EXPERIMENTAL STUDY OF TIMBER–TIMBER COMPOSITE MEMBERS

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ABSTRACT
Timber is a sustainable construction material having a higher strength to density ratio, lower embodied energy and a lower carbon footprint when compared with conventional construction materials such as steel and concrete. Furthermore, the advent of engineered wood products including glued laminated timber (Glulam), cross laminated timber (CLT) and laminated veneer lumber (LVL) with improved mechanical properties and dimensional stability has provided the opportunity to construct multi-storey timber buildings with robustness and reliability comparable to steel and reinforced concrete structures, but with far less environmental intrusion. This paper investigates the behaviour of CLT panels connected to LVL and/or Glulam timber joists by coach screws, creating a timber–timber composite (TTC) member. The load-slip behaviour and failure modes of the CLT–LVL and CLT–Glulam composite members are characterised by conducting push-out tests and the effect of the CLT lamellae orientation, screw size and inclination and the edge distance in conjunction with the type of timber joist (LVL, softwood/hardwood Glulam) on the structural behaviour of the TTC members are investigated. Finally, an empirical model for the load-slip response of the TTC members with dowel connections is developed and calibrated from non-linear regression of the push-out test data.
Keywords: cross laminated timber (CLT), load-slip, screw, shear connector, timber–timber composite (TTC).

1 INTRODUCTION
Timber is a sustainable construction material having a higher strength to density ratio, less embodied energy and a lower carbon footprint than conventional construction materials such as steel and concrete. Furthermore, the advent of engineered wood products including glued laminated timber (Glulam), cross laminated timber (CLT) and laminated veneer lumber (LVL) with improved mechanical properties and dimensional stability has provided the opportunity to construct multi-storey timber buildings with robustness and reliability comparable to those of steel and reinforced concrete structures, yet with much less adverse effect on the environment [1], [2]. Apart from the obvious environmental advantages of timber, in mid- to high-rise buildings, light-weight timber floors can significantly reduce the self-weight of the structure. This attribute in turn can reduce the cost of footings, particularly in construction sites with problematic soil, and it also reduces seismic induced inertia forces. Timber floors with mechanical shear connectors (screws or bolts) can also increase the speed of construction, reduce the cost of labour at construction sites and provide much flexibility in terms of deconstruction, recycling and/or reuse of the construction materials and structural components at the end of the service life of the building.

The structural performance of timber-to-steel composite joints and beams has been comprehensively studied by Hassanieh et al. [3]–[5] and Loss and Davison [6] and Loss et al. [7], but research on timber-to-timber connections mainly focuses on the behaviour, analysis and modelling of dowel type connectors and the structural performance of lap and/or edge joints [8], [9], with less attention being paid to the structural behaviour of timber-to-timber composite connections [10], [11]; in particular to CLT–LVL and CLT–Glulam composite connections for the development of prefabricated timber–timber composite (TTC)

floors. Recently, Branco et al. [12] investigated the in-plane behaviour of traditional timber floors strengthened with CLT panels using SFS, HBS and VGZ screws installed normal and inclined (at 45°) to the shear plane.

Due to a dearth of test data on TTC joints with screw connections, the short-term behaviour of CLT–LVL and CLT–Glulam composite joints is evaluated herein by conducting symmetric push-out tests. The failure mode, load-slip response, peak load carrying capacity and stiffness of TTC joints with LVL and softwood/hardwood Glulam beams and with different coach screw sizes, inclination and edge distance are reported and discussed. Non-linear regression of the push-out test results is then carried out and empirical load-slip formulae for CLT–LVL and CLT–Glulam composite joints with coach screw shear connectors are derived.

