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Optimizing Lumber Densification for Mitigating Rolling Shear Failure in Cross-Laminated Timber (CLT)

Suman Pradhan [1], Mostafa Mohammadabadi [1,*], Roy Daniel Seale [1], Manikanta Thati [2], Edward D. Entsminger [3] and William Nguegang Nkeuwa [4,5]

1. Department of Sustainable Bioproducts, Mississippi State University, Starkville, MS 39762, USA
2. Computational Engineering Graduate Program, Mississippi State University, Starkville, MS 39762, USA
3. Department of Wildlife, Fisheries and Aquaculture, Mississippi State University, Starkville, MS 39762, USA
4. Engineered Wood, Application Engineering, Henkel, Mississauga, ON L5N 6C3, Canada
5. Department of Sustainable Biomaterials, College of Natural Resources and Environment, Virginia Tech, Blacksburg, VA 24061, USA

* Correspondence: mm5132@msstate.edu

Abstract: Rolling shear in cross-laminated timber (CLT) has been identified as the governing factor influencing design value. Likewise, densification has been found to be an effective method of enhancing the rolling shear strength of lumber and in turn, CLT. In this study, utilizing knowledge of material properties, optimization of the compression ratio for densification has been presented. Three-layered CLT beams made from non-densified lumber, grade #1 loblolly pine (*Pinus taeda* L.), were subjected to a bending load at a span-to-depth ratio of eight and had a rolling shear failure at the mid-layer with a shear strength of 3 MPa. Assuming the same modulus of rupture (MOR) for both lumber and CLT made from the same species and grade, the MOR of lumber was used to calculate the minimum required shear strength (MRSS) of the transverse mid-layer to change the failure mode of the CLT beam from rolling shear to tensile failure. Using the relationship between the compression ratio and the increase in rolling shear strength, the optimized compression ratio for densification was calculated. This procedure resulted in a compression ratio of 16.67% for densification of the mid-layer to avoid rolling shear in the case of CLT beams with a span-to-depth ratio of eight. To verify this process, CLT beams with mid-layers densified at 16.67% were fabricated and submitted to a bending test. Rolling shear failure was mitigated and densified CLT beams failed in tension with a MOR similar to that of lumber, 47.45 MPa. Likewise, rolling shear strength was observed to increase by 48% for CLT that had a densified mid-layer at 16.67%.

Keywords: cross-laminated timber (CLT); densification; southern yellow pine (SYP); bending test; rolling shear strength; failure mode

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1. Introduction

Cross-laminated timber (CLT), an engineered wood product, was developed between 1970 and 1980 [1] as a solution to utilize sawmill resources in innovative ways, diverging from conventional applications. Notable characteristics of CLT included its large dimensions and a higher-value use for sideboards [2]. The motivation behind CLT development was driven by the desire to elevate the utility of timber and expand its applicability. This allowed timber engineering to penetrate markets that were dominated by traditional building materials like steel and concrete. CLT typically comprises an odd number of layers—often three, five, or seven—constructed from boards positioned side by side. These boards are layered crosswise to each other at a 90° angle, enabling CLT to support loads both in-plane and out-of-plane effectively. The arrangement of layers in a crosswise direction allows CLT to provide enhanced dimensional stability and consistent stiffness, surpassing that of the individual timber lamellae used in its manufacturing process. Additionally, CLT provides better structural integrity and consistent mechanical properties [3]. Being an orthotropic material, wood exhibits weaker material properties in radial and tangential directions in comparison to the longitudinal direction [4]. The mid-layer of CLT under a bending load experiences higher shear stress because it is sandwiched between the top and bottom layers. Hence, it is subjected to the relative sliding or shearing forces between the outer layers. The shear stresses occurring in directions perpendicular to the grain are specifically known as rolling shear. Due to the relatively low shear modulus and strength in the rolling shear direction, the properties related to shear in the cross layers significantly impact the overall deflection and shear capacities of CLT panels. Rolling shear failure is characterized by wood fibers rolling over each other due to shear stress, resulting in failure between the wood fibers. Considering the critical role that rolling shear plays in CLT design [5], it is necessary to understand influencing factors. This understanding is essential for advancing CLT design methodologies and achieving enhanced structural performance. The mechanical properties of wood, specifically rolling shear characteristics, are susceptible to various influencing factors, such as the sawing pattern [6], aspect ratio [5,7–13], wood species [5,14,15], density [5,13,16], and the overall condition of the board [3,17]. Researchers have pursued improving CLT performance by utilizing the relationship between rolling shear and these influencing factors.

