Evaluation of connection performance of various mixed species CLTs for furniture-style joinery

Chih-Cheng Chen†
Ph.D. Candidate
Department of Forestry and Natural Resources
Purdue University
West Lafayette, IN 47906
E-mail: chen3871@purdue.edu

Daniel P. Hindman†
Associate Professor
Department of Sustainable Biomaterials
Virginia Tech
1650 Research Center Dr.
Blacksburg, VA, 24061
E-mail: dhindman@vt.edu

Henry J. Quesada†
Professor
E-mail: quesada@purdue.edu

Ting-Ho Tsai
Master's Student
E-mail: tsai181@purdue.edu

*Eva Haviarova**†
Professor
Department of Forestry and Natural Resources
Purdue University
West Lafayette, IN 47906
E-mail: ehaviar@purdue.edu

(Received 24 September 2024)

Abstract. This study investigated the connection performance of various mixed-species cross-laminated timber (CLT) panels used in furniture-style joinery. A combination of yellow-poplar and southern pine were used to assesses the mechanical performance of L-shaped dowel and lap joints under compression and tension loads. Mechanical testing was conducted to evaluate the connection moment resistance of each joint configuration. Dowel joints generally exhibited higher connection moment resistance, particularly under compression, which was attributed to superior mechanical interlocking and load distribution. Conversely, lap joints demonstrated higher variability in performance, with some configurations showing inconsistency, particularly under tension. Failure modes, such as delamination and rolling shear, were observed, highlighting the need for improved adhesion and joint design. These findings suggest that dowel joints are the preferred joinery method due to higher compressive strength. In contrast, lap joints may benefit from optimization in adhesive bonding techniques to enhance performance under tension. This research provides valuable insights into the structural integrity and durability of CLT joinery, guiding future improvements in design and application for engineered wood products.

Keywords: Mixed species CLTs, Furniture joinery, Joinery performance, Joint strength

Introduction

The growing demand for timber in cross-laminated timber (CLT) construction necessitates sustainable resource management strategies. Utilizing materials efficiently during CLT processing and from deconstructed CLT buildings offers compelling end-of-life solutions (for example, the production of CLT furniture). This approach directly addresses the principles of the circular economy by ensuring materials are repurposed or recycled at the end of their lifecycle. While first-generation CLT buildings rarely require dismantling and planning for their eventual decommissioning, recycling is essential for maintaining environmental responsibility and circular economy principles. Recycling these materials minimizes waste and reduces the built environment's carbon footprint (Chúláin et al. 2023).

---

* Corresponding author
† Society of Wood Science & Technology member

Wood and Fiber Science, 57(1), 2025, pp. 41–51
https://doi.org/10.22382/wfs-2025-04

CLT is typically manufactured from softwood species (Sciomenta et al. 2021), but with the increase in consumption of softwood lumber, incorporating hardwood lumber into CLT production could present a valuable opportunity for the construction industry (Adhikari et al. 2020). Hardwoods are finding new applications in mass timber due to their density and high mechanical strength, and some manufacturers view hardwood CLT as a new market opportunity (Hassler et al. 2022; Thomas and Buehlmann 2017). Da Rosa Azambuja et al. (2022) focused on the potential of utilizing low-grade yellow-poplar (*Liriodendron tulipifera*) lumber for CLT production. NHLA-graded No. 2A and below-grade yellow-poplar lumber were evaluated for structural suitability in CLT panels. Results suggested that a significant portion of low-grade yellow-poplar lumber regraded for structural use, met or exceeded the required grade values for CLT production, offering the potential to enhance CLT manufacturing with cost-effective, reclaimed feedstock. Similarly, Ma et al. (2021) studied the performance of hybrid CLT panels combining sugar maple (*Acer saccharum*) and white spruce (*Picea glauca*) bonded with melamine adhesive. The findings indicated that sugar maple improved bending strength, with notable shear properties. This hybrid CLT met PRG-320 mechanical standards and offered enhanced structural capabilities.

Incorporating CLT (softwood, hardwood, or hybrid) into furniture products represents an innovative approach that enhances the durability and functionality of wooden structures. This technique exploits the structural benefits of CLT, such as its dimensional stability and load-bearing capacity, which surpass those of traditional wood products. By utilizing the inherent strengths of CLT, furniture designers can create robust, long-lasting, and environmentally friendly furniture due to CLT's ability to be sourced from sustainable forestry practices. Furthermore, the flexibility of CLT allows for innovative design choices, such as integrating cutouts from CLT construction projects like windows and door openings into unique furniture products or repurposing leftover CLT materials, thereby promoting a circular economy. The potential for recycling CLT also contributes to environmental sustainability, making it a compelling choice for modern furniture design.

This integrated process is facilitated by computer numerical control (CNC) technology, where building smaller products from recycled CLT panels (new or old) could be a simple design process. CNC machines enable complex cuts and patterns, significantly simplifying the design process while ensuring minimal material waste and promoting sustainable practices. However, despite the design flexibility and waste reduction benefits offered by CNC, the structural integrity of CLT joinery is also critical. Addressing this ensures the development of durable and stronger products, thereby maximizing the functional and environmental benefits of CNC-facilitated CLT applications in furniture design. As noted by Eckelman (2003), joints in furniture are common points of failure. The durability of furniture, particularly plate construction type furniture, largely depends on the strength of corner joints (Altinok et al. 2009). Material selection, joint strength, and end-use are crucial in determining joinery methods, affecting the longevity and performance of the structure (Nicholls and Crisan 2002). Standard techniques like butt and miter joints, alongside dowels, a favored fastener for ease and strength, are integral to the quality of wooden furniture (Altinok et al. 2009; Chen and Lyu 2018; Maleki et al. 2012).