2 EXPERIMENTAL PROGRAM

Thirteen different TTC push-out specimens (two identical specimens of each TTC type) with symmetric configuration were fabricated and tested. The push-out specimens comprised of two CLT panels connected to either LVL or Glulam (hardwood and softwood) timber joints by coach screws. The main variables in the push-out tests were the type of timber joists (LVL, softwood Glulam, hardwood Glulam), size of the screws (12, 16 and 20 mm) and the inclination angle of the screws with respect to the shear or interface plane (45° and 90°) and the direction of shear/loading with respect to the grain of outer layer of the CLT panels. The loading and geometric configuration, dimensions and details of the push-out specimens and the type of screws are shown in Fig. 1 and in Table 1.

The CLT panels used in the fabrication of the push-out specimens were 120 mm thick and 400 mm wide (Fig. 1). The CLT panels were made of five Spruce lamellae of strength class C24 according to BS EN 338 [13]. The mean moisture content (MC) of the panels measured by oven dry testing according to AS/NZS 2098.1 [14] was MC = 11% and the mean density of the CLT panels was 500 kg/m^3. The mechanical properties of the CLT panels were as reported in Hassanieh [15] and given in Table 2. In the push-out specimens, the CLT panels were loaded either parallel or perpendicular to the direction of the grain in the outer layers and accordingly the push-out specimens were categorised into two different classes: parallel and perpendicularly loaded (Table 1).
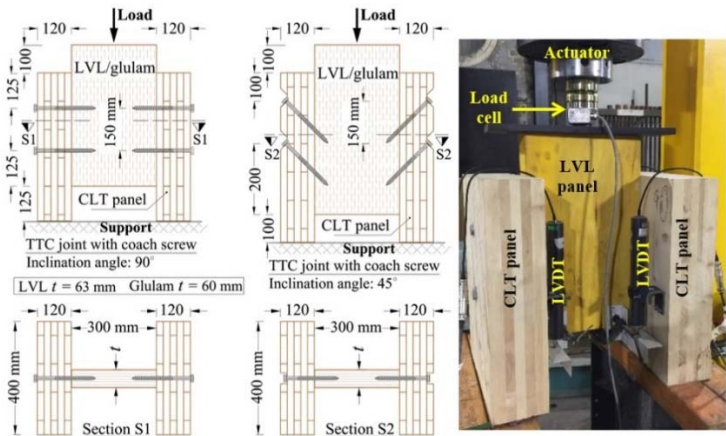

Figure 1: Outline of push-out tests and specimens with 90° and 45° coach screw inclination.

Table 1: Details of push out specimens.

Specimen No.	Connector size Dia. × Length (mm)	Timber joist type	CLT panel orientation#	Screw angle to shear plane
1	12×200			
2	16×200	LVL	Parallel	90°
3	20×200			
4	16×200	Glulam	Parallel	90°
5	20×200	Pacific Teak		
6	16×200	Glulam	Parallel	90°
7	20×200	Slash Pine		
8	12×200			
9	16×200	LVL	Parallel	45°
10	20×200			
11	12×200			
12	16×200	LVL	Perpendicular	90°
13	20×200			

Direction of loading (shear force) with respect to outer layers of CLT panels.

Table 2: Mechanical properties of CLT panels (in MPa).

Bending (f_b)	Tension ‖ to grain (f_t)	Shear in beams (f_s)	Compression ‖ to grain (f_c)	Compression ⊥ to grain (f_p)	Elastic modulus (E)	Rigidity modulus (G)
24	16.5	4.6	24	2.7	12000	690

Table 3: Mechanical properties of LVL panels (in MPa).

Bending (f_b)	Tension ‖ to grain (f_t)	Shear in beams (f_s)	Compression ‖ to grain (f_c)	Compression ⊥ to grain (f_p)	Elastic modulus (E)	Rigidity modulus (G)
50	25	4.6	41	12	13200	660

The LVL panels used in the fabrication of the TTC specimens were 63 mm thick and the panels were made from Radiata Pine laminated veneers. The mechanical properties of the LVL panels obtained in accordance with the specifications of AS/NZS 4357.0 [16] are given in Table 3. Before testing, the LVL panels had MC = 11% and the mean density of the LVL panels was 600 kg/m³.