The sawing pattern, characterized by the annual ring orientation, plays a crucial role in rolling shear strength. A higher percentage of high annual-ring-orientation angles with the board edge, typically falling between 30° and 60° grain angles, have been linked to an increased rolling shear modulus [5,9]. With comparable outcomes, Aicher et al. [6] classified sawn lumber based on the annual ring angle. This classification included flat-sawn (0° to 30°), semi-quarter-sawn (30° to 60°), and quarter-sawn (60° to 90°) lumber. Notably, semi-quarter-sawn lumber exhibited both greater rolling shear strength and modulus. Likewise, Aicher and Dill-Langer [18] obtained the highest apparent rolling shear modulus at a 45° angle, and explained the phenomenon based on the load transfer mechanism as a stiff diagonal in radial and tangential directions like a truss system.

The aspect ratio, which is the ratio of a lamella's width to its thickness, significantly impacts the rolling shear properties of CLT. Recognizing the positive influence of the aspect ratio of lumber on rolling shear, a suggested minimum ratio of four has been advised to produce CLT [5,15]. However, beyond a certain aspect ratio, a further increase has less influence on enhancing rolling shear strength in CLT [9]. Moreover, opting for larger-dimension lumber to attain a higher aspect ratio could notably escalate the overall material costs associated with CLT production.

A novel approach, the development of hybrid cross-laminated timber (HCLT), wherein various engineering wood products [12,19–24] and varying species [5–7,14] were employed in the transverse layer, has emerged to enhance rolling shear properties. However, besides glued laminated bamboo (GLB), all the other engineering wood products like laminated veneer lumber (LVL), parallel strand lumber (PSL), plywood, and oriented strand board (OSB) were found to have lower rolling shear strength compared to Spruce Pine fir (SPF). Species like European ash and beech were found to have higher rolling shear strength, almost three times that of spruce [5], as the mechanical properties vary with lumber species. Similarly, researchers have delved into exploiting the superior mechanical characteristics inherent in lumber aligned longitudinally by examining the orientation of the transverse layer within CLT [25,26]. The orientation angle yields noticeable enhancements in the rolling shear strength of CLT. This experimental observation underscores the strategic importance of optimizing the layout of CLT components to harness the inherent strength of lumber fibers oriented in the longitudinal direction, thereby bolstering structural robustness and performance.

Knots as a defect in lumber are traditionally viewed as detrimental to their bending stiffness. However, recent research has revealed that knots can have a positive impact on the rolling shear properties of CLT panels, particularly when located in the cross-layer [27]. Cao et al. [28] underscored the significance of knots in determining shear properties and failure modes, with their findings showing that knots, whether sound knots or encased decayed knots, did not negatively affect rolling shear strength and, in fact, had slightly higher rolling shear strength when compared to specimens without knots. In addition, the study concluded that knots could affect the failure mechanism instead of reducing rolling shear strength.

Through the densification process, a higher density can be achieved, resulting in improved mechanical strength [29–36]. Pradhan et al. [10] used thermomechanical densification at varying compression ratios and reported a linear relationship between the percentage increase in rolling shear strength and the compression ratio. The study also reported that at a 50% compression ratio, the rolling shear strength of the lumber increased by double with respect to non-densified lumber. Similarly, Pradhan et al. [36] evaluated the bending performance of densified lumber and reported a change in failure mode from rolling shear failure to bending failure when the transverse mid-layer was densified at a 50% compression ratio. Furthermore, in the case of all three-layer densified samples, CLT experienced failure in rolling shear, with the rolling shear strength elevated by 115% compared to that of normal, non-densified CLT samples.