This investigation focused on measuring the structural performance of different furniture-style joints using CLT panels made from repurposed recycled/salvaged yellow-poplar (*Liriodendron tulipifera*) and southern pine (*Pinus* spp.). The study assessed the connection moment resistance of lap and dowel joinery in compression and tension and explored the potential of various complex joinery types. The research analyzed the strength and stiffness of variable hybrid CLT joints and observed their failure modes. The findings were expected to validate the practicality of utilizing recycled/salvaged CLT materials for robust furniture and to innovate stronger and more durable joinery methods for other engineered wood products.

Materials and methods

The specimens utilized in this study, sourced from Satir et al. (2024), were constructed from salvaged CLTs made of yellow-poplar (*Liriodendron tulipifera*) and southern pine (*Pinus* spp.), with undamaged portions cut to size after prior bending and shear tests. Three types of CLT were examined: entirely yellow-poplar (YYY), hybrid panels with yellow-poplar face layers and southern pine cores (YPY), and hybrid panels with southern pine outer layers and yellow-poplar cores (PYP). All CLT panels were produced at Texas CLT (Magnolia, AR). The manufacturing process involved nominal 2 x 6 pieces, planed to a width of 34.9 mm. Number 2 southern pine lumber was obtained on-site at Texas CLT, while yellow-poplar lumber, upgraded from No. 2 Common to at least No. 2 yellow-poplar, was sourced from various sawmills in Virginia and transported to the production facility. The CLT panels were face-glued using a one-component polyurethane adhesive and assembled in a cold press for 60 min under a pressure of 620 kPa.

Yellow-poplar (*Liriodendron tulipifera*) dowels sourced from Madison Mill Co (Ashland City, TN) were employed in the

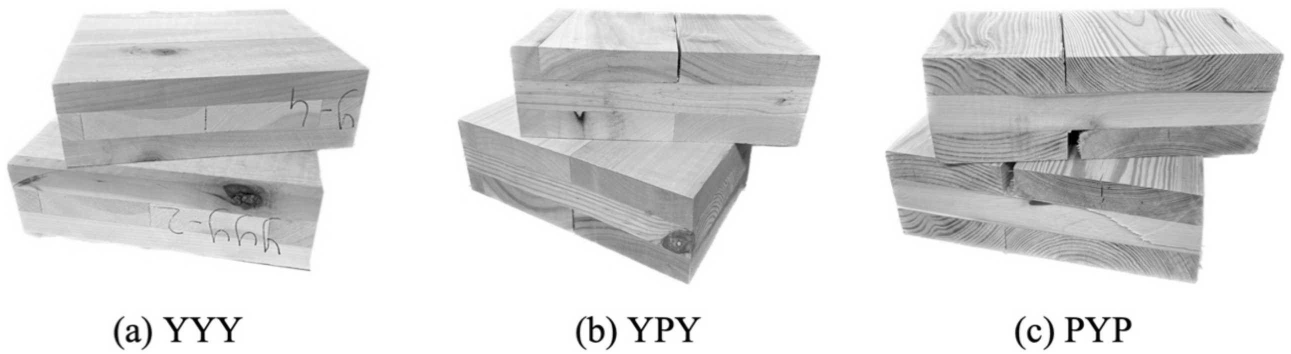

(a) YYY (b) YPY (c) PYP

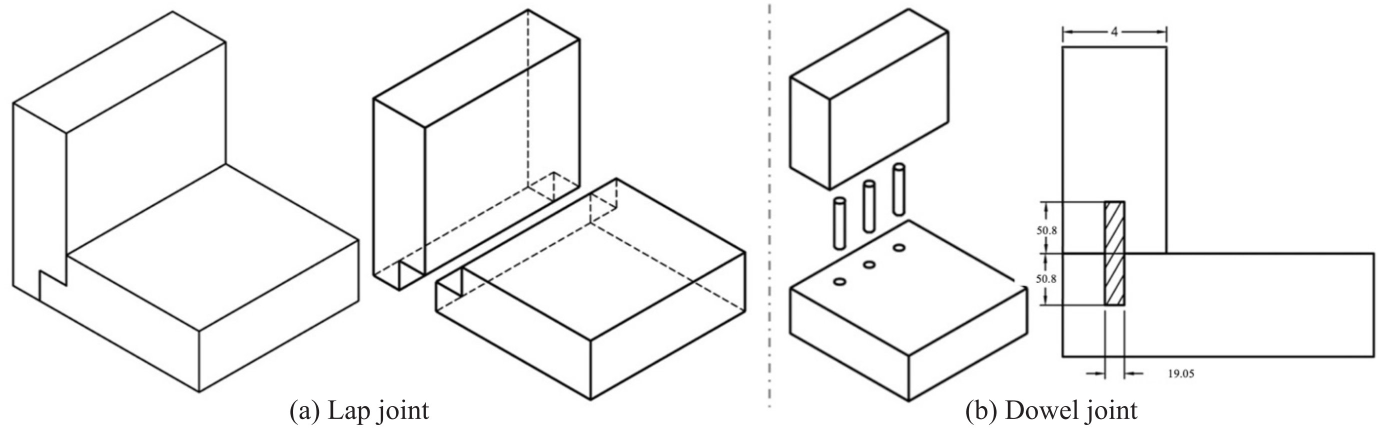
Figure 1. Examples of CLTs composed of yellow-poplar (Y) or southern pine (P).

construction of dowel joints. These 19.05 mm plain dowels featured a straight grain pattern that offered dimensional stability, with chamfering on both ends to facilitate easy insertion and secure fit in the drilled holes. For adhesive, Titebond III wood glue (Franklin International, Columbus, OH) was utilized, characterized by a solid content of 48-52% and a viscosity of 4200 cps. This waterproof adhesive is known for its strong, permanent bond suitable for woodworking, with a longer open time allowing adjustments during assembly. It is recommended to be spread at a rate of 6.1335 m²/L, ensuring adequate coverage. All specimens were clamped for a minimum of 24 h post-assembly to allow for complete curing.

