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Mechanical behaviour of connections between CLT panels under monotonic and cyclic loading

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Abstract. The experimental research presented in this paper investigates the mechanical behaviour of commercial metal connections in three-ply Chinese-manufactured cross-laminated timber (CLT) panels. Monotonic and cyclic loading tests were conducted at Tongji University on angle bracket and joints with inclined self-tapping screws. According to the standard EN 12512, the force-displacement curves are exploited to assess the mechanical properties of the connections such as the strength capacity, yielding point, ductility and equivalent damping ratios. From the test results, the main load-carrying direction of the angle bracket is shear direction but the connection exhibits more ductile and dissipative behaviour in tension direction. In general, screwed joints demonstrate relatively brittle behaviour except in the case of shear wall-to-wall connection. Based on the capacity-based design principles, the experimental results and the failure modes are discussed to propose some design suggestions.

1. Introduction

Cross-laminated timber (CLT) is gaining a growing popularity worldwide for its broad application in building construction. On account of diverse advantages in terms of structural strength, modularization and environmental attributes, the new engineered wood product represents a viable alternative to conventional construction materials such as concrete, steel and masonry.

CLT panels behave mainly in linear-elastic range by reason of high in-plane rigidity and stiffness [1]. In accordance to the capacity-based design, the overall performance and stability of the structure depend on the ductile joints assembling the CLT panels such as wall-to-wall and wall-to-floor connections [2-4]. In CLT structures, the metal connections are indeed key components in regards of the seismic behaviour as they resist the lateral loads but also concentrate most of the deformation and energy dissipation of the building [5]. Nevertheless, the determination of fastening capacity in CLT is complex and more difficult to predict than in traditional timber materials. The estimation by means of simplified analytical models provided in design codes may significantly differ from actual mechanical properties values. Therefore, an experimental investigation on connections between CLT panels is essential for a reliable evaluation of the mechanical behaviour.

This article focused more particularly on the structural behaviour of the wall-to-wall and wall-to-floor joints adopted for the Chinese project Otto Cafe in Ninghai which used entirely CLT panels as structural elements. The connections were subjected to both monotonic and cyclic loading tests to evaluate essential mechanical properties for structural and seismic characterization of CLT structures. Finally, design suggestions were proposed for a better mechanical performance of the connections.

2. Experimental program

The CLT panels were manufactured in China from Northern Hemlock wood material. The panels of mean density ρ_m=400 kg/m^3 were composed of three layers of 35 mm thick with a total thickness of 105 mm. Each connection configuration was subjected to one monotonic and three cyclic loading tests according to the European standard EN 12512 [6]. In total, 24 tests were conducted, including 6 monotonic and 18 cyclic tests.

2.1. Test setup and protocol

The monotonic tests were carried out under displacement control at a constant slip rate of 0.05 mm/s. The tests were stopped when a load reduction of 80% was reached after maximum load. The input displacement for cyclic tests followed the procedure prescribed by EN 12512 (Figure 1a). The displacement rate varied from 0.3 to 0.6 mm/s depending on the yielding displacement obtained from the monotonic test as shown in Figure 1b. For all shear tests, a reversed cyclic procedure was applied whereas all tension tests were subjected to a non-reversed cyclic loading due to restrained movement in compression direction. The testing machine was a hydraulic actuator POPWILL vertically installed on a steel frame to apply load. Force-displacement curves were measured through the load cell located between the actuator and the specimen. One panel was anchored to a concrete base reaction ground with two steel tube profiles while the other panel was lifted by the actuator. Meanwhile, two additional displacement transducers (LVDT) were installed at both sides of each panel during the connection test to measure the global displacement and the relative slip between the two panels.

