Performance of Polyurethane Adhesive in Hardwood Cross-Laminated Timber

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As hardwood cross-laminated timber (CLT) gains attention due to its construction potential, understanding the interaction between hardwood panels and adhesives is critical for ensuring structural integrity and longevity of buildings. This study investigated adhesive bonding properties in hardwood CLT made from red oak (*Quercus* spp. L.), sweet gum (*Liquidambar styraciflua* L.), and yellow poplar (*Liriodendron tulipifera* L.), using southern pine (*Pinus* spp. L.) (SP) as a control. Adhesive performance was evaluated through shear block tests to assess the bond line shear strength and delamination tests to measure the bond durability under cyclic moisture conditions. Results indicated significant variations in adhesive performance among the hardwood CLT specimens compared to SP, with differences in both shear strength and delamination resistance. Red oak CLT exhibited significantly greater delamination compared to all the other species. The delamination observed among the yellow poplar samples was not significantly different than that of the control SP samples. The shear block results indicated that the bond line strength of both red oak and yellow poplar samples was significantly greater than that of the control samples. These findings provide critical insights into selecting and optimizing adhesives for hardwood CLT production.

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INTRODUCTION

For decades, wood has been the preferred construction material because of its affordability, sustainability, abundance, and weight to strength ratio (Panshin and de Zeeuw 1970; Ratnasingam *et al.* 2018). Although wood is an excellent building material, its heterogenous and anisotropic nature can pose challenges related to use and service life. Engineered wood products have been designed to contend with the underlying variability of wood. These products are unique in the sense that they demonstrate improved mechanical properties and a more uniform nature in terms of performance (Cai and Ross 2010). These products are also beneficial because they provide a new market for low-value logs that could not be used to produce solid sawn lumber. Examples of successful engineered wood products, primarily fabricated with softwoods, include oriented strand board (OSB), medium density fiberboard (MDF), laminated timber, more commonly known as glulam, and cross laminated timber (CLT), which is considered one of the more recent engineered wood products. To configure CLT panels, the boards are glued alongside each other to form a single layer. These layers are then glued together at a 90-degree angle to one another. This alternating orientation of the layers is intended to improve the mechanical strength properties of the overall CLT product (Lehmann 2012).

There is general agreement that the amount of low-quality timber, encompassing both hardwood and softwood, that is currently available for harvest in the U.S. is greater than can be consumed by traditional markets (Laguarda Mallo and Espinoza 2015). However, the quality of individual boards is not as important when used in CLT as it is in other solid sawn timber building components because it is composed of smaller pieces that are bonded together (Laguarda Mallo and Espinoza 2015; Brandner *et al.* 2016). The possibility of substituting these lower value hardwood materials for traditional softwood materials at economically advantageous rates will help to offset higher forest management expenses due to increased demand from newly established markets, such as CLT. The utilization of hardwoods in the production of CLT has gained significant attention in recent years. Hardwood lumber manufacturers view this as an opportunity to develop new markets for hardwood lumber. However, profitability is a major concern when entering a new market (Adhikari *et al.* 2020).

Despite the promising attributes of using hardwoods in CLT production, several challenges persist. Typically, hardwoods are used for non-structural purposes and are usually graded based on appearance, which poses a challenge for CLT panel manufacturing since knowing the mechanical properties of the lumber is of high importance if it is to be used for structural purposes. Hardwood grades include First and Seconds (FAS), Select, and Common, whereas, softwoods are often graded for structural integrity, making them more suitable for load-bearing purposes. Softwood grades include No. 1, No. 2 and No. 3. Economic considerations provided by Hassler *et al.* (2022) indicated that it would be more economical to incorporate hardwoods of grade No. 2A and below into CLT manufacturing. Another challenge is related to dimensional size. Typically, hardwoods are produced in random lengths and widths, with sizes usually specified as 4/4, 6/4, 8/4, *etc.* which denotes 1-inch, 1 ½ inch and 2 inches, respectively. In contrast, softwoods are generally available in standardized sizes, such as 2x4 in and 2x6 in. Currently, railroad ties and pallet cants are the only “standard-size” materials that are produced at hardwood sawmills (Hassler *et al.* 2022).

Apart from grading and sizing challenges, the moisture content (MC) of hardwood boards must be taken into consideration. For furniture and cabinetry markets, hardwood lumber is typically dried to 6 to 8% MC (Bergman 2010). For the purposes of CLT panel products, hardwood sawmills must adjust their drying schedules and kiln operations to achieve a higher MC of 12 to 15% (Wang and Simpson 2020). Considering that the required MC for structural application is higher, this factor could potentially reduce the cost of kiln-drying for hardwood sawmills depending on the length of drying time required.

