Moment connections in the minor strength axis of cross-laminated timber panels

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Abstract:
Cross-laminated timber (CLT) panels are an engineered wood product that can provide two-way span action in point-supported timber floors. Due to the width limitations of CLT panels and transportation restrictions, there are challenges when designing CLT floors for two-way action with a large structural grid, amongst them the need for continuity in the minor strength axis. Most previous research focused on in-plane shear performance of the panel-to-panel connections in CLT floors. This paper presents experimental investigations assessing the structural performance of four different connections in the minor strength axis: i) plywood splines attached with inclined self-tapping screws (STS); ii) glued-on plywood splines; iii) recessed screwed-in T-joints; and iv) wooden X-Fix shear keys. Four-point bending tests were conducted to determine the bending moment capacity and rotational stiffness of these connections. The glued splines exhibited superior connection stiffness, with performance significantly influenced by plywood quality. Screwed spline connections achieved similar load-carrying capacity, accompanied with lower rotational stiffness and lower sensitivity to plywood quality. The T-joint can provide adequate rotational stiffness while the X-Fix is better suited to provide in-plane resistance and stiffness. The experimental results can be used to determine the required number of connectors to achieve the required bending moment capacity and rotational stiffness as a function of floor boundary conditions.

Keywords:
Cross-laminated timber, Rotational stiffness, Self-tapping screws, Spline connection.

1. Introduction

Cross-laminated timber (CLT) elements serve as versatile plate and shell components capable of bearing loads in out-of-plane and in-plane directions, with current applications primarily in flooring systems. The optimal utilization of CLT involves harnessing its two-way resistance, where both major and minor directions play a role in load transfer [1]. However, the out-of-plane behavior of CLT panels connected in the minor axis has only been investigated sparsely [2-4].

Connections between CLT panels play a crucial role in determining the structural performance of a floor. The most common connection technologies include spline or half-lap connections with self-tapping screws (STS) [5-6]. STS are popular due to their efficiency in distributing forces without requiring predrilling, with studies demonstrating their high strength capacity and moderate ductility. T-joints take advantage of the high STS withdrawal resistance to transfer tension and bending loads between two components [7]. T-joints resemble a root and serve as focal point where the heads of multiple STS from different directions installed at different angles converge. Alternatively, wooden shear keys like the X-Fix [8] offer self-tightening properties, and adhesive bonds like the TS3™ system [9] offer a metal-free connection option.

This research aimed to examine the structural performance of four types of connections in the minor strength axis: i) plywood splines attached with inclined STS; ii) glued-on plywood splines; iii) recessed screwed-in T-joints; and iv) wooden X-Fix shear keys.

2. Materials and methods

The experimental program employed CLT of V2M6 grade manufactured by Kalesnikoff in accordance with ANSI/APA PRG 332 [10]. A 245 mm thick CLT panel comprising seven layers, each 35 mm thick, was selected for this study to provide solutions for longer two-way spans in point-supported CLT floors.

Two variants of 18 mm (¾”)-thick Baltic birch plywood panels were utilized as spline plates: high quality grade (B) and low quality grade (C), with the latter including overlapping veneer and scattered voids. The study utilized fully threaded ASSY plus VG screws: Ø8×160 mm and Ø10×320 mm [11].

The screwed spline connection (series S1) consisted of two plywood sheets attached at the bottom of the CLT panels, effectively providing a thickness equal to that of the removed 7th CLT layer. The plywood sheet, 400 mm long in its major direction and 600 mm wide, was connected to the panels using 12 STS on each side, installed at 45-degree, see Figure 1.

Similarly, in the glued spline connections (series S2), the 7th layer of the CLT panels was removed within the connection area. Two plywood sheets, each 17 mm thick, 400 mm long, and 600 mm wide, were bonded together using Titebond III wood glue. The resulting 35 mm thick composite sheet was then adhered to the CLT panels using PL Premium Max adhesive. To ensure proper compression between the CLT panel and plywood surface, 16 STS were installed to clamp the plywood onto the CLT panels.

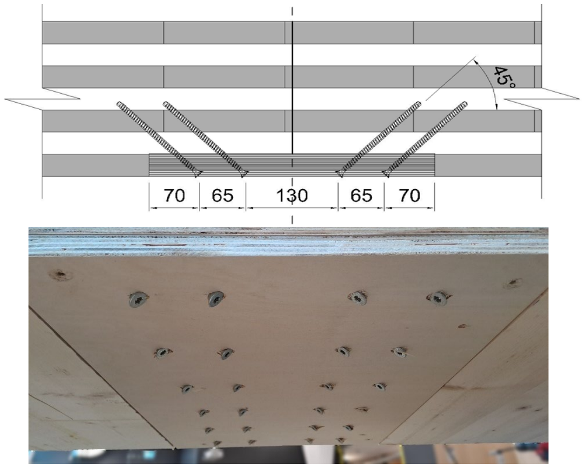

Fig 1: Spline connection with inclined STS

In series S3, four T-joints were arranged in a zigzag pattern, with a center-to-center spacing of 120 mm along the CLT panel width, as depicted in Figure 2. Each T-joint was attached with two Ø8×160 mm STS on one side at a 28˚ angle to the surface, and one Ø10 × 320 mm STS at a 30˚ angle on the other side. To achieve a flush surface, the T-joints were installed recessed into the 7th layer, approximately 18 mm based on the height of the T-joint.