Selected Joinery and Construction

The experimental design incorporated L-shaped lap and dowel joints, as depicted in Figure 2. The lap joint, a prevalent choice in woodworking due to its strength and ease of fabrication, was precisely crafted using computer numerical control (CNC) machinery. The lap joint consisted of a face member measuring 304.8 × 304.8 × 101.6 mm and a butt member measuring 254.0 × 304.8 × 101.6 mm. Each member was machined with a corresponding 50.8 mm deep notch, resulting in a precisely mated, flush connection when assembled. The joint was then secured with clamps for at least 24 h after adhesive application to ensure a durable bond.

Similarly, the dowel joint assembly involved a face and a butt members, measuring 304.8 × 304.8 × 101.6 mm and 203.2 × 304.8 × 101.6 mm, respectively, both constructed from the same CLT material. A three-dowel system was used in this study to construct the corner joints because it is widely employed in the construction of bookcases and cabinets. This design choice aligns with the recommendations of Zhang and Eckelman (1993), who demonstrated that spacing dowels 76.2 mm apart optimized joint strength in multi-dowel assemblies. The dowels utilized in this study were 19.05 mm in diameter, selected for their ability to provide adequate dimensional stability within the joint. To accommodate potential variations in dowel size and facilitate the application of adhesive, the corresponding holes in both the face and butt members were drilled slightly larger, with a diameter of approximately 20.64 mm. This provided a clearance of 1.6 mm, ensuring a precise fit. Additionally, the



(a) Lap joint (b) Dowel joint

Figure 2. Selected joinery for CLT connections.

depth of each hole was maintained at 50.8 mm, a measurement chosen to guarantee sufficient engagement of the dowels, thereby enhancing the robustness of the connection.

Test procedure

L-shape corner joint test

To comprehensively understand the mechanical behavior of L-shaped joinery specimens, specimens were subjected to both compression and tension load tests. Specifically, the moment resistances of cross-laminated timber (CLT) joints were assessed under loads that applied a closing force, known as compression moments, at point A and loads that applied an opening force, referred to as tension moments, at point B in Figure 3. This approach was essential, as corner joints experience both compression moment and tension moment loading configurations when case furniture was subjected to lateral loading. Evaluating the performance under these distinct loading conditions ensured that the findings were applicable to a variety of practical scenarios where these joints may be employed.

Thirty-six CLT corner joint specimens were tested, with eighteen subjected to compression and the other eighteen to tension. These specimens were evaluated for connection moment resistance using an MTS universal testing machine (MTS Systems Corp., Minneapolis, MN, USA). The loading configurations for testing joint moment resistances to closing and opening action forces are shown in Figure 4. The L-shaped specimens were secured to a robust, heavy metal base using bolts and nuts for stability, with a bar clamp employed to prevent base movement and restrict displacement of the vertical member. Specimens were constructed using the three types of CLTs, identified as YYY, YPY, and PYP, and were tested as both lap and dowel joints. Each specimen was subjected to a constant displacement rate of 1.27 mm/min to determine the maximum load capacity before failure.

In both compression and tension bending tests, the connection moment resistance of CLT joinery was determined by multiplying the ultimate failure load (F) by the moment arm, representing the distance from the loading head to the CLT joint face. A 215.9 mm moment arm was utilized for YYY and YPY specimens, while PYP specimens used a 165.1 mm arm, allowing for a thorough assessment of the bending performance across different configurations.

$$\mathrm{M}\ (N\text{ - }mm) = \mathrm{F}\ (N) \times \mathrm{L}\ (mm) \tag{1}$$

where M is connection moment resistance, $N{\cdot}mm$; F is applied load, N; and L is moment arm, mm.

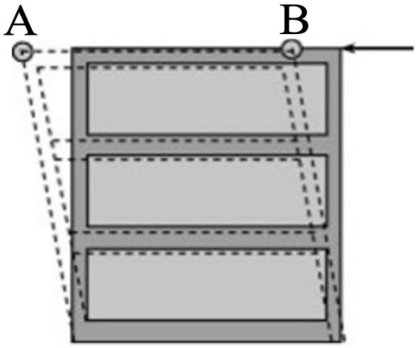


Figure 3. A typical case-type construction loaded by a vertical force (adapted from Çetin Yerlikaya and Aktaş, 2012).

Corner joint failure behavior of CLT

Failure modes of CLT corner joint specimens were assessed through mechanical testing of dowel and lap joint configurations. Failure mechanisms were categorized as material glue failure (MGF), joint glue failure (JGF), rolling shear (RS), and wood failure (WF) based on visual inspection and digital analysis. High-resolution imaging was used to document failure characteristics, and the extent of each failure type was estimated through a manual visual assessment as a percentage of the total failure area for comparative analysis. The failure percentage of each joint specimen was then correlated with connection moment resistance, and the results were compiled into a single figure to facilitate direct comparison.

Descriptive statistics

Each test variable was limited to three repetitions due to the restricted availability of CLT materials, which were donated by Virginia Tech as leftover CLT specimens from their previous experiments. CLT thickness, measuring 101.6 mm (4 in), represented the maximum that could be processed given the constraints of the laboratory's CNC machining capabilities. Additionally, issues such as delamination occurred during specimen preparation due to the limited and inconsistent quality of the material, which further reduced the number of usable specimens. As a result, this study employed descriptive statistics to analyze the data, presenting differences between groups as percentages and discussing the range of values, including the maximum and minimum observed in each combination.

