Influence of Densification on Structural Performance and Failure Mode of Cross-laminated Timber under Bending Load

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The effect of densification of the laminas was studied relative to the shear performance of cross-laminated timber (CLT) specimens submitted to the bending test. The three-layered CLT panels were fabricated using loblolly pine (*Pinus taeda* L.). A compression ratio (CR) of 50% was used to densify the lumber using the thermomechanical densification technique. The process included plasticizing the lumbers by soaking them in boiling water for 10 minutes and then hot-pressing to the target thickness at 140 °C. Four groups were made, *i.e.*, a control sample with all three layers non-densified, only mid-layer densified, all layers densified, and all layers planed to the same thickness of densified layers. Specimens were tested in short-span bending with a span-to-depth ratio of eight. For specimens having densified mid-layer, the failure mode changed from rolling shear to tensile failure of the outer layer, and the maximum shear stress was increased by 34%. Densification of the mid-layer at CR of 16% was sufficient to change the failure mode from rolling shear in mid-layer to tensile in outer layer. In the case of all-layer-densified specimens, the maximum rolling shear strength was increased by 129% compared to the control.

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INTRODUCTION

Cross-laminated timber (CLT) is a novel product that has attracted a lot of interest in recent years. Cross-laminated timber is an engineered wood product made of odd layers of boards bonded together in a perpendicular arrangement to produce a stiff plate-like structure. Nevertheless, such orientation makes the panels susceptible to rolling shear, and the poor shear strength of the wood in the perpendicular direction (*i.e.*, radial, and tangential direction) might lead to shearing failure in transverse layers when exposed to bending. Hence, a lower value of the ASD reference design value of rolling shear (RS) stress of lamination ranging from 0.24 MPa (35 psi) to 0.41 MPa (60 psi) has been defined in PRG 320-2019 (American National Standards Institute 2019). Thus, it is essential to carefully consider the impacts of rolling shear while designing the CLT members.

Research work has been conducted to enhance the rolling shear strength of CLT panels. Bahmanzad *et al*. (2020) reported higher ultimate loads and lower shear deformation with a brittle failure mechanism when the transverse layer was also oriented parallel to the outer layers rather than in a perpendicular arrangement. Similarly, Buck *et al*. (2016) also reported an increase of 35% in modulus of rupture (MOR) when the transverse layer was oriented at 45°. Likewise, the sawing pattern or annual ring orientation has also been found to influence the rolling shear strength of the CLT (Zhou *et al.* 2014; Aicher *et al.* 2016; Ehrhart and Brandner 2018; Wu *et al*. 2021). Wu *et al*. (2021) presented higher shear strength of CLT panels when the transverse layer had an annual ring grain angle of 45° compared to 0° and 90°. A similar conclusion was also made by Aicher *et al*. (2016), resulting in lower shear strength of flat-sawn lumber having grain angle between 30° and 57° than to semi-quarter sawn lumber.

Lumber's properties vary with species, which significantly affects the rolling shear strength of CLT panels (Bendtsen 1976; Li 2017; Ehrhart and Brandner 2018). Additionally, different engineering products including laminated veneer lumber (LVL), oriented strand board (OSB), plywood, and glulam laminated timber (GLT) have been used as laminas to form a hybrid cross-laminated timber (HCLT). Wang *et al*. (2015) reported enhancement of bending properties with HCLT made with laminated strand lumber (LSL) as transverse and outer layers compared to normal CLT. When LSL was used as a transverse layer, the modulus of elasticity (MOE) increased by 13% and MOR by 24%. Likewise, a change in failure mechanism from rolling shear to tension failure was also observed. However, in a study conducted by Xu *et al*. (2021) using the planar shear test, rolling shear strength was observed to be reduced from 2.21 MPa for CLT panels made from spruce pine fir (SPF) lumber to 1.6 MPa for LVL. Likewise, the rolling shear strength was higher with plywood than OSB (Sretenovic *et al*. 2005; Xu *et al*. 2021) but was still lower than the SPF when used as a cross-layer (Xu *et al*. 2021). In contrast, a higher value of rolling shear was observed (Li *et al*. 2020) when OSB was used as mid-layer orienting in both parallel and perpendicular directions. Pradhan *et al*. (2023) studied the effect of densification on rolling shear strength using the modified planar shear test. The study showed an increase in rolling shear strength by a factor of two when the lumber pieces were densified by 50% CR (compression ratio).