One of the primary challenges associated with adhesive bonding of hardwoods is their anatomical structure. Hardwoods typically have a more complex and variable cellular structure than softwoods, including a higher density of fibers, vessels, and pores (Frihart 2005). This complexity can lead to uneven adhesive penetration and distribution, potentially resulting in weak bond lines and reduced shear strength (River 2003). Furthermore, hardwoods often have a higher extractive content, such as tannins, oils, and resins, which can interfere with adhesive curing and bonding (Yoshimoto 1989). These extractives can cause adhesive failure over time, particularly when exposed to fluctuations in moisture and/or temperature.

Moisture content and swelling behavior further complicate adhesive bonding in hardwoods. Hardwoods generally have higher density and lower permeability than softwoods, which can slow down the drying process and lead to moisture retention in the wood (Shmulsky and Jones 2019). Retained moisture can adversely affect adhesive bond strength and durability because many adhesives used in the fabrication of engineered wood products are sensitive to moisture and excess moisture can disrupt the curing process, preventing the adhesive from forming a strong bond (Kamke and Lee 2007). Additionally, the differential swelling and shrinkage of hardwoods when exposed to varying humidity levels can induce stresses at the bond line, promoting delamination and adhesive failure (Frihart 2005).

Another critical factor influencing the adhesive bonding of hardwoods is surface preparation. Due to the harder and denser nature of hardwoods, achieving an optimal surface roughness for bonding can be more challenging than with softwoods (Dunky 2018). Insufficient surface preparation can lead to poor adhesive penetration and weak bonds (Knorz *et al.* 2015). Furthermore, the compatibility between adhesive type and hardwood species is a significant concern. Some adhesives that perform well with softwoods may not be effective for bonding hardwoods due to differences in surface energy and chemical composition, necessitating the development of specialized adhesives or bonding techniques for hardwood CLT (Bockel *et al.* 2019).

To address these challenges, further research is needed focusing on hardwood species-adhesive interactions (Mendoza *et al.* 2012). While some progress has been made in identifying suitable adhesives and optimizing bonding processes, there is still a significant gap in knowledge regarding the long-term performance of hardwood CLT, particularly under cyclic moisture conditions and varying environmental stresses (Wang *et al.* 2018). Addressing these challenges is essential for advancing the use of hardwoods in CLT production and expanding their application in sustainable construction.

For this study, adhesive bond properties of CLT made from low-grade red oak (*Quercus* spp. L.), yellow poplar (*Liriodendron tulipifera* L.), and sweet gum (*Liquidambar styraciflua* L.) were evaluated *via* shear and delamination tests. These species were selected due to their diverse density profiles, potential for use in structural applications, and availability of material. Red oak, known for its high density and strength, was chosen to explore bonding challenges associated with denser hardwoods. Yellow poplar, with a medium density, represents a more moderate option, offering a balance between workability and strength. Sweet gum, another hardwood with a similar density to yellow poplar, was included to compare species with similar densities but different anatomical features including but not limited to vessel characteristics, grain orientation and texture. Southern pine (*Pinus* spp.) (SP), a commonly used softwood in CLT production, served as a control due to its lower density and established adhesive performance. By comparing these different wood species, this study aimed to provide insight into how density and anatomical differences affect adhesive performance in hardwood CLT. Results from this research will help to inform the development of more efficient bonding techniques and material selection criteria for future hardwood CLT applications.

For this work, a polyurethane (PUR) adhesive was chosen because of its versatility and suitability for a broad range of applications, as highlighted by Lay *et al.* (2018). One component PUR adhesives can be formulated to provide structural integrity under limited exterior conditions, meaning they can withstand short-term water exposure but have limited resistance to prolonged and repeated wetting and drying cycles. This makes them appropriate for certain structural applications where full exterior exposure is not a primary concern. However, with the addition of primers and/or proper surface preparation, the water resistance of these adhesives can be significantly enhanced, making them more suitable for applications with higher moisture exposure. Polyurethane adhesives are known for their highly durable adhesive films, which provide high dry and wet strength and are resistant to water and damp atmospheres; however, their water resistance is highly dependent on the specific formulation and application. Additionally, they possess gap-filling properties, which is beneficial when bonding uneven or rough surfaces, a common challenge with hardwoods (Hassler *et al.* 2022). Polyurethane adhesives also cure well at room temperature and are less sensitive to moisture content of wood, making them easier to use in a variety of environments (Frihart 2005). This characteristic allows them to perform better at higher moisture contents, reducing the risk of bonding failures associated with improper moisture levels. Furthermore, PUR adhesives are among the simplest to use because there is no need for mixing components, minimizing the potential for preparation errors in adhesive application (Frihart and Hunt 2010). These properties make polyurethane adhesives a practical choice for the fabrication of CLT in hardwoods, where variations in wood density and moisture content can complicate the bonding process. These findings have significant implications for expanding the use of hardwoods in sustainable construction, potentially enhancing the structural capabilities and marketability of CLT products.