Results and discussion

Delamination was observed during the CNC machining of the PYP CLT. Additionally, limitations in the available CLT inventory necessitated using smaller specimen sizes (Table 1). This constraint required an adjustment in calculating the

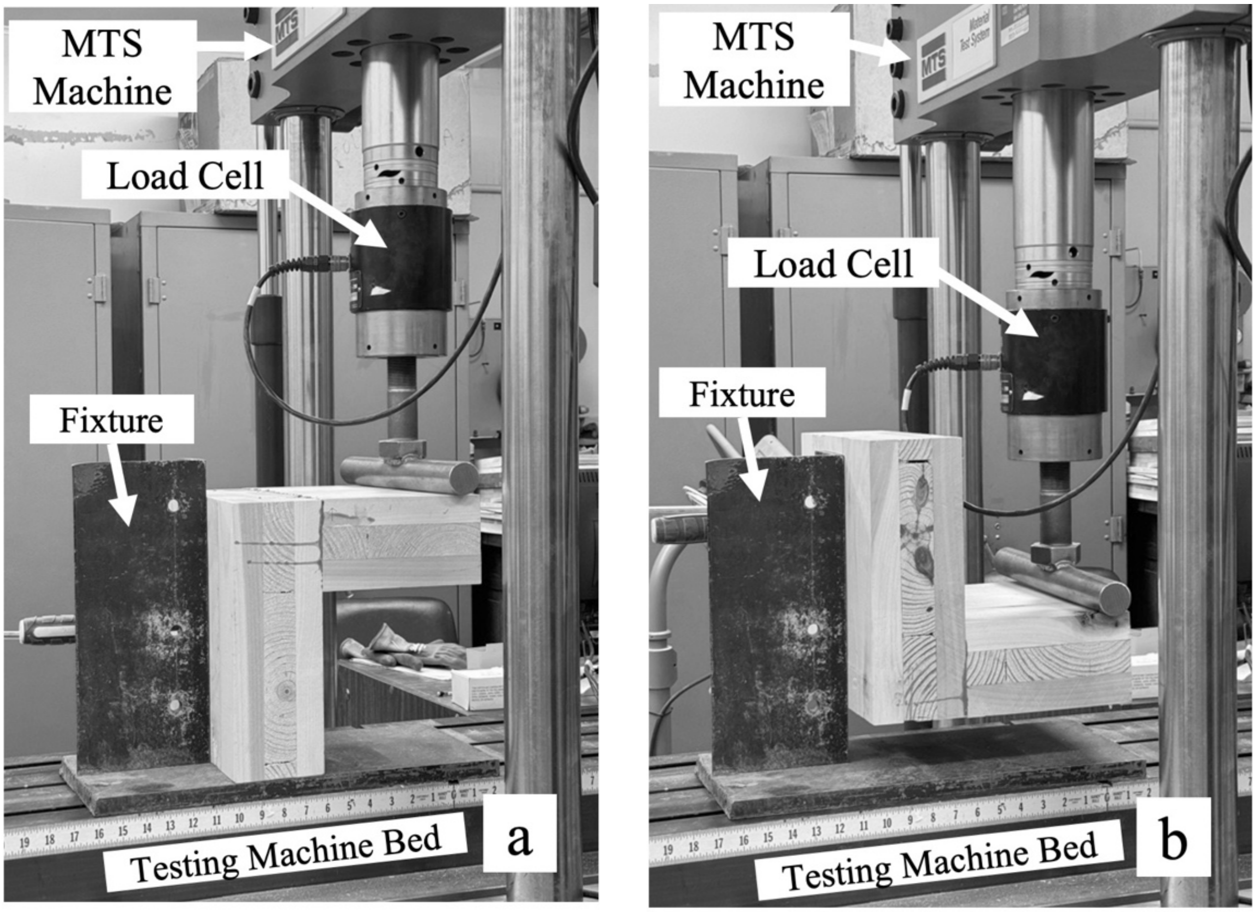


Figure 4. Method of loading the L-shape corner joint under compression (a) and tension moments (b).

Table 1. Specification of L-shaped joint specimens.

Load	Species	Specific gravity	Joint type	Face member dimension (L × W × T)	Butt member dimension (L × W × T)	Number of specimens tested
Compression	YYY	0.493	Lap	304.8 × 304.8 × 101.6	254.0 × 304.8 × 101.6	3
			Dowel	304.8 × 304.8 × 101.6	203.2 × 304.8 × 101.6	
	YPY	0.497	Lap	304.8 × 304.8 × 101.6	254.0 × 304.8 × 101.6	3
			Dowel	304.8 × 304.8 × 101.6	203.2 × 304.8 × 101.6	
	PYP	0.483	Lap	254.0 × 304.8 × 101.6	203.2 × 304.8 × 101.6	3
			Dowel	254.0 × 304.8 × 101.6	152.4 × 304.8 × 101.6	
Tension	YYY	0.493	Lap	304.8 × 304.8 × 101.6	254.0 × 304.8 × 101.6	3
			Dowel	304.8 × 304.8 × 101.6	203.2 × 304.8 × 101.6	
	YPY	0.497	Lap	304.8 × 304.8 × 101.6	254.0 × 304.8 × 101.6	3
			Dowel	304.8 × 304.8 × 101.6	203.2 × 304.8 × 101.6	
	PYP	0.483	Lap	254.0 × 304.8 × 101.6	203.2 × 304.8 × 101.6	3
			Dowel	254.0 × 304.8 × 101.6	152.4 × 304.8 × 101.6	

Note: Y: Yellow-poplar, P: Southern pine; Specific gravity unit: kg/m^3; Member unit: mm

connection moment resistance, with the moment arm reduced from 215.9 mm to 165.1 mm.

Table 2 presents the average connection moment resistance and coefficient of variation (COV) of the L-shaped joints under compression and tension, considering various corner joint configurations. Among the three CLTs tested, the dowel joint configuration often exhibited a higher connection moment resistance than the lap joint configuration. However, this trend was not consistent across all species and loading conditions. YYY dowel joints subjected to a compression moment had

Table 2. Average connection moment resistance of L-shaped joints.