Rolling shear strength can also be improved by increasing the aspect ratio of the transverse layer (Ehrhart and Brandner 2018; Li *et al*. 2019; Ukyo *et al*. 2019; Gui *et al*. 2020; Li *et al.* 2021; Nero *et al.* 2022; Sun *et al.* 2022; Pradhan *et al.* 2023). This can be achieved by either increasing the width or decreasing the thickness of the laminas. Increasing the width could be a possibility, but the cost of material would be expensive. Hence, decreasing the thickness of laminas has more economic justification. However, PRG 320-2019 (American National Standards Institute 2019) limits the thickness of CLT lamina from a minimum of 16 mm to a maximum of 51 mm. That means that decreasing the thickness to increase the aspect ratio can be completed only up to a certain extent.

Previous research focused on the impact of wood properties and the use of engineered wood products on the rolling shear strength of CLT, but there has been a notable deficiency in understanding the effect of densified lumber. Densification enhances the rolling shear strength, but the effect of densification of laminas on the performance of CLT under a bending load has not been evaluated. In this study, uniform densification CLT panels were made, and the effect of densification for the case of densified transverse layer and all three layers were investigated on the short span bending performance of loblolly pine CLT specimens.

EXPERIMENTAL

Material Selection and Fabrication

Flat-sawn loblolly pine (*Pinus taeda* L.) lumber produced by Shuqualak, Mississippi, USA was used to evaluate the influence of densification on CLT. The lumber was carefully selected, ensuring the absence of defects such as knots, wanes, shakes, and cracks. Additionally, to avoid the confounding effect of pith distance on the study's outcomes, lumber with similar pith distances was selected. This approach ensured that the evaluation of densification was not biased by varying pith locations and the presence of defects within the samples.

Four groups were meticulously prepared, with each group consisting of precisely six individual specimens (Fig. 1). Virgin and non-densified lumber pieces with an average thickness of 35 mm were used to fabricate the first group, UD-1.50, as control specimens. Densified lumber at 50% CR with a final thickness of 19 mm (0.75 inches) was used to develop two densified groups, *i.e.*, DM-0.75 (mid-layer densified) and DA-0.75 (all layer densified). Likewise, another non-densified group, UD-0.75, having virgin and non-densified lumber planned to a thickness of 19.00 mm was also fabricated to observe the effect of densification and aspect ratio. The average density of the non-densified lumber was 497.66 kg/m^3 with a coefficient of variation (COV) of 9% while it was 919.50 kg/m^3 with COV of 8% after densification.

Fig. 1. Bending samples: (a) UD-1.50, (b) DM-0.75, (c) UD-0.75, and (d) DA-0.75

Three-layer CLT bending test specimens were prepared using a one-component polyurethane adhesive. The bonding surface was prepared by applying a 5% by-weight solution of Loctite PR 3105 PURBOND primer (produced by Henkel) in water at a rate of 20 grams per square meter. Then, the adhesive (Loctite HB X202 PURBOND produced by Henkel) was applied at a rate of 180 grams per square meter. The dimensional detail of the samples has been tabulated in Table 1.

Table 1. Dimension for Third-point Short-span Bending Samples

Sample No.	Group ID	Overall Length (mm)	Width (mm)	Thickness (mm)	Span Length (L) (mm)
1	UD-1.50	1016	136	35/35/35	838
2	DM-0.75	835	136	35/19/35	711
3	DA-0.75	533	136	19/19/19	457
4	UD-0.75	533	136	19/19/19	457
*UD = non-densified lumber; DM = mid-layer densified lumber; and DA = all-layer densified lumber					

Densification Process

Densification was conducted with a thermomechanical densification process, which requires the softening of the lumber to avoid damage. The softening process is obtained when the amorphous wood component (*i.e.*, hemicellulose and lignin) changes the stage from a rigid glassy state to rubbery-elastic state. This occurs when the wood is heated to a glass transition temperature (T_g), which differs for cellulose, hemicellulose, and lignin. Back and Salmén (1982) reported the softening effect of water in reducing the glass transition temperature of wood species.

