Cross-laminated timber concrete composite systems for long-span floors

M. Shahnewaz, Ph.D.[1], R. Jackson P.Eng., Struct.Eng., P.E.[2], and T. Tannert, P.Eng., Ph.D. M.ASCE[3]

[1] Specialist Engineer, Fast + Epp, Vancouver, Canada; mshahnewaz@fastepp.com
[2] Associate Principal, Robert Jackson, Fast + Epp, Vancouver, Canada; rjackson@fastepp.com
[3] Professor, UNBC, Prince George, Canada; thomas.tannert@unbc.ca

ABSTRACT

Experimental investigations on full-scale (30') and half-scale (15') cross-laminated timber (CLT) timber-concrete-composite (TCC) slab bands are presented. The out-of-plane shear and ultimate flexural capacities of these TCC floors utilizing several types of shear connectors were determined. The TCC system was comprised of a 245mm thick, 7-ply cross-laminated timber (CLT) with 150 mm concrete topping joined with shear connectors. The efficiency of three types of shear connectors: self-tapping screws, steel kerf plates, and proprietary glued-in connectors was evaluated. Six series of floor systems, one control series of raw CLT floors (without concrete topping) and five TCC series were tested for a total of 6-half scale control slabs, 18-half scale, and 6-full scale TCC slabs were tested under four-point bending. The results from this research were utilized to make project-specific design decisions for "The Arbour", a 10-storey mass timber building for George Brown College, located in Toronto, Canada.

INTRODUCTION

Cross-laminated timber (CLT) is gaining popularity in residential and non-residential structural applications in North America. CLT panels can offer many advantages compared to traditional light-frame wood construction, e.g. the cross-lamination provides improved dimensional stability (Karacabeyli and Gagnon 2019) and high in-plane strength and stiffness (Shahnewaz et al. 2017). However, long-span CLT floors suffer from poor vibration performance. Adding a structural concrete topping and connecting the components with shear connectors results in Timber-Concrete Composite (TCC) floor systems which can overcome some of the inefficiencies associated with conventional reinforced concrete or light wood frame floors regarding section depth, stiffness, and vibration performance (Yeoh et al. 2011, Dias et. al. 2016).

The efficiency of TCC depends largely on the material properties of timber and concrete and the shear connections between the two materials. A wide range of TCC systems has been extensively studied in recent years, using mechanical connectors such as self-tapping screws (STS) (Derikvand and Fink 2021), adhesive bonds (Tannert et. al. 2017), or hybrid bonded systems (Tannert et al. 2019). The objective of the research program presented herein was to investigate long-span CLT TCC floors systems with three different shear connectors.

EXPERIMENTAL INVESTIGATION

Materials

The composite floors were comprised of 245 mm thick, 7-ply CLT with 150 mm concrete topping. The CLT was manufactured from SPF lumber, strength grade 2100 Fb-1.8E according to CSA O86 (2019). The minimum specified concrete compressive strength was 35 MPa. The concrete was made of Type I Portland cement with maximum aggregate size of 10 mm and with a superplasticizer to achieve a high slump of minimum of 80 mm. Grade A36 steel plates, with 6 mm thickness were used as TCC connectors, installed into 7mm wide kerfs without adhesive.

Connectors and reinforcements

Three types of shear connectors were applied. Type 1 connectors were fully threaded STS 11× 250 mm installed at an angle of 45^0 and spaced 150 mm and 300 mm, for the outer and middle one-third span, respectively (Figure 1a). Type 2 connectors were 2100 mm long and 75 mm deep steel kerf plates are placed at 300 mm for the outer one-third spans and space of 1000 mm for the middle span (Figure 1b). Type 3 TCC connectors were proprietary glued-in Holz-Beton-Verbund (HBV) meshes, 90 mm deep with the spacing and length shown in Figure 1c.

The estimated stiffness for Type 1, 2, and 3 TCC connectors were 83 kN/mm, 524 kN/mm (Shahnewaz et al. 2021), and 412 kN/mm, respectively. Additionally, the CLT panels were also half-reinforced or full-reinforced with fully threaded STS 11×300 mm screws at 45^0 (Table 1).