	Joinery	YYY	YPY	PYP
Average connection moment — Compression, N·mm (COV)	Dowel	4560 (12.2%)	5170 (9.27%)	3610 (9.39%)
	Lap	4660 (28.1%)	2930 (14.7%)	2850 (9.82%)
Average connection moment — Tension, N·mm (COV)	Dowel	3070 (5.28%)	3250 (16.0%)	2780 (11.2%)
	Lap	3190 (15.2%)	2980 (16.3%)	1840 (17.1%)

Note: Y: Yellow-poplar, P: Southern pine; COV: Coefficient of Variation

a connection resistance of 4560 N·mm, approximately 1.6% lower than the lap joint capacity of 4660 N·mm. Tension test results indicated a different pattern, where the lap joint was 4.1% greater (3190 N·mm) than the dowel joint (3070 N·mm).

The YPY dowel joint configuration in compression produced a higher connection moment resistance of 5170 N·mm, 76.6% higher than the lap joint's capacity of 2930 N·mm. Conversely, the difference between the dowel and lap joints in tension was minimal, with the dowel joint showing only a 9.4% higher capacity (3250 N·mm) than the lap joint (2980 N·mm).

The PYP dowel joint configuration in compression showed a 26.7% higher connection moment resistance (3610 N·mm) than the lap joint (2850 N·mm). However, in tension, the lap joint displayed a capacity 34% lower (1840 N·mm) than the dowel joint (2780 N·mm).

The variability across different species and loading conditions indicated that while dowel joints tended to offer higher moment resistance, the differences were not uniform and can vary markedly depending on the specific configuration and material properties. Additionally, the YYY species lap joint demonstrated substantial variability under compression, with a high coefficient of variation (28.1%), indicating an inconsistent response, which may be attributed to the quality of the raw CLT materials. This variability could be linked to the bonding quality issues in the materials, as highlighted by Mohamadzadeh and Hindman (2015), who suggested that yellow-poplar CLT's inherent strength might lead to adhesive rather than wood failure under shear loads, underscoring the importance of bonding quality in joint integrity.

The average connection moment results indicated that the compression moment values of the L-shaped joint generally exceeded those observed in tension (Figure 5), which is consistent with the inherent mechanical behavior of wood. Wood typically exhibits higher strength in compression, particularly along the grain, due to the thin-walled cells undergoing lateral compression when a load is applied perpendicular to the grain. This process leads to the gradual cell collapse under increasing stress until the fibers are entirely crushed, after which the load can still increase (Karacabeyli et al. 2013; Ali et al. 2014). In contrast, the tensile strength of wood is limited by the capacity of individual cell walls to resist separation under tension. The higher connection moment resistance observed in the dowel joint configuration, as compared to the lap joint configuration, can be attributed to the superior interlocking and mechanical support provided by the dowels. Mechanical support refers to the dowels embedding tightly into the wood fibers with adhesives, which enhances load transfer and joint stability while minimizing movement under load. Additionally, the use of three dowels in our tests facilitated even load distribution across the CLTs, thereby reducing the likelihood of localized stress concentrations that could lead to failure.

Connection moment resistance values for the different joinery types and species demonstrated notable variations (Table 3). Under compression, the YPY dowel joint configuration exhibited the greatest connection moment resistance at 5170 N·mm, 52% above the average value across all 36 specimens. Similarly, the YYY dowel joint under compression also showed a greater connection moment resistance, with a

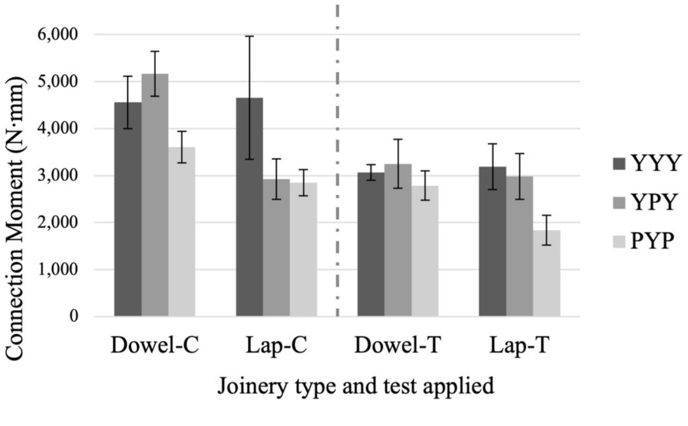


Figure 5. Average connection moment resistance of corner joints in compression and tension tests.

Table 3. Connection Moment Resistance, Coefficient of Variation, and Percentage Differences for L-Shaped Joints.

Joint type	Load	Species	Avg. Connection Moment Resistance, N-mm	COV (%)	% Difference (from Avg.)
Dowel	Compression	YYY	4560	12.2	33.8
Dowel	Compression	YPY	5170	9.27	51.7
Dowel	Compression	PYP	3610	9.39	5.86
Lap	Compression	YYY	4660	28.1	36.7
Lap	Compression	YPY	2930	14.7	-14.1
Lap	Compression	PYP	2850	9.82	-16.4
Dowel	Tension	YYY	3070	5.28	-9.95
Dowel	Tension	YPY	3250	16.0	-4.60
Dowel	Tension	PYP	2780	11.2	-18.2
Lap	Tension	YYY	3190	15.2	-6.26
Lap	Tension	YPY	2980	16.3	-12.4
Lap	Tension	PYP	1840	17.1	-46.1

Note: Y: Yellow-poplar, P: Southern pine; Unit: mm

value of 4560 N·mm, representing a 34% increase from the average. In contrast, the YPY lap joint configuration under compression showed a lower connection moment resistance of 2930 N·mm, 14% below the average. The PYP dowel joint under compression, while showing a relatively moderate connection moment resistance of 3610 N·mm, was 6% above the average. Overall, the dowel joints generally exhibited greater connection moment resistance than the lap joints, with a few exceptions depending on the species and load type. The variability in connection moment resistance, as reflected by the coefficient of variation (COV), also indicated differences in material behavior and joint performance, particularly in the lap joint configurations, which exhibited higher COV values than the dowel joints.

