notched 3-ply CLT samples to evaluate the influence of notches and stitching reinforcement on panels.
The preliminary test was developed and confirmed the effect of the stress concentration caused by the notches on tension side as well as the necessity of increasing the panels’ ductile behavior. A CLT large scale experiment was designed to address performance limitations by notches as well as to explore MOE and MOR calculation methods for design values and the efficiency of NDE on CLT panels. A total of twenty-four 8 ft x 16 ft 3-ply commercial cross-laminated timber panels were purchased. Twenty of those panels were used on a notched CLT performance study with five treatment groups, while the remaining panels were added to a control group design values case study and to the non-destructive evaluation.

This dissertation document aims to elucidate on the endeavors of the said study by dividing the findings into four chapters:

Chapter II: Technical note: Ductility and brittleness in small clear notched S-P-F beams.

Chapter III: Evaluation of the modulus of elasticity and modulus of rupture of cross-laminated timber with longitudinal vibration NDE techniques.

Chapter IV: Case study of 3-ply commercial southern pine CLT mechanical properties and design values.

Chapter V: Effect of notching on 3-ply southern pine cross-laminated timber panels stiffness and strength.
2.1 Abstract

Because wood has both brittle and ductile behaviors, the impact of stress concentration around notches is difficult to quantify. This research used the bending stiffness to strength ratio as a means of evaluating stress concentrations in the tension and compression faces of small clear spruce-pine-fir beams. The bending strength and stiffness behavior of wood and wood composites is of particular interest in ladder rails, laminated beams, and structural cross laminated timber, and other heavy timber construction. It was found that rectangular notches up to half of the beam depth located on the tension face reduced the bending strength by 10.5%. The drop in ductility, as measured by MOE/MOR, was significantly higher, up to 52%. Beams loaded with the notch on the compression face had no statistically significant change in the MOR; however, ductility dropped by as much as 30%.
2.2 Introduction

The terms ductile and brittle are generally used to describe structural materials which yield before failing and fail before yielding, respectively. Malleable metals such as copper and steel are often described as ductile. Mild steel e.g., can be cold-drawn to about 25% elongation before failure. Ceramics, concrete, and mineral-based structural materials are typically described as brittle and they generally fail at relatively low strain levels (Horath 1995). Wood exhibits both ductile and brittle behaviors, and thereby varying theories exist regarding the significance of stress concentrations on the bending strength of wood. Stress concentrations are localized areas of increased stress which occur in structural materials wherever imperfections in the said material occur. Some examples of stress concentrations include portholes in ships, rivet holes in airplane construction, and adhesive junctions of dissimilar materials. These concentrations are caused by a physical disruption or discontinuity in the structural material and subsequent redistribution of stresses there about.

Traditional fracture mechanics theory (based on relatively brittle materials) indicates that large stress concentrations exist in wood beams at knots, notches, splits, corners, etc. (FPL 2010). To a large degree, structural composites develop relatively high design properties not by being stronger than solid wood but by randomly distributing the natural characteristics in wood about which stress concentrations may develop and thereby improving uniformity (Sasaki 1989). Another theory implies that because wood is basically a composite of elongated and oriented cells embedded in a lignin-rich matrix, it is highly resistant to stress concentrations (Gordon 1988), and thus, notches in beams are of little consequence. This theory goes back half a century and says that when a notch is at or near the center of the beam, the net minimum depth should be used for calculating the strength (Hanson 1948). Only minor differences are suggested for
tensile-vs compression-face stress. Roughly 50 yr after that, one of the most telling descriptions for notched beams comes from Breyer et al: “The effect of a notch on the bending strength of a beam is not fully understood and convenient methods of analyzing the bending stress at a notch are not currently available...The problem is best handled by avoiding notches (Breyer et al 2015).” All of those are classic references, based on fundamental points which are constant through time.

Most recently, the 2018 International Residential Code for one- and two-family dwellings (International Code Council 2017) prescribed the requirements for cutting, drilling, and notching floor and wall systems. Considering floor systems using saw lumber, the instruction is that “notches shall not exceed one-sixth of the depth of the member, shall not be longer than one-third of the depth of the member, and shall not be located in the middle one-third of the span.” In addition, “notches at the end of the member shall not exceed one-fourth the depth of the member.” Regarding engineered wood products, notches are prohibited, unless the member capacity has been proved by product manufacturer or design professional. When it comes to wall studs, any stud in an exterior wall/bearing partition and nonbearing partition may be notched, as long as the notch depth does not meet more than 25% and 40% of stud width, respectively. Although these sources provide designers with some guidance toward using notched beams, they do little to fundamentally explain how wood beams respond to notches.

Another factor that may contribute to the behavior of notched structural members is that deflection or strain is focused at the notch. Because the notch has a necessarily smaller section depth as compared with the remainder of the beam, the strain is much more localized at the notch. When visualized, if one loads an ordinary meter stick like a long column, it bends or bows more or less uniformly along its length. If one takes a larger wood member and notches it such
that the effective section modulus at midspan equals that of a meter stick and then loads it like a long column, it appears more like two relatively stiff pieces of wood with a hinge at the midspan.


However, a more practical method from the user’s point of view would be to quantitatively compare the nature of deformation and strength of notched wood in tension vs compression, to compare the stiffness to strength ratios of each property. Regarding such ratios, lower numeric values correspond to more ductile materials, i.e. relatively high strength compared with stiffness. For example, Kevlar is a relatively tough fiber and has a stiffness to strength ratio of approximately 20. Cast iron, known to be brittle, has a ratio of approximately 550.

Using data from Kretschmann and Green (1996), the parallel-to-grain stiffness to strength (MOE: MOR) ratios in tension and compression for clear southern pine are 106 and 317, respectively. This 3-fold difference is primarily due to differences in MOR i.e. wood’s stress–strain relationship is similar for both compression and tension parallel-to-grain. Wood is
significantly stronger, however, in tension parallel-to-grain, which suggests that wood has better ductility characteristics in tension than in compression.

By comparison, in bending, the same two species of southern pine (loblolly and shortleaf) have an average stiffness to strength ratio of about 136 (FPL 2010), near that of wood stressed in tension parallel-to-grain. This comparison illustrates that the ultimate breaking strength of wood in bending is governed primarily by the stiffness to strength properties in tension which provide the highest strength and the highest ductility, although normal wood in bending virtually always fails initially in compression parallel-to-grain.

Qualitative failure modes for tension and compression seem, however, to be reversed. Typically, compression parallel-to-grain failure is viewed as ductile, manifesting itself as a crushing and folding of the lignocellulosic wood matrix. This failure precedes the seemingly more brittle catastrophic tension failure that is noted as the cellulose fibers fail under stress and release their stored energy. Thus, it is difficult to classify wood in only one or the other category (ductile vs brittle) because the quantitative and qualitative properties do not seem to agree. Parallel-vs perpendicular-to-grain strength differences in compression, shear, and tension further complicate classification. For structural applications, beams that exhibit relatively ductile failure are generally safer because the strain deflection caused by overloading becomes apparent well before catastrophic failure. Fundamental information in this regard is necessary for safe and efficient design with both solid and new wood-based composite products and for the development of new wood-based composite architectures. Cross-laminated timber is one such example wherein the structural behavior around notches in panels may be important.
This research focused on using notched beams to investigate ductile and brittle performance in wood beams. Secondarily, it investigated the effect of notches on the performance of wood beams in a cursory manner.

2.3 Materials and methods

To better understand the brittle and ductile performance of wood, a comparison of beams with and without notches was carried out. Matched, clear, straight-grained beams were manufactured from a parent population of kiln-dried 38 x 140-mm (2 x 6 in.) spruce-pine-fir lumber. The candidate stock for the small clear beams was randomly matched. All beams, both notched and non-notched controls, had a maximum depth at point of loading of 19 mm and a constant width of 38.1 mm. Test beams were notched at midspan to induce stress concentration points near the location of maximum bending moment. Thirty beams of each type were manufactured and tested for a total of 150 beams. Both notched and control beams were destructively tested to failure. Notched beams were tested in both orientations i.e. with the notch upward on the compression face and downward on the tension face (Figure 2.1). Notches were 25 mm wide and of rectangular shape. This rectangular shape created an abrupt transition in the beam surfaces, and thus enhanced stress concentrations. At midspan, horizontal shear stress was the same for all beam types and thus was not considered a treatment factor.

