Post-failure performance of point supported CLT floors

H. Ganjali [a,*], M. Shahnewaz [b], C. Dickof [b] ,T. Tannert [a]

[a] University of Northern British Columbia, Prince George, Canada
[b] Fast+Epp, Vancouver, Canada
* Corresponding author; ganjali@unbc.ca

Abstract:
Cross-laminated timber (CLT) is an engineered wood product capable of providing two-way span action in point-supported floors. Such floor systems offer increased free story height and flexible room layout. Recent studies showed that the CLT punching shear strength close to point-supports is increased compared to the pure material rolling shear strength. However, there is a lack of understanding of post-failure performance of point-supported CLT floors and the feasibility of repairs by means of reinforcement. In this paper, experimental research on the post failure performance of CLT panels is presented. Point-supported panels were tested under punching shear condition. The first re-tested group was re-loaded until another major load drop was observed. Another group of tested panels was reinforced and repaired by means of fully threaded self-tapping screws in major and minor directions and re-tested until failure. The re-tested unreinforced and non-repaired CLT panels reached up to 85% of their initial capacity. The reinforced re-tested panels exhibited a punching shear capacity of 96% to 110% of their initial capacities. The reinforcement also helped the panels to sustain larger displacements. Furthermore, the non-repaired and reinforced re-tested panels reached 61% and 91% of their initial elastic stiffness, respectively. These findings highlight the resiliency of CLT floors and indicate the potential of repairing point supported CLT floors to regain their design strength and stiffness.

Keywords:
Cross-laminated timber, punching shear, reinforcements, self-tapping screws

1. Introduction

Cross-laminated timber (CLT) has gained popularity in as a sustainable and cost-effective alternative to traditional construction materials, particularly for floor applications [1]. This includes point-supported flat-slabs, also called post+plank, such as in the 18-storey Tall Wood House in Vancouver. In this system, the CLT panels are supported directly by columns, without the need for beams and their connections, reducing installation cost and time while allowing the layout to be readily changed by altering wall locations as well as increasing the free floor height. One of the key properties in these applications is the CLT punching shear resistance, which refers to its ability to resist concentrated loads or "punching" through the material. Recent studies showed that the CLT punching shear strength is enhanced when point-supported compared to the pure material rolling shear strength [2–4].

Self-tapping screws (STS) are recognized as state-of-the-art in fastener technology for timber structures [5,6]; they often do not require pre-drilling, are quick to install, and are therefore cost efficient. The thread provides a full mechanical connection along the screw's embedded length, which makes STS suited for the reinforcement of timber elements and connections prone to splitting [7,8]. Installed at an inclination of 45°, STS have been suggested to locally reinforce the point support zones [9]. However, there is a lack of understanding of post-failure performance of point-supported CLT and the feasibility of repairs by means of reinforcement.

2. Materials and methods

The post failure punching-shear behavior of CLT was evaluated under an edge column condition where the point support is located at the edge of two adjacent panels, as shown in Fig. 1(a). The panels were sized 1.7 m × 1.8 m in minor and major directions, respectively; however, they were cut in half to represent an edge column condition. All panels were 5-ply 175 mm thick, E1 stress grade, but made from different species.

The testing program had three phases: (I) intact panels (18), (II) non-repaired re-tested panels (3), and (III) STS reinforced re-tested panels (10). The overview of the punching shear tests is presented in Table 1.

The panels were tested under a monotonic loading protocol according to ISO 6891 [10] using a 500 kN hydraulic actuator at a loading rate of 5 mm/min; the load was applied on a 200×200 mm steel plate at the center of the panels. The panels were line-supported on four edges along the length. A steel column stub connection was used to hold the half panels together, Fig. 1(b).

The panels were re-loaded after failure to 150 kN to measure their post failure stiffness. Once the first round of loading was completed and the panels failed in punching shear, 3 specimens from the series were re-tested to failure with a non-repaired condition and the rest of the panels in each series were repaired and reinforced with STS and subsequently loaded until failure. Failure was defined as a major drop in the load carrying capacity curves of the panels.

