Influence of Laminate Twist and Clamping Pressure on Bonding Performance of Low-Grade Lumber in Cross-Laminated Timber

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Abstract

The geometric variations of low-grade lumber raise concerns about bond strength of cross-laminated timber (CLT) produced from such lumber. This study seeks to investigate the effect of low clamping pressure and geometric variations of laminates on the bond strength of CLT. CLT panels were manufactured from low-grade grand fir (*Abies grandis*). Block shear tests and cyclic delamination tests were conducted on specimens randomly taken at specific points that correspond to a wide range of twist magnitude. Twist distribution in the lumber used as laminates in the CLT ranges from 0 to 160 mm. Results showed that twist magnitude and clamping pressure have significant effect on bond performance, with twist magnitude having an overriding effect on pressure.

Cross-laminated timber (CLT) is a structural engineered wood product made by bonding crosswise layers of sawn lumber to create larger timber panels. A CLT panel's cross section typically consists of three to seven bonded layers of dimension lumber arranged orthogonally opposite to one another. CLT continues to gain popularity in the building environment for its load-bearing capacity, dimensional stability, and strength-to-weight ratio. CLT offers several advantages, including comparable mechanical properties in orthogonal directions, high levels of prefabrication, in-plane strength and stiffness, and thermal performance (Brandner et al. 2016). Because of these benefits, CLT is an acceptable and cost-effective construction material for mid- and high-rise structures. Generally, CLT is prefabricated in factories into the required panel size and can be precisely engineered for a variety of structural uses (Wang et al. 2011).

The key to a successful CLT manufacturing process involves consistent control and management of the key process variables. Some of the major process variables affecting the quality of CLT products during manufacturing are the lumber quality, adhesive type and spread rate, lamination grade, moisture content (MC), temperature, assembly time, applied pressure, and press time (Gagnon and Pirvu 2011). Investigations into the use of lower-quality materials, particularly low-grade wood material, are currently being explored by researchers (Concu et al. 2013, Sigrist and Lehmann 2014, Thomas and Buehlmann 2017, Crovella et al. 2019, Azambuja et al. 2022, Rafael da Rosa et al. 2023). The use of low-grade wood materials for CLT could decrease the cost of production and provide a high value use for nonstructural-grade and damaged lumber.

Like all glued engineered wood products, the integrity and quality of the CLT products are greatly influenced by the properties of the interfacial adhesive bond. Before gluing, the lumber's bonding faces must be planed to eliminate thickness variations, provide a smooth and fresh surface for the adhesive, and ensure that the glue joints form properly. However, there will still be geometric variation among lumber pieces because of lumber characteristics like twist, warp, density, and the presence of knots that the planing procedure cannot address. Twist in lumber results from

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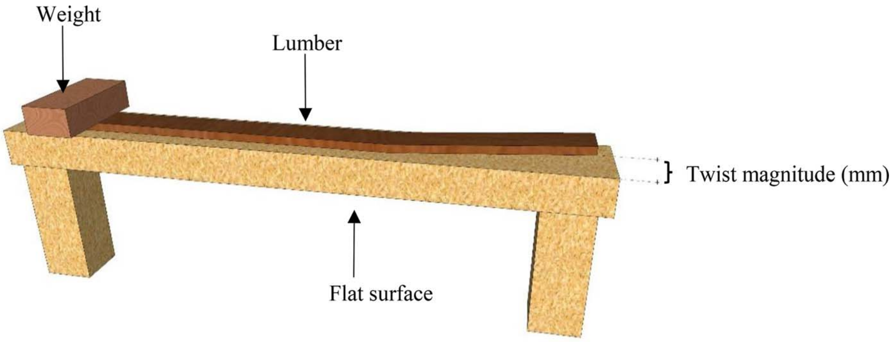

Figure 1.—Sketch of measuring the twist profile of the cross-laminated timber lamstock.

uneven swelling and shrinking in the anisotropic directions of wood. Wood shrinks and swells most in the tangential direction, less in the radial direction, and very little longitudinally (Peck 1957). The different shrinkage factors within a board cause warping due to induced tension and may result in twisted lumber.

To ensure a proper bond along each glue line, it is necessary to apply pressure to flatten the layers against one another. Bonding pressure aligns the opposing surfaces to create an intimate contact, such that after the glue is cured, a satisfactory bond is achieved. Harder, more dense wood or wood with the presence of imperfections like knots requires a higher bonding pressure to create a satisfactory bond, whereas softer wood that deforms readily or wood that is free of imperfections requires a lower bonding pressure (Lim et al. 2020).