Lumber was softened by soaking in boiling water for 10 minutes followed by hot-pressing at 140 °C, using a Clifton hydraulic open hot press (Clifton, New Jersey, USA). The load increment rate in the hot press was set to obtain the target thickness of 19.00 mm in 5 minutes. After the target thickness was reached, the samples remained under the pressure required to reach the target thickness, while the heating element of the hot press was turned off. Once the pressurized samples reached the temperature below the boiling point of water at ambient pressure, the pressure was released, and they were removed from the press. The samples had been kept under pressure until the overall temperature dropped below the boiling point of water, ensuring no spring-back (Seborg *et al.* 1953). The CR has been used to define densification, which is the ratio of change in the thickness of the sample after densification to the initial thickness. The densification was completed at CR of 50 % for both DM-0.75 and DA-0.75 specimens.

Test Method

A flatwise third-point loading (four-point) bending test was conducted in accordance with ASTM-D198. The bending test provided a more consistent value of rolling shear (Zhou *et al.* 2022) and insight into the performance of the outer layer of CLT panels (Li *et al.* 2022). The short-span bending with a span-to-depth ratio of 8 has been used to ensure the occurrence of shear failure. The width was kept consistent at 136 mm for all specimens, and the maximum load at failure was recorded. The displacement control load was applied at a constant rate reaching the maximum loading time from 4 min (for UD-1.50) to 5.7 min (for DA-0.75). The deflection was measured with a linear variable differential transformer (LVDT) at the center of the span to calculate the apparent modulus of elasticity (E_{app}). The bending test was conducted using Tinius Olsen satec universal mechanical testing machine (Tinius Olsen Testing Machine Company Inc., Horsham, PA).

Apparent modulus of elasticity (E_{app}), modulus of rupture (MOR), and maximum shear stress (τ_{max}) were calculated as per ASTM D198 table X2.1, which are presented in equations below,

$$\mathrm{E_{app}} = \frac{23*P*L^3}{108*b*h^3*\Delta} \tag{1}$$

$$\mathrm{MOR} = \frac{P_{max} * L}{b * h^2} \tag{2}$$

$$\tau_{\max} = \frac{3 * P_{max}}{4 * b * h} \tag{3}$$

where P_{max} is maximum bending load (N) at failure, L is span length (mm), b is width of the panel (mm), Δ is mid span deflection at applied bending load P for elastic region, and h is thickness of the panel (mm).

RESULTS AND DISCUSSION

The test results from the short-span third point bending are tabulated in Table 2. The load *vs*. deflection was plotted, and the slope from the plot was used to obtain the P/Δ ratio to compute apparent modulus of elasticity (E_{app}) in Eq. 1. Likewise, the maximum load at failure P_{max}, and the failure mechanism have been reported. The E_{app}, MOR, and τ_{max} were calculated and presented in Table 2 using Eqs. 1, 2, and 3, respectively.

Failure Mode

Failure modes observed during the short-span bending test are illustrated in Fig. 2. Sample group UD-1.5 (Fig. 2a) displayed a typical rolling shear failure in the transverse layer. Initial cracks formed at a 45° angle with the horizontal axis propagating towards the interface of the outer layer.