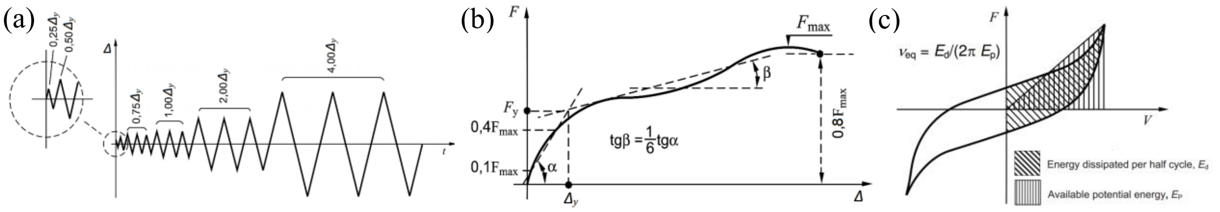


Figure 1. Procedure of EN 12512 for cyclic testing: (a) input displacements; (b) definition of yielding point; (c) definition of equivalent damping ratio for half-cycle.

2.2. Test configurations

Three commercial connections of Rothoblaas were investigated in both tension and shear directions. Table **1** reports the different test configurations and specimens geometry. The angle bracket TTF200 was fixated to panels with 30 LBS screws 5x50 mm per shear plane. For screwed joints, a pair of fully threaded self-tapping screws was inserted in CLT with an angle of 45° with respect to the grain direction. The test specimens reproduced as accurately as possible the on-site geometry through non-symmetric configuration and similar number of fasteners.

3. Experimental results and discussion

The experimental results were processed in accordance to the provisions of EN 12512. The backbone curve was defined as the envelope curve connecting the points of maximum displacement per cycle. For reversed cyclic tests, the mechanical properties were assessed by analysing both sides of hysteretic loops. Table 2 displays the experimental values obtained from both the monotonic and the cyclic tests of each connection configuration. Mean values were calculated based on the three cyclic tests. F_{max} and Δ_{max} refer to the maximum load and slip; F_u and Δ_u represent the ultimate load and slip; F_y and Δ_y indicate the yielding load and slip; K_{ser} and K_{pl} denote the initial and plastic stiffnesses. Moreover, a ductility class (low/medium/high) was assigned depending on the ductility ratio D taken as the ratio between the ultimate slip and the yielding slip [7]. $\Delta F_{1\text{-}3}$ is the impairment strength defined as the percentage difference ratio between the maximum loads of 1st and 3rd cycle backbones. Energy dissipation capacity was quantified by the total dissipated energy $E_{d,total}$ and the equivalent damping ratios $\nu_{eq(1st)}$ and $\nu_{eq(3rd)}$ of 1st and 3rd cycles at maximum slip loop as defined in Figure 1c.

Table 1. Test configurations and specimens geometry.

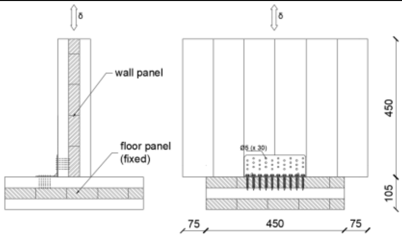
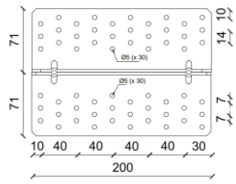
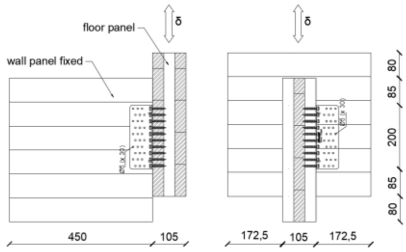
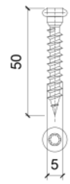
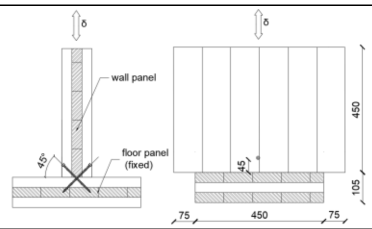
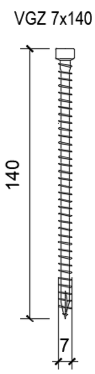
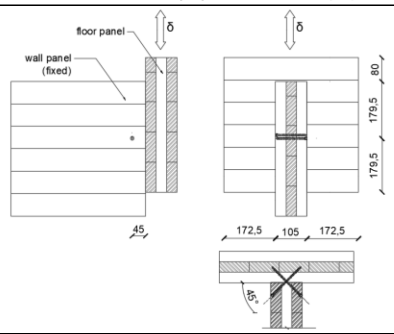
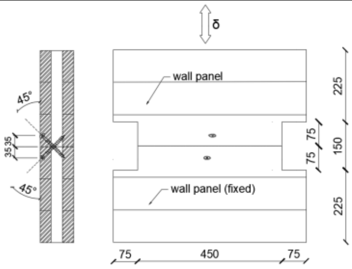
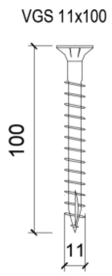
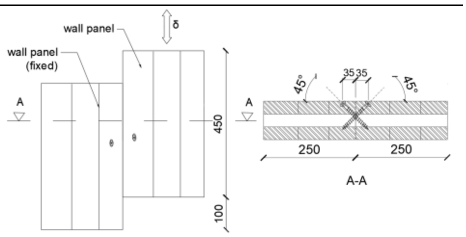
Conf. no.	Loading direction	Test configuration	Geometry	Joint type
		Wall-to-floor connections		
1-T	Tension		Angle bracket: 	Angle bracket TTF 200x71x71x3mm Fasteners: 30+30 Screws LBS ϕ5x50 mm
1-S	Shear		Fasteners: 	
2-T	Tension			Crossed self-tapping screws 2 VGZ ϕ7x140 mm
2-S	Shear			
		Wall-to-wall connections		
3-T	Tension			Simple-butt joint with self-tapping screws 2 VGS ϕ11x100 mm
3-S	Shear			