EXPERIMENTAL

Panel Preparation

Prefabricated, three-ply CLT panels consisting of either sweet gum, yellow poplar, red oak, or SP lumber were used for this study. The hardwood lumber, which was used to manufacture the panels, was obtained from the southeastern United States. The hardwood boards for each species were processed into lengths of 213 cm and 244 cm before being visually graded in accordance with the National Hardwood Lumber Association (NHLA) grading system (NHLA 2019). The SP CLT panels were acquired from a commercial CLT producer.

The boards were conditioned for 30 days at an approximate relative humidity (RH) of 65 to 85% and a temperature between 27 and 37 °C to obtain a moisture content of approximately 12%. The 244 cm boards of each hardwood species were used for the core and the 213 cm boards were used for the outside layers of the three-ply panels. All boards for each of the hardwood species were manufactured into panels with dimensions of 244 x 152 x 11 cm (LxWxT).

The adhesive used in the production of the panels was a one-component polyurethane (PUR) resin supplied by Henkel Corporation (Bridgewater, NJ), namely, LOCTITE UR 5151. This adhesive is a one-component, solvent-free, moisture-curing polyurethane (PUR) hot melt adhesive designed for high-performance bonding applications. It has a viscosity of approximately 5,000 cps at application temperature and is composed of isocyanate-terminated prepolymers that react with moisture to form strong, durable bonds (Henkel Corporation 2020; Richelieu, n.d.). The adhesive was applied at a spread rate of 165 g/m^2. The three-layered panels were cold pressed under 689.5 kPa atm of hydraulic pressure for 1.5 h according to the manufacturers' guidelines. Curing time was conducted according to the adhesive manufacturer, which was achieved after 25 min at ~ 20 °C and 65% RH (Henkel Corporation 2020). The fabricated panels were stored indoors in a humidity-controlled environment (conditioned to 12% equilibrium moisture content) for an additional 90 days before being further processed into the various dimensions used in this study. Additional details on panel preparation are presented in Omotayo *et al.* (2024). These panels were then stripped and planed into the dimensions 213 x 15 x 9 cm (LxWxT) and samples for both delamination and shear block tests were then cut from these panels (exact dimensions are given in the following sections).

Moisture Content Measurements

The initial weights of the samples for all species were recorded before they were placed into an oven at 40 °C for approximately two weeks. This low temperature was selected to prevent defects such as warping, cracking, or splitting of the samples during the drying process. The weights of the samples were taken regularly, and the samples were removed from the oven once reaching a constant weight. The moisture content (*MC*) of the samples was then calculated based on the recorded measurements according to Eq. (1) from Bergman (2010),

$$MC\ (\%) = ((W_g - W_o) / W_o)) * 100 \qquad (1)$$

where W_g is initial weight of the wood (g), and W_o is oven dry weight of the wood (g).

Delamination Test Method

Delamination specimens were prepared and tested according to ANSI/APA PRG 320 Standard for Performance Rated Cross Laminated Timber (ANSI/APA 2018). The specimens were cut to 76.2 x 76.2 mm as shown in Fig. 1 from Quin (2023). The weight of each specimen was recorded before they were conditioned at 21 °C and 50% relative humidity. During this time, the specimens were weighed regularly until a constant weight was achieved after two weeks. Ten replicates were tested for each species. Both end grain faces of each specimen were captured using a Canon EOS 7D digital camera which has a resolution of 18 MP. The equipment used for delamination tests are shown in Fig. 2a-c.

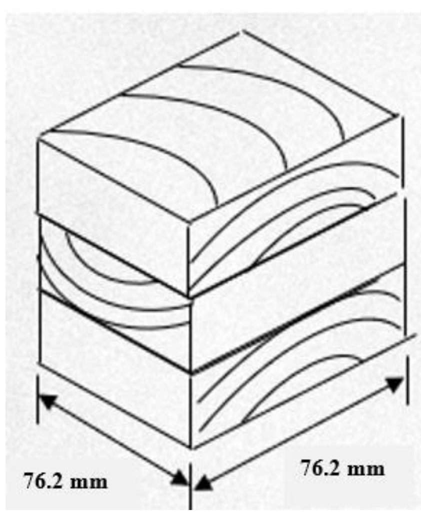

Fig. 1. Schematic of delamination test specimen and dimensions (Quin 2023)