Figures 6(a) through 6(h) illustrate the stiffness characteristics of the evaluated joints, detailing the relationship between applied load and the resulting deflection. The data revealed a non-linear correlation, suggesting that joint failure occurred beyond the linear elastic range. The joints generally exhibited greater strength under compression moment compared to tension moment loading. Figures 6(a), 6(c), 6(e), and 6(g) present segments of the load-deflection curves from Figures 6(b), 6(d), 6(f), and 6(h), focusing on the linear elastic range for deflections not exceeding 7.62 mm for comparison.

No clear trend in stiffness was observed in Figure 6(a); however, the second specimen constructed with a PYP dowel joint (PYPDC2) showed the lowest initial slope, indicating potential weakness. Interestingly, slope increased when deflection reached approximately 3 mm, unexpectedly maintaining strength levels. Figure 6c offered a more explicit depiction of strength variations, with YPYDT1 predicted to have the highest strength while PYPDT2 appeared to be the weakest. Nonetheless, YPYDT1 experienced a decrease in strength and eventual failure at a deflection of 8.9 mm (Figure 6(d)), primarily due to the dowel being pulled out from the specimen, indicating a critical failure mode.

Specimen YPYLC2 exhibited a reduction in slope beginning at a deflection of 3.8 mm, which continues until failure (Figure 6(e)). Although this specimen did not demonstrate exceptionally high strength, as corroborated by Figure 6(f), the main damage to YPYLC2 occurred in the core layer of the CLT material, with a distinctive split along the growth rings. Figure 6(f) also highlights that YYYLC1 displayed relatively higher strength than other specimens.

Specimen PYPLT1 experienced a reduction in strength starting at a deflection of 6.35 mm, indicating a weakening of material integrity (Figure 6(g)), which was further evidenced in Figure 6(h). PYPLT1 exhibited substantial weakness, primarily due to the delamination of the CLT material shortly after initial loading. This analysis emphasized the importance of considering both mechanical properties and failure modes when assessing the performance of CLT joints under various loading conditions.

Failure Modes Analysis

The observed failure mechanisms were categorized into four types, as outlined in the methodology. Material glue failure

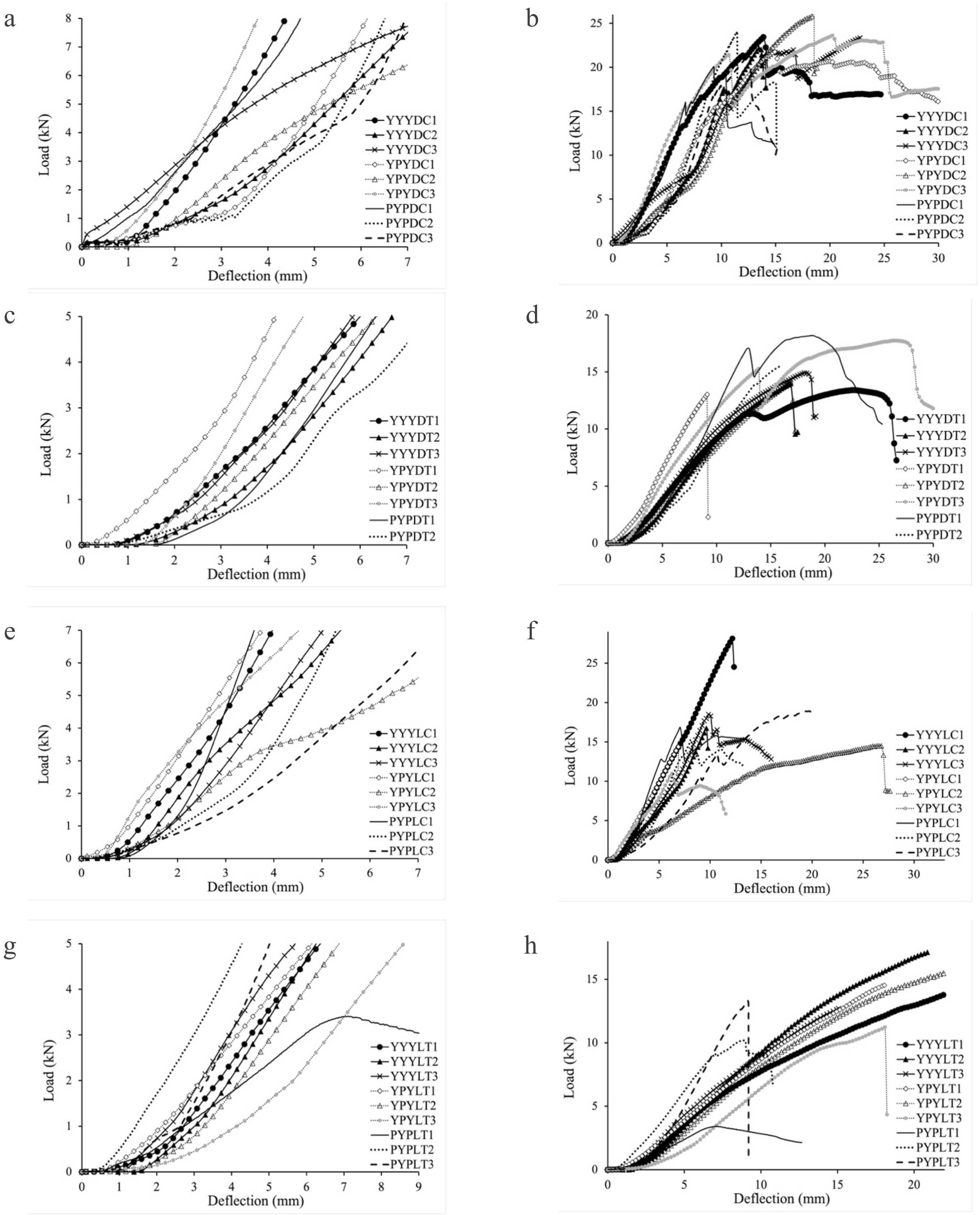
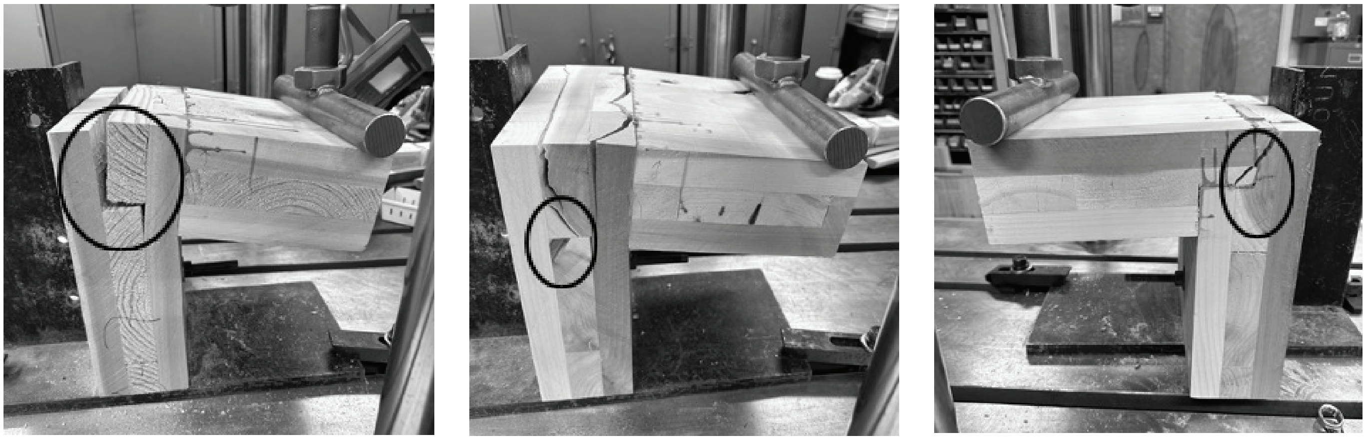