Two different Glulam beams, made of Slash Pine (softwood) and Pacific Teak (hardwood) lumbers, were used in the fabrication of the push-out specimens. The Glulam beams were 60 mm wide and 300 mm deep. The average moisture content of the specimens obtained from oven dry testing was MC = 10%. The mean density of the Slash Pine and Pacific Teak Glulam beams were 690 kg/m³ and 780 kg/m³ respectively, while the elastic modulus of Slash Pine and Pacific Teak Glulam beams were 12.6 and 14.3 GPa respectively. Hexagonal coach screws having 12, 16 and 20 mm diameters were used in the fabrication of the specimens. The overall length of coach screws was 205–210 mm and the coach screws were made of Grade 4.6 steel with characteristic yield and ultimate strengths of 240 MPa and 400 MPa respectively. Uniaxial tension tests were conducted on three identical screws and the stress–strain response and mechanical properties of the screws were determined. The mean yield and ultimate strength and elastic modulus of the tested screws were 305 MPa, 430 MPa and 195 GPa respectively.

To facilitate the testing, to minimise the unwanted friction between the CLT panel and LVL/Glulam beams and to achieve a relatively uniform load distribution along the connectors, a symmetric configuration was used for the push-out specimens. The CLT panels and LVL/Glulam joists were pre-drilled to facilitate the installation of coach screw shear connectors and to minimise the risk of splitting the LVL/Glulam beams. The diameter of predrilled holes was 2 mm smaller than the diameter of the coach screw shear connectors. Each CLT panel was connected to the timber joists by two coach screws (Fig. 1). The two coach screw shear connectors on each side of the push-out specimens were 150 mm apart (Fig. 1), that complies with the minimum spacing requirements of $7d_s$ (d_s = screw shank) for the inclined screws [17].

The relative displacement (slip) between the CLT panels and LVL/Glulam beams was measured by four linear variable displacement transducers (LVDTs) having a maximum stroke of 100 mm mounted on four sides of each specimen (Fig. 1). The relative slips measured by the four LVDTs were also used to ensure that the specimens were not tilting or twisting during the tests. An actuator with a capacity of 500 kN was used to apply the load in the vertical direction on the LVL/Glulam joists as shown in Fig. 1.

The loading regime for push-out tests followed the protocol specified in BS EN 26891-1991 [18], consisting of three stages. In the first stage, the specimen was loaded up to 40% of the estimated ultimate strength F_{est} in 120 seconds and the load remained steady at $0.4F_{est}$ for 30 seconds. In the second stage, the specimen was unloaded to $0.1F_{est}$ in 120 seconds and maintained at $0.1F_{est}$ for 30 seconds. In the final stage, the specimen is reloaded up to 70% of the ultimate load carrying capacity using a load-controlled regime, and then testing was conducted under a displacement-controlled regime (with a rate of 2 mm/s) until the onset of failure. The ultimate strength of the TTC joints in the current study was estimated using the European Yield Model (EYM) considering the plastic behaviour of the timber and mechanical fasteners [18].

3 DISCUSSION OF TEST RESULTS

Assuming a single shear plane for each mechanical fastener connecting the two timber components in TTC joints with unequal embedment strengths and different thickness (f_{e1}, f_{e2}, t_1, and t_2), six distinctive failure modes can be identified in general as shown in Fig. 2. The occurrence of each failure mode depends on the embedment strength of the timber components, the effective thickness of each component (or embedment length of the fastener) and the yield moment (strength) of the mechanical fasteners. The first two modes of failure (Modes I and II) are associated with lateral crushing of the timber (either in the CLT or LVL/Glulam joists) near the mechanical connectors without significant deformation in the shear connectors. In failure Mode III, lateral yielding occurs in both timber components simultaneously. The failure Modes IV and V are associated with formation of only one plastic hinge within the shear connectors, whereas in Mode VI two plastic hinges develop within the connectors. The failure modes I to III are brittle, but modes IV to VI can be categorised as ductile modes of failure. Apart from the six distinctive failure modes shown in Fig. 2, possible splitting of the timber joists and withdrawal of the coach screws should be also considered as separate failure modes.