The delamination specimens were weighed to the nearest 1 g before the test was started. The specimens were then placed in a wire mesh basket (Fig. 2A) before being inserted into the pressure vessel (Fig. 2B). The pressure vessel was sealed and filled with water at a temperature of 27 °C. The vessel was then placed under vacuum at 206.8 kPa for 30 min. Once the vacuum was released, the vessel was then pressurized to 517.1 kPa and held at this pressure for 2 h. The specimens were then removed from the vessel and weighed to the nearest 1 g. The specimens were then placed into a drying oven (Fig. 2C) at 65 °C with the test bond lines parallel to the flow of air. The drying time for the specimens was approximately 18 h. The specimens were dried to within 15% of their original weights. Once the drying cycle was complete, another photo of the two end grains of each sample was captured and the delamination of the test bond lines was measured and recorded.

A 0.08 mm feeler gauge was used to determine separations in the glue line. Additionally, the final images of the specimens were processed using ImageJ software to calculate the percentage of the bond line that was separated as a result of delamination. The total delamination ($Delam_{TOT}$) of a test specimen was calculated according to Eq. 2,

$$Delam_{TOT}\ (\%) = (l_{delam}/l_{total}) * 100 \quad (2)$$

where l_{delam} is the total length of delamination (mm) and l_{total} is the sum of the bond lines for both end grain faces (mm).

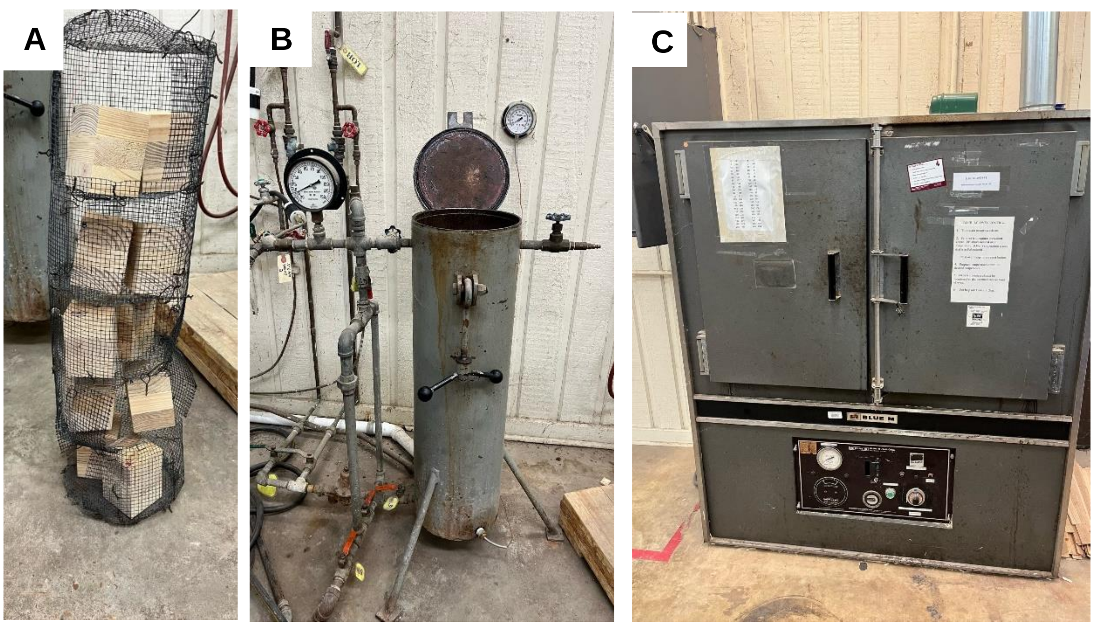

Fig. 2. A) Wire mesh basket used in delamination test, B) Pressure vessel, and C) Blue M oven

Block Shear Test Method

Shear block specimens were prepared according to the ASTM D2559 (2018) standard (ASTM 2018). The shear block specimens were first cut to 63.5 mm x 50.8 mm. The specimens were stair-stepped, a configuration referred to as ‘stair-stepping’ in the above-mentioned standard, with a shearing area of 50.8 mm x 38.1 mm, as shown in Fig. 3. Eight replicates were tested for each species. The shear block specimens were conditioned at 21 °C and 65% RH for at least 3 months prior to testing.