Table 2. Experimental mechanical properties for monotonic (M) and mean values for cyclic (C) tests.

Test	1-T		1-S		2-T		2-S		3-T		3-S	
	M	C	M	C	M	C	M	C	M	C	M	C
F_{max} (kN)	41.77	41.56	57.67	54.71	11.46	12.84	11.09	11.74	9.75	11.39	9.93	12.76
Δ_{max} (mm)	40.85	40.16	31.02	26.27	2.75	3.04	14.08	15.53	3.61	4.03	25.37	38.68
F_u (kN)	33.42	33.27	46.14	43.77	9.17	10.27	8.88	9.49	7.8	9.11	7.94	10.21
Δ_u (mm)	47.93	51.40	35.67	38.85	5.32	5.76	17.6	20.04	5.25	6.24	52.52	57.01
F_y (kN)	22.50	18.51	46.09	41.42	10.80	12.09	10.26	8.93	7.78	9.77	7.37	6.98
Δ_y (mm)	5.73	3.82	11.08	9.20	2.02	2.10	8.68	5.16	1.39	1.85	4.67	3.64
K_{ser} (kN/mm)	4.76	4.44	4.38	4.71	5.55	5.98	1.24	1.89	5.42	5.31	1.61	1.96
K_{pl} (kN/mm)	0.68	1.04	0.74	0.82	0.92	0.98	0.21	0.33	0.90	0.88	0.13	0.33
Ductility class	H	H	L	M	L	L	L	M	L	L	H	H
D (-)	8.36	13.56	3.22	4.54	2.63	2.76	2.03	4.54	3.78	3.44	11.26	16.12
$\Delta F_{1\text{-}3}$ (%)		13.39		6.28		4.35		33.38		4.55		13.19
$\nu_{eq(1st)}$ (%)		22.26		7.51		7.42		11.30		9.65		15.73
$\nu_{eq(3rd)}$ (%)		14.80		5.69		4.90		10.46		4.94		6.42
$E_{d,total}$ (J)		7345		1456		205		632		158		2061

3.1. Tests of angle brackets for wall-to-floor joints

The angle bracket TTF200 exhibited different behaviour in the two loading directions. For instance, the connection was found to be more ductile and dissipative in axial direction, proven by a five times higher amount of energy dissipated and an equivalent damping ratio ranging from 14.8 to 22.36% in tension direction as opposed to 5.69-7.51% in shear direction.