All beams were center-point loaded at a rate of 2.5 mm per minute. To maintain a span to depth ratio of 14, all beams were tested across a 266-mm span. This span to depth ratio was determined as per ASTM (2017) D143. Table 2.1 shows the beam dimensions and loading schemes. MOR values for the beams were calculated by using MOR equation 2.1 (flexure formula) and compared for notched and control beams.
MOR Equation (flexure formula):

\[
MOR \ (psi) = \frac{M}{Z}
\]  

(2.1)

Here, \(M\) = maximum moment (pound inches) = \(P \cdot \frac{l}{4}\); \(P\) = maximum load (pounds); \(l\) = span (inches); \(Z\) = section modulus (\(\text{inch}^3\)) = \(b \cdot h^2/6\) (for a rectangular section where): \(b\) = width of the beam (inches) & \(h\) = depth of the beam (inches) at midspan.

Figure 2.1  Depiction of the loading schemes on the five beam types. 1 is straight, 2 & 3 are notch to one-third beam depth, and 4 & 5 are notch to one-half beam depth. All beams had a constant width of 38.1 mm.
Table 2.1 Beam loading parameters.

<table>
<thead>
<tr>
<th>Class</th>
<th>n</th>
<th>Maximum depth (mm)</th>
<th>Minimum depth (mm)</th>
<th>Depth ratio minimum:maximum</th>
<th>Beam type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>19.1</td>
<td>19.1</td>
<td>1.00</td>
<td>Control</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>28.6</td>
<td>19.1</td>
<td>0.67</td>
<td>Comp. // @ notch</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>28.6</td>
<td>19.1</td>
<td>0.67</td>
<td>Tens. // @ notch</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>38.1</td>
<td>19.1</td>
<td>0.50</td>
<td>Comp. // @ notch</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>38.1</td>
<td>19.1</td>
<td>0.50</td>
<td>Tens. // @ notch</td>
</tr>
</tbody>
</table>

Strength results were analyzed to address two objectives. First, to evaluate strength differences in notched vs straight control beams of equal minimum cross section. This subdivision of the analysis provided insight into wood’s ability to dissipate stress concentrations and thus provide a qualitative indicator of ductility. Second, with regard to notched beams, the comparison of strength values for compression- vs tension-face beams provided data for contrasting wood’s ductility/brittleness for tension to that for compression. The strength and stiffness were evaluated as completely randomized designs. The \( \alpha = 0.05 \) was used for statistical tests of significance. Significance was determined by one-way analysis of variance and mean separations were calculated by least significant difference analyses.

2.4 Results and discussion

No statistically significant interaction was found between loading scheme (controls, tension-notched, or compression-notched) and notch depth. As main effects, however, the loading scheme was statistically significant (\( p = 0.0065 \)) and notch depth was not. Therefore, further analysis was conducted regarding the effect of loading scheme. With respect to MOR, there were statistically significant differences for the different loading schemes (\( p = 0.0351 \)). In
general, the straight control beams and those loaded with the notch in compression were not statistically different. Considering beams with notches on the tension side, Class 3 beams (those with 0.67 depth ratio) were significantly weaker than the control and the beams notched on the compression side. However, no statistical difference was seen between the two groups (Class 3 and 5) with notches under tension (Table 2.2).

Table 2.2 Separation of average beam MOR values (MPa) by class.

<table>
<thead>
<tr>
<th>Class</th>
<th>Average MOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>83.2 a</td>
</tr>
<tr>
<td>1</td>
<td>82.5 a</td>
</tr>
<tr>
<td>4</td>
<td>81.6 a</td>
</tr>
<tr>
<td>5</td>
<td>77.5 ab</td>
</tr>
<tr>
<td>3</td>
<td>73.7 b</td>
</tr>
</tbody>
</table>

Least significant difference is 6.90 MPa. Letters “a and b” indicate the statistical grouping. Averages with the same letter are not significantly different.

Maximum deflection at time of failure was also evaluated. With regard to loading scheme, it was highly significant (p < 0.0001). Maximum center-point deflections are shown (Table 2.3). In general, the straight control beams deflected the most, whereas the beams loaded with the notches in tension deflected the least, again suggesting the lowest ductility.

Table 2.3 Separation of average maximum deflection values (mm) by class.

<table>
<thead>
<tr>
<th>Class</th>
<th>Average deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.97 a</td>
</tr>
<tr>
<td>2</td>
<td>7.80 b</td>
</tr>
<tr>
<td>4</td>
<td>7.11 bc</td>
</tr>
<tr>
<td>5</td>
<td>6.78 cd</td>
</tr>
<tr>
<td>3</td>
<td>6.25 d</td>
</tr>
</tbody>
</table>

Least significant difference is 0.752 mm. Letters “a, b, c, and d” indicate the statistical grouping. Averages with the same letter are not significantly different.
To better discern the stiffness to strength relationships, an additional analysis was run which compared the ratio of MOE with MOR for each beam type and loading scheme, similar to the comparisons made in the Introduction section. Recall that lower stiffness to strength index values indicate greater deflection at the time of failure and better ductility. Differences in values were highly significant ($p < 0.0001$). Mean separation for this ratio is shown in Table 2.4. The control beams performed the best i.e. they exhibited the highest deflection at the time of failure. This result was expected because of the straight control beams’ ability to strain more evenly along their length and the tendency of notched beams to concentrate bending strain at the notch.

Table 2.4  Separation of average MOE/MOR values by class.

<table>
<thead>
<tr>
<th>Class</th>
<th>Average ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>140.9 a</td>
</tr>
<tr>
<td>5</td>
<td>127.6 ab</td>
</tr>
<tr>
<td>4</td>
<td>121.0 cb</td>
</tr>
<tr>
<td>2</td>
<td>107.4 cd</td>
</tr>
<tr>
<td>1</td>
<td>92.7 d</td>
</tr>
</tbody>
</table>

Least significant difference is 15.5. Letters “a, b, c, and d” indicate the statistical grouping. Averages with the same letter are not significantly different.

With the deeper sections along most of their lengths, the notched beams had higher bending strain levels localized at the notches despite their lower total deflections. Generally, the beams with the notch loaded in tension parallel-to-grain deflected the least before full failure as noted by their relatively high stiffness to strength values (Table 2.4). Among these beams, tension perpendicular-to-grain failure (cleavage type splitting) was frequently noted at the notch’s corners before full failure. This failure likely served to relieve localized strain at the point of maximum bending moment and, theoretically, should not have appreciably weakened the straight-grained beams.
2.5 Conclusions

Evidently, the wood was better able to dissipate stress concentrations for notches in compression parallel-to-grain better than for notched in tension parallel-to-grain, suggesting better ductility for wood in compression. This finding supports the old school of thought that notched beams may be analyzed as straight beams using their minimum cross section, provided that the notches are loaded in compression only. A reasonable explanation for this is found at the molecular level. The three-dimensional lignin matrix has the ability, to some extent, to deform under compression and shear stress (as found in the notches).

Regarding strength performance, all beams exhibited characteristics of both ductile and brittle materials. The notches had less of an effect on strength than would be predicted based on stress concentrations alone. This is evidenced by the lack of statistically significant differences between beams with notches of differing depths when the loading scheme was constant (either tension or compression). Whereas notches in these wood beams had some effect on strength, as noted by reductions of as much as 10.5%, the effect on ductility is perhaps equally important. Compared with un-notched straight controls, beams loaded with notches in tension had stiffness to strength ratios up to 52% higher (140.9 vs 92.7), indicating less deflection before failure, i.e. lower ductility.

To improve the safe and efficient design of composite wood products and structural design with all wood products, it is prudent to increase the incidence of ductile type failure. In that case, high levels of deflection can alert individuals that structures are overloaded before full failure occurs. This is largely the case with solid wood beams that are overloaded. In wood-based composites, internal voids can act as areas of stress concentration along with post-manufacture boring, routing, or other machining operations that remove significant amounts of wood. In
addition to strength performance, it is prudent to consider ductility in the design, manufacture, and application of such products.

2.6 Acknowledgments

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2.7 References


CHAPTER III

EVALUATION OF THE MODULUS OF ELASTICITY AND MODULUS OF RUPTURE OF CROSS-LAMINATED TIMBER WITH LONGITUDINAL VIBRATION NDE TECHNIQUES.