The manufacturing of CLT panel in the United States and Canada is governed by American National Standards Institute/APA—The Engineered Wood Association (ANSI/APA PRG 320-2019; ANSI/APA 2019). ANSI/APA PRG 320-2019 is a standard that provides guidelines for the structural performance and design of CLTs. ANSI/APA PRG 320-2019 specifies the acceptable material properties, design values, and construction considerations for CLT panels, ensuring that they meet safety and performance requirements in building construction. The standard permits a degree of flexibility concerning the various manufacturing parameters associated with CLT production, including variables such as adhesive type, pressure, adhesive spread rate, and pressing duration. The standard recommends that the pressure applied to bonding laminates during CLT production should be "high enough" to ensure that bonding faces are in intimate contact. Additionally, the standard implies that other factors should be determined by the specific standards of the manufacturing facility or by an "approved agency" (ANSI/APA 2019).

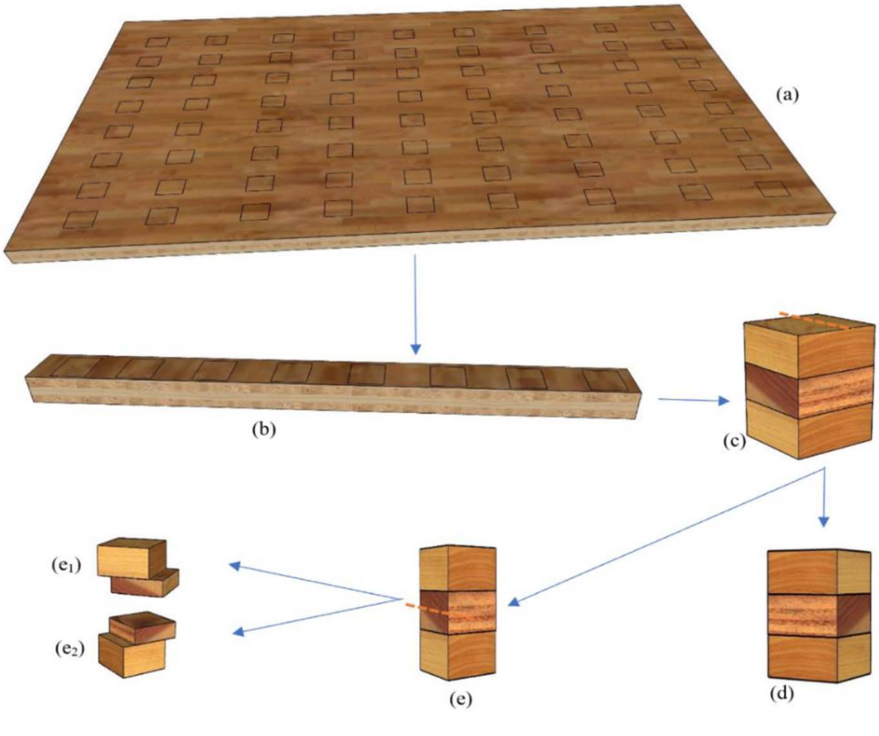

Figure 2.—Sketch of specimen cutting procedure. (a) Cross-laminated timber (CLT) panel with sample points. (b) Billet: CLT panels sawn into billets. (c) Block (150 by 150 by 105 mm): billets crosscut into blocks of sample points. (d) Cyclic delamination specimen (76.2 by 76.2 by 105 mm). (e) Shear specimen (50.8 by 50.8 by 52 mm).

Table 1.—Sample size of test specimens.

	Sample size (*N*)	
	Delamination (%)	Wood failure (%)
CLT 1[a]	140	128
CLT 2	162	134
CLT 3	132	95

[a] CLT = cross-laminated timber. CLT 1, CLT 2, and CLT 3 = CLT panels manufactured with vertical clamping pressure of 0.03, 0.14, and 0.28 N/mm^2 respectively.

There have been debates on the amount of pressure that is high enough to ensure effective bonding of laminate in CLT production (Sharifnia and Hindman 2017, Santos et al. 2019, Brunetti et al. 2020). The amount of pressure required is influenced by variables such as type of press and adhesive type. The two types of presses commonly used in CLT production are the hydraulic press and the vacuum press (Gagnon and Crespell 2010). A hydraulic press has rigid plates and can generate high vertical pressures, whereas the vacuum press has a flexible membrane that generates lower pressure and exploits the vacuum to favor the penetration of the adhesives inside the wood. The prevailing adhesive types in the CLT industry are polyurethane resins (PUR) and melamine–urea–formaldehyde resins. Phenolic resins and emulsion polymer isocyanate are also suitable for CLT (Wang et al. 2011). However, because of concerns regarding formaldehyde's carcinogenic properties, PUR remains the most widely used adhesive because of its formaldehyde-free composition (Gagnon and Crespell 2010).