The TTC specimens tested in this study mostly exhibited two failure modes, i.e. Modes V and VI, depending on the size and inclination angle (i.e. 90°, 45°) of the coach screw shear connectors, as in Fig. 3. However, in TTC joints with inclined (45°) coach screw shear connectors, only failure Mode V was observed irrespective of the screw size. Furthermore, in the TTC joints with inclined screws, signs of withdrawal failure (i.e. separation of the CLT
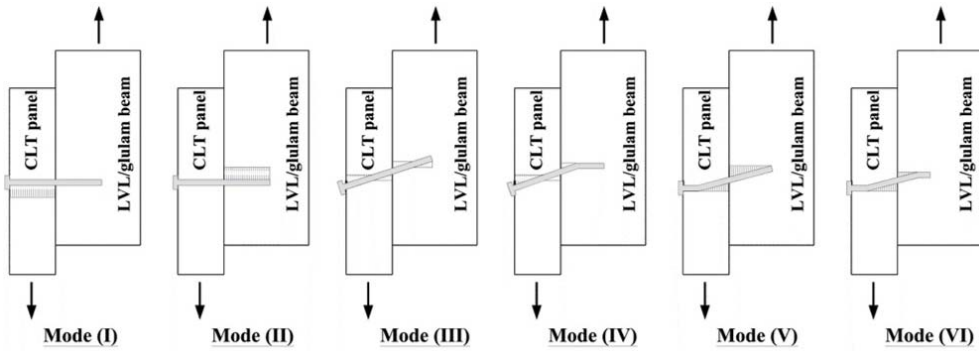
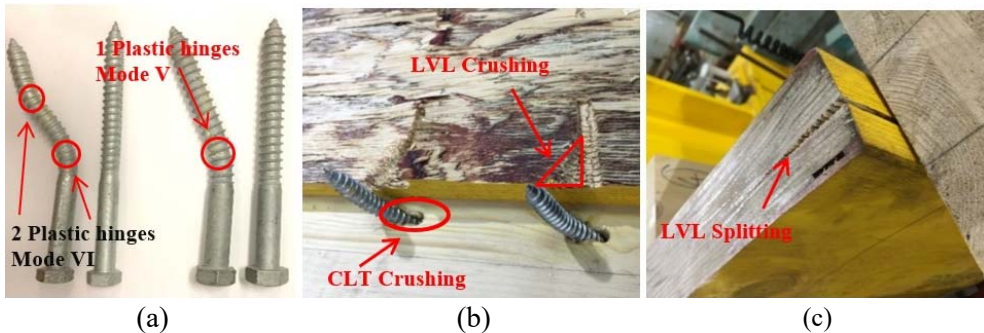Figure 2: Different modes of failure in TTC joints.

Figure 3:   (a) Development of plastic hinges in 12 mm and 20 mm coach screw shear connectors; (b) Lateral crushing of CLT and LVL in failure Mode V; and (c) Splitting of LVL joist in TTC joint with 20 mm coach screw shear connectors.

panel from the LVL joist) was observed at later stages of the push-out tests. The failure modes of all TTC joints are summarised in Table 4.

In TTC joints with large diameter coach screws, apart from lateral crushing of the timber and plastic deformation in the coach screw shear connectors, splitting of the timber joist and withdrawal of the shear connectors were also observed during large slips exceeding 30 mm (Fig. 5(c)). In TTC joints with softwood Glulam (Slash Pine) and LVL joists, splitting of timber was only evident in specimens with 20 mm coach screw shear connectors (edge distance
< $1.6d_s$). However, in TTC joints with hardwood Glulam (Pacific Teak) joists, splitting of the joist was observed in specimens with 16 and 20 mm screws (edge distance < $1.9d_s$). Considering the width of the LVL joists (63 mm) and Glulam joists (60 mm), it was concluded that the minimum edge distance of 2ds specified in the timber design code EC5 [17] can adequately safeguard the composite connections between CLT and LVL/Glulam joists against splitting.