In tension direction, the failure mode was the high plasticization of the angle bracket's steel plate which induced a combination of screw withdrawal in the floor panel and yielding at level of the screws head, particularly the screws closest to the base plate (Figure 2a). Nevertheless, the screws inserted in the floor panel were pulled out before that the screws in the wall panels started to deform. The energy dissipation could be even higher in case of simultaneous ductile shear deformation of the screws attached to the wall panel. Moreover, it is suggested to take into account the deformability of the steel plate in design rules instead of only considering the contribution of the fasteners.

In shear direction, the collapse of the connection occurred in CLT panel due to the block shear of the wood (Figure 2b). This brittle failure is illustrated by a sudden drop of resistance (Figure 3b). The phenomenon occurred even earlier in the case that the screws subjected to highest shear stress were located near a seam. Due to an excessive number of screws per shear plane inserted in the panels, the strength resistance of the group of fasteners was too high to achieve its full yielding capacity. Instead, brittle components (CLT panels) were seriously damaged by cracks and possible delamination.

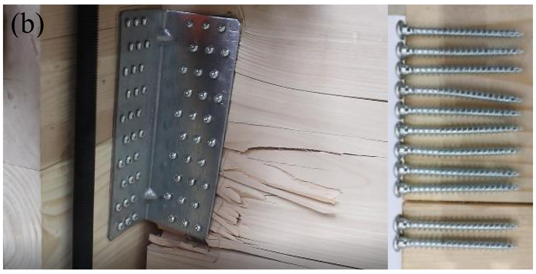


Figure 2. Typical failure modes of angle brackets (a) under tension and (b) under shear

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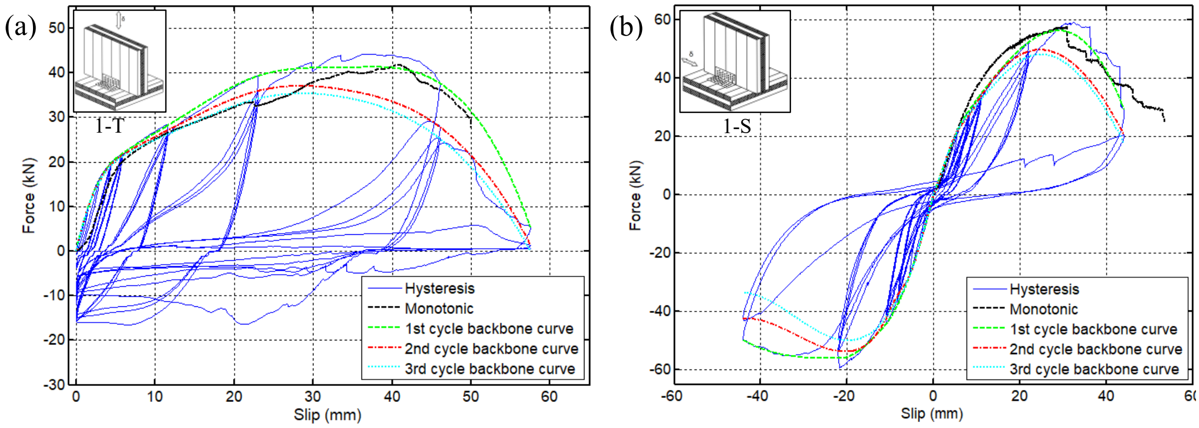

Figure 3. Monotonic load-slip curve and typical hysteretic curves of angle bracket (a) under tension and (b) under shear.

3.2. Tests of crossed self-tapping screws for wall-to-floor joints

The crossed self-tapping screws were initially installed during the project by means of resisting wall uplift to replace the function of hold-downs. For inclined screws, withdrawal component seemed to dominate the overall joint behaviour. The performance of the screwed joints was found to be poorer if the screws were located in proximity to a seam due to possible voids between the wood boards.

The axially loaded self-tapping screws had higher strength resistance and stiffness compared to laterally loaded self-tapping screws. However, the behaviour was very brittle as proved by the average ductility ratio inferior to 3. The connection was characterized by a high stiffness but also an ultimate load at very low displacements (Figure 5a). The typical failure mode was the withdrawal of the screws with possible slight head pull-through (Figure 4a). The screws suffered few deformations, resulting in very low equivalent damping ratio and energy dissipation.