Adhesive manufacturers often provide manufacturing guidance on optimum bonding pressure and this is usually in different ranges for hydraulic press and vacuum press. The recommended bonding pressure for the one-component PUR used in this study under hydraulic press is usually between 0.55 and 0.83 N/mm^2. However, Silva do Carmo et al. (2022) suggest that bonding pressure of 0.28 N/mm^2 is sufficient to produce effective bonding when low-quality laminates with significant distortions are used in CLT manufacturing. This present study seeks to investigate the effect of clamping pressure and geometric variations of laminates from low-quality grand fir (*Abies grandis*) lumber on bond strength of CLT. The objectives of this study are to examine the impact of low clamping pressure on the bond strength of CLT panels manufactured using low-grade lumber; determine how twist magnitude influences the bond strength of CLT panels produced using low-grade lumber; and examine the relationship between twist magnitude and clamping pressure on bond performance, with a focus on understanding how these variables interact and influence bond strength. This study hypothesizes that low clamping pressure and the presence of twist in laminate does not affect bond strength of CLT. The findings of this study offer valuable insights into understanding the implications of twist and clamping pressure on bond quality in CLT panels that utilize low-grade lumber.

Materials and Methods

Materials

Grand fir boards with dimensions of 38 mm thick, 140 mm wide, and 3.66 m long were supplied by Idaho Forest Group (Lewiston, Idaho, USA) as raw material for this study. The lumber used in this study is regarded as low grade because it is of lower quality than structural-grade timber No. 3 and does not meet the minimum required grade recommended by ANSI/APA PRG 320-2019 (ANSI/APA 2019). PRG 320-2019 requires that minimum structural-grade timber No. 2 is used in longitudinal direction and minimum grade No. 3 is used in the transverse direction to make commercial CLT (Gagnon and Pirvu 2011). Boards were conditioned in a conditioning room (65% relative humidity [RH], 18°C) for 4 weeks to reach average equilibrium MC of 12 percent (ovendry method) before CLT fabrication. The adhesive used in this research was a single-component PUR (1C PUR) from Henkel (Purbond HBX 602), manufactured and certified for structural load-bearing applications. The 1C PUR adhesives used in this study require the MC of wood to be above a certain threshold for a complete curing process (Lehringer and Gabriel, 2014). The MC of the board was kept at 12 percent, which aligns with the recommended range for 1C PUR.

Twist profiling

The magnitude of twist present in individual pieces of lumber used as laminates in CLT production was measured

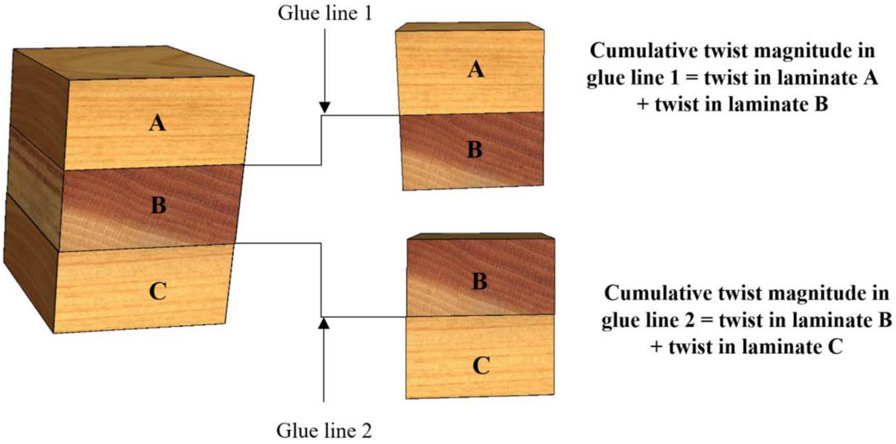

Figure 3.—Estimation of cumulative twist magnitude between glued layers.

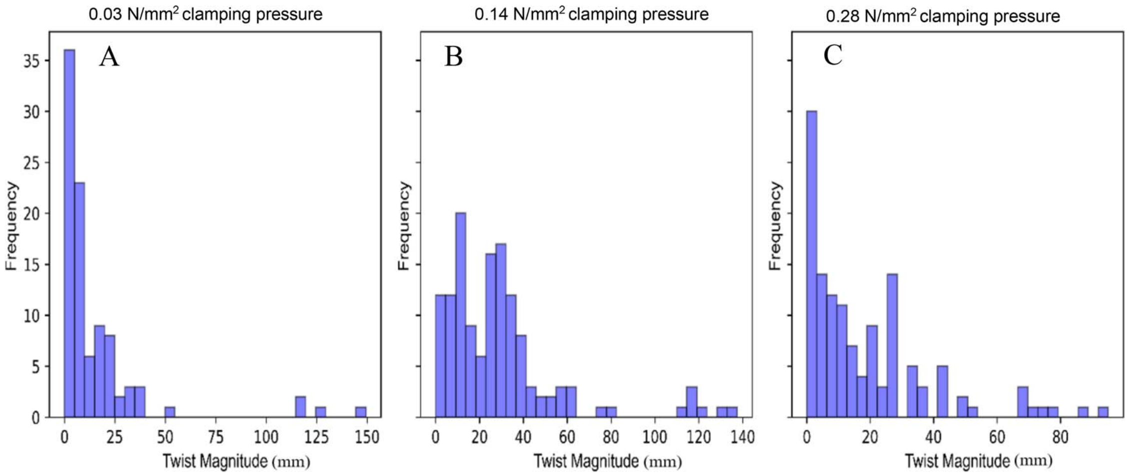

Figure 4.—Distribution of twist magnitude in selected specimens from (A) cross-laminated timber (CLT) 1 (0.03 N/mm^2 clamping pressure), (B) CLT 2 (0.14 N/mm^2 clamping pressure), and (C) CLT 3 (0.28 N/mm^2 clamping pressure).