3.1 Abstract

The research presented in this paper was conducted to examine the potential of using longitudinal vibration techniques to evaluate the modulus of elasticity and strength of cross-laminated timber. Twenty-eight cross-laminated timber (CLT) panels were manufactured from southern pine dimension lumber in accordance with accepted manufacturing standards. Nominal 2 by 8 in. southern pine lumber specimens were used for the three-ply panels. A ten ft long specimen, having 4.125 by 18 in cross-section dimensions, was obtained from each panel. Weight and dimensions were determined for each specimen and longitudinal vibration nondestructive evaluation techniques were used to determine frequency of oscillation and energy loss characteristics of the specimens. The dynamic modulus of elasticity was then determined. Each specimen was then tested to failure in a flatwise (third point) bending mode. Flatwise bending modulus of elasticity and strength (modulus of rupture) were determined. Excellent correlative relationships were observed between dynamic and flatwise bending moduli. A
strong, positive relationship was observed between the dynamic modulus and flatwise bending strength. NDT evaluation of CLT panels is recommended for quality control protocols.

### 3.2 Introduction

There has been significant growth in the use and production of mass timber products in the United States and North America in the past three years. There are over one hundred structures built using cross-laminated timber (CLT) and other mass timber panel products, with hundreds of additional projects under development (WoodWorks, 2021). The primary markets include commercial and multi-family residential buildings, but there is interest in single-family homes and timber bridge decks. There are currently four CLT producers in the U.S. and at least five more manufacturing facilities announced or under construction. To support production, an American National Standard, Standard for Performance-Rated Cross-Laminated Timber PRG 320 (ANSI/APA 2019), has been developed and approved through a consensus process. The original was published in 2017, and updated in 2018 and 2019. Delamination tests and visual quality inspection of panels are required for industrial mass production as part of an in-plant quality control program.

CLT is a multi-layer wood composite material manufactured from structural lumber. Depending on how the properties of the lumber change or on which adhesive is used, its manufacture may adversely influence its performance. The ability to detect the presence of delamination and determination of stiffness and strength of CLT is important in its production and in-service.

The wood nondestructive evaluation community has been investigating techniques to locate delamination in wood composite materials since the 1960’s. One of the earliest efforts were made Jayne (1965) and Suddarth (1965). They worked jointly on a study funded by the
Department of Defense designed to investigate the possibility of using mechanical impedance to locate poorly bonded or deponded areas in the nose cones of Polaris missiles.

A variety of techniques have been investigated since then, with a significant effort aimed at investigating acoustic (stress wave, ultrasound) techniques in a variety of modes (through transmission, pulse echo, contact, non-contact). Most composite manufacturing facilities (OSB, particleboard, plywood) currently use some type of non-contact acoustic sensing system to monitor their products, on-line. They specifically look for delamination, commonly referred to as “blows”, caused by an excess of steam buildup during the pressing operation. These systems are commercially available. They are designed for use in large production facilities. Portable equipment, that utilizes the same concepts, is widely available and used for inspection of wood structures around the world.

Several studies were conducted (Ross and Pellerin, 1988; Vogt, 1986) that investigated the relationship between sound transmission (sound), bending and tension strength of wood composites. Excellent correlative models were developed relating sound transmission properties and the strength of wood composites.

This research aims to develop quality assurance procedures for monitoring the quality of mass timber and CLT after manufacturing and to develop assessment techniques to assess mass timber in-service and summarizes results of our first study. Its objective was to investigate the use of a longitudinal vibration nondestructive technique to predict the static bending properties of southern pine CLT panels. To achieve this, 1) the longitudinal stress wave signal was recorded and analyzed; 2) Correlations between NDT variables with CLT stiffness and strength were analyzed; 3) regression models were developed to predict bending MOE and MOR.
3.3 Materials and methods

In this study, 24 8 x 16 ft (2.43 x 4.88 m) 3-ply commercial panels were procured. The panels were made per PRG-320 from 2 x 8 (nominal) No. 2 southern yellow pine (SYP) lumber and with core layer from No. 3 SYP. Table 3.1 shows the design values for lamination in longitudinal layers. Per ANSI / APA PRG 320-2019 this material is classified as V3.

Table 3.1 Design values (MPa) for laminations in longitudinal layers, per V3.

<table>
<thead>
<tr>
<th>$F_b^a$</th>
<th>Characteristic value$^b$</th>
<th>$F_b$ for #2 2x8 lumber$^c$</th>
<th>MOE$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.17</td>
<td>10.86</td>
<td>6.38</td>
<td>9,653</td>
</tr>
</tbody>
</table>

a: PRG-320, Table A1; b: PRG-320, Table 1. (Note: $F_b = \text{Characteristic value} / 2.1$); c: SPIB 2014.

Twenty-eight specimens were tested. One test specimen was ripped from each of 20 panels. From the four panels remaining, two test specimens were ripped (Figure 3.1). Each specimen was cut from the original CLT panel with approximately 4.125 in. thick (105 mm), 18 in. (457 mm) wide, and crosscut to 120 in. (3.05 m) long.

Final dimensions of each specimen were measured, and weight was recorded for density ($\rho$) estimation. Specimen density was determined using the bulk weight and bulk volume. Moisture content (MC %) was determined using a Model MMC 220 electric moisture meter (Wagner Meters, Rogue River, Oregon). Longitudinal vibration signal (also called longitudinal stress wave signal) was obtained and recorded for every specimen using a Hitman HM 200 tool (Fibregen, Ltd., Christchurch, New Zealand).
An impact was applied on each test specimen in the longitudinal direction per ASTM E1876 (2015). A consistent impact was done using a hammer, trying to ensure similar level of impact energy for all specimens. There was no effect of which ply was impacted as panels vibrated as a single piece. The direction of the wave motion occurs in the same direction as the longitudinal vibration mode. Dynamic MOE was calculated for the information collected by the longitudinal vibration tool (Figure 3.2) applying Equation 3.1.

\[
E_L = \rho \cdot v^2
\]  

(3.1)

Where: \(E_L\) = dynamic MOE (MPa), \(\rho\) = density (kg.m\(^{-3}\)), \(L\) = length of the piece (m), \(f\) = first harmonic longitudinal vibration frequency (Hz), \(v\) = wave velocity (m.s\(^{-1}\)).
A linear regression analysis was conducted to determine the values for the unknown empirical constants, $K$ and $x$, for flexural MOE and MOR, following the procedure described by Senalik and Ross (2015). The model was implemented using the dynamic MOE as the sole nondestructive variable (Equation 3.2).

$$\ln P = \ln K + x \cdot \ln E_d$$

(3.2)

Where: $P$ is the property being estimated, $K$ is a constant, and $E_d$ is the dynamic MOE.

The Hitman HM 200 software converts the time-domain into a frequency-domain signal through a fast Fourier transform. The software output permits the visualization of the time-domain and frequency-domain graph (Figure 3.3).
The identification of the fundamental frequency was possible for every CLT specimens. A consistent longitudinal strike (hammer hit) on the cross section excited the CLT specimen and generate the fundamental frequency. Note that the fundamental frequency is very prevalent however the sub sequential harmonics were not detectable for most of the specimens.

Figure 3.3  Longitudinal vibration signal output from the Fibregen HM 200.

After the acoustic signals were recorded for all specimens, the sample was tested destructively via third point bending over a 9 ft 6 in. (2.9 m) span. This set up provided a span to depth ratio of 27.6 and consistent with PRG-320s guidance “specimen width not less than 12 inches (305 mm) and the on-center span equal to approximately 30 times the specimen depth for the tests in the major strength direction...” Flexure testing was conducted on each specimen using a four-point bending setup per ASTM D 5456 (2017a).

Evaluation of the energy loss (damping) was conducted. The calculation of the frames’ hysteresis damping using the logarithmic decrement method (LD) collected from in longitudinal
vibration. LD is calculated from the exponential covering curve over the time-domain senoidal curve (Figure 3.4), given by Equation 3.3. The LD of every piece was recorded in the data base.

\[
LD = \beta . t
\]

(3.3)

Where: \(LD\) = Logarithmic decrement; \(\beta\) = is the parameter of the exponential covering curve; \(t\) = period of time (s), inverse of the frequency (Hz).

Figure 3.4 Logarithmic decrement exponential (\(\beta\)) over the time domain signal.

An approach following the one described by Senalik et al. (2020b) was conducted. Their focus was in two regions in the time domain are the focus of preliminary assessment: the earliest arrival of the signal and late in the signal when the wave energy begins to attenuate. A CLT specimen should have disruption to the wave as it travels due to features such as knots and slope of grain, the signal will be disrupted through reflection, mode conversion, and increased attenuation.
The areas under the curve in the time-domain signal (TDA) and the frequency-domain signals (FDA) in specific segments were calculated. The region between 300 and 400 µs was chose to measure the area in the time-domain signal (Figure 3.5-a). The natural frequency peak was the second area measured for each specimen (Figure 3.5-b).