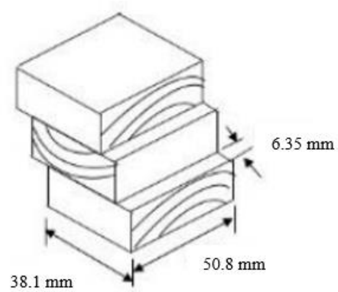

Fig. 3. Stair-stepped sample (Quin 2023)

The shear tests were performed according to ANSI/APA PRG 320 Standard (ANSI/APA, 2018). The shearing tool applied a force through adjacent laminations at a rate of 5 mm/min until failure. Block shear strength (f_v) was calculated according to Eq. 3,

$$f_v = F_u / A \tag{3}$$

where F_u is failure load (N), and A is sheared area (mm^2). The percentage of wood failure on the shear blocks was measured with ImageJ software (Schneider *et al.* 2012).

RESULTS AND DISCUSSION

Delamination Test

The average delamination values for each species are given in Table 1. Among the species tested, red oak samples displayed significantly more delamination than the others species tested. The southern pine controls exhibited an average delamination of 15.9%. While this group showed the least delamination, this average value was not significantly different than that of yellow poplar. The density of each species tested was plotted against the average delamination, and the chart is presented in Fig. 4.

Table 1. Average Delamination and Standard Deviation Values Based on Species

Species	Average Delamination (%)	Standard Deviation of Delamination (%)
Red oak	73.9[a]	14.7
Sweet gum	50.9[b]	26.0
Yellow poplar	33.6[bc]	18.9
SP	15.9[c]	15.4
Groups with the same letter are not significantly different SP = Southern Pine		

A one-way analysis of variance (ANOVA) was performed on the delamination means for the four species. It was found that the average delamination among each species was significantly different at a 0.05 significance level with a p-value <0.0001. According to the ANSI/APA PRG-320 standard, the maximum allowable delamination for softwoods is 5% and 8% for hardwoods (ANSI/APA, 2018). These maximum values were exceeded for the majority of the samples evaluated in this study. Southern pine was selected as the control, since this is the species that is currently used in the building and construction sector. As previously stated, the control panels that were used in this study were industrially manufactured. Among the 10 samples that were tested for this species, only 3 met the criteria specified in the standard. Apart from these samples, the others exhibited values that exceeded the minimum of 5% delamination rate per the PRG 320 standard (ANSI/APA 2018). In comparison, the average delamination observed among the yellow poplar samples was not significantly different than that of the control group. However, only one of these samples met the criteria of less than 8% delamination for hardwoods as given by the standard. These results suggest that the yellow poplar species has the potential as an alternative to southern pine in some applications. Compared to the control group, sweetgum and red oak displayed significantly higher delamination percentages, and none of the samples from these species groups met the criteria given in the standard. The significant variability in delamination observed across the different species, indicated by the standard deviation values given in Table 1, indicates substantial inconsistencies in bonding performance. This high variability may be attributed to a range of factors, including species-specific properties such as density, anatomical structure, and extractive content, which have all been shown to influence adhesive bond strength.

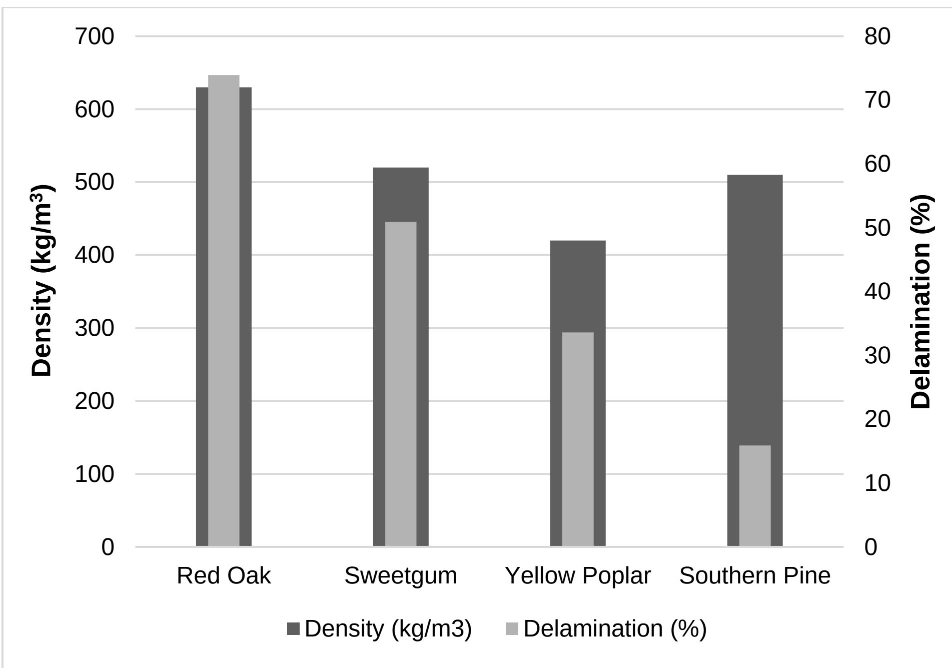

Fig. 4. Bar chart illustrating density and average delamination values of each of the species