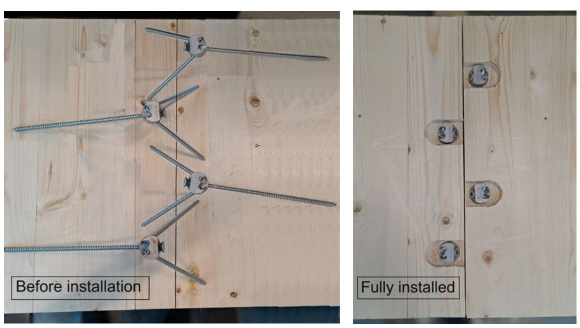

Fig 2: T-joint layout

Series S4 involved two X-Fix type C joints to secure the panels to each other, as shown in Figure 3. The X-Fix were positioned with a spacing of 300 mm at the center of the panel width. Similar to spline connections, the 7th layer was removed; however, the X-Fix were engaged the 6th, 5th, and part of the 4th layers.

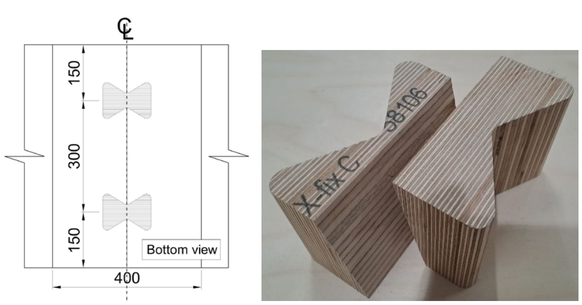

Fig 3: X-Fix connection

Four-point bending tests were performed at the Fast+Epp Concept Lab in Vancouver, BC. The length of the two connected panels was 3450 mm, and the span between the two supports was 2730 mm. The width of the panels (in the major direction) was 600 mm. The load was applied as two lines at a distance of 495 mm from the connection. Simple line supports without constraining rotational movement were provided. Two linear variable differential transformers (LVDTs) were installed to measure the mid-span deflection (Figure 4).

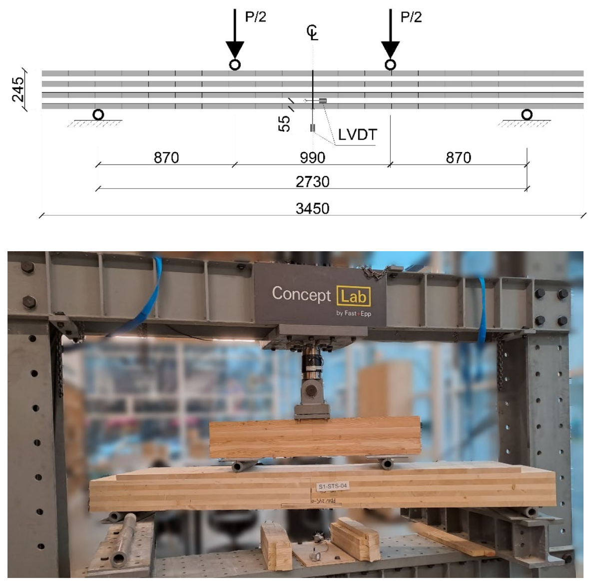

Fig 4: Four-point bending test

3. Results and discussions

Representative load-displacement curves from the four connection configurations are presented in Figure 5. Table 1 summarizes the load-carrying capacities (F_{ult}) and rotational stiffnesses (k_{φ}) for the range of 10% to 40% of the moment-rotation response.

In the screwed splines (S1), ductile performance was observed, characterized by three stages: a linear part up to a load of approximately 55 kN (about 70% of peak load), at an average deflection of 22 mm, a nonlinear part with reduced stiffness leading up to the peak load, and a gradual drop in load-carrying capacity towards the failure point. The average maximum F_{ult} of the samples was 77 kN with a coefficient of variation (CoV) of 4%, at an average displacement of 42 mm.

The load-deflection characteristics of glued spline connections (S2) exhibited linear behavior up to peak loads, immediately followed by brittle failure, rendering the connection non-functional. Specimens with high-quality plywood (S2B) exhibited an average F_{ult} and maximum deflection of 82 kN and 20 mm, respectively. Two samples fabricated with low-quality plywood (S2C) only achieved 34 kN and 11 mm, respectively, on average.

The load-deflection curve of the T-joint (S3) can be divided into three distinct segments: an initial linear phase, a subsequent phase characterized by reduced stiffness leading up to peak loads, and a final segment characterized by a descent from peak loads that resulted in failure. The average F_{ult} was 39 kN, at an average displacement of 30 mm. The linear range does not extend beyond 19 kN and 8 mm deflection. All samples demonstrated ductile behavior and the ability to experience about a 50% drop in load-carrying capacity without experiencing any failures.