Prior investigations have predominantly concentrated on assessing the rolling shear properties of CLT considering various influencing factors. While densification has been demonstrated to improve rolling shear strength, there is a gap in understanding the specific compression ratio required for densification to effectively endure rolling shear stress and alleviate rolling shear failure. Densification demands a substantial amount of energy; therefore, optimizing the densification process and understanding the required quantity would contribute to a more sustainable solution. This study aims to address this gap by evaluating the maximum compression ratio needed to densify the transverse mid-layer in loblolly pine CLT panels to meet the minimum required shear strength (MRSS), with the goal of mitigating rolling shear failure under short-span bending.

2. Materials and Methods

2.1. Materials

Three-layered CLT beam samples were constructed using loblolly pine (*Pinus taeda* L.), with grade #1, 2 × 6-dimensional lumber. Grade #1 is visually graded dimensional lumber that has been standardized by the Southern Pine Inspection Bureau (SPIB) as "No. 1" for Southern Pine species. It is characterized by minimal defects and excellent structural integrity, making it suitable for various construction and woodworking applications where strength and durability are paramount. To capture the true effect of densification, defect-free lumber was chosen to eliminate additional variables associated with rolling shear strength. The average density of the non-densified lumber was 619.59 kg/m^3 with a coefficient of variation (COV) of 6%.

Two groups of CLT samples with six specimens in each group were prepared; (a) specimens made from non-densified lumber (ND), and (b) specimens having densified lumber only as the mid-layer (D). During the fabrication of CLT, lumber underwent planning to ensure optimal bonding with the adhesive. A one-component polyurethane adhesive was employed, beginning with the preparation of the bonding surface. This process entailed the application of a primer solution at a rate of 20 g per square meter, consisting of a 5% by-weight solution of Loctite PR 3105 PURBOND primer (manufactured by Henkel, Mississauga, ON, Canada) which was dissolved in water. Subsequently, the adhesive (Loctite HB X202 PURBOND, produced by Henkel) was applied at a rate of 180 g per square meter. The non-densified specimens had an average dimension, featuring a span length of 838 mm, a width of 138 mm, and a total thickness of 103 mm, while densified specimens with a similar width, 139 mm, had an average length and thickness of 838 mm and 104 mm, respectively.

2.2. Methodology for Densification

Densification was carried out based on the compression ratio, which was calculated as the ratio of the change in thickness of a densified sample to the initial thickness of a non-densified sample. The densification process involved a thermomechanical process requiring lumber softening to prevent damage. Softening was achieved by soaking the wood in boiling water for 10 min, ensuring that the glass transition temperature was reached. This allows the amorphous polymers in wood, such as hemicellulose and lignin, to undergo a change from a glassy state to a more elastic state. The specimens were then subjected to hot-pressing at 140 °C, using a Clifton hydraulic open hot press (Clifton, NJ, USA). The load increment rate was adjusted to achieve a target thickness of 5 min. After reaching the target thickness, samples were held under pressure until the temperature dropped below the boiling point of water to prevent spring-back. Densified lumber was used as a transverse mid-layer while non-densified virgin lumber was used as a longitudinal outer layer to develop CLT beams denoted as densified groups in this study and identified as "D" (i.e., mid-layer densified CLT beams).