![Figure 3.5](image-url)

Figure 3.5  Area under the curve for (a) time-domain signal between 300 and 400 µs; (b) natural frequency peak between 550 and 620 Hz.

Statistical analyses and associated graphs were completed according to ASTM D 2915 (2017b) using SAS version 9.4 (SAS Institute 2013). Bivariate correlation among variables were evaluated. The variables MOE and MOR were used as multiple linear functions of density and NDT properties. To predict the MOE and MOR using NDT variables, stepwise procedure was used for fitting models. For each relationship obtained, the coefficient of correlation (R) and
coefficient of determination ($R^2$) were calculated. The following equations were used to predict the MOE (Equation 3.4) and MOR (Equation 3.5).

$$MOE = f(dMOE, LD, TDA, FDA) + \varepsilon_1$$ (3.4)

$$MOR = f(dMOE, LD, TDA, FDA) + \varepsilon_2$$ (3.5)

3.4 Results and discussion

The result summary for each physical and mechanical property for the CLT specimens tested is shown in Table 3.2. The overall means for MOE and MOR were 8,057 and 34.87 MPa, respectively. The values found in this study showed a narrow range for both properties when compared to structural lumber. Low coefficient of variation (2.63%) was found for density among specimens. Dynamic MOE values found in this study were lower than the related static MOE. It is due the low longitudinal vibration velocities found in CLT when compared to 2 × 8 SYP lumber (~4500 m·s$^{-1}$) and explained by the low length-width ratio (6.6 to 1).

Table 3.2 Bending modulus of elasticity (MOE), modulus of rupture (MOR), density, stress wave velocity and dynamic MOE values for CLT specimens.

<table>
<thead>
<tr>
<th></th>
<th>MOE (MPa)</th>
<th>MOR (MPa)</th>
<th>Density (kg·m$^{-3}$)</th>
<th>Velocity (m·s$^{-1}$)</th>
<th>dMOE (MPa)</th>
<th>LD</th>
<th>FDA</th>
<th>TDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave</td>
<td>8,057</td>
<td>34.87</td>
<td>535</td>
<td>3.563</td>
<td>6,800</td>
<td>0.044</td>
<td>6,575</td>
<td>940</td>
</tr>
<tr>
<td>Min</td>
<td>5,755</td>
<td>23.07</td>
<td>503</td>
<td>3.110</td>
<td>4,865</td>
<td>0.035</td>
<td>4,444</td>
<td>197</td>
</tr>
<tr>
<td>Max</td>
<td>10,277</td>
<td>44.90</td>
<td>561</td>
<td>3.940</td>
<td>8,600</td>
<td>0.055</td>
<td>9,541</td>
<td>1817</td>
</tr>
<tr>
<td>COV (%)</td>
<td>12.46</td>
<td>14.67</td>
<td>2.63</td>
<td>5.22</td>
<td>12.09</td>
<td>11.33</td>
<td>15.86</td>
<td>57.07</td>
</tr>
</tbody>
</table>

*COV = coefficient of variation (%). dMOE – Dynamic modulus of elasticity; LD – Logarithmic Decrement; FDA – Frequency-domain Area; TDA – Time-domain Area.
Comparing the static MOE values found in this study with the current design value for 2 x 8 SYP N. 2 lumber (9,653 MPa), the results show that the MOE values for CLT specimens were lower than the published design value (ALSC, 2013). The overall MOR was lower than the values reported for southern pine lumber by other authors: Dahlen et al. (2014; 40.7 MPa) for different No. 2 lumber sizes; Yang et al. (2017; 38.26 MPa) for No. 2 2 × 4; França et al. (2020; 39.60 MPa) for No. 2 2 × 8.

Bivariate correlations among the variables under investigation are presented in Table 3.3. For MOR, the highest correlation was seen for dMOE (R = 0.63). Logarithmic decrement had a negative correlation with MOE (R = -0.43) and MOR (R = -0.26) where higher decrement is related to weaker pieces. Similar LD results were found by Divós and Sismándi-Kiss (2010) spruce, larch and pine structural lumber. França et al. (2019) found an R = -0.22 studying southern pine 2 × 4 and 2 × 6 lumber.
Table 3.3  Pearson’s bivariate correlation (r) among modulus of elasticity (MOE), modulus of rupture (MOR), density, longitudinal stress wave velocity, dynamic MOE, logarithmic decrement, frequency-domain area, and time-domain area for the tested CLT sample.

<table>
<thead>
<tr>
<th></th>
<th>MOE (MPa)</th>
<th>MOR (MPa)</th>
<th>Density (kg/m³)</th>
<th>Velocity (m/s)</th>
<th>dMOE (MPa)*</th>
<th>LD</th>
<th>FDA</th>
<th>TDA</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOE (MPa)</td>
<td>1</td>
<td>0.58 (&lt;0.01)</td>
<td>0.85 (&lt;0.01)</td>
<td>0.90 (&lt;0.01)</td>
<td>0.95 (&lt;0.01)</td>
<td>-0.43 (0.02)</td>
<td>-0.50 (&lt;0.01)</td>
<td>0.61 (&lt;0.01)</td>
</tr>
<tr>
<td>MOR (MPa)</td>
<td></td>
<td>0.41 (0.03)</td>
<td>0.57 (&lt;0.01)</td>
<td>0.63 (&lt;0.01)</td>
<td>-0.26 (0.18)</td>
<td>-0.57 (&lt;0.01)</td>
<td>0.62 (&lt;0.01)</td>
<td></td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td></td>
<td>1</td>
<td>0.67 (&lt;0.01)</td>
<td>0.75 (&lt;0.01)</td>
<td>-0.37 (0.06)</td>
<td>-0.38 (0.05)</td>
<td>0.47 (0.01)</td>
<td></td>
</tr>
<tr>
<td>Velocity (m/s)</td>
<td></td>
<td></td>
<td>1</td>
<td>0.98 (&lt;0.01)</td>
<td>-0.50 (&lt;0.01)</td>
<td>-0.48 (0.01)</td>
<td>0.48 (0.01)</td>
<td></td>
</tr>
<tr>
<td>dMOE (Mpa)</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>-0.48 (&lt;0.01)</td>
<td>-0.50 (&lt;0.01)</td>
<td>0.54 (&lt;0.01)</td>
<td></td>
</tr>
<tr>
<td>LD</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>0.18 (0.35)</td>
<td>-0.27 (0.16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency-domain area</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td>-0.72 (&lt;0.01)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time-domain area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* dMOE – Dynamic modulus of elasticity; LD – Logarithmic Decrement; FDA – Frequency-domain Area; TDA – Time-domain Area.

Frequency-domain area had a negative correlation with MOR (R = -0.57). It was noticed that narrow base peak contributes to a smaller fundamental frequency area. Time-domain area exhibited a positive correlation with MOR (R = 0.62). Higher quality piece had greater area under the time-domain curve segment. Figure 3.6 exhibits the linear regression plots for 3-ply SYP cross laminated timber showing (a) bending MOE vs dynamic MOE, and (b) bending MOR vs dynamic MOE.
Figure 3.6  Linear regression plots for 3-ply SYP cross laminated timber showing (a) bending MOE vs dynamic MOE, and (b) bending MOR vs dynamic MOE.

The $R^2$ for MOE prediction was 0.90, showing an increase when compared to lumber, due to panels homogeneity. Yang et al. (2015) studying the prediction of MOE of southern pine dimensional lumber using longitudinal vibration waves found $R^2$ values ranging from 0.77 to 0.86. França et al. (2020) studying SYP No. 2 lumber found a higher $R^2$ equal to 0.76 and 0.77 (2 x 8 and 2 x 10 respectively) using the Director HM 200. The results found in this study emphasize the potential of longitudinal vibration wave techniques to estimate MOE.

Although the results for predicting static MOE are favorable and accurate ($R^2 = 0.90$), the relationships for MOR are still limited (Figure 3.6). The $R^2$ for MOR prediction found in this study was 0.33. Yang et al. (2017) found $R^2$ values for dMOE and bending MOR ranging from 0.23 to 0.28. França et al. (2020) studying SYP No. 2 lumber found $R^2$ equal to 0.15 and 0.20 (2 x 8 and 2 x 10 respectively) using the Director HM 200.

Two possible outliers were detected in Figure 3.6-b. A further evaluation of the specific specimens led to the detection of knots on the tension surface of the specimen (Figure 3.7). Although the knots affected panels performance, the size of the knots are accepted in visually
No. 2 graded lumber. The presence of knots on the tension face reduced the static bending strength values of the two specimens. Moreover, higher grade lumber on outer layers is recommended and would increase strength values of CLT panels.