by placing the lumber on a warpage platform as shown in Figure 1. The lumber is weighed down on one end while the deviation of the opposite end from the flat surface is measured. Twist magnitude is quantified by the extent to which the other end deviates above the level of the flat warpage platform. This deviation is then precisely measured using a caliper positioned at the other end of the lumber. The twist present in individual lumber used in this study ranges from 0 to 83 mm. Twist profiling was conducted before planing to replicate conditions achievable in the manufacturing plant. Laminates must be glued within 24 hours of planing. Planing and the application of adhesive primer were usually integrated into a single-line process in many instances. It is important to note that planing cannot eradicate geometric variations such as twist, warp, density, and the presence of knots. However, it is executed to eliminate thickness variation and ensure a smooth, fresh surface for the adhesive.

CLT panel production

Three-ply CLT panels were fabricated using the 1C PUR glue. In the process of fabricating the CLT panels, the laminae were selected at random from the stack of twist-profiled boards without any randomization scheme. Before the adhesive application, the laminae were planed to uniform dimensions of 35 mm thick, 135 mm wide, and 3,660 mm long with a four-sided knife planer to achieve a dimension variation <0.2 mm in width and <0.3 mm in longitudinal directions, respectively per PRG 320. Loctite PR3105 primer (10% weight per weight concentration in water) was then applied on the basis of the recommendation of the adhesive manufacturer at the rate of 20 g/m^2. The longitudinal laminates that made up the first tier of the CLT were laid up on the glue spreader for adhesive application after a minimum of 15 minutes of primer application. A bead coating technique was used to apply the liquid glue over the primed boards at an average spread rate of 171 g/m^2 and 10 mm in distance among each bead line. Transverse laminates were then laid orthogonally on the first ply and adhesive was applied before the third ply of the CLT was laid using longitudinal laminates. The layup is thereafter transferred into a hydraulic press and clamped together under a predetermined vertical pressure and a constant side pressure of 0.35 N/mm^2. Vertical clamping pressures of 0.03, 0.14, and 0.28 N/mm^2 were used to create three CLT panels referred to hereafter as CLT 1, CLT 2, and CLT 3, respectively.

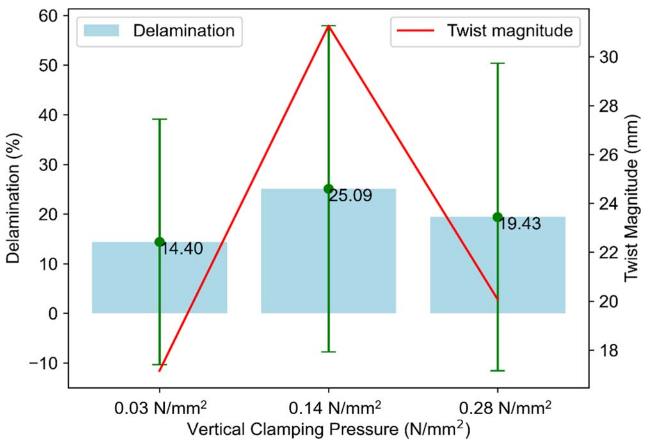

Figure 5.—Mean percent delamination and twist magnitude by pressure. Green error bars display standard deviation.

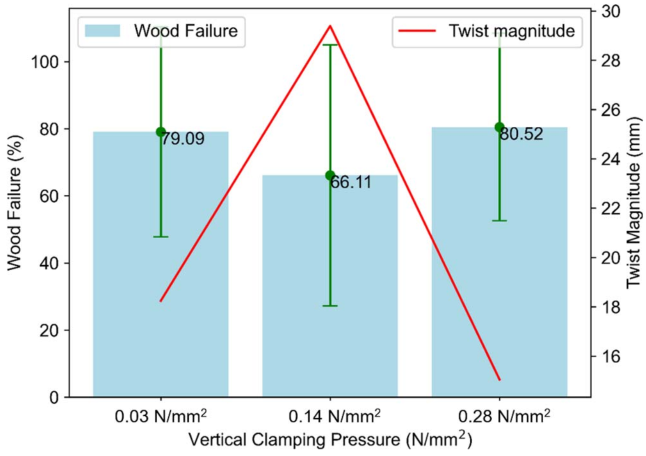

Figure 6.—Mean percent wood failure and twist magnitude by pressure. Green error bars display standard deviation.