Figure 6. Load deflection curves of joints tested in: (a) compression with dowel in linear-elastic range; (b) compression with dowel in entire range; (c) tension with dowel in linear-elastic range; (d) tension with dowel in entire range; (e) compression with lap in linear-elastic range; (f) compression with lap in entire range; (g) tension with lap in linear-elastic range; (h) and tension with lap in in entire range.

(MGF) refers to delamination caused by adhesive failure between CLT layers, resulting in layer separation. Joint glue failure (JGF) occurred within the glue line at the joint interface and included instances where dowels were pulled out due to insufficient bonding. Rolling shear (RS) is commonly observed in the core layers of CLT and involves shear failure caused by the rolling action of wood fibers under stress. Wood failure (WF) was defined as the physical breakage of wood fibers and layers when the material exceeded its mechanical limits. The findings emphasize the prevalence of delamination and rolling shear failures, particularly within the core layers of CLT materials, highlighting the necessity for improvements in adhesive bonding techniques when fabricating CLT, particularly in lap joints, to enhance the structural integrity and durability of CLT assemblies under various stress conditions.

Figure 7 illustrates the characteristic failure modes observed in the tested CLT dowel and lap specimens. Dowel joints primarily exhibited failure modes characterized by the extraction of the dowel (Figure 7(e)), leading to reduced in strength and subsequent failure. In contrast, lap joints demonstrated a range of failure modes, including JGF, RS, and WF. Detailed descriptions of specific failure scenarios include dowel joint failures under compression (Figure 7(b)), and under tension (Figure 7(e)). Figures 7(c) and 7(f) show the lap joint failures under compression and tension. Notably, Figure 7(b) highlights a distinct instance of rolling shear failure shown by the marked circles. RS is a phenomenon particularly characteristic of CLT materials, which demonstrates the unique structural challenges posed by this type of construction material.

A comparative assessment of failure distribution quantified the occurrence of each failure mechanism. Figure 8 presented the failure distribution as percentages, with trend lines depicting structural patterns, providing a graphical representation for assessing the structural integrity of various CLT configurations. The result in Figure 8 indicated that a high proportion of specimens exhibited MGF and JGF, with approximately 20-



(a) DC-MGF (b) DC-RS (c) LC-WF

(d) LT-MGF (e) DT-JGF (f) LT-JGF and WF

Figure 7. Examples of failure modes of CLT specimens showing (a) to (f).