Figure 3.7 Static bending failure due to presence of knot.

The natural logarithmic relationship between predicted bending MOE versus static bending MOE is shown in Figure 3.8-a. This study data was compared to Ross and Pellerin (1988) wide range of composite panels. The $R^2$ value from the composite specimens, 0.93, was slightly higher than the CLT specimens ($R^2 = 0.90$). It can be concluded that the CLT specimens fit in the original MOE composite model from Ross and Pellerin (1988) reconstructed by Senalik and Ross (2015).

The relationship between the predicted natural logarithmic MOR and the bending MOR from the CLT specimen testing is shown in Figure 3.8-b. Once again, the CLT specimens fit in the original MOR composite model from Ross and Pellerin (1988). However, the $R^2$ value from
the CLT specimens ($R^2 = 0.33$), was significantly lower than the composite specimens ($R^2 = 0.89$) from Ross and Pellerin (1988).

Figure 3.8 Natural logarithmic of (a) predicted bending MOE vs bending MOE, and (b) predicted MOR vs bending MOR.

After the evaluation of the potential of dMOE on CLT stiffness and strength prediction, extra nondestructive variables exhibiting potential use were added to the models to improve the prediction of MOE and MOR. Several studies showed the benefit of combining different grading variables (Diebold et al. 2000, Denzler et al. 2005, Hanhijarvi and Ranta-Maunus 2008, França et. al. 2019).

To determine the best-fit multiple regression equation, a stepwise regression approach was employed. Tables 3.4 and 3.5 show the regression model, coefficient of determination ($R^2$), standard error, and improvement of the linear regression for MOE and MOR on CLT sample. Time-domain area was the most significant secondary variable to predict MOE ($R^2 = 0.91$), adding an improvement of 5.33%.
The combination of dMOE with TDA + FDA, and TDA + FDA + LD presented slightly higher $R^2$ (0.91 and 0.92, respectively) but were not significant. In addition, the combination of this variables resulted in higher standard error when compared to dMOE + FDA model (Table 3.4).

<table>
<thead>
<tr>
<th>Predictors</th>
<th>$R^2$</th>
<th>$p$-value</th>
<th>Standard error (MPa)</th>
<th>Improvement (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic MOE (dMOE)</td>
<td>0.90</td>
<td>&lt;.001</td>
<td>346.9</td>
<td>—</td>
</tr>
<tr>
<td>dMOE + LD</td>
<td>0.90</td>
<td>0.042</td>
<td>352.7</td>
<td>-1.67</td>
</tr>
<tr>
<td>dMOE + FDA</td>
<td>0.90</td>
<td>0.038</td>
<td>351.3</td>
<td>-1.27</td>
</tr>
<tr>
<td>dMOE + TDA</td>
<td>0.91</td>
<td>0.021</td>
<td>328.4</td>
<td>+5.33</td>
</tr>
<tr>
<td>dMOE + TDA + FDA</td>
<td>0.91</td>
<td>0.052</td>
<td>331.3</td>
<td>N.S.</td>
</tr>
<tr>
<td>dMOE + TDA + FDA + LD</td>
<td>0.92</td>
<td>0.061</td>
<td>336.4</td>
<td>N.S.</td>
</tr>
</tbody>
</table>

* Improvement (%) is in reference to the single predictor dMOE; N.S.: not significant. dMOE – Dynamic modulus of elasticity; LD – Logarithmic Decrement; FDA – Frequency-domain Area; TDA – Time-domain Area.

Logarithmic decrement did not support the MOE and MOR prediction ($R^2 = 0.90$ and $R^2 = 0.33$ respectively). Time-domain area exhibited a potential increase of 8.52% when combined with dMOE ($R^2 = 0.46$). The combination of all NDT variables slightly improved the regression model ($R^2 = 0.48$). However, the model was not significant (Table 3.5).
Table 3.5  Modulus of rupture (MOR) regression model, coefficient of determination ($R^2$), p-value, standard error of the estimate, and improvement of the linear regression.

<table>
<thead>
<tr>
<th>Bending strength (MOR)</th>
<th>$R^2$</th>
<th>$p$-value</th>
<th>Standard error (MPa)</th>
<th>Improvement (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic MOE (dMOE)</td>
<td>0.33</td>
<td>&lt;.0001</td>
<td>4.11</td>
<td>—</td>
</tr>
<tr>
<td>dMOE + LD</td>
<td>0.33</td>
<td>0.062</td>
<td>4.19</td>
<td>N.S.</td>
</tr>
<tr>
<td>dMOE + FDA</td>
<td>0.44</td>
<td>0.035</td>
<td>3.84</td>
<td>+6.57</td>
</tr>
<tr>
<td>dMOE + TDA</td>
<td>0.46</td>
<td>0.046</td>
<td>3.76</td>
<td>+8.52</td>
</tr>
<tr>
<td>dMOE + TDA + FDA</td>
<td>0.48</td>
<td>0.058</td>
<td>3.77</td>
<td>N.S.</td>
</tr>
<tr>
<td>dMOE + TDA + FDA + LD</td>
<td>0.48</td>
<td>0.089</td>
<td>3.85</td>
<td>N.S.</td>
</tr>
</tbody>
</table>

* Improvement (%) is in reference to the single predictor (dMOE). N.S.: not significant. dMOE – Dynamic modulus of elasticity; LD – Logarithmic Decrement; FDA – Frequency-domain Area; TDA – Time-domain Area.

The result shows that the capability of prediction can be improved when two or more variables are added to the model. The result agrees with Senalik et al. (2020), who found an increase in $R^2$ from 0.52 to 0.71 testing southern pine lumber pieces. The regression equations with the best models to predict MOE and MOR are shown on Table 3.6. Models with independent variables whose addiction did not improve the model are not shown.

Table 3.6  Linear regression models with the largest coefficient of determination ($R^2$) and smallest error of estimate ($\mu$) for dependent variables modulus of elasticity (MOE) and modulus of rupture (MOR).

<table>
<thead>
<tr>
<th>MOE = $\beta_0 + \beta_1 \cdot$dMOE + TDA</th>
<th>$\beta_0$</th>
<th>$\beta_1$</th>
<th>$\beta_2$</th>
<th>$\mu$</th>
<th>$R^2$</th>
<th>Durbin-Watson</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>388</td>
<td>1.09</td>
<td>0.27</td>
<td>328</td>
<td>0.91</td>
<td>2.26</td>
</tr>
<tr>
<td>MOR = $\beta_0 + \beta_1 \cdot$dMOE + TDA</td>
<td>17.6</td>
<td>0.002</td>
<td>0.004</td>
<td>3.76</td>
<td>0.46</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Figure 9 exhibits linear regression plots for 3-ply SYP cross laminated timber using the models from Table 3.6. The predicted MOE using the generated model slightly increased the MOE estimation (from $R^2 = 0.90$ to $R^2 = 0.91$). In contrast, the predicted MOR using two nondestructive variables highly increased the bending MOR ($R^2 = 0.33$ to $R^2 = 0.46$).
Figure 3.9  Linear regression plots (from Table 3.6) for 3-ply SYP cross laminated timber showing (a) predicted MOE vs bending MOE, and (b) predicted MOR vs bending MOR.

3.5 Conclusions

- Longitudinal vibration dynamic modulus of elasticity exhibited a high correlation with bending properties of CLT.
- Longitudinal vibration can be used to evaluate bending properties of CLT panels.
- The presence of knots on the outer layers of panels affected the strength the panels. Therefore, lumber with higher quality should be recommended for external layers.
- The addition of time-domain area in the regression model increased the MOE and MOR predictions.
- NDT evaluation of CLT panels is recommended for quality control protocols.
3.6 Acknowledgments

This research was funded by a grant from USDA Forest Service. This publication is a contribution and is approved as journal article SB 1044 of the Forest and Wildlife Research Center, Mississippi State University.
3.7 References


CHAPTER IV

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

Spinelli Correa, L. M.; Shmulsky, R.; França, F. J. N. Case study of 3-ply commercial southern pine CLT mechanical properties and design values. Wood and Fiber Science. (Submitted)

4.1 Abstract

This work elucidates on a case study of industrially manufactured cross-laminated timber (CLT). Two methods are used to calculate specimens section modulus, $S_{\text{gross}}$ and $S_{\text{effective}}$. The first assumes that specimens behave as a continuous material, while the second considers the cross laminations (shear analogy method). Although the shear analogy method is indicated for construction purposes, applications as 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 MOR and MOE of southern pine CLT to compare the previously mentioned calculation methods. Both parametric and non-parametric 5th 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 to the constituent lumber.