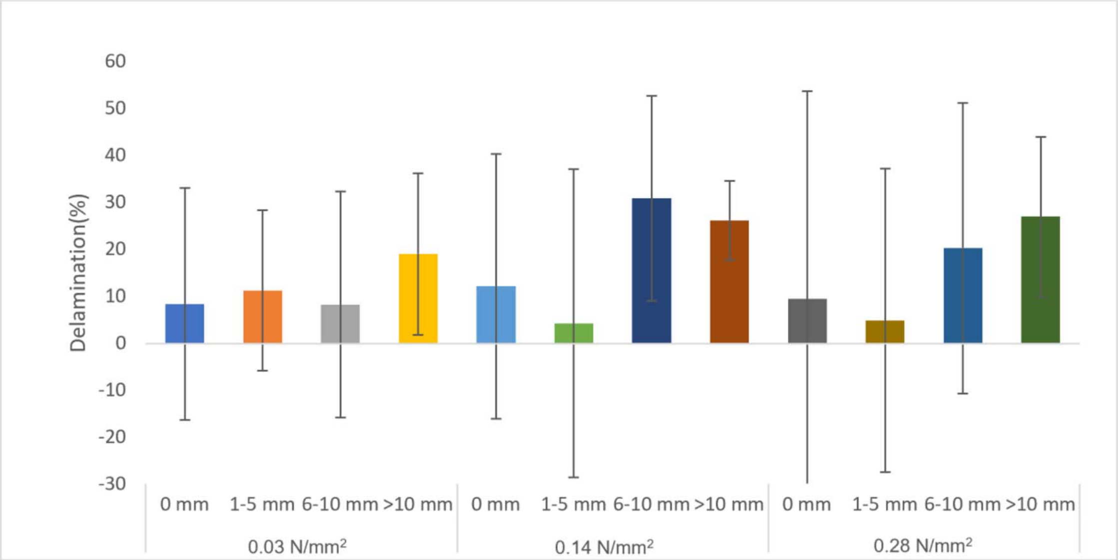

Figure 7.—Mean percent delamination at different categories of twist magnitude and levels of clamping pressure. Black error bars display standard deviation.

Specimen cutting

Specimens were taken randomly from the three CLT panels with dimensions of 1,828 by 3,658 mm 105 mm for each level of clamping pressure for block shear and cyclic delamination testing procedures in accordance to the American Institute of Timber Construction (AITC) tests (AITC 2007), specifically AITC test T107 for block shear and AITC test T110 for cyclic delamination. Eighty-five blocks of specimens were taken at random positions from each CLT panel. These random positions corresponded to a wide range of twist magnitude spanning from 0 to 160 mm (Fig. 2). From each of these blocks, two glue-line specimens were extracted, resulting in a targeted sample size of 170 glue-line specimens for each CLT panel. However, specimens were eliminated before testing because of the presence of knots, obvious interlammelar gaps, and damage in some samples. The finalized sample size of the specimens tested and results used for data analysis are presented in Table 1.

Estimation of cumulative twist magnitude of sample blocks

Each specimen block contains two glue lines that bond two cross layers of laminate together. Each individual glue line is treated as a separate specimen. Cumulative twist magnitude of the glued layer is estimated as the summation of twist magnitude of each individual laminate that shares the same glue line (Fig. 3). In Figure 3, the twists in laminate A and laminate B were measured during the initial profiling of each lumber sample. Thus in the glue-line specimens (comprising laminate A and laminate B) the cumulative twist magnitude of the glued layer was estimated by adding the twist magnitudes of individual laminates that shared the same glue line.

Testing procedures

Cyclic delamination test.—A cyclic delamination test was performed following the procedure outline in AITC T110

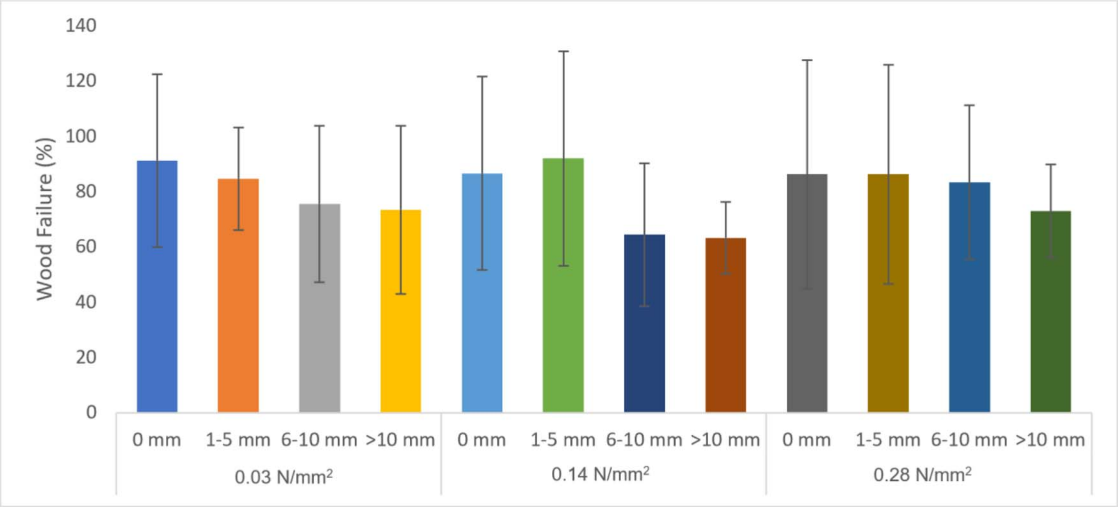

Figure 8.—Mean percent wood failure at different categories of twist magnitude and levels of clamping pressure. Black error bars display standard deviation.