The experimental load-slip behaviour of two identical CLT–LVL symmetric joints with S12 and S16 coach screw shear connectors (in total four plots for each shear connector size) is shown in Fig. 4 to demonstrate the variability of the push-out test results. The coefficient

Table 4: Mean ultimate strength, ultimate slip and serviceability slip modulus k_s,0.6.

Specimen No.	Mean ultimate strength (kN)	Mean ultimate slip (mm)	Slip modulus $k_{s,0.6}$ (kN/mm)[#]	Failure mode (Fig. 3)[##]
1	19.0	34.5	0.91	VI
2	23.6	21.5	1.87	VI
3	27.7	31.0	2.27	V
4	26.4	30.5	2.87	VI
5	31.9	23.5	3.10	V
6	21.9	30.9	2.88	VI
7	27.3	24.1	1.79	V
8	15.3	5.4	6.87	V
9	17.3	6.9	5.38	V
10	20.9	7.8	6.07	V
11	17.9	37.5	0.80	VI
12	19.7	30.3	1.63	VI
13	26.2	25.9	1.73	V

The slip modulus $k_{s,0.6}$ is slope of line between 10% and 60% of peak load capacity.
Splitting of timber joist with large slips observed in TTC joints with 20 mm coach screw shear connectors. Failure mode V in TTC joints with inclined screws associated with withdrawal of 16 and 20 mm coach screws.
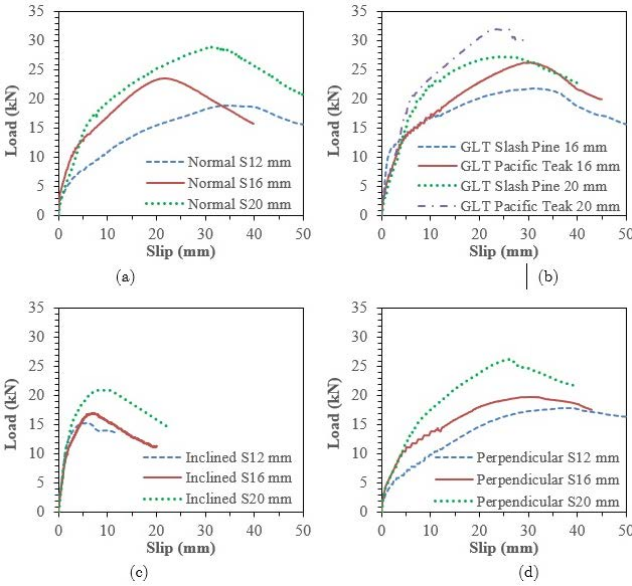

Figure 4: Mean of experimental load-slip plots for specimens. (a) No. 1–3; (b) No. 4–7; (c) No. 8–10; and (d) No. 11–13.