The load-deflection response of the X-Fix (S4) was initially almost linear, continuing up to approximately 70% of F_{ult} which averaged 19 kN, at a deflection of 32 mm. Subsequently, as the load-displacement curve slope gradually decreased, slight fluctuations in loading were observed. Overall, these samples demonstrated a moderately ductile performance.

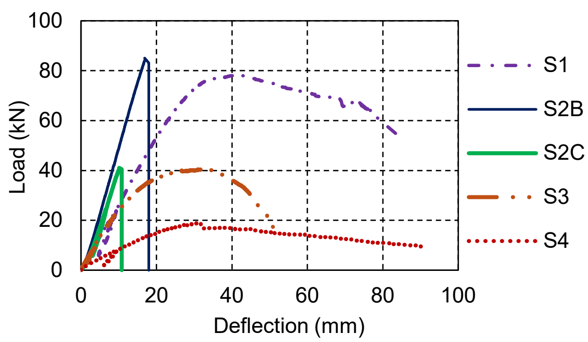

Fig 5: Typical load-deflection curves

Table 1: Results summary from 4pt bending tests

Series	F_{ult}		k_ϕ	
	[kN]	CoV [%]	[kNmrad⁻¹]	CoV [%]
S1	76.6	4	3,555	34
S2B	77.9	9	47,834	54
S2C	32.7	-	24,085	-
S3	39.2	7	2,476	32
S4	18.7	7	853	33

The corresponding moment capacities are illustrated in Figure 6. Glued splines (S2) exhibited the highest bending moment capacity, followed by the screwed spline (S1), T-joint (S3), and X-Fix (S4), with capacities at 94%, 47%, and 23% respectively, relative to S2B.

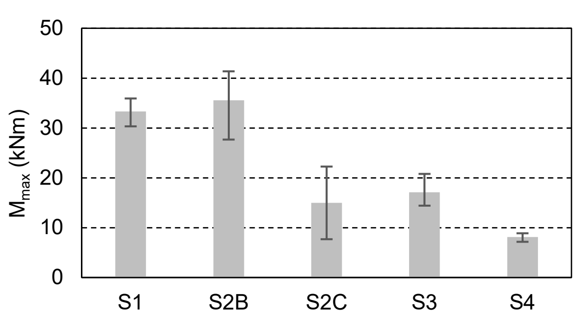

Fig 6: Moment resistance of connections

The rotational stiffness is illustrated in Figure 7. S2 samples demonstrated superior rotational stiffness, at 47,800 kNmrad⁻¹m⁻¹. Screwed connections, S1 and S3, achieved approximately 3,500 kNmrad⁻¹m⁻¹ and 2,500 kNmrad⁻¹m⁻¹, respectively. In contrast, X-Fix connections (S4) exhibited rotational stiffness values of less than 1,000 kNmrad⁻¹m⁻¹.

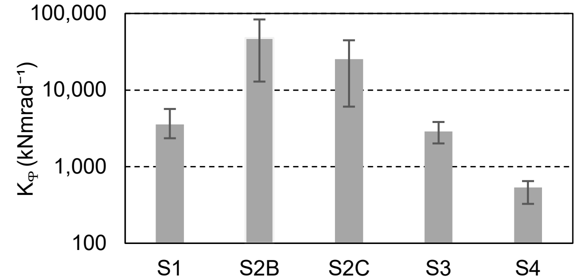

Fig 7: Rotational stiffness of connections

The failure modes of the tested connections are shown in Figures 8-12. For screwed splines (S1), ductile behavior was observed with two distinct failure modes: tension-induced failure in plywood leading to a sudden decrease in loading capacity, and screw withdrawal. In glued spline samples (S2), failure occurred at the interface between spline plate and CLT panels, with different failure patterns based on plywood grade. T-joint connections (S3) exhibited three failure modes: crushing perpendicular to the grain, withdrawal of short screws, and bending of screws due to joint rotation. X-Fix connections (S4) experienced shear failure parallel to the grain throughout the panel height and perpendicular to the grain in the 5th layer. Shear damage was also observed in the X-Fix.

Fig 8: Failure mode series S1

Fig 9: Failure mode series S2B

Fig 10: Failure mode series S2C

Fig 11: Failure mode series S3

Fig 12: Failure mode series S4

4. Conclusions and outlook

The out-of-plane behavior of connections in the minor direction of edge-connected CLT floor segments of four distinct connections were evaluated. The following conclusions can be drawn.

- Glued spline joints exhibited the highest connection stiffness, advantageous to meet serviceability requirements; however, their performance was significantly influenced by plywood quality.
- Screwed spline connections achieved a similar load-carrying capacity as the glued splines, accompanied by lower rotational stiffness and lower sensitivity to plywood quality.
- The T-joint can provide adequate rotational stiffness while the X-fix is better suited to provide in-plane resistance and stiffness.
- The experimental results can be used to determine the required number of connectors to achieve the required bending of moment capacity and rotational stiffness as a function of floor boundary conditions.

Acknowledgements

The project was supported by the Natural Sciences and Engineering Research Council of Canada through an Alliance grant. The support by Fast + Epp Concept Lab manager Brandon Sullivan and Concept Lab technician Bernhard Zarnitz is appreciated.

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