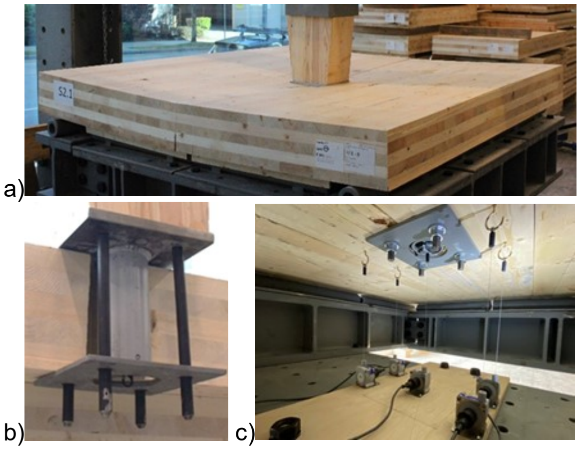


Fig 1: Test setup (a); column-to-column connection (b); location of displacement measuring sensors (c).

Table 1: Punching shear test overview.

Series	Species	Renforcement	Replicates
S07	SPF	None	6
S08	Douglas fir	None	6
S09	Hemlock	None	6
S07 R	SPF	None	1
S08 R	Douglas fir	None	1
S09 R	Hemlock	None	1
S07 RR	SPF	STS	4
S08 RR	Douglas fir	STS	3
S09 RR	Hemlock	STS	3

To measure the displacements on the underside of the specimens, one string pot was used in the center of the CLT panels with reference to the column stub, and four string pots were attached close to the corners of the underside washer plate to measure the vertical displacement of the tension face of the panel (bottom face), see Fig. 1(c). The linear part of the load vs. displacement of the CLT panels was taken the initial stiffness of the panels. It was obtained using the actuator force and the average displacement readings of the four sensors mounted on the surrounding of the underside washer plate.
The STS-reinforced series in this study were designed based on the model proposed by Mestek and Dietsch [9]. The reinforcement was expected to add roughly 30% to the punching shear capacity of an intact panel. Fig. 2 shows screw reinforcement pattern; due to symmetry, only a half panel is shown.

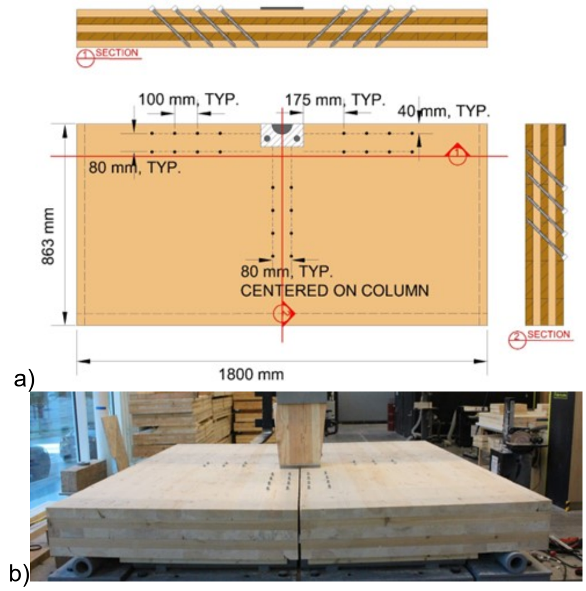


Fig 2: Self-tapping screw shear reinforcement pattern schematic (a); exemplary photo (b).

3. Results and discussions

The load vs. displacement curves of the original CLT panels vs. non-repaired retested specimens are depicted in Fig. 3 and those of the intact CLT panels vs. STS reinforced specimens are presented in Fig. 4. In both figures, the solid lines represent the intact panels. Under the first loading, panels exhibited a quasi-linear behavior up to the peak (ultimate load), however prior and after the peak load minor drops in the curves can be observed which indicate local failures and redistribution of the load. As shown in Fig. 3 and as expected, the non-repaired re-tested panels were softer compared to the intact panels. Nevertheless, although once failed in punching shear, they were able to carry loads close to those of an intact CLT panel while exhibiting lower stiffness; indicating high load re-distribution ability of CLT.