4.2 Introduction

The research reported herein provides a case study of industrially manufactured CLT. Over the past decade, cross laminated timber (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 has published a related product standard (APA 2018). 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 (Fb·S) as well as sectional stiffness, that is, the product of modulus of elasticity times the moment of inertia (E·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\text{gross} method assumes that the CLT panel behaves as a continuous composite material through its thickness, while the S\text{effective} method uses shear analogy applied to CLT. As such the S\text{effective} is less than the S\text{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 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 (MOR and Fb) 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, in order to compare the previously mentioned calculation methods.

4.3 Materials and methods

In this case study, 24 2.44-m (8-ft) x 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 x 20.3-cm (2x8-inch) nominal Number-2 southern yellow pine lumber. According to PRG-320, this material is classified as V3 (Table 4.1).

Table 4.1 Design values (MPa) for laminations in longitudinal layers, per V3.

<table>
<thead>
<tr>
<th>Fb^a</th>
<th>Characteristic value^b</th>
<th>Fb for #2 2x8 lumber^c</th>
<th>MOE^c</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.17</td>
<td>10.9</td>
<td>6.38</td>
<td>9,650</td>
</tr>
</tbody>
</table>

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

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.

From each of twenty 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 ASTM D2915 (2017), for estimation of a non-parametric 5\textsuperscript{th} percentile. Each specimen was approximately 10.5-cm (4.125-inches) thick, 45.7-cm (18 inches) wide, and crosscut to 3.05 m (120 inches) long.

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-inch) span (Figure 4.1) and at a span to depth ratio of 27.6 according to a modified ASTM 5456 (2017) and with consideration of PRG-320 “specimen width not less than 12 inches 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. A 600 kN capacity hydraulic universal test frame was used for testing. In order to record the deflection, a string gage deflectometer was placed at midspan and at the panel’s neutral axis. Load, deflection, testing rate, time to failure, and failure mode were recorded.

Figure 4.1   Test setup.
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 $S_{\text{gross}}$ method assumes that the CLT panel behaves as a continuous composite material, while the $S_{\text{effective}}$ 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 ($S_{\text{gross}}$) for determination of $F_b$ as it is readily calculable.

\[ S_{\text{gross}} = \frac{b \cdot h^2}{6} \]  

(4.1)

Where: $b = \text{width}; h = \text{thickness}$.

\[ S_{\text{eff}} = \frac{2E_{\text{eff}}}{E_1 \cdot h} \]  

(4.2)

Where: $E_{\text{eff}} = \text{Effective bending stiffness}; E_1 = \text{Modulus of elasticity of outermost layer}\ (9.65 \times 10^3 \text{ MPa (1.4 }\times 10^6 \text{ psi per SPIB, 2014)}); h = \text{Entire thickness of the panel (CLT handbook, 2013)}$.

\[ E_{\text{eff}} = \sum(E_i \cdot b_i \cdot \frac{h_i^3}{12}) + \sum(E_i \cdot A_i \cdot z_i^2) \]  

(4.3)

Where: $E_i = \text{“i” layer’s design value modulus of elasticity} \ (9.65 \times 10^3 \text{ MPa (1.4 }\times 10^6 \text{ psi per SPIB 2014)}); b_i = \text{“i” layer’s width}; h_i = \text{“i” layer’s thickness}; A_i = \text{“A” layer’s section area}; z_i = \text{distance from the neutral axis of the panel to the center of respective layer}$. 

42
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 \( S_{\text{gross}} \), \( F_b \) effective was calculated as maximum moment divided by \( S_{\text{effective}} \). 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 \((F_b 
abla S)\). In order to calculate the stiffness of the panel, the traditional calculation method for lumber was applied.

\[
E_{\text{app}} (\text{gross}) = \frac{23P \cdot l^3}{108b \cdot d^3 \cdot \Delta} \tag{4.5}
\]

Where: \( P \) = load; \( l \) = span; \( b \) = width; \( d \) = panel thickness; \( \Delta \) = increment of deflection.

### 4.4 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 non-parametric 5\(^{\text{th}}\) percentiles (ASTM D2915-17) and associated \( F_b \) values are reported. MOE was calculated based on the gross moment of inertia. The summary statistics are presented in Table 4.2. Both parametric and non-parametric \( F_b \) 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 4.2
illustrates the cumulative frequency distribution of MOR values. Figure 4.3 illustrates the relationship between MOE and MOR. The $r^2$ value for this relationship is 0.33.

Table 4.2 Summary statistics for the flexural testing.

<table>
<thead>
<tr>
<th></th>
<th>Load (KN)</th>
<th>MOR gross (MPa)</th>
<th>MOR effective (MPa)</th>
<th>MOE gross (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Average</td>
<td>65.4</td>
<td>34.9</td>
<td>35.9</td>
<td>8,142</td>
</tr>
<tr>
<td>Maximum</td>
<td>81.6</td>
<td>44.9</td>
<td>45.9</td>
<td>10,469</td>
</tr>
<tr>
<td>Minimum</td>
<td>42.2</td>
<td>23.1</td>
<td>23.9</td>
<td>5,755</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>9.58</td>
<td>4.9</td>
<td>5.09</td>
<td>1,068</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>14.7%</td>
<td>14.1%</td>
<td>14.2%</td>
<td>13.1%</td>
</tr>
<tr>
<td>K factor</td>
<td>1.88</td>
<td>1.88</td>
<td>1.88</td>
<td>1.88</td>
</tr>
<tr>
<td>Parametric 5th percentile</td>
<td>47.4</td>
<td>25.7</td>
<td>26.4</td>
<td>-</td>
</tr>
<tr>
<td>Order statistic</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Non parametric 5th percentile</td>
<td>42.2</td>
<td>23.1</td>
<td>23.9</td>
<td>-</td>
</tr>
<tr>
<td>Factor for conservatism</td>
<td>-</td>
<td>0.85</td>
<td>0.85</td>
<td>-</td>
</tr>
<tr>
<td>Combined load duration and safety factor (ASTM D5456)</td>
<td>-</td>
<td>2.1</td>
<td>2.1</td>
<td>-</td>
</tr>
<tr>
<td>$F_b$ (parametric)</td>
<td>-</td>
<td>10.4</td>
<td>10.7</td>
<td>-</td>
</tr>
<tr>
<td>$F_b$ (non-parametric)</td>
<td>-</td>
<td>9.34</td>
<td>9.67</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 4.2  Cumulative frequency distribution of MOR values.

Figure 4.3  Relationship between MOE and MOR for the 28 specimens.
4.5 Conclusions

- For MOR, empirical testing provided favorable results as compared to those of 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 to 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 and MOE was relatively weak. This finding indicates the limitations of non-destructive evaluation based on MOE, for evaluating ultimate or allowable strength characteristics.

- In the case of matting, heavier loads applied over softer soils require increasingly predictable 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, etc.
4.6 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) 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 author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture.
4.7 References


CHAPTER V
EFFECT OF NOTCHING ON 3-PLY SOUTHERN PINE CROSS-LAMINATED TIMBER PANELS STIFFNESS AND STRENGTH.

Spinelli Correa, L. M.; Shmulsky, R.; Ross, R.J. Effect of notching on 3-ply southern pine cross-laminated timber panels stiffness and strength.

5.1 Abstract

Considering the high demand for housing and the ongoing environmental issues our society faces, its crucial to opt for more eco-friendly 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 print 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 need. Although CLT use has been expanding in USA for the last years, there is still a high necessity on understanding this composite behavior. One of those needs is accessing 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 testing of 3-ply CLT samples was performed to evaluate the influence of notches and stitching reinforcement on panels. The strength reduction caused by notching was successfully measured. In addition, it was found that the deeper the notch, the more effective the stitching can be regards to strength. This information is of great value toward updating manufacturing, design, and use criteria for notched CLT panels and can be potentially used on future building codes.
5.2 Introduction

As the population grows so too does the demand for housing. Considering the need for sustainability, due to recurring environmental issues, renewable materials such as engineered wood products play an important role on future building structures. For the last few decades, the use of cross-laminated timber (CLT) on low to mid rise constructions 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 to other common construction practices, in many instances building with prefabricated CLT is cleaner, faster, and it requires less intensive labor. In addition, it has been noted that living/working in wood buildings can reduce stress levels and improve people’s well-being (Rice et al. 2006). Regarding the high demand for carbon sequestration and sustainability, there are currently no other materials which are as favorable as wood. While many studies have been completed in support of CLT development and adoption, there are some current and pressing research needs.