of variation (CoV) for joints with S12, S16 and S20 shear connectors were 5.5%, 2.2% and 4.2%, respectively. The mean of the experimental load-slip plots for all TTC joints are shown in Fig. 5. Furthermore, the mean of the peak load carrying capacity, the slip corresponding to the peak load capacity and the serviceability slip modulus $k_{s,0.6}$ for the TTC joints are given in Table 4. The serviceability slip modulus $k_{s,0.6}$ refers to the slope of the line between 10% and 60% of the peak load capacity. The maximum CoV for all tested specimens was limited to 5.5% which corresponded to the CLT–LVL composite joint with S12 screw shear connectors.
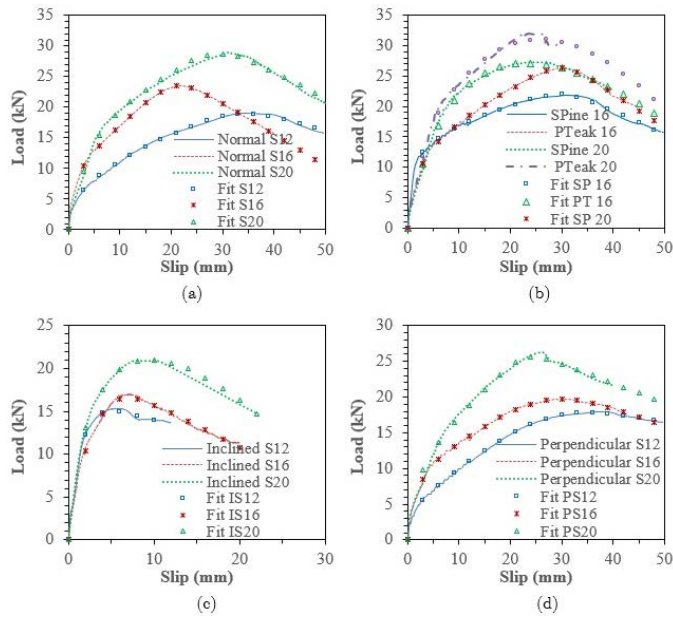
Figure 5:   Correlation between empirical model and mean of experimental load-slip for (a) Parallel CLT–LVL connections; (b) Perpendicular CLT–LVL connections; (c) CLT–Glulam connections; and (d) Inclined CLT–LVL connections.

4 ANALYTICAL MODEL

An empirical load-slip model proposed by Hassanieh et al. [4] was calibrated against the experimental push-out tests by means of non-linear regression. The proposed model has seven parameters comprising three asymptotic lines that can represent the ascending and descending parts of the TTC load-slip behaviour by a single function. The load-slip function $f(s)$ is given by

$$f(s) = \frac{\left(k_0 - k_p\right)s}{\left\{1 + \left[\left(k_0 - k_p\right)\frac{s}{f_0}\right]^{n_1}\right\}^{\frac{1}{n_1}}} + \frac{\left(k_p + k_s\right)s}{\left\{1 + \left[\left(k_p + k_s\right)\frac{s}{f_1 - f_0}\right]^{n_2}\right\}^{\frac{1}{n_2}}} - k_s s, \qquad (1)$$

where k_0, k_p and k_s are the initial, pre-peak and post-peak stiffnesses of the load-slip curve respectively, f_0 and f_1 the first and second reference shear forces corresponding to the pre-peak and post-peak branches, and n_1 and n_2 control the curvature of the load-slip curve before and after the peak respectively. The non-linear regression scheme in MATLAB with the trust region algorithm accompanied with bi-square robustness was used to determine the seven parameters of the empirical model with best fit to the experimental load-slip results. The seven input parameters for establishing the empirical load-slip model of the CLT–LVL/Glulam composite joints with coach screw shear connectors are given in Table 5. The goodness-of-fit and close correlation between the analytical model and experimental data is evident from the R-square values given in Table 5 and the load-slip curves shown in Fig. 6.

Table 5: Input parameters for analytical model.