2.3. Bending Test Procedure

To obtain the bending properties, a flatwise four-point bending test was conducted following ASTM-D198 standards as shown in Figure 1. The load on the specimen was applied at two points, each positioned equidistant from the support. The load heads were located at a distance from their respective support, equivalent to one-third of the span (L/3), adhering to the principle of third-point loading. Thus, to ensure clarity from this point onward, we have referred to the third-point bending test instead of the four-point bending test. During the test, thorough documentation was conducted to record the maximum load experienced at the point of failure, along with observations of the deflection exhibited by the material under stress. Short-span bending with a span-to-depth ratio of eight was employed to induce high shear stress and ensure rolling shear failure. To perform the bending test, the displacement-controlled load was applied at a constant rate of 2.5 mm/min, reaching the average loading time of 5 min. The bending test was executed using the Tinius Olsen Satec Universal Mechanical Testing Machine (Tinius Olsen Testing Machine Company Inc., Horsham, PA, USA). The maximum developed normal (σ_{max}) and shear stresses (τ_{max}) were determined by Equations (1) and (2), respectively. Additionally, the apparent modulus of elasticity (E_{app}) was computed using Equation (3). To compute E_{app}, the deflection (Δ) was measured in a linear region utilizing an LVDT positioned at the bottom center of the CLT span.

$$\sigma_{max} = \frac{P_{max} \times L}{b \times h^2} \tag{1}$$

$$\tau_{\mathrm{max}} = \frac{3 \times P_{max}}{4 \times b \times h} \tag{2}$$

$$E_{\mathrm{app}} = \frac{23 \times P \times L^3}{108 \times b \times h^3 \times \Delta} \tag{3}$$

Note: P_{max} is the maximum bending load (N) at failure, L is the span length (mm), b is the width of the panel (mm), h is the thickness of the beam (mm), and Δ is the mid-span deflection at the instance of bending load P. To compute the apparent modulus of elasticity (E_{app}) given in Equation (3), the slope of the load–defection curve in the linear region was used as P/Δ.

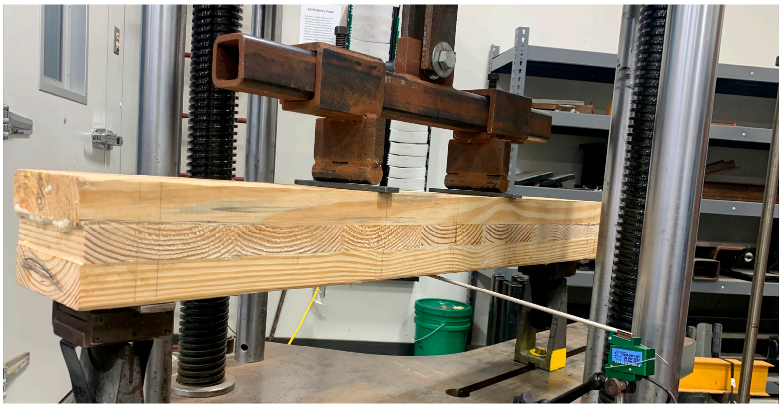


Figure 1. Third-point bending set-up as per ASTM D198.

2.4. Required Densification to Meet MRSS

Tensile failure of a CLT beam under a bending load typically occurs when the normal stress surpasses the modulus of rupture (MOR), particularly for beams with a high span-to-depth ratio. Conversely, in instances of a small span-to-depth ratio, shear failure predominates, as the maximum shear stress generated in the mid-layer exceeds the shear strength of lumber across the grain. An innovative solution would involve enhancing shear strength to withstand the maximum shear stress, thereby transitioning the failure mechanism from shear to tensile even in cases with a small span-to-depth ratio.

During tensile failure, the maximum tensile stress (σ_{max}) exceeds the tensile bending strength (i.e., MOR), likewise, shear strength should be ample to withstand the maximum developed shear stress. The MOR at tensile failure for both single lumber and CLT constructed from the same species and grade of lumber should be identical under equivalent loading conditions. During rolling shear failure, however, the maximum shear stress (τ_{max}) exceeds the shear strength. Hence, the minimum required shear strength (MRSS) of the mid-layer must be higher than the maximum shear stress developed (τ_{max}) in CLT at the time of tensile failure to avoid rolling shear failure. Therefore, using Equations (1) and (2), the minimum required shear strength of the transverse mid-layer to shift rolling shear failure to tensile failure in CLT can be computed in terms of bending strength as given in Equation (4).