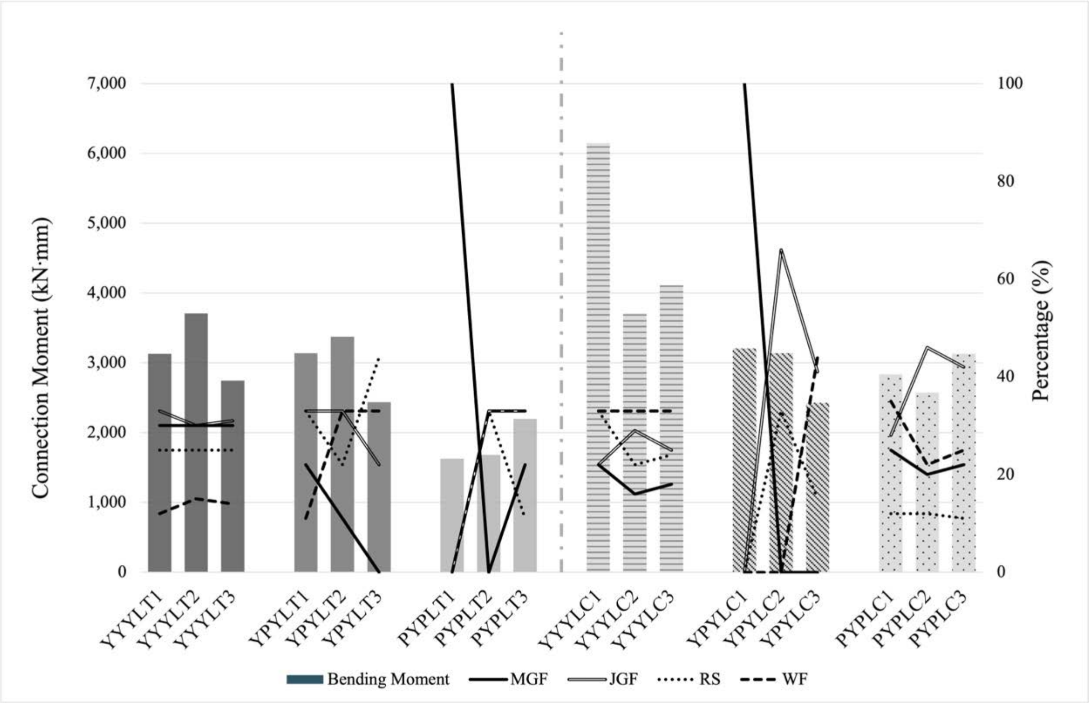


Figure 8. CLT connection moment resistance and failure modes for connections in CLT assemblies with different wood combinations.

40% experiencing MGF and 30-60% showing JGF. Specimens PYPLT1 and YPYLC1 demonstrated complete failure within the CLT material, exhibiting 100% MGF, indicating delamination. These findings emphasize the need to enhance the adhesive strength of the raw CLT materials. Additionally, there is a critical need to improve the adhesive bonding quality during the fabrication of lap joints, potentially through controlling the moisture content of the materials and utilizing adhesives more suitable for end-grain wood bonding, to improve the overall durability and structural integrity of CLT assemblies.

Conclusions

Dowel joints may offer advantages over lap joints, particularly under compression, due to their mechanical interlocking, which can enhance connection moment resistance. In contrast, lap joints were more variable, with some configurations demonstrating more inconsistency, particularly under tension loading. The study also identified potential trends across different materials and wood species, such as YPY, showing a tendency for improved performance when configured as dowel joints under compression.

Dowel joints may be more suitable for applications requiring higher resistance to compressive forces. Conversely, lap joints may require further optimization to improve their performance under tension, particularly in adhesive bonding techniques. The observed delamination and rolling shear failures highlight the need for improved adhesion and better control of properties of the parent CLT during manufacturing.

Overall, this study provides valuable insights into the performance of different CLT joinery configurations. It offers preliminary guidance for future improvements in design to optimize structural integrity and durability in furniture and other engineered wood products made of CLTs. However, further research with increased replication and broader material testing is essential to validate and expand these findings.

References

Adhikari S, Quesada H, Bond B, Hammett T (2020) Potential of hardwood lumber in cross laminated timber in North America: A CLT manufacturer's perspective. MTCJ 3(1):1–9.

Altinok M, Taş HH, Çimen M (2009) Effects of combined usage of traditional glue joint methods in box construction on strength of furniture. Mater Des 30(8):3313–3317. https://doi.org/10.1016/j.matdes.2008.12.004

Çetin Yerlikaya N, Aktaş A (2012) Enhancement of load-carrying capacity of corner joints in case-type furniture. Mater Des 37:393–401. https://doi.org/10.1016/j.matdes.2012.01.010

Chen M, Lyu J (2018) Properties of double dowel joints constructed of Medium Density Fiberboard. Maderas. Ciencia y Tecnología 20(3):369–380. https://doi.org/10.4067/S0718-221X2018005003801

Chúláin CU, Llana DF, Hogan P, McGetrick P, Harte AM (2023) Bending characteristics of CLT from recovered spruce. World Conference on Timber Engineering (WCTE 2023):888–894. https://doi.org/10.52202/069179-0121

Hassler C, McNeel JF, Denes L, Norris J, Bencsik B (2022) Challenges facing the development and market introduction of hardwood cross-laminated timbers. For Prod J 72(4):276–283. https://doi.org/10.13073/FPJ-D-22-00048

Karacabeyli E, Douglas B, FPInnovations (Institute), Binational Softwood Lumber Council (2013) CLT handbook: Cross-laminated timber.

Ma Y, Si R, Musah M, Dai Q, Xie X, Wang X, Ross RJ (2021) Mechanical property evaluation of hybrid mixed-species CLT panels with sugar maple and white spruce. J Mater Civ Eng 33(7):04021171. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003760

Maleki S, Haftkhani AR, Dalvand M, Faezipour M, Tajvidi M (2012) Bending moment resistance of corner joints constructed with spline under diagonal tension and compression. J For Res 23(3):481–490. https://doi.org/10.1007/s11676-012-0288-7

Nicholls T, Crisan R (2002) Study of the stress-strain state in corner joints and box-type furniture using finite element analysis (FEA). Holz Als Roh-Und Werkstoff 60(1):66–71. https://doi.org/10.1007/s00107-001-0262-0

Satir E, Adhikari S, Hindman DP (2024) Evaluation of bending and shear properties of mixed softwood & hardwood cross-laminated timbers. J Build Eng 96:110646. https://doi.org/10.1016/j.jobe.2024.110646

Sciomenta M, Spera L, Bedon C, Rinaldi V, Fragiacomo M, Romagnoli M (2021) Mechanical characterization of novel homogeneous beech and hybrid beech-Corsican pine thin cross-laminated timber panels. Constr Build Mater 271:121589. https://doi.org/10.1016/j.conbuildmat.2020.121589

Thomas RE, Buehlmann U (2017) Using low-grade hardwoods for CLT production: A yield analysis. *In* Möttönen V, Heinonen E, eds. *Proceedings of the International Scientific Conference on Hardwood Processing* (ISCHP2017) September 25-28, 2017, Lahti, Finland (Natural Resources Institute of Finland, Helsinki):199-206, USDA Forest Service, Northern Research Station. https://research.fs.usda.gov/treesearch/55018