Table 1. Shear connector description

Type	Connector	Description
TCC Type 1	STS 11x250	Installed at 45^0 to grain
TCC Type 2	6x75x2100 mm grade A36 steel plates	Installed into 7 mm wide saw kerf
TCC Type 3	90 mm deep HBV mesh	Glued into 3 mm wide saw kerf with polyurethane adhesive

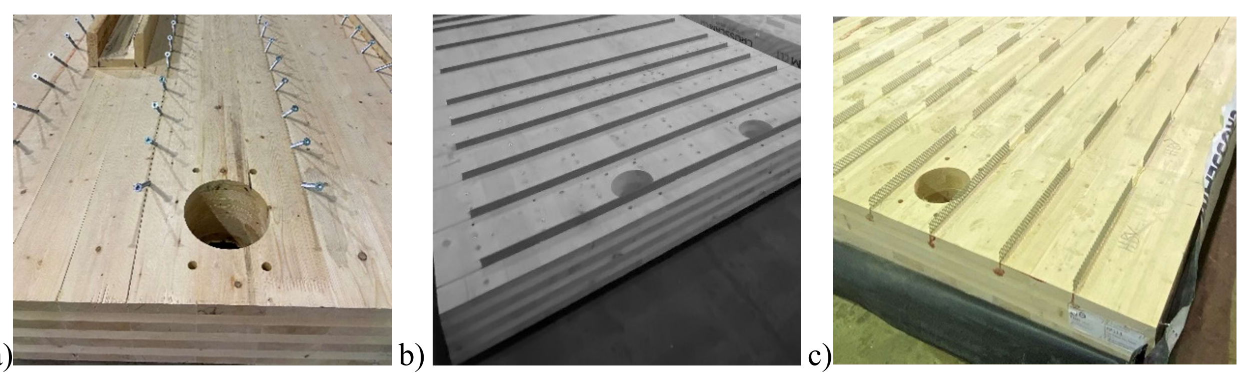
a)  b) c)

Figure 1. a) Type 1 screws, b) Type 2 kerf plate, c) HBV mesh.

Half-scale floor tests

Half-scale specimens were 2.4 m wide and 4.8 m long, tested under four-point bending at the University of Northern British Columbia Wood Innovation and Research Laboratory in Prince George. Series S-2 consisted of CLT panels with no concrete topping (Figures 2a-c). Two replicates of unreinforced, half-reinforced, and full-reinforced CLT panels were tested.

Figures 2d-f show the half-scale TCC specimens. All half-scale TCC floor systems in series 3 to 5 were tested as unreinforced, half-reinforced, and full-reinforced CLT panels for a total of 18 specimens. The floors were connected to 430 × 1178 mm glulam columns by 12.7 mm diameter, 250 mm long glued-in threaded rods. The glulam columns are connected to the concrete strong floor by steel angles and bolts. Loads were applied to the floors at approximately one-third points using four hydraulic actuators with a total capacity of 1500 kN. The actuator loads were distributed equally to one-third points using steel beams and a timber spreader bearing strip.