$$\text{MRSS} = \frac{3 \times \text{MOR}}{4 \times \left(\frac{L}{h}\right)} \tag{4}$$

It should be noted that MRSS is also dependent on the span length-to-depth ratio of the CLT beam. Utilizing Equation (4), with the known value of MOR for specific species and grades of lumber, the minimum required shear strength to resist the maximum shear stress developed in CLT made from the same species and grade can be calculated for all the span-to-depth ratios. For loblolly pine lumber, #1 grade, with an average MOR of 42.28 MPa reported by Pradhan et al. [36], a graphical representation illustrating the relationship between the minimum MRSS and the span-to-depth ratio (L/h) was generated from Equation (4), as shown in Figure 2. This graph serves as a valuable tool to determine the precise MRSS requirement based on the specific span-to-depth ratio of their CLT beam configurations.

To evaluate the compression ratio of densification, the linear relationship between the increase in shear strength and the compression ratio of loblolly pine, shown by green bars and blue line in Figure 3, reported by Pradhan et al. [10] has been utilized. For this purpose, it is necessary to evaluate the initial shear strength of non-densified virgin lumber in order to calculate the necessary increment required to achieve the minimum required shear strength for a specific span length-to-depth ratio to endure the maximum developed shear stress.

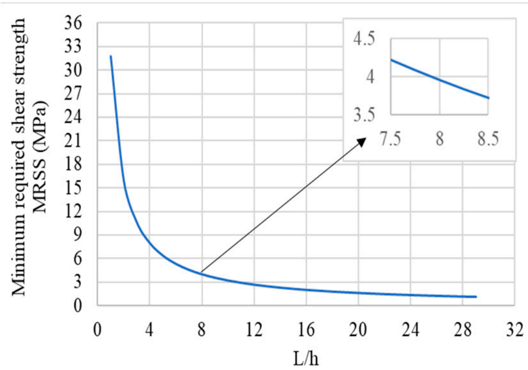


Figure 2. Relationship between the minimum required shear strength (MRSS) and span-to-depth ratio (L/h) to avoid rolling shear failure in CLT fabricated from loblolly pine lumber #1 grade with an average MOR of 42.28 MPa.

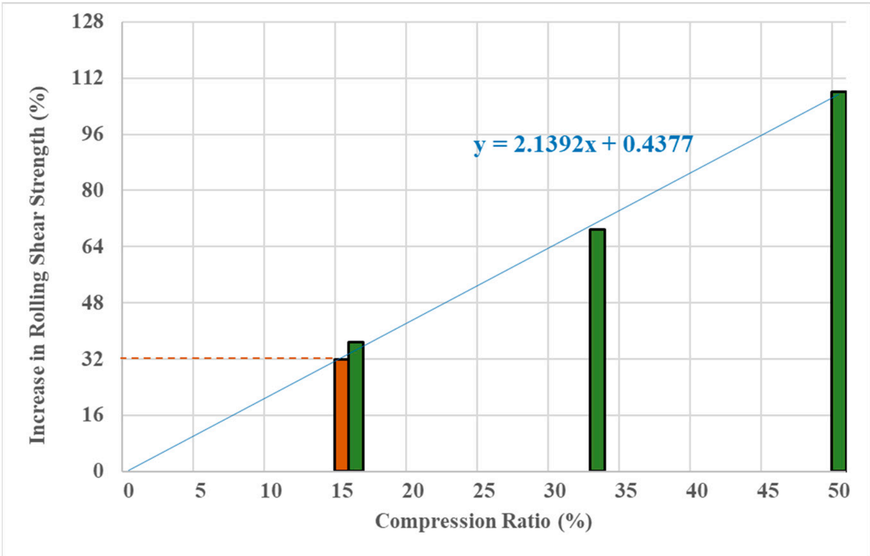


Figure 3. Relationship between compression ratio and percentage of increment of rolling shear strength for loblolly pine shown by green bars and blue line. Reproduced from ref. [10].