Currently, the use of CLT in United State is restricted by some recurring limitations. For instance, the price is yet not as competitive as desirable due to the current relatively small number of manufacturers in the country. In addition, as 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, adjustments due to notches haven’t yet been thoroughly explored, which increases the complexity of design calculations and limits panels’ applications.
Notches are often employed as construction details to facilitate mechanical interlocking and adjacent member placement, which can improve and facilitate building design and construction. However, notches influence on 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’s otherwise expected to have ductile behavior, which may lead to premature failure. Per 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 panel’s failure modes, ductility, and strength can allow the safe application of notches on 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 a 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 mode 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 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, 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 the beam volume. Therefore, the fracture in the notch area is not necessarily proportional to the beam size. He also concluded that the fracture energy and material properties can be of big importance to notch strength; that the failure can be analyzed by fracture mechanics; and that strength of notch has no correlation with tensile strength perpendicular to grain. Zalph and McLain (1992), used a critical fillet hoop stress (CFHS) model to predict tension side notched-beams 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 beams 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 (2019), Mohler and Mistler (1979) tested glulam beams comparing numerous notch geometries, notch depths, and reinforcing technics aiming to reinforce notched glulam beams capacity. In addition, 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 in order 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) explains 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, while considerable large notches in large glulam beams under high shear forces ultimately reduce load capacities.

When it comes to CLT, Flaig (2014) tested CLT beams in order 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 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 3-ply CLT samples was performed to evaluate the influence of notches and stitching reinforcement on panels.

5.3 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 8 ft x 16 ft 3-ply (approximately 4.25-in. thick) commercial cross-laminated timber panels were used in this study. Each of twenty 8 ft x 16 ft 3-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 120 inches long and one approximately 66 inches long. In sum, two-hundred specimens were generated; 100 long-span (120 inches) specimens and 100 short-span (66 inches) 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 $4 \frac{1}{4} \times 18 \times 120$ in. The long-span specimens are shown on the left side of the master cut up schematic of Figure 5.1. 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% of first layer depth; (3) Notch to 33% of first layer depth with stitches; (4) Notch to 66% of first layer depth; and (5) Notch to 66% of first layer depth with stitches (Table 5.1). Each treatment group contained 20 specimens, that is, one specimen from each of the parent panels. Stitching consisted of installing four 3.5-in.-long construction screws in an evenly spaced row along each edge of each notch as described below.

![Figure 5.1 Panel’s cutting layout.](image)

<table>
<thead>
<tr>
<th>Treatment ID</th>
<th>Notch condition</th>
<th>Stitch condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Non notched (control)</td>
<td>Non stitched (control)</td>
</tr>
<tr>
<td>2</td>
<td>Notched 33% of first layer depth</td>
<td>Non stitched</td>
</tr>
<tr>
<td>3</td>
<td>Notched 33% of first layer depth</td>
<td>Stitched</td>
</tr>
<tr>
<td>4</td>
<td>Notched 66% of first layer depth</td>
<td>Non stitched</td>
</tr>
<tr>
<td>5</td>
<td>Notched 66% of first layer depth</td>
<td>Stitched</td>
</tr>
</tbody>
</table>
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 four would have the label P18-L3-T4. Treatments two through five 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 0.20 inches. For treatments 2 & 3 the notch depth was approximately 0.47 in. (33% of the outer layer’s depth). For treatments 4 & 5 the notch depth was approximately 0.94 in. (66% of the outer layer’s depth). Specimens in treatments 3 and 5 were stitched with premium exterior wood screws (Number 10 x 3 ½ in.). Each screw was installed 4 in. away from the notch line. Screws were installed 4 ½ in. The outermost screws in the stitch line were installed 2 ¼ in. from the edges. Panels were made per PRG-320 from 2x8 (nominal) Number-2 southern yellow pine lumber. Per PRG this material is classified as V3. Table 5.2 illustrates the allowable design properties for this raw material.

<table>
<thead>
<tr>
<th>F_b^a</th>
<th>Characteristic value^b</th>
<th>F_b for #2 2x8 lumber^c</th>
<th>MOE^c</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.17</td>
<td>10.9</td>
<td>6.38</td>
<td>9,650</td>
</tr>
</tbody>
</table>

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

All specimens were destructively tested in third-point bending (Figure 5.2) according to ASTM D198 and in compliance with PRG-320. The span for testing was of 114 in. This span to depth ratio (approximately 27.6) was chosen in order to facilitate bending, rather than rolling shear, failure. In order to record the deflection, a string gage type deflectometer was placed on the center of panel’s neutral axis. During 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. A typical load vs. displacement curve obtained during test can be seen on Figure 5.3. In order to access the influence of notches on 3-ply CLT panels, calculations of MOE, MOR and work were applied. Failure mode was also observed.

Figure 5.2 Test setup.

Figure 5.3 Typical load vs. displacement curve (Specimen P01-L1-T4).
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 panel’s final application. The first, named here as $S_{\text{gross}}$ method, considers the CLT panel as one continuous non-composite material. While 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 such as matting. The calculations for each method are as follows.

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

Where: $S_{\text{gross}}$ = gross section modulus; $b$ = width; $h$ = thickness.

\[ S_{\text{effective}} = \frac{2EI_{\text{eff}}}{E_1h} \]  

Where: $S_{\text{effective}}$ = effective section modulus; $EI_{\text{effective}}$ ($EI_{\text{eff}}$) = Effective bending stiffness; $E_1$ = Modulus of elasticity of outermost layer (1.4*10^6 psi per SPIB 2014); $h$ = Entire thickness of the panel.

\[ EI_{\text{eff}} = \sum E_i \cdot b_i \cdot \frac{h_i^3}{12} + \sum E_i \cdot A_i \cdot z_i^2 \]  

Where: $E_i$ = Layer’s modulus of elasticity (1.4*10^6 psi per SPIB 2014); $b_i$ = Layer width; $h_i$ = Layer thickness; $A_i$ = Layer’s section area; $z_i$ = distance from the neutral axis of the panel to the center of respective layer.
In order to calculate the stiffness of the panel, the same concept may be applied. However, as many testing facilities might only use a string gage 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.

\[
E_{app\ (gross)} = \frac{23Pl^3}{108bd^3\Delta}
\]  
(5.4)

Where: E_{app} = apparent Elasticity; P = Load; l = Span; b = Width; d = Panel thickness; \Delta = Increment of deflection.

### 5.4 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 three and five were expected to contain the crack propagation to 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’s 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 on Table 5.3. Therefore, the information collected in this project might serve as data for the international building code and consequently, the expansion of CLT use in USA.

A statistical analysis using one-way 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 $S_{\text{gross}}$ and $S_{\text{effective}}$), MOE, and Work (Table 5.4). Thus, a Tukey HSD test was used to identify the significance between groups.

Table 5.3 Descriptive Statistics.