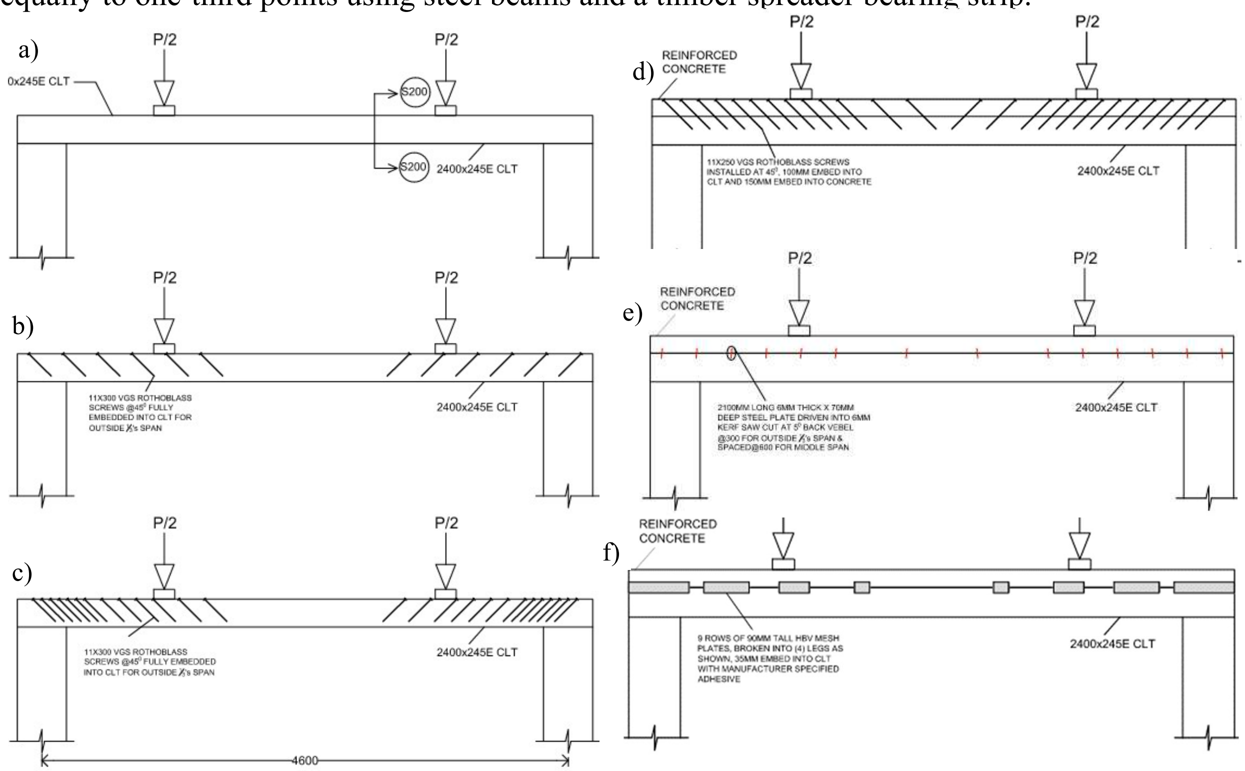


Figure 2. Half-scale CLT panels: a) unreinforced, b) half-reinforced, and c) full-reinforced; half-scale TCC floor specimens with: d) Type 1, e) Type 2, and f) Type 3 connectors

Full-scale floor tests

Two TCC floors from each system with Type 1, 2, and 3 connectors, a total of 6 floors were tested which were comprised of half-reinforced CLT. The full-scale TCC specimens were 2.4 m wide and 9.6 m long and were tested with all three types of TCC connectors (Figure 3) under four-point bending. The support and loading conditions, shown in Figure 4, were identical to those described for the half-sale floors.