3. Results

3.1. Shear Strength Assessment of Non-Densified Lumber

The short-span third-point bending test results for the non-densified samples have been presented in Table 1. As all the samples failed in rolling shear as shown in Figure 4, the rolling shear strength of the sample was equal to the maximum shear stress developed in CLT.

Table 1. Results from third-point short-span bending tests of non-densified samples.

S. No	Sample ID	P_{max} (N)	P/Δ (N/mm)	Apparent Modulus of Elasticity, E_{app} (MPa)	Rolling Shear Strength, τ_{max} (MPa)
1	ND1	50,483	6896.85	8488.62	2.68
2	ND2	62,048.6	7674.77	9435.65	3.22
3	ND3	58,211.7	9300.82	11,587.4	3.06
4	ND4	61,821.4	7420.48	9000.71	3.2
5	ND5	67,046.5	7699.46	9506.11	3.48
6	ND6	44,366.8	6951.67	8772.12	2.41
Average		57,329.7	7657.34	9465.1	3
COV		13%	10%	11%	12%

Figure 4. Rolling shear failure in non-densified CLT samples.

As the failure was governed by shear, the average rolling shear strength of CLT constructed from non-densified loblolly pine #1 grade with a span length-to-depth ratio of eight was observed to be 3 MPa as shown in Table 1. Likewise, with reference to Figure 2, the minimum required shear strength of CLT beams with the same span-to-depth ratio of eight and constructed from the same lumber, loblolly pine #1 grade, must be a minimum of 3.96 MPa to avoid rolling shear failure. In other words, the mid-layer lumber should have a 32% higher value of rolling shear strength compared to that of virgin (non-densified) #1 grade loblolly pine lumber species. After referencing Figure 3 and examining the linear relationship, it was determined that to achieve a 32% increase in rolling shear strength densification, a maximum compression ratio of 15% was required as shown by orange bar. This ensures that the rolling shear strength of the lumber matches the maximum shear stress developed in CLT.

3.2. Effect of Densification on Failure Mode and Rolling Shear Strength

As densification at a 15% compression ratio will enhance rolling shear strength to satisfy the maximum developed shear stress, a higher compression ratio of 16.67% was undertaken to ensure tensile failure. The average density of the densified lumber samples was 741.45 kg/m^3 with a COV of 5% after densification. The average dimension of CLT specimens with a densified mid-layer (D) was as follows: a span length of 838 mm, a width of 139 mm, and a total thickness of 104 mm. The thickness of the non-densified and densified specimens was not much different. The densification of the mid-layer lumber reduced the thickness to 31.75 mm; however, during fabrication the total depth of CLT was comparable to the non-densified sample. Similarly, for the densified samples, the short-span bending test results have been presented in Table 2 with the failure mechanism for each sample. The bending properties, i.e., MOR, τ_{max}, and E_{app}, have been calculated using Equations (1), (2) and (3), respectively, and tabulated in Table 2.