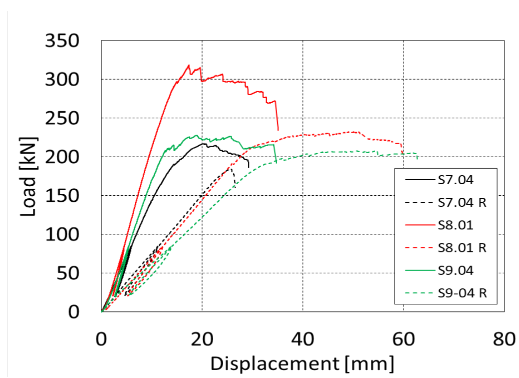
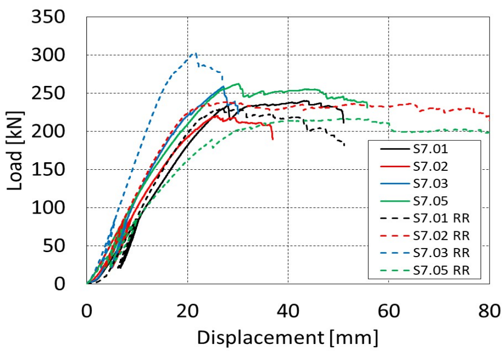
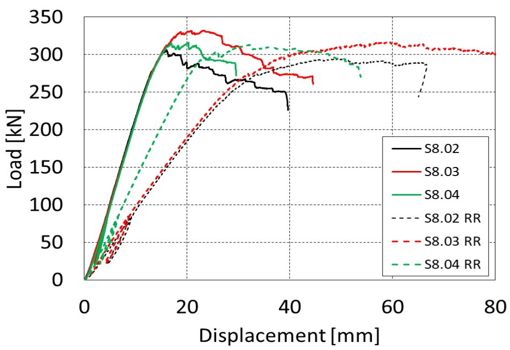


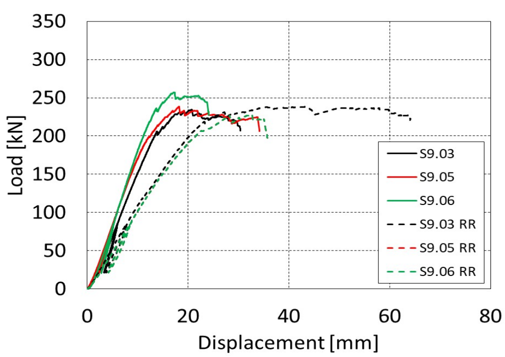
Fig 3: Intact CLT (solid line) vs. non-repaired re-tested (dashed line) specimens.



a)



b)

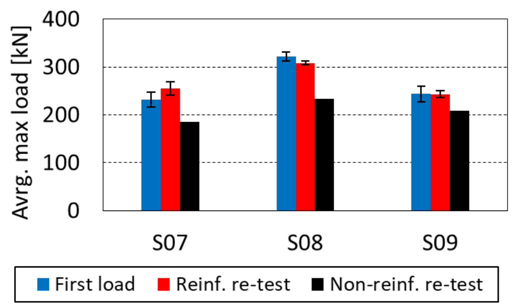


c)

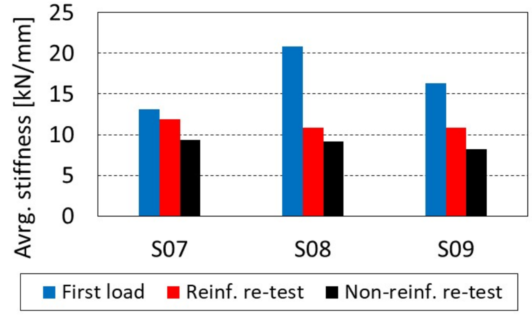
Fig 4: Intact CLT vs. STS reinforced specimens: S7 (a); S8 (b); and S9 (c).

As depicted in Fig. 4, most reinforced specimens were able to reach at least the intact CLT initial capacity and a stiffness close to that of the intact panels. The STS reinforcement also helped the panels to sustain larger displacements before experiencing a major drop in load.

The averages of the punching shear capacities are listed in Table 2 and compared in Fig. 5(a). The non-repaired CLT panels reached between 72% and 85% of the capacity of an intact CLT. Furthermore, the reinforced re-tested panels exhibited a capacity of 96% to 110% of the intact specimens. The average initial stiffness values of the series are reported in Fig. 5(b). The non-repaired and STS reinforced re-tested panels reached 45% to 61% and 52% to 91% of the elastic stiffness of the intact series, respectively. As Fig. 5(b) shows, the STS reinforcement helped the panels to partially regain their lost stiffness.



a)



b)

Fig 5: Punching shear capacity (a); initial stiffness (b).

a)

b)

c)

d)

Fig 6: Rolling shear failure close to the point support (a); non-reinforced re-tested panel (b); reinforced re-tested panel (c); and reinforced re-tested panel at a large displacement amplitude (d).