These findings align with previous studies on the adhesive performance of hardwoods in CLT applications, which have reported varying degrees of delamination based on wood species and adhesive type. While this study focused exclusively on a one component PUR adhesive, the results revealed varying degrees of delamination among the hardwood species tested, demonstrating that wood species characteristics such as density, anatomical structure, and extractive content play a critical role in bonding performance. This is consistent with results from other studies, which also reported different delamination percentages depending on the wood species and the adhesive used. Norris *et al.* (2024) examined adhesive performance in CLT mats fabricated from low-grade red oak, comparing phenol-resorcinol-formaldehyde (PRF), one-component PUR, and emulsion polymer isocyanate (EPI) adhesives. Their results showed that PRF adhesive outperformed both PUR and EPI, particularly in terms of bond strength and resistance to delamination under cyclic moisture conditions. Similarly, Martins *et al.* (2017) fabricated glulam made from poplar and compared the delamination rates among samples using PRF, PUR, melamine-urea-formaldehyde (MUF), and EPI adhesives. They found PRF adhesive resulted in the lowest delamination values, indicating superior moisture resistance and bond durability.

Musah *et al.* (2021) tested a combination of various adhesives for bonding both hardwood and softwood species and found red oak cross-laminated samples exhibited no delamination when bonded with a commercially available melamine formaldehyde adhesive, highlighting the effectiveness of this adhesive for high-density hardwoods such as red oak. In contrast, Luedtke *et al.* (2015) investigated the effect of primer application and surface quality on the bonding quality in face gluing using a one component PUR adhesive. They found that priming significantly enhanced the bonding quality by activating the surfaces of hardwood species. While beech (*Fagus sylvatica* L.) glulam samples met delamination requirements (per EN 391 standard) after both peripheral planing and face milling, the delamination degree for ash (*Fagus excelsior* L.) and oak was too high after face milling, even when primed. However, peripheral planing produced acceptable results for these species. This suggests that the application of a primer system in combination with a one component PUR adhesive can be a promising approach for bonding several hardwood species in engineered wood products, depending on the surface preparation technique.

Block Shear Test

The descriptive statistics for the calculated block shear strengths (BSS) and wood failure percentages (WFP) for the four species groups are shown in Table 2. On average, the shear strength of wood perpendicular-to-grain is less; therefore, the major failure mode for the shear blocks was perpendicular-to-grain. Figure 5 illustrates the difference in a load applied parallel-to-grain and perpendicular-to-grain. The BSS of the control SP samples ranged from 395 psi (2.72 MPa) to 859 psi (5.92MPa) with a coefficient of variation (COV) of 27%. An average wood failure percentage (WFP) of 69.3 % was observed among the control SP samples. The highest average BSS value of 837 psi (5.77 MPa) was observed among the red oak samples. This species group had a COV for BSS and average WFP of 26% and 12.6%, respectively.

Table 2. Descriptive Statistics of BSS (Block Shear Strength) and WFP (Wood Failure Percentage) and Specific Gravity for Different Species Groups

Species group	Specific gravity (green/dry) [a]	Sample size	BSS Mean (psi)	BSS Median	BSS COV (%)	WFP Mean (%)	WFP Median (%)	No. <80% WFP[b]
Red oak	0.56/0.63	16	836.84	852.91	26	12.63	5.81	15
Sweetgum	0.46/0.52	16	656.99	697.92	36	59.81	66.21	9
Yellow Poplar	0.40/0.42	16	742.05	747.64	10	97.31	100.00	0
SP	0.47/0.51	16	584.40	590.70	27	69.19	69.26	8

[a] Williams, 2010
[b] Number of specimens with less than 80% Wood Failure Percentage
SP= Southern Pine

A one-way ANOVA on the BSS means showed the block shear strengths were significantly different between at least 2 of the species groups at a 0.05 significance level with a p-value of 0.0025. Both red oak and yellow poplar samples displayed significantly higher BSS values than the controls. Another ANOVA was conducted on the WFP means and found that the WFP was significantly different among at least 2 of the species groups at a 0.05 significance level. This was indicated by a p-value of <0.0001. The yellow poplar samples exhibited the highest WFP values, with an average of 97.3%. All of the yellow poplar specimens that were tested met the minimum requirement of 80% WFP based on PRG 320 standard (ANSI/APA 2018). The remaining hardwood species had lower percentages of wood failure compared to the control and on average, did not meet the minimum requirement of the referenced standard.