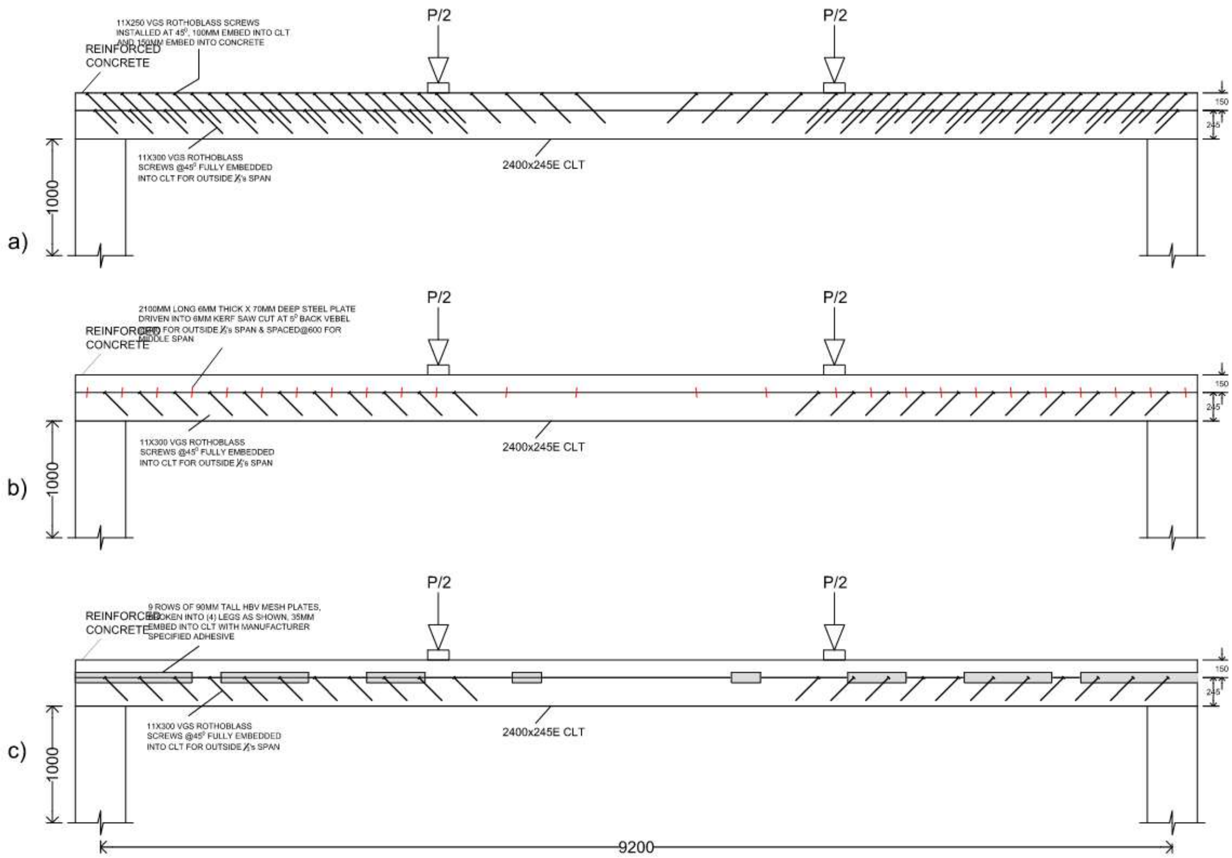


Figure 3. Series 6: Full-scale TCC floor specimens with: a) Type 1, b) Type 2, and c) Type 3 connectors

Figure 4. Test Setup of a Full-Scale TCC Floor

Half-scale test results

The mid-span load-deflection curves of all specimens from series S2 are illustrated in Figure 5a. The unreinforced panels failed in shear at an average load of 885 kN and reached a displacement of on average 53 mm. The half-reinforced and full-reinforced panels failed in shear at an average load of 968 kN (+9%) and 968 kN (+26%), respectively, and reached an average displacement of 61 mm and 66 mm, respectively. Results showed that by fully reinforcing the CLT, the failure mechanism is moved from shear to bending.

The mid-span load-deflection curves of all six specimens from series S3 with Type 1 composite connectors, 45^0 inclined screws, are illustrated in Figure 5b. The unreinforced panels failed in shear at an average load of 1445 kN and reached a displacement of on average 52 mm. One of the half-reinforced TCC panels failed in shear at 1487 kN (+9%) at a displacement of 53 mm. The second half-reinforced panel as well as the two fully reinforced panels did not fail after reaching loads of approx. 1480 kN and displacements of on average 44 mm. These three panels were re-tested with a three-point bending configuration and all failed in bending when reaching a maximum bending moment of on average 1142 kNm.