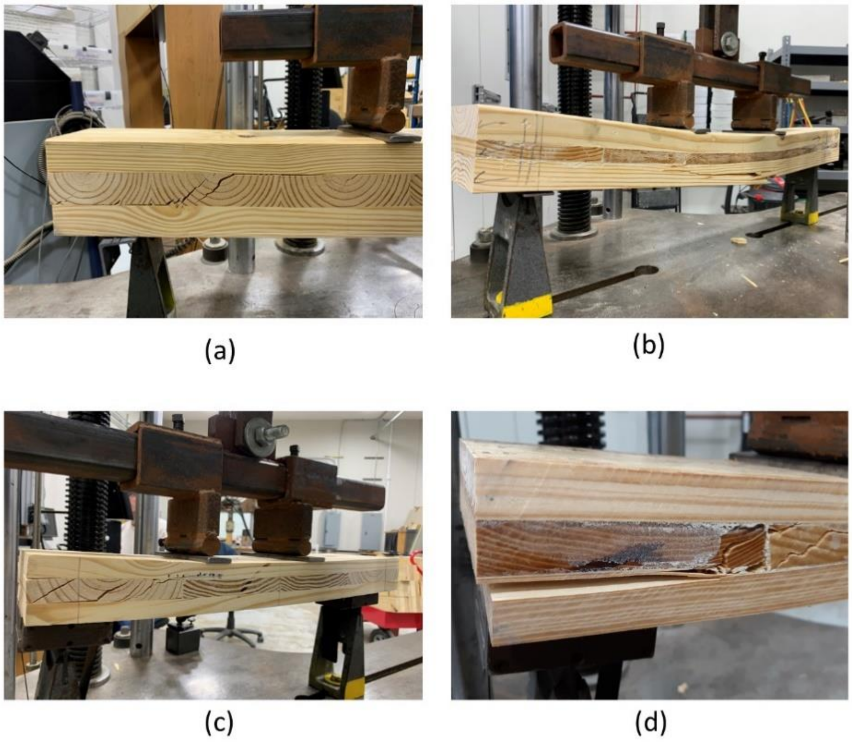

Fig. 2. Failure modes in short-span bending samples; (a) UD-1.50, (b) DM-0.75, (c) UD-0.75, and (d) DA-0.75

Table 2. Result from Third-point Short-span Bending Test

Group ID	Sub-Group	Slope P/Δ (N/mm)	P_{max} (N)	Modulus of rupture (MPa)	Apparent modulus of elasticity (MPa)	Maximum Shear Stress (MPa)	Failure Mode
DA-0.75	1	11022	64457.66	66.96	8999.64	6.22	Rolling Shear
	2	11202	72039.87	75.11	9210.97	6.95	Rolling Shear
	3	11380	62298.34	65.05	9363.07	6.03	Rolling Shear
	4	10149	74605.65	77.64	8322.26	7.20	Rolling Shear
	5	10700	74954.08	77.73	8730.09	7.21	Rolling Shear
	6	11085	70356.51	74.28	9237.61	6.87	Rolling Shear
	Mean	10923	69785.40	72.79	8977.27	6.75	
	COV	4%	7%	7%	4%	7%	
UD-0.75	1	7864.40	31265.46	30.90	5967.91	2.94	Rolling Shear
	2	6338.30	34733.47	34.63	4850.62	3.29	Rolling Shear
	3	6437.50	38595.03	37.54	4773.98	3.60	Rolling Shear
	4	7497.7	35257.36	34.84	5693.55	3.31	Rolling Shear
	5	6981.60	26565.37	26.86	5405.92	2.56	Rolling Shear
	6	7590.50	38088.66	38.29	5822.99	3.66	Rolling Shear
	Mean	7118.33	34084.20	33.84	5419.16	3.23	
	COV	8%	12%	12%	9%	12%	
DM-0.75	1	7868.7	68424.50	45.43	6353.49	4.24	Tensile Failure
	2	7612.7	79921.79	53.29	6189.34	4.96	Tensile Failure
	3	7317.1	65765.09	43.34	5860.44	4.05	Tensile Failure
	4	6615	56261.30	37.31	5337.02	3.48	Tensile Failure
	5	7969.9	61113.18	40.96	6534.29	3.80	Tensile Failure
	6	10159	49927.54	33.36	7948.99	3.10	Tensile Failure
	Mean	7923.73	63568.90	42.28	6370.60	3.94	
	COV	14%	15%	15%	13%	15%	
UD-1.5	1	8435.40	50294.34	29.34	7101.20	2.72	Rolling Shear
	2	6620.20	53550.88	30.96	5497.35	2.89	Rolling Shear
	3	8103.70	58839.45	34.32	6807.00	3.19	Rolling Shear
	4	8738.10	54719.14	31.70	7271.57	2.96	Rolling Shear
	5	7819.30	57622.08	33.68	6584.32	3.13	Rolling Shear
	6	6913.60	51058.29	29.95	5866.94	2.77	Rolling Shear
	Mean	7771.72	54347.36	31.66	6521.40	2.94	
	COV	10%	6%	6%	10%	6%	
	*UD = non-densified lumber; DM = Mid-layer densified lumber; and DA = all-layer densified lumber						

In the case of the transverse mid-layer densified group, DM-0.75, the bottom layer of CLT experienced a flexural crack, leading to a tensile failure (Fig. 2b). This indicates that densification increased the shear stress capacity of the transverse layer, causing failure to occur in the outer layer. The ultimate failure was attributed to rolling shear failure for the all-layer densified sample, DA-0.75, as shown in Fig. 2c. Cracks due to rolling shear developed at the transverse mid-layer, propagating, and causing failure. Similarly, in the non-densified samples with all layers planed, UD-0.75, shear failure was observed. Rolling shear cracks were developed in the transverse mid-layer, propagating at a 45° angle (Fig. 2d). No glue line failures (delamination) were noticed throughout the test. Although there were a few cracks close to the bond line, they were caused by the timber itself failing rather than the glue.