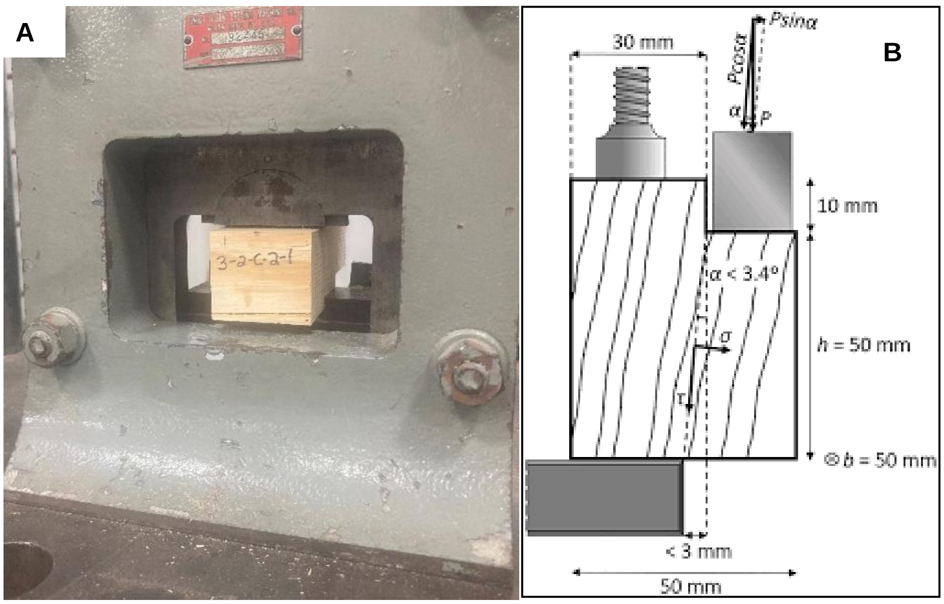

Fig. 5. A) Load being applied perpendicular to the grain (Quin, 2023); B) Schematic of a load being applied parallel to the grain (Riesco Munoz 2021)

These observations are consistent with prior studies on hardwood adhesive performance in CLT applications, yet they also highlight significant variations between the different studies (see Fig. 6). For example, Mohamadzadeh and Hindman (2015) reported a mean shear strength of 785 psi and an average WFP of 72% in their study investigating resistance to shear by compression loading using a PRF adhesive to bond yellow poplar CLT. These results are comparable to the findings reported here for yellow poplar, indicating a strong adhesive bond and high wood failure percentage PRF adhesive, although slightly below the 80% cutoff. Additionally, da Rosa Azambuja *et al.* (2021) reported an average BSS and WFP of 741 psi and 95%, respectively for yellow poplar CLT fabricated with an EPI adhesive system. These results align closely with that of the current study and highlights the importance of adhesive selection. The combined results of all the studies emphasize the varying performance of different adhesives. Comparing the results for red oak in this study with those from Norris *et al.* (2024) and Musah *et al.* (2024) further illustrates the variability in adhesive performance based on different adhesives and bonding conditions. Norris *et al.* (2024) found that none of their red oak CLT combinations passed the minimum WFP requirement of 80% when tested with EPI, PRF and PUR adhesives under different bonding parameters. However, the PRF adhesive setup (spread rate of 250 g/m^2, clamping pressure of 200 psi, 8% moisture content, and 60-grit surface roughness) performed best, achieving an average WFP of 76.35% and a shear strength of 780 psi. The PUR adhesive set up yielded the highest shear strength vale of 1,046 psi but only a 57.5% WFP, emphasizing the challenge of balancing high shear strength with adequate wood failure. In contrast, Musah *et al.* (2024) reported that red oak CLT bonded with PRF had an average bonding strength of 915 psi and a WFP of 81.4%, and with MUF adhesive, a strength of 860 psi and a WFP of 74%. These results suggest the resorcinol adhesives may provide better bonding performance for red oak compared to other adhesives, achieving higher wood failure percentages that meet or exceed standard requirements.