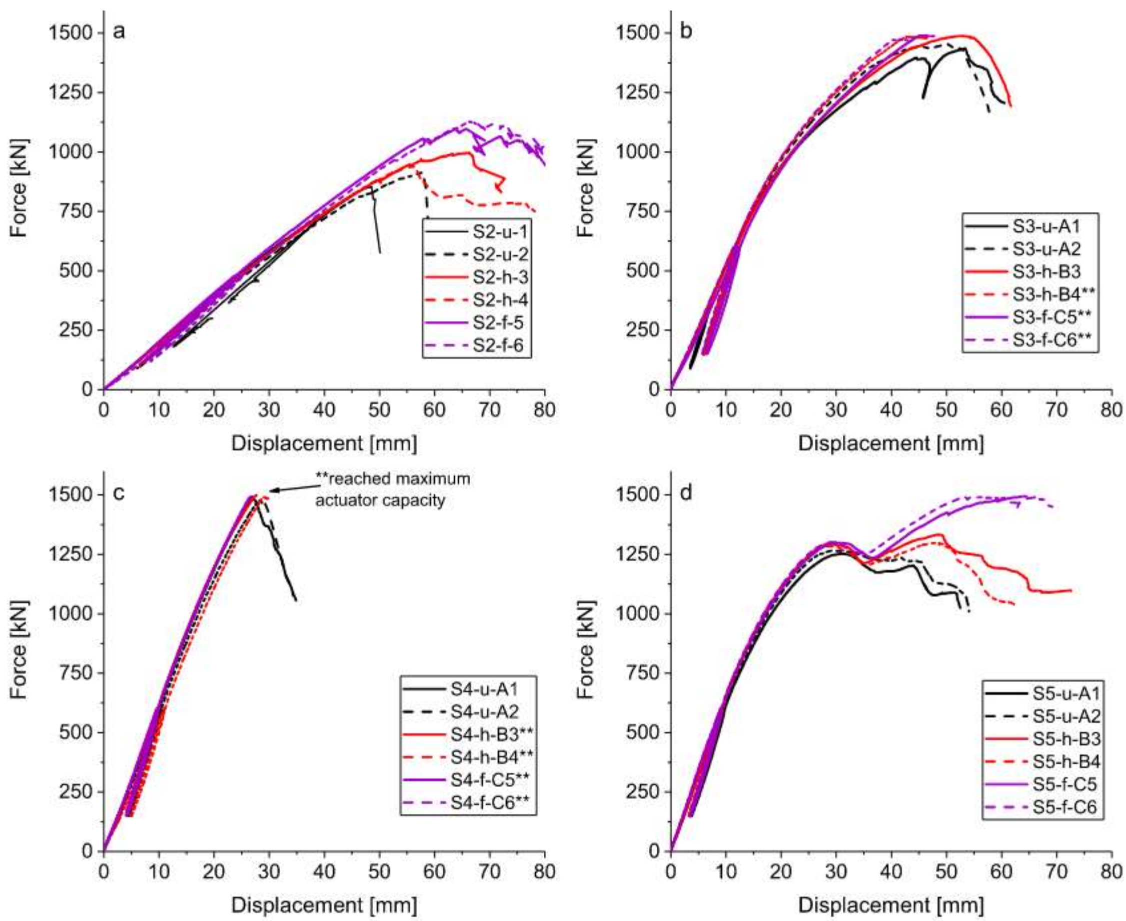


Figure 5. Half-scale load-deflection curves: a) Series S2, b) Series S3, c) Series S4, d) Series S5

The mid-span load-deflection curves of the six TCC floors from Type 2 composite connectors, steel kerf plates, are illustrated in Figure 5c. The unreinforced panels failed in shear at an average load of 1482 kN and reached a displacement of on average 28 mm. All half- and fully reinforced panels did not fail under 4pt-bending after reaching loads of 1490 kN and displacements of on average 27 mm. These panels were re-tested under 3pt bending and all failed when reaching a maximum bending moment of on average 1517 kNm and 1431 kNm for specimens B and C, respectively. The initial stiffness of all panels was very similar with the only panel being 6% less stiff than the average.

The mid-span load-deflection curves of all six TCC floors from series S5 with Type 3 composite connectors using HBV are illustrated in Figure 5d. The unreinforced panels failed in shear at average loads of 1261 kN at displacements of on average 30 mm. The connectors in the half-reinforced and full-reinforced panels yielded at a load where the HBV mesh capacity was reached at on average 1295 kN at displacements of on average 31 mm. Due to the reinforcement, a further increase in load was possible and these panels failed in shear at average loads of 1313 kN at displacements of on average 48 mm 1492 kN at 60 mm. The initial stiffness of all panels was very similar.

Full-scale test results

The mid-span load-deflection curves of all six full-scale TCC specimens in Series 6 tested with all 3 types of composite connectors are illustrated in Figure 6a. The panels with composite connector Type 1, screws failed in bending at an average load of 706 kN and a displacement at failure of on average 124 mm. The panels with composite connector Type 2, steel kerf plates failed in bending at an average load of 1,040 kN and a displacement at failure of on average 124 mm. The panels with composite connector Type 3, HBV mesh failed in connector shear at an average load of 670 kN and a displacement at failure of on average 76 mm. The initial stiffness of the panels with screws and the HBV mesh was similar, the stiffness of the panels with steel kerf plates was approximately twice as high.

The average flexural demand of the full-scale TCC specimens was 677 kN.m. When compared to the capacity observed from the full-scale testing, the average capacity-to-demand ratio at the service loading for the TCC specimens with screws (S6-A), kerf plates (S6-B), and HBV mesh (S6-C) were estimated at 1.62, 2.39, and 1.54, respectively. At service loads, the average mid-span deflection observed in the TCC specimens with screws (S6-A), kerf plates (S6-B), and HBV mesh (S6-C) were 70 mm, 59 mm, and 63 mm, respectively. The full-scale specimens with Type 1 and Type 2 connectors failed in bending at mid-span (Figures 6b and 6c). The initial failure in the TCC specimens with Type C connectors, HBV mesh, happened in the connector with the final subsequent failure occurred at mid-span due to bending (Figure 6d).