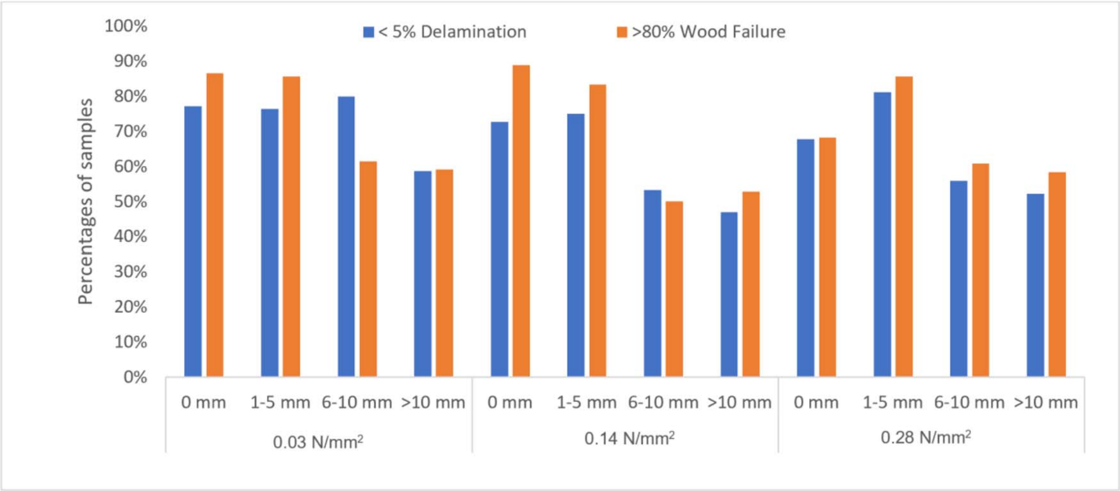

Figure 9.—Proportion of specimens with >80 percent wood failure and <5 percent delamination.

(AITC 2007) as used by Silva do Carmo et al. (2023). Before testing, the specimens were cut to 76.2 by 76.2 by 105-mm blocks and conditioned at 25°C and 65% RH for 7 days. The initial weight of the specimen was taken and recorded before placing the specimen in a pressure vessel. The specimens were weighted down and covered with water at a temperature of 20°C ± 2°C. A vacuum of 640 mmHg was drawn and held for 30 minutes before the vacuum was released and a pressure of 520 kPa was applied for 2 hours. The specimens were removed from the pressure vessel and dried in an oven with convective air circulation at a temperature of 71°C until their weight was about 110 to 115 percent of their original weight. After drying, the specimens were removed, delamination measured, and recorded immediately (AITC 2007).

Block shear test.—The block shear test was carried out in accordance with AITC test T107 and ASTM D905 (AITC 2007, ASTM 2021). Shear specimens of 50.8 by 50.8 by 52 mm were taken from each sample to determine bond line strength and percentage of wood failure. The specimens were placed in a shear test apparatus so that the vertical load was applied in the direction of the grain for the timber on one side of the glue line and perpendicular to the grain for the timber on the other side of the glue line. The vertical load was applied by a load cell that had been calibrated before testing at a constant rate of 12.7 mm/min to ensure that failure occurred after roughly 20 seconds. After each test, the wood failure was visually estimated and expressed as a percentage of the sheared area.

Data analysis

The means and standard deviations of percent delamination and percent wood failure were presented in bar graphs; the values for individual specimens were plotted on a scatterplot at the three different levels of clamping pressure to show the performance of each individual specimen. To assess the quality of the bonding, a pass/fail evaluation was conducted for the percent delamination and percent wood failure results according to the requirements of PRG 320-2019, with ≤5 percent being pass criteria for delamination and ≥80 percent the pass criteria for wood failure. Finally, the effect of clamping pressure and twist magnitude on bonding performance was determined. To do this, the data obtained were subjected to a normality check with the Shapiro-Wilk normality test (Ghasemi and Zahediasl 2012), and the Levene test was also conducted to check for the homogeneity of variances involved (Kim and Cribbie 2018). The test revealed that assumptions of normality and assumptions of homogeneity of variances were not reasonable; hence a nonparametric alternative to analyses of variances, the Kruskal-Wallis test, was conducted to investigate the association between the factors (pressure and twist magnitude) on the response variables (percent delamination and percent wood failure). Dwass-Steel-Critchlow-Fligner (DSCF) multiple comparisons post hoc procedure was performed to determine which pairs of vertical clamp pressure and twist category differ.