Effect of Densification

Densification of the transverse mid-layer decreased the overall thickness of the sample DM-0.75 compared to UD-1.50. As the short-span bending test was conducted, E_{app} was observed to be similar at 6370.60 and 6521.40 MPa for DM-0.75 and UD-1.50, respectively. The difference between these results is 2.3%, which is much lower than the variation in bending modulus of elasticity of solid wood that has been reported at 22% by the Wood Handbook (1987*)*. This shows that the small difference could be due to the inherent variation in mechanical properties of solid wood rather than densifying the mid-layer. The flexural rigidity (EI) of DM-0.75 was 38% lower than UD-1.50 because of a reduction in thickness. However, the sample DM-0.75 had increased both the maximum shear stress and MOR by 34% compared to UD-1.50. The sample DM-0.75 failed in tensile at the bottom longitudinal layer even with the increased bending stress due to smaller thickness. The densification increased the transverse layer's rolling shear strength, allowing efficient utilization of the tensile strength of the longitudinal outer layer.

Likewise, densification of all three layers and reduction in overall thickness, DA-0.75, decreased flexural rigidity (EI) by 77% compared to UD-1.50. However, the E_{app}, MOR, and maximum shear stress for sample DA-0.75 increased by 38%, 130%, and 129%, respectively, compared to UD-1.50. The occurrence of a rolling shear failure mechanism suggests that after densification, the tensile strength of the outer layer was higher and increased enough to utilize the shear capacity of densified transverse mid-layer CLT panel. When the group with the same slenderness ratio, *i.e.*, DA-0.75 and UD-0.75, are compared, DA-0.75 had increased MOR, E_{app}, and maximum shear stress by 115%, 66%, and 109% higher than UD-0.75, respectively. However, for UD-0.75, a shear failure mechanism, both in the transverse and longitudinal layer utilizing the shear capacity of all three layers, was observed.

Considering the parabolic distribution of shear stress in bending specimens, maximum shear stress happens in the mid-layer. Therefore, the average maximum shear stress of 6.75 MPa reported in Table 2 for DA-0.75 specimens could be considered as the shear capacity of densified lumber at 50% CR under bending load as these specimens failed due to rolling shear. In addition, the shear capacity of DM-0.75 and DA-0.75 was equivalent, as both had densified lumber in the mid-layer. However, the results indicate that the shear capacity of densified lumber at 50% CR had not been fully utilized by DM-0.75 specimens. The average maximum shear stress developed in these specimens was 3.94 MPa, which is lower than their actual shear capacity, 6.75 MPa. The question arises of what CR should be used to develop densified lumber with a shear capacity of 3.94 MPa. Knowing such optimized CR would make it possible to densify the mid layer of CLT enough to increase the shear capacity from 2.94 MPa for virgin lumber to 3.94 MPa, about a 34% increase, to avoid rolling shear failure and change the mode of failure to tension in the outer layer.

Pradhan *et al*. (2023) reported a linear relationship, as shown in Fig. 3, between the CR and the percentage of increment of rolling shear strength of CLT specimens submitted to the modified planar shear test. By assuming the same trend for shear strength of CLT specimens submitted to bending test in this study, a linear relation was drawn by plotting the percentage of increase in shear strength *versus* CR in Fig. 3. To plot this graph, the maximum shear stress of UD-1.50 at 0% CR (*i.e*., non-densified) and DA-0.75 at 50% CR was used, as they fully utilized the shear capacity and failed due to rolling shear. The plot presented by Pradhan *et al*. (2023) has also been added to Fig. 3. This linear graph and interpolation technique can be used to find the optimized CR to reach a 34% improvement in shear capacity. As shown in Fig. 3, densification at a CR of 13.17% will result in a 34% improvement in the shear capacity mid-layer of CLT. Likewise, using the plot provided by Pradhan *et al.* (2023), as shown in Fig. 3, the densification at 15.88% CR would result in a 34% increase in rolling shear strength. The discrepancy between these two linear graphs and estimated CR can be attributed to the testing methods and variation in lumber density between the two studies. Pradhan *et al*. (2023) used a modified planar shear test which generated pure shear in the mid-layer, while this study used a bending test which generated both normal and shear stresses in the mid-layer. In addition, Pradhan *et al.* (2023) utilized lumber with an average density of 641.00 kg/m^3, which is higher than the density employed in the current study, which was 497.66 kg/m^3. Therefore, it can be asserted that densification beyond a compression ratio of 15.88% would result in a transition of the failure mechanism from rolling shear failure to tensile failure. Similarly, in the case of sample DM-0.75, the rolling shear strength capacity had not been fully utilized, suggesting that employing an outer longitudinal layer with a higher stress capacity could maximize it.