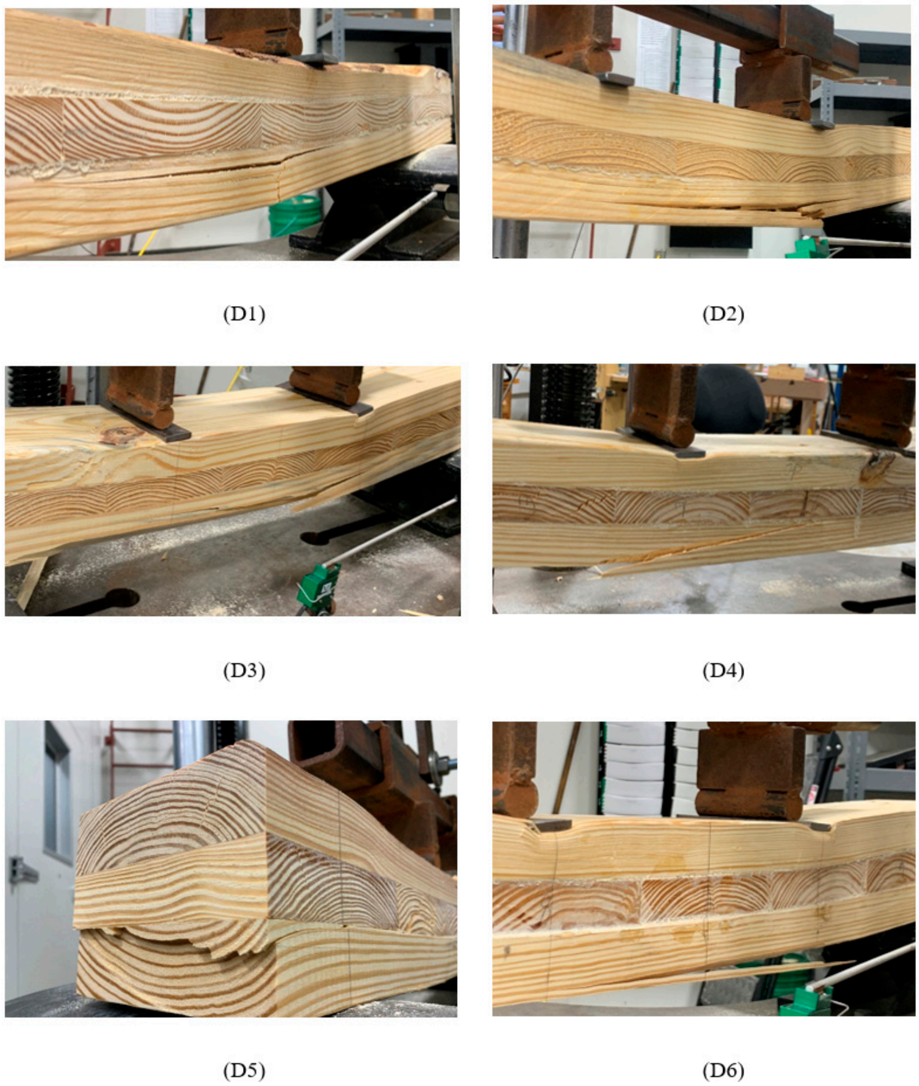
During the test, no instances of glue line failures or delamination were observed. All the densified samples failed in tension except sample D5 which failed in horizontal shear in the bottom longitudinal layer as shown in Figure 5. Except for sample D5, every specimen experienced clear and sharp fractures, featuring abrupt and brittle failures. For sample D5, the failure occurred along the horizontal plane within the bottom layer of the CLT. The shear strength of densified lumber perpendicular to the grain surpassed the shear strength of the lumber parallel to the grain, primarily ascribable to the grain orientation. This was due to a steeper slope of the grain at the bottom longitudinal lumber of sample D5, leading to reduced shear strength in the longitudinal direction of the lumber. Two different types of tensile failure were observed: simple tension and cross-grain tension failure. Samples D1, D2, D3, and D6 experienced simple tension failure, whereas sample D4 exhibited cross-grain tension failure. However, on closer inspection, although the ultimate failure occurred due to tensile failure, for a few samples, initiation of shear cracks was also detected. This points out the fact that densification of the mid-layer at a compression ratio of 16.67% increased the rolling shear strength of CLT, which was just enough to resist the maximum developed shear stress and allowed tensile failure.

Table 2. Results from third-point short-span bending tests of densified samples.

S. No	Sample ID	P/Δ (N/mm)	P_{max} (N)	Modulus of Rupture (MPa)	Apparent Modulus of Elasticity, (MPa)	Maximum Shear Stress, (MPa)	Failure Mode
1	D1	8738.31	83,548.35	45.08	10,205.05	4.24	Tensile
2	D2	8276.33	78,239.92	42.21	9583.99	3.97	Tensile
3	D3	8456.71	90,446.67	49.95	10,102.93	4.68	Tensile
4	D4	9403.62	96,728.70	52.08	10,915.23	4.90	Tensile
5	D5	9476.47	87,517.13	47.30	11,072.67	4.44	Horizontal Shear
6	D6	9367.37	88,425.19	48.09	11,068.69	4.50	Tensile
Average		8953.13	87,484.33	47.45	10,491.43	4.45	
COV		5%	7%	7%	5%	7%	