| Specimen No.	f_0	f_1	k_0	k_p	k_s	n_1	n_2	R^2
1	40.7	58.94	50.00	0.21	0.33	0.27	10.00	0.9960
2	16.21	39.94	35.00	0.58	0.54	0.51	11.96	0.9996
3	15.00	43.81	3.416	0.54	0.44	2.56	9.92	0.9959
4	14.88	45.89	6.97	0.45	0.58	1.15	14.83	0.9985
5	11.42	130.1	4.00	1.41	1.54	5.01	1.61	0.9934
6	17.7	37.44	43.94	0.23	0.42	0.62	13.00	0.9995
7	10.00	120.5	35.00	4.99	0.99	0.00	0.77	0.9962
8	16.4	17.25	12.6	5.00	0.32	2.59	17.3	0.9936
9	7.62	21.3	8.31	2.00	0.53	1.92	4.08	0.9964
10	50.00	54.72	8.99	1.61	1.22	0.94	6.44	0.9972
11	10.00	27.68	59.99	0.43	0.16	0.35	5.59	0.9992
12	12.87	30.6	8.00	0.33	0.28	0.86	6.91	0.9987
13	25.00	43.82	20.00	0.48	0.34	0.47	20.71	0.9947
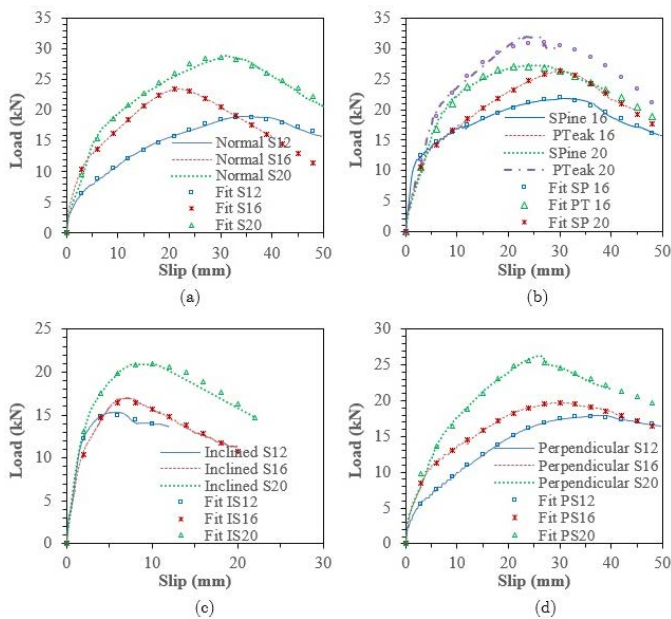
Figure 6:   Correlation between empirical model and mean of experimental load-slip for (a) Parallel CLT-LVL connections; (b) Perpendicular CLT-LVL connections; (c) CLT-glulam connections; and (d) Inclined CLT-LVL connections.

5 CONCLUSIONS

The results of push-out tests on CLT–LVL and CLT–Glulam composite joints with coach screw shear connectors were reported and effect of the Glulam type (softwood or hardwood), shear connector size (S12, S16 and S20) and inclination angle of the screws (90°, 45°) and orientation of load with respect to the outer lamellae of the CLT panel (parallel and perpendicular to the grain) on the serviceability stiffness, ultimate strength and load-slip behaviour of the TTC joints were investigated. The following conclusions can be drawn from the results of laboratory push-out experiments on the TTC joints:

- The dominant failure mode in CLT–LVL composite joints with inclined coach screw shear connectors was associated with lateral crushing of the timber and the development of one plastic hinge within the connectors' length embedded in the CLT panel. However, in the failure mode of CLT–LVL/Glulam joints with normal coach screw shear connectors, either one plastic hinge formed in the connectors' length embedded in the CLT panel or two plastic hinges developed within the length of the connector.

- The orientation of the outer lamellae of the CLT panel with respect to the direction of loading affected the stiffness of CLT–LVL composite joints by 13% to 24% and the ultimate strength of the CLT–LVL joints by 6% to 16%.

- Depending on the diameter of the coach screw shear connectors, the serviceability stiffness of the CLT–LVL joints with inclined shear connectors was 2.67 to 7.55 times higher than identical joints with normal shear connectors.

- Using hardwood Glulam instead of softwood Glulam in CLT–Glulam composite joints with normal coach screw shear connectors increased the ultimate strength by 17% to 21%, depending on the size of screws. Furthermore, a maximum 76% enhancement in the serviceability stiffness of the CLT–Glulam joints were achieved when softwood Glulam joists were replaced by hardwood Glulam joists.

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