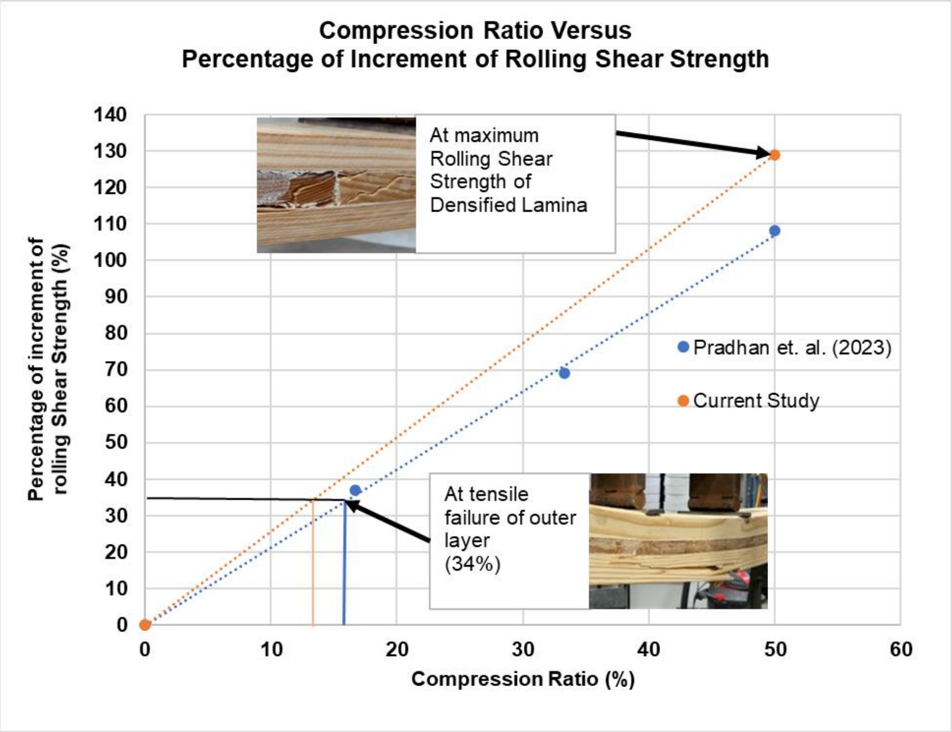

Fig. 3. Compression ratio versus percentage of increment of rolling shear strength

The findings of this study highlight the effectiveness of densification in enhancing the rolling shear strength of CLT panels made from southern yellow pine. Optimal densification levels coupled with appropriate stiffness matching across the layers can lead to improved mechanical properties and the overall performance of the CLT panels. These findings may require the assumption that the CLT has been prepared with an adhesive system that is good enough that failure will have occurred at some point within the wood.

CONCLUSIONS

1. Densification at a compression ratio of 50% in the transverse mid-layer effectively increased the mechanical properties in that critical layer and altered the failure mechanism, leading to tensile failure occurring in the longitudinal bottom layer. Because failure predominantly occurred in the longitudinal layer without significant damage in the transverse mid-layer, it suggests that the rolling shear capacity was not fully utilized.
2. To fully harness the improved rolling shear strength achieved through densification at a 50% compression ratio, it is necessary to ensure that the longitudinal layer also possesses higher strength. Increasing the density of all layers resulted in an observed rise in shear strength, accompanied by a 37% increase in the apparent modulus of elasticity when compared to the control. This emphasizes the potential benefits of thorough densification. Nevertheless, it is crucial to highlight that the reduction in thickness within densified layers led to a decrease in the moment of inertia (I), consequently causing a decline in the flexural rigidity (EI) associated with the comprehensive densification of all layers.
3. By leveraging the linear correlation between the increase in rolling shear strength and compression ratio, it is possible to achieve a rolling shear strength comparable to that of mid-layer densification at 50% compression ratio when operating at a lower densification level of 15.88%. This level of strength would be adequate to transition the failure mode from rolling shear in the mid-layer to tension in the outer layer at the bottom.

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