Given that the majority of densified specimens experienced tensile failure at the bottom layer, comprehensive analysis led to the determination that the developed bending stress (σ_{max}) corresponds to the bending strength (MOR) of the sample. This observed bending strength value averaged 47.45 MPa, closely aligning with the initial value reported by Pradhan et al. [36]. This observation underscores the fact that the bending strength of CLT is predominantly governed by the bending strength of the bottom layer. Moreover, it was observed that the mid-layer-densified specimens failed in tensile strength at the bottom longitudinal layer, resulting in the development of an average maximum shear stress of 4.45 MPa, which was 48% higher than that of non-densified lumber. Despite both cases having similar moments of inertia due to their comparable thickness, it is noteworthy that the apparent modulus of elasticity for the mid-layer-densified specimens was 10% higher than that of the non-densified specimens.

The findings clearly demonstrated that densification at 16.667% notably enhanced rolling shear strength, leading to a shift in the failure mechanism from rolling shear to tension. Similarly, in the study conducted by Pradhan et al. [36], densification at 50% also induced a tension failure mode, restricting overall strength, primarily governed by the bending strength of the outer layer. However, densification at higher compression ratios would decrease the overall moment of inertia as higher densification is associated with a reduction in thickness, thereby impacting the bending stiffness of CLT. This underscores the importance of achieving an optimized compression ratio for densification to mitigate rolling shear failure as well as provide better bending stiffness. Therefore, by understanding the bending strength, shear strength of the lumber, and the span-to-depth ratio of CLT, one can determine the necessary compression ratio for densification to mitigate the risk of rolling shear failure, thereby ensuring optimization.



(D1) (D2) (D3) (D4) (D5) (D6)

Figure 5. Failure mode for all the densified samples in short-span bending samples.

4. Conclusions

Densification shows promise in improving the mechanical properties of lumber. This study presented an approach to optimize densification by leveraging the material properties of non-densified lumber to mitigate the occurrence of rolling shear failure in short-span bending. The study was conducted on loblolly pine #1 grade, one of ten species known as Southern Yellow Pine (SYP). The shear strength of the non-densified sample was assessed through a short-span third-point bending test. The acquired values of shear strength were then methodically used to ascertain the necessary compression ratio for densification. This determination was based on understanding the linear relationship that exists between the compression ratio and the corresponding percentage increase in shear strength. This approach aimed to enhance shear strength adequately to withstand shear stress at the bending strength of CLT. Densification of the mid-layer of a three-layered CLT beam was performed at a compression ratio of 16.67%, guided by the shear strength and bending strength of non-densified lumber. Subsequently, the mechanical properties of the densified CLT were assessed using a third-point bending test. Tensile failure was evident in all cases of densified samples, occurring at the bottom longitudinal layer of CLT with a small shear crack at the mid-layer. This observation indicates that the rolling shear capacity was fully utilized and substantial enough to transition the failure mode from rolling shear in the mid-layer to tension in the bottom outer layer of loblolly pine CLT beams with a span length-to-depth ratio of eight.

This study underscores the efficacy of densification in improving the rolling shear strength of CLT panels constructed from loblolly pine. Moreover, it presents a method for optimizing densification levels contingent on the initial material properties of non-densified lumber and loading conditions. This optimization approach results in enhanced mechanical properties and overall performance of CLT panels, contributing to a more energy-efficient and sustainable solution. However, it is essential to acknowledge the limitations of this study, which primarily focused on the investigation conducted within a specific span-to-depth ratio and the scope of loblolly pine species. Future research endeavors could substantially validate our theory by exploring a wider array of wood species with varying span-to-depth ratios. By delving into diverse species and configurations, researchers can enhance the current result for densification processes and their significance in bolstering rolling shear properties in CLT, thus facilitating its optimization and wider application within the construction industry.

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