Results and Discussion

The distribution of twist magnitude in the selected specimens is presented in Figure 4. The presented results indicate dissimilarity in the twist magnitude distribution among the CLT panels. This dissimilarity can be attributed to the random selection of lamstock for each CLT panel, irrespective of the initially established twist magnitude. The results

Table 2.—Kruskal-Wallis test.

	% Delamination			% Wood failure		
	Krukal-Wallis *H*	df	*P* value	Krukal-Wallis *H*	df	*P* value
Pressure	9.8675	2	0.0072*	11.9830	2	0.0025*
Twist magnitude	20.8042	3	0.0001*	16.3239	3	0.0010*

* Significant at $P < 0.05$.

revealed that most specimens taken from CLT 1 (vertical clamping pressure 0.03 N/mm^2) and CLT 3 (vertical clamping pressure 0.28 N/mm^2) had twist deflections between 0 and 15 mm, whereas the distribution of twist magnitude of specimens taken from CLT 2 (vertical clamping pressure 0.14 N/mm^2) was spread between 0 and 50 mm.

Figure 5 illustrates the average percent delamination and averaged twist magnitude in the CLT manufactured at different vertical clamping pressures. From this data, the averaged delamination and twist magnitude follow the same trend. As twist magnitude increases, percent delamination also increases, independent from the overall clamping pressure applied.

Delamination is an important indicator to evaluate bonding properties other than shear bond strength and wood failure. Delamination is generated by the internal shear stress between the bonded surfaces, resulting in swelling and shrinkage (Sikora et al. 2016). In the cyclic delamination test, swelling and shrinkage are deliberately induced in CLT specimens to assess bond performance. The relationship that was observed in Figure 5 might mean that the induced swelling and shrinkage during the cyclic delamination test amplifies the internal stress of twist that is already present in the laminates. Separation of the layers then took place at the interface because of the inability of the adhesive to hold and keep twisted laminates in close surface contact with the adjacent laminate. The average percentage of wood failure and average twist magnitude in CLT produced at various vertical clamping pressures are shown in Figure 6. The bar chart shows an inverse relation between twist magnitude and wood failure. Aicher et al. (2018) stated that in any glued assemblies, the evaluation of bonding strength is based on both the shear bond strength and percentage of wood failure. A good bonding is usually followed by high shear and high percentage of wood failure. Silva do Carmo et al. (2023) pointed out with a discretization analysis that wood with twist generates both negative and positive pressures, and that the negative pressures lead the lumber away from the flat condition. The negative pressures developed have the potential to prevent the lumber from being in close enough contact with the other lamstock layers, thereby reducing the effective bond area. A high amount of twist in lumber would affect the bonding quality of the laminated product, since a higher amount of pressure is required to negate the influence of the negative pressure of the twist.

Results in Figures 5 and 6 also revealed that the highest bond performance is seen in CLT produced at 0.03 N/mm^2, followed by panels produced at 0.28 and 0.14 N/mm^2 (lowest bond performance). Figures 7 and 8 present the mean delamination and mean percent wood failure values at various twist categories and different levels of clamping pressure. It can be deduced from the plot that specimens that are within the twist category of 0 mm and 1 to 5 mm have mean wood failure of >80 percent for the three levels of clamping pressure. Specimens having >10 mm twist magnitude exhibit the poorest adhesive bond performance at all levels of clamping pressure.

Table 3.—Pairwise comparison of the effect of clamping pressure on percent delamination and percent wood failure.

Vertical clamping pressure	DSCF[a] *P* value Delamination (%)	Wood Failure (%)
0.28 N/mm^2 vs. 0.14 N/mm^2	0.2274	0.0459*
0.28 N/mm^2 vs. 0.03 N/mm^2	0.3743	0.6997
0.14 N/mm^2 vs. 0.03 N/mm^2	0.0048*	0.0030*

* Pairs with *P* value < 0.05 are significantly different.

[a] DSCF = Dwass-Steel-Critchlow-Fligner two-sided *P* value for each paired comparison.

The standard deviation indicated by the error bars in Figures 5 through 8 also shows that there is a high degree of variability in the reported percent delamination and wood failure. This suggests that apart from twist magnitude, other out-of-plane defects such as cup and bow may have influenced the bond performance of the manufactured CLT panels and glue-line failure is amplified by superposition of several defects. This present study only analyzed twist magnitude as a contributory defect to glue-line failure.

For CLT to meet the requirement for structural performance, the average failure in the wood should be >80 percent when subjected to block shear test, and delamination should be <5 percent after a cyclic delamination test. Figure 9 presents the percentage of specimens with >80 percent wood failure after the block shear test and percentage of specimens with <5 percent delamination after the cyclic delamination procedure. The results revealed that at high levels of twist magnitude, fewer specimens meet the requirement of >80 percent wood failure and <5 percent delamination.