In shear direction, the connection under monotonic loading demonstrated very low stiffness and poor ductility. However, the cyclic behaviour was found to be relatively better through higher stiffness and earlier yielding displacement. Since the connection collapsed after that the screws deformed until breakage, the laterally-loaded screws achieved failure at higher displacements than the axially-loaded screws, although the strength degradation was significant with 33% reduction of strength (Figure 4b). The screw failure and the wood crushing are two ductile mechanisms which allowed to achieve a ductility ratio of over 4 and a damping ratio for 3rd cycle more than two times higher compared to the case of tension load. The shear performance could be enhanced if the screws had larger diameter.

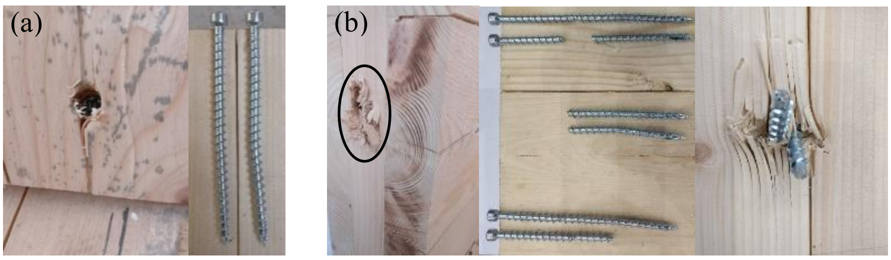

Figure 4. Typical failure modes of self-tapping screws (a) under tension and (b) under shear.

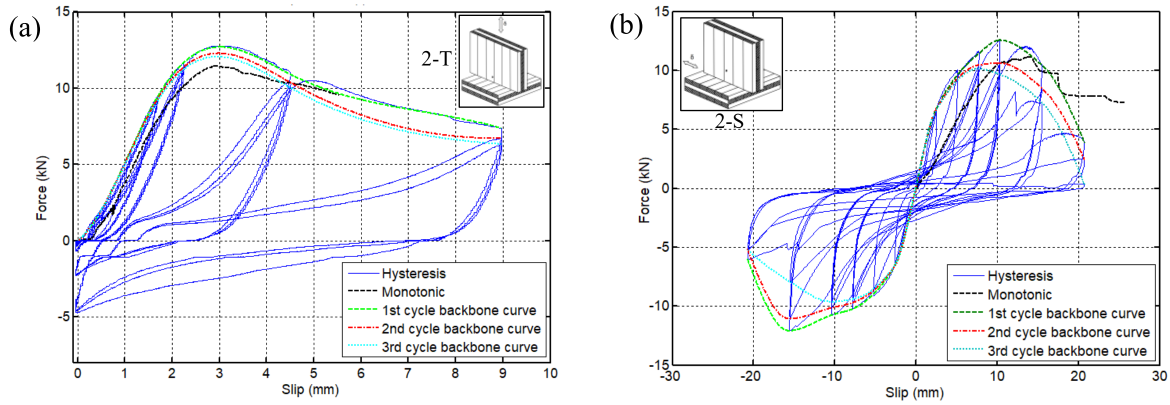

Figure 5. Monotonic load-slip curve and typical hysteretic curves of crossed self-tapping screws (a) under tension and (b) under shear.

3.3. Tests of simple butt joints with crossed screws for wall-to-wall joints

Unlike the traditional in-plane shear connections between CLT panels, the simple butt joint requires no additional CLT panel machining. The function as a shear connection was justified by a good performance in shear direction. The experimental results demonstrated a high ductility ratio of over 16 since failure occurred at very high displacements under cyclic loads. The ductile failure was obtained through consequent wood crushing along the screws and yielding of the screws under shear, resulting in high energy dissipation and equivalent viscous damping (Figure 6b).

In tension, the connection was found to be less performant than expected. The stiffness was high but the load-carrying resistance was lower in axial direction. Besides, the connection exhibited low ductility behaviour with early stage brittle failure at very low displacements. The failure mechanism was the withdrawal of the screw followed by a wood tear-off (Figure 6a). This rupture was caused by the non-respect of the minimum spacing between the screw and the panel edge. Consequently, it is suggested to use longer self-tapping screws in order to better anchor the screws into the panel.