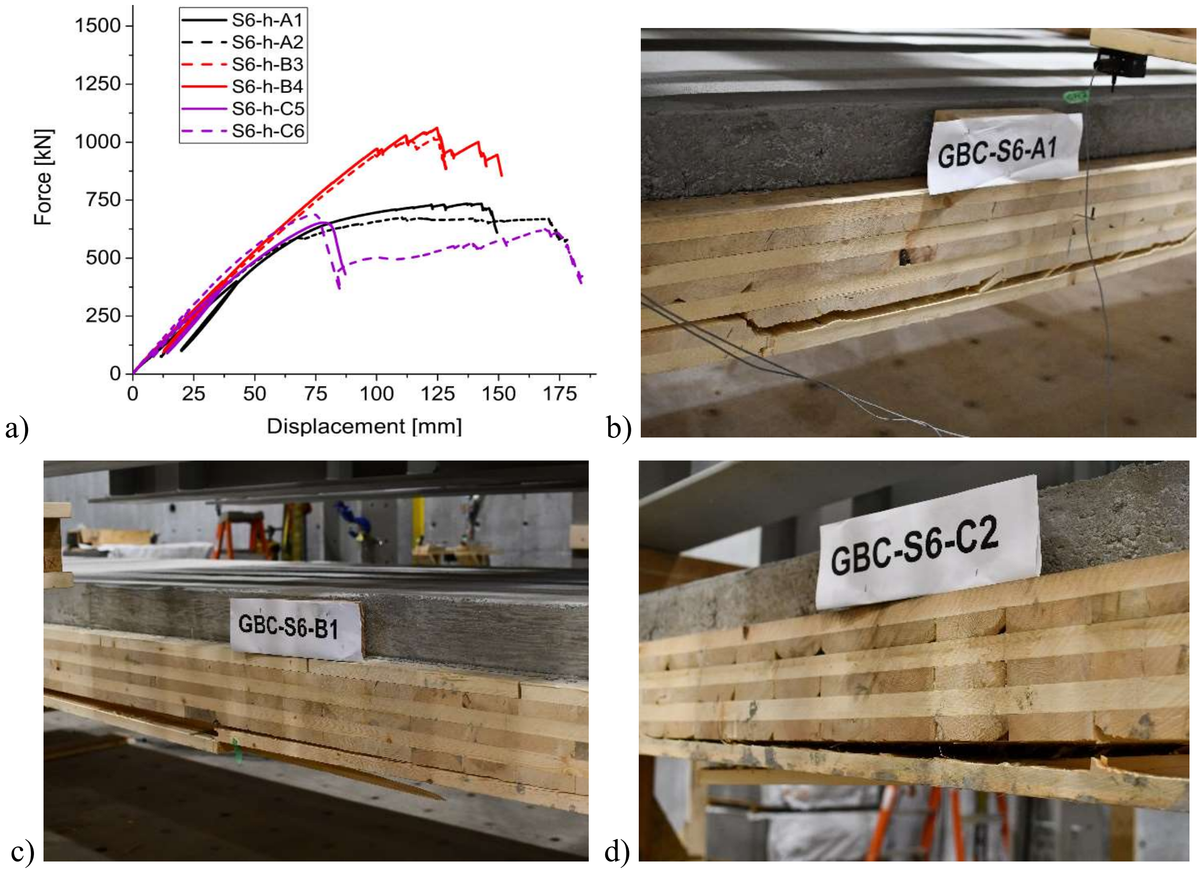


Figure 6: a) Full-scale load-deflection curves; Failure at mid-span in b) S6-A, c) S6-B and d) S6-C

CONCLUSIONS

A comprehensive test program was designed to systemically investigate the performance of various TCC floor systems with screws, steel kerf plates, and HBV as shear connectors. The following key conclusions can be drawn from this testing program:

1) The screw reinforcement in the CLT itself greatly increased the shear capacity of the panels, shifting the mode of failure from shear to bending.
2) The 150 mm concrete topping compositely connected to the CLT panel significantly improved out-of-plane shear capacity by up to 167% when compared to raw CLT panels.
3) Under short-term loading, sufficient shear capacity was observed in all TCC floors, including unreinforced specimens. However, considering the reduced rolling shear capacity of CLT under long-term loading, half-reinforced CLT panels were selected for the actual project.
4) Weak-axis shear failure can be avoided by adding diagonal reinforcing screws in the transverse direction at the end of slab bands, which was incorporated.
7) TCC with steel kerf plates exhibited the highest capacity and stiffness and were priced by multiple suppliers to be the most economical option.

The results from this research were utilized to make project-specific design decisions for "The Arbour", a 10-storey mass timber building for George Brown College, located in Toronto, Canada.

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