This finding aligns with Sikora et al. (2016), who noted that higher bonding pressures results in deeper adhesive penetration and enhanced bond durability of 1C PUR on wood substrate. Conversely, lower pressures may struggle to adequately compress and maintain intimate contact in twisted laminates, potentially leading to shallower penetration and the formation of a thick glue line, contributing to suboptimal bond quality.

The penetration of adhesive into the wood cell structure involves both gross and cell wall penetration. Gross penetration occurs through the forcing of adhesive into the cell lumina during compression clamping, whereas cell wall penetration involves the diffusion of adhesive into the cell walls because of the interaction of charged elements in the adhesive and wood striving to achieve a state of neutrality (Kamke and Lee 2007). It is crucial to note that both gross and cell wall penetration occur only when bonding surfaces are in intimate contact, underscoring the significance of

Table 4.—Pairwise comparison of the effect of twist categories on percent delamination and percent wood failure.

Twist magnitude categories	DSCF[a] *P* value Delamination (%)	Wood failure (%)
0 mm vs. 1–5 mm	0.8526	0.9
0 mm vs. 6–10 mm	0.3181	0.1323
0 mm vs. >10 mm	0.0020*	0.0015*
1–5 mm vs. 6–10 mm	0.1588	0.5599
1–5 mm vs. >10 mm	0.0058*	0.1271
6–10 mm vs. >10 mm	0.7359	0.7057

* Pairs with *P* value < 0.05 are significantly different.

[a] DSCF = Dwass-Steel-Critchlow-Fligner two-sided *P* value for each paired comparison.

clamping pressure in determining adhesive penetration quality and, consequently, bond performance.

Sikora et al. (2016) highlighted the PUR adhesive manufacturer's recommendation of a pressing pressure range of 0.6 to 1 N/mm^2 for softwoods, with 1 N/mm^2 yielding the most durable bonds. However, they observed that a lower clamping pressure of 0.4 N/mm^2 was sufficient to meet the EN 16351 (CEN, 2015) shear strength requirements for Irish sitka spruce. This reinforces the variability in optimal clamping pressures. In a related study, Liao et al. (2017) demonstrated that higher pressing pressures facilitated increased adhesive penetration of 1C PUR into the wood substrate, resulting in improved bonding strength. These findings collectively emphasize the nuanced relationship between clamping pressure and adhesive penetration, influencing the overall performance and durability of bonded materials.

The Kruskal-Wallis test was conducted to examine the differences in percent delamination and percent wood failure according to the level of vertical clamping pressure and magnitude of twist. Results are presented in Table 2. Significant differences were found among at least two groups of three levels of vertical clamp pressure and five categories of twist magnitude. However, the Kruskal-Wallis test is unable to provide an indication of which groups are different without also performing post hoc tests. The DSCF multiple comparisons post hoc procedure was performed to determine which pairs of vertical clamp pressure and twist category differ. Results from the DSCF analysis (Tables 3 and 4) revealed that significant differences between pairs of vertical clamp pressure do not follow any definitive pattern. However, significant differences between pairs of twist magnitude are only found in pairs farther from each other. As such the Kruskal-Wallis test and DSCF analysis imply that although both pressure and twist magnitude significantly influence the bonding performance of CLT produced from low-grade lumber, twist magnitude has a dominating effect on bond performance.

Conclusions

The findings of this study provide significant insights into the influence of laminate twist and clamping pressure on the bond performance of CLT manufactured from low-grade lumber. Contrary to the hypothesis positing that low clamping pressure and the presence of twist in the laminate do not affect the bond strength of CLT, the results indicate that clamping pressure and twist magnitude influence bond performance. The study reveals that at low clamping pressure, twist magnitude has an overriding effect on bond strength, with a decrease in bond performance corresponding to an increase in twist magnitude. Significant differences were observed in bond performance between twist magnitudes of 0 mm and 11 to 20 mm, as well as 0 mm and >20 mm. Twist magnitudes <5 mm demonstrated a lower percentage of delamination and a higher percentage of wood failure. It can therefore be concluded that clamping pressure of $\leq$0.28 N/mm^2 may only be sufficient to produce CLT if the twist magnitude in the laminate is <5 mm. This outcome of this study underscores the importance of considering both clamping pressure and twist magnitude in optimizing the bond quality of CLT panels, offering valuable guidance for future manufacturing practices in the utilization of low-grade lumber.

Limitations of the study

The study acknowledges specific limitations that should be considered when interpreting the findings. The selection of lamellae used to produce CLT panels was done randomly, without consideration of the amount of twist present, resulting in a dissimilar distribution of twist magnitude among the three CLT panels. Despite the utilization of DSCF statistical analysis, the limited sample size of only three panels without repetitions poses a challenge to the robustness and generalizability of the results. Moreover, the elimination of samples with knots at locations of high twist magnitude may introduce bias, and the exclusion of these samples could affect the overall understanding of bond quality in CLT panels. Last, the absence of replications in the experimental design emphasizes the need for cautious interpretation, and the study suggests that future research with a more extensive data set is warranted to strengthen the validity of conclusions.

Acknowledgments

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