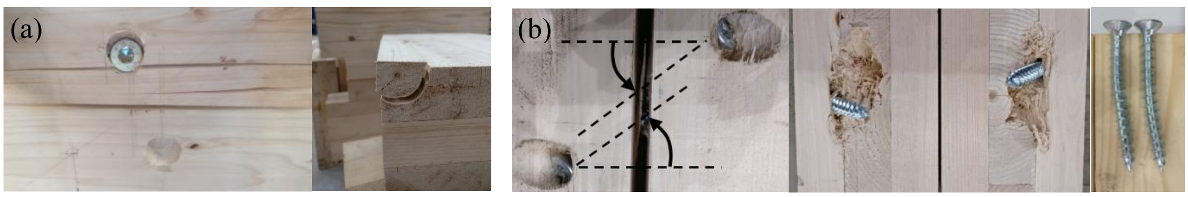

Figure 6. Typical failure modes of simple butt joint with screws (a) under tension and (b) under shear.

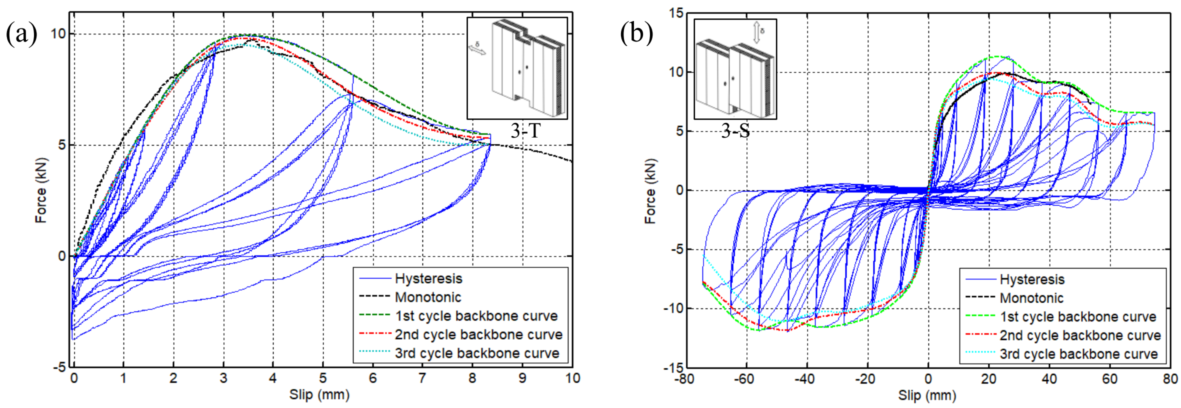

Figure **7.** Monotonic load-slip curve and typical hysteretic curves of simple butt joint with self-tapping screws (a) under tension and (b) under shear.

4. Conclusion

This paper presented the main results of the experimental research on the mechanical behaviour of wall-to-wall and wall-to-floor connections between Chinese-manufactured CLT panels. Monotonic and cyclic tests were carried out on angle bracket and screwed joints. The experimental study allowed to determine the failure mechanisms and reliable estimates of essential properties for CLT design.

From the test results, the angle bracket had better strength capacity in shear direction but the failure was found to be brittle with early stage delamination in CLT since plasticization of the fasteners was not achieved. In tension, the angle brackets exhibited relatively good resistance but also high energy dissipation, allowing its response to be classified as highly ductile.

In general, diagonally placed screws were found to be less performant than typical connections with relatively brittle behaviour except when used as shear wall-to-wall connection. Provided that the spacing requirements were respected, significantly higher stiffness and strength capacity were found for axially loaded inclined self-tapping screws while significantly higher ductility was recorded in shear direction. For screwed joints, poorer performance was observed in the case that the self-tapping screws were located close to a board seam.

Based on the experimental study, design suggestions were given in order to prevent any brittle failure and to improve the mechanical performance of the connections. Further research could be done on the optimized number of fasteners for angle bracket as well as the appropriate angle between the screw axis and the grain direction for screwed joints.

5. Acknowledgements

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