In the original panels, failure always started with minor audible cracks (not visible), followed by rolling shear failure of lamellas near the loading area, see Fig. 6(a). Unlike the failure of the intact panels, the non-reinforced re-tested panels showed signs of delamination of the boards on the compression face of the panel (top face), also the rolling shear cracks were not limited to the vicinity of the loading zone. Pronounced rolling shear cracks were observable on the outside edge of the panels, Fig. 6(b). In the reinforced re-tested panels, however, due to the presence of the STS, no delamination was observed at the ultimate load level, Fig. 6(c). Since the reinforced panels sustained the load for larger displacements, delamination was observed outside the reinforced zones, close to the supports, Fig. 6(d).

Table 2: Average punching shear capacities.

ID	Initial test		Re-test		Re-test reinf.	
	F_{max} [kN]	COV [%]	F_{max} [kN]	COV [%]	F_{max} [kN]	COV [%]
S07	231.2	6.8	185.0	-	254.9	14.5
S08	322.2	3.2	232.5	-	308.0	3.9
S09	243.7	4.8	207.9	-	242.9	6.9

4. Conclusions and outlook

Post failure punching shear behavior of non-reinforced and STS shear reinforced point supported CLT panels were investigated. The following observations were made:

- Once re-loaded, the non-repaired CLT panels reached between 72% and 85% of their initial capacity before experiencing a major load drop.
- The STS reinforced panels reached between 96% and 110% of their initial capacities.
- Reinforcement helped the panels to maintain their load carrying capacity for larger displacements.
- The non-repaired re-tested and STS reinforced panels reached 45%-61% and 52%-91% of their initial elastic stiffness, respectively. The STS shear reinforcement helped the panels to partially regain their lost stiffnesses due to the first loading.
- STS reinforcement helped the panels to sustain their integrity to a higher extent where the repaired panels did not show major signs of delamination on the compression face (top) of the panel at the ultimate load level.

The findings of this research highlight the resiliency of CLT panels and indicate the potential of repairing point supported CLT floors with STS to meet their design strength and stiffness. A higher level of STS reinforcement could be used to see its effect on the stiffness recovery of the panels.

Acknowledgements

The project was supported by the Province of British Columbia's 'Green Construction Through Wood' program and the Natural Sciences and Engineering Research Council of Canada through an Alliance grant. The support by the UNBC technicians James Andal and Ryan Stern, as well as Fast + Epp Concept Lab manager Brandon Sullivan and Concept Lab technician Bernhard Zarnitz is appreciated.

References

[1] E. Karacabeyli, S. Gagnon, Canadian CLT handbook, (2019), FPInnovations, Canada.

[2] H. Ganjali, et al., Punching-shear strength of point-supported CLT floor panels, In proc. INTER. Biel, Switzerland (2023).

[3] M. Muster, Column-Slab Connection in Timber Flat Slabs, Doctoral Thesis, ETH Zurich, (2020).

[4] P. Mestek, Punktgestützte Flächentragwerke aus Brettsperrholz (BSP) – Schubbemessung unter Berücksichtigung von Schubverstärkungen, PhD dissertation, Technische Universität München (2011).

[5] Dietsch, P., Brandner, R. (2015). Self-tapping screws and threaded rods as reinforcement for structural timber elements – A state-of-the-art report. Construction and Building Materials, 78-89.

[6] Hanna, D., Tannert, T. (2021) Glulam connections assembled with a combination of screws. Madera ciencia y tecnologia, 62(3): 1-23

[7] Tannert, T., Lam, F. (2009). Progress in Structural Engineering and Materials : Timber Construction Self-tapping Screws as Reinforcement for Rounded Dovetail Connections. Structural Control and Health Monitoring, 16(3), 374-384.

[8] Jockwer, R., Steiger, R., Frangi, A. (2014). Design model for inclined screws under varying load to grain angles. In Proceedings of International Network on Timber Engineering Research. Bath, United Kingdom.

[9] P. Mestek, P. Dietsch, Design concept for CLT-reinforced with self-tapping screws, in: Focus Solid Timber Solutions-European Conference on Cross Laminated Timber (CLT). Graz, Austria (2013).

[10] ISO 6891, Timber structures, Joints made with mechanical fasteners, General principles for the determination of strength and deformation characteristics, International Organization for Standardization (ISO), (1983).