<table>
<thead>
<tr>
<th></th>
<th>T</th>
<th>N</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Std. Error</th>
<th>Min.</th>
<th>Max.</th>
<th>Strength Reduction (%)*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MOE</strong> (psi)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>1166770.2</td>
<td>153103.2</td>
<td>34234.9</td>
<td>834723.1</td>
<td>1490581.2</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>20</td>
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<td>157009.5</td>
<td>35108.4</td>
<td>870250.7</td>
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<td>-</td>
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</tr>
<tr>
<td>3</td>
<td>20</td>
<td>1203812.6</td>
<td>127691.9</td>
<td>28552.8</td>
<td>1005761.6</td>
<td>1522873.4</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>1039096.5</td>
<td>145320.5</td>
<td>32494.7</td>
<td>769434.7</td>
<td>1325350.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>1064495.2</td>
<td>86643.3</td>
<td>19374.0</td>
<td>909894.1</td>
<td>1203439.7</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>MOR</strong> (psi) $S_{\text{gross}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>20</td>
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<td>798.6</td>
<td>178.6</td>
<td>3346.4</td>
<td>6512.2</td>
<td>-</td>
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<tr>
<td>2</td>
<td>20</td>
<td>3879.0</td>
<td>738.6</td>
<td>165.2</td>
<td>2519.4</td>
<td>5200.4</td>
<td>23%</td>
<td></td>
</tr>
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<td>3</td>
<td>20</td>
<td>4102.8</td>
<td>805.3</td>
<td>180.1</td>
<td>3002.8</td>
<td>6670.5</td>
<td>19%</td>
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<td>4</td>
<td>20</td>
<td>2015.2</td>
<td>353.0</td>
<td>78.9</td>
<td>1437.7</td>
<td>2901.7</td>
<td>60%</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>2256.6</td>
<td>380.6</td>
<td>85.1</td>
<td>1681.2</td>
<td>3016.6</td>
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<td></td>
</tr>
<tr>
<td><strong>MOR</strong> (psi) $S_{\text{effective}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>1</td>
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<td>6650.8</td>
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<td>3993.5</td>
<td>762.8</td>
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<td>20</td>
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<td>824.4</td>
<td>184.3</td>
<td>3107.6</td>
<td>6812.4</td>
<td>19%</td>
<td></td>
</tr>
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<td>2075.1</td>
<td>357.5</td>
<td>79.9</td>
<td>1468.3</td>
<td>2963.4</td>
<td>60%</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>2320.7</td>
<td>386.2</td>
<td>86.4</td>
<td>1739.9</td>
<td>3080.7</td>
<td>56%</td>
<td></td>
</tr>
<tr>
<td><strong>Work</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>20</td>
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<td>9223.4</td>
<td>5843.6</td>
<td>13194.8</td>
<td>106497.1</td>
<td>-</td>
<td></td>
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<tr>
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<td>20</td>
<td>9223.4</td>
<td>9223.4</td>
<td>2418.2</td>
<td>5815.2</td>
<td>50985.5</td>
<td>-</td>
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<td>20</td>
<td>9223.4</td>
<td>9223.4</td>
<td>3195.2</td>
<td>10362.4</td>
<td>61653.6</td>
<td>-</td>
<td></td>
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<td>20</td>
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<td>2927.5</td>
<td>654.6</td>
<td>3547.1</td>
<td>16811.8</td>
<td>-</td>
<td></td>
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<td>5</td>
<td>20</td>
<td>8490.7</td>
<td>3199.5</td>
<td>715.4</td>
<td>3871.6</td>
<td>14756.2</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

* The strength reduction percentage for each treatment is based on the control group.
Table 5.4  Mean comparison of treatment groups 1 through 5 – ANOVA.

<table>
<thead>
<tr>
<th></th>
<th>SS.</th>
<th>df</th>
<th>Mean Square</th>
<th>F</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MOE (psi)</strong></td>
<td>Btw. Groups</td>
<td>37826135179</td>
<td>3</td>
<td>94565337948</td>
<td>5.08</td>
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<tr>
<td></td>
<td>Within Groups</td>
<td>17674354572</td>
<td>95</td>
<td>18604583760</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>21456968090</td>
<td>99</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>MOR (psi)</strong></td>
<td>Btw. Groups</td>
<td>132327030</td>
<td>4</td>
<td>33081758</td>
<td>78.7</td>
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<tr>
<td>$S_{gross}$</td>
<td>Within Groups</td>
<td>39926188</td>
<td>95</td>
<td>420276</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>172253219</td>
<td>99</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>MOR (psi)</strong></td>
<td>Btw. Groups</td>
<td>142238937</td>
<td>4</td>
<td>35559734</td>
<td>80.2</td>
</tr>
<tr>
<td>$S_{effective}$</td>
<td>Within Groups</td>
<td>42133307</td>
<td>95</td>
<td>443508</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>184372244</td>
<td>99</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Work</strong></td>
<td>Btw. Groups</td>
<td>1.87E+10</td>
<td>4</td>
<td>4673799547</td>
<td>22.8</td>
</tr>
<tr>
<td></td>
<td>Within Groups</td>
<td>1.94E+10</td>
<td>95</td>
<td>204580162</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>3.81E+10</td>
<td>99</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Based on the Tukey HSD test, MOR (based on both $S_{gross}$ and $S_{effective}$) and Work can be divided into three statistical groups: a) Treatment 1 (control), b) Treatments 2 and 3, and c) 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 based on stitching condition (Table 5.5). With respect to MOE, the differences among treatments did not appear as straightforward as treatments 4,5 & 2; 5,2 & 1; and 2, 1 & 3 were not statistically different (Table 5.6). Therefore, based on the Tukey HSD test, no separation can be done considering notch size or presence of reinforcement method for MOE.
Table 5.5  
Tukey HSD test for MOR (both $S_{\text{gross}}$ and $S_{\text{effective}}$) and Work – Subset for alpha = 0.05.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>N</th>
<th>MOR (psi) $S_{\text{gross}}$</th>
<th>MOR (psi) $S_{\text{effective}}$</th>
<th>Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tukey HSDa</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>2015 A</td>
<td>2075 A</td>
<td>7543 A</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>2257 A</td>
<td>2321 A</td>
<td>8491 A</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>3879 B</td>
<td>3994 B</td>
<td>21882 B</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>4103 B</td>
<td>4221 B</td>
<td>24986 B</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>5039 C</td>
<td>5217 C</td>
<td>45132 C</td>
</tr>
</tbody>
</table>

Table 5.6  
Tukey HSD test for MOE – Subset for alpha = 0.05.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>N</th>
<th>MOE (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tukey HSDa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>1039096 A</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>1064495 AB</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>1128752 ABC</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>1166770 BC</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>1203813 C</td>
</tr>
</tbody>
</table>

To further investigate, independent samples t-tests were applied to compare treatment 2 versus 3 and treatment 4 versus 5, as both groups present the same notch depth with stitched versus non-stitched conditions. For the comparison between treatments 2 and 3 (Table 5.7), the t-test indicated that there is no statistically significant difference for panels notched to 33% of the depth of the outermost layer either with or without stitches. Therefore, based on 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 5.8), the data indicates that there is a statistically significant difference for MOR (both $S_{\text{gross}}$ and $S_{\text{effective}}$) for stitched versus non stitched panels notched to 66% 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 deeper the notch, more effective the stitching can be regards to strength.

Table 5.7 Independent Samples t-test comparing means for treatments 2 and 3.

<table>
<thead>
<tr>
<th></th>
<th>Levene's Test for Equality of Variances</th>
<th>t-test for Equality of Means</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>Sig.</td>
</tr>
<tr>
<td>MOE (psi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EVVA</td>
<td>.656</td>
<td>.423</td>
</tr>
<tr>
<td>EVNA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOR (psi)</td>
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<td></td>
</tr>
<tr>
<td>EVVA</td>
<td>.062</td>
<td>.804</td>
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<tr>
<td>EVNA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MOR (psi)</td>
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<td></td>
</tr>
<tr>
<td>EVVA</td>
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<td>.773</td>
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<td>EVNA</td>
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<td></td>
</tr>
<tr>
<td>Work</td>
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<td></td>
</tr>
<tr>
<td>EVVA</td>
<td>.832</td>
<td>.368</td>
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<tr>
<td>EVNA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*EVA = Equal variances assumed; EVNA = Equal variances not assumed.

As expected, wherein the controls were compared to all the treatments the control group was significantly stronger (MOR) and developed significantly higher work than all notched groups. However, in the analysis wherein the controls were compared to all the treatments, MOE for the controls was neither statistically different than either of the 33% depth notched panels (i.e. stitched and non-stitched) nor was it statistically different than the 66% notch depth stitched panels. When comparing means for all treatments treatment 4 (panels with 66% of the first layer notched and non-stitched) developed the lowest stiffness. The result indicated that stitching can improve stiffness to certain extent, but its effectiveness might be affected by other factors as such as screw length, diameter, and number.
Table 5.8  Independent Samples t-test comparing means for treatments 4 and 5.

<table>
<thead>
<tr>
<th></th>
<th>Levene's Test for Equality of Variances</th>
<th>t-test for Equality of Means</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>Sig.</td>
</tr>
<tr>
<td><strong>MOE (psi)</strong></td>
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</tr>
<tr>
<td>EVA</td>
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<td>.020</td>
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<td>-.671</td>
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<tr>
<td><strong>MOR (psi)</strong></td>
<td></td>
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</tr>
<tr>
<td>S\textsubscript{gross}</td>
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<td></td>
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<td>EVA</td>
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<td>.682</td>
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<td>EVNA</td>
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<tr>
<td><strong>MOR (psi)</strong></td>
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<td></td>
</tr>
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<tr>
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<td>.655</td>
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<td>EVNA</td>
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*EVA = Equal variances assumed; EVNA = Equal variances not assumed.

5.5  Conclusions

This study was successful in quantifying the extent of strength decrease caused by notching 3-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 in order to better define notched CLT reinforcement possibilities and limitations.

5.6  Acknowledgments

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5.7 References