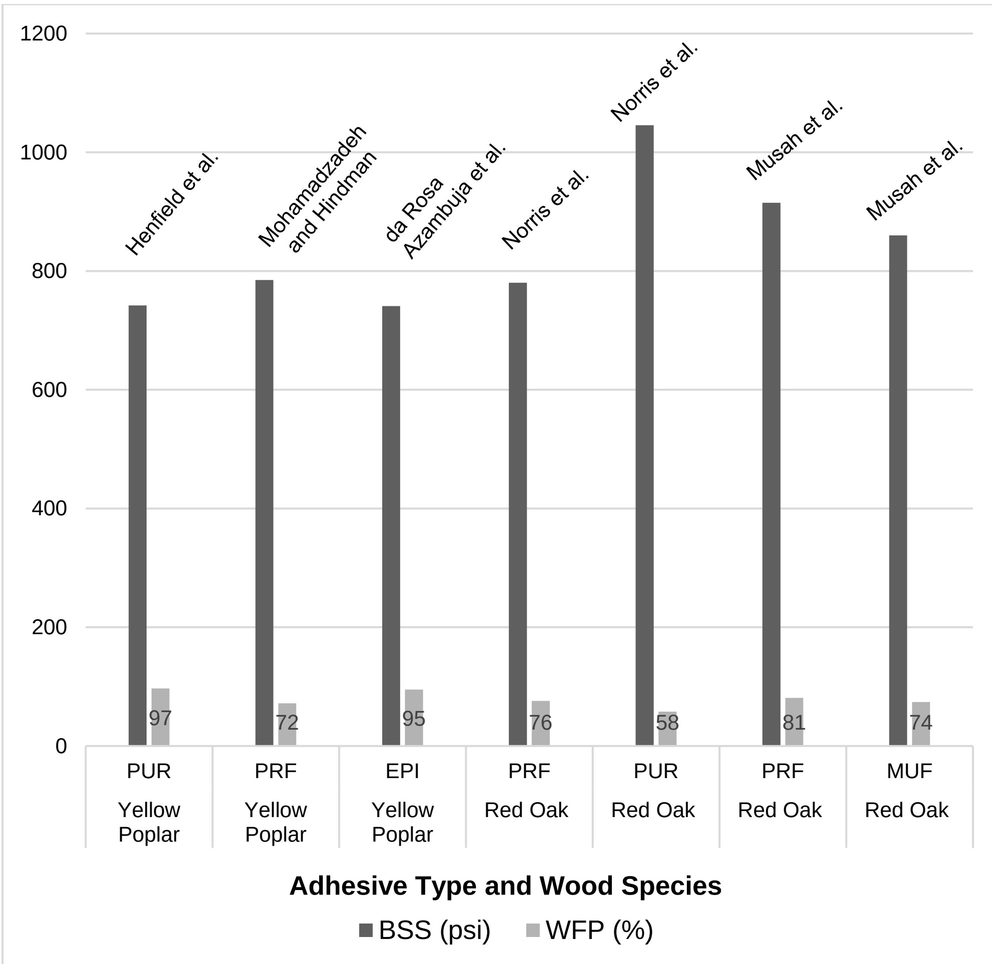

Fig. 6. Comparison of adhesive performance: block shear strength and wood failure

Aicher *et al.* (2018) conducted shear block tests on glulam red oak and found a mean bond line shear strength of 2,045 psi and a WFP of 89%, which are significantly higher than the values obtained in the current study or those presented in other studies. The discrepancy can be attributed to the orientation of the grain during testing; glulam beams are typically loaded parallel to the grain direction, where wood exhibits its highest mechanical strength. In contrast, CLT panels often involve bonding layers in perpendicular grain orientations, which may result in lower shear strengths due to rolling shear effects and the challenges associated with bonding end-grain surfaces.

Despite a thorough review of the existing literature, no studies were found that specifically investigated the adhesive bond strength of sweetgum in CLT or other engineered wood products. This gap highlights a significant opportunity for further research to understand how sweetgum performs in terms of adhesive bonding and structural integrity. The findings from this study provides preliminary insights into the adhesive properties of this species, but additional research is necessary to validate these results and explore the potential of sweetgum in CLT applications.

CONCLUSIONS

1. Yellow poplar (*Liriodendron tulipifera* L.) demonstrated a favorable balance with high block shear strength and wood failure percentage, and lower delamination percentages, making it a strong candidate for CLT applications where both strength and resistance to environmental stress are critical.
2. Red oak (*Quercus* spp. L.) exhibited the highest block shear strength among the tested species, indicating its excellent mechanical properties and potential for use in high stress applications. However, it also exhibited the highest delamination percentages and lowest wood failure percentages, indicating that the current bonding techniques and adhesive selection may not be optimal for this species.
3. The results of this study indicate that woods with varying density profiles exhibit distinct bonding behaviors, suggesting that the physical characteristics of wood significantly influence adhesive performance and overall material integrity in engineered applications.
4. Phenol resorcinol formaldehyde (PRF) adhesives demonstrated the strongest and most consistent correlation with APA criteria, followed by EPI and MUF adhesives. PUR adhesives, while achieving high shear strength, often failed to meet the wood failure percentage requirement, emphasizing the importance of surface preparation and bonding parameters for APA compliance.

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