EVALUATION ON THE BEHAVIOR OF SCREWED CONNECTIONS BETWEEN CROSS-LAMINATED TIMBER PANELS AND STEEL PLATES

Xijun WANG [1], Minjuan HE [2], Zheng LI[3], Hanlin Dong[4]

ABSTRACT: Despite the extensive use of steel-to-CLT screwed connections in CLT structures, there is still a lack of detailed knowledge on the mechanical performance of these connections. This paper presents experimental investigations on the behavior of screwed connections between cross-laminated timber (CLT) panels and steel plates. Experimental tests were conducted on a series of steel-to-CLT screwed connection specimens designed with different distances between narrow faces and screws. Failure modes, load-displacement responses, capacities, stiffnesses, and deformability of the specimens were obtained and compared. The effects of narrow faces and orthogonally placed layers on the connection behavior were studied. The results showed that the steel-to-CLT screwed connection specimens failed in either screw fracture or screw yielding. The specimens could reach a larger deflection if they failed in screw yielding compared to screw fracture. The distance between narrow faces and screws greatly influenced the deformability and ultimate shear capacity of the connections. The ultimate shear capacity of the connections with screws far from the narrow face was 34.9 % larger than that of the connections directly fastened to the narrow face.

KEYWORDS: Cross-laminated timber (CLT), Screwed connections, mechanical behavior, Experimental testing

1 – INTRODUCTION

Cross-laminated timber (CLT) is a type of engineered wood product (EWP) that consists of multiple orthogonally placed layers of lumber boards glued together [1]. It was first developed in Austria and Germany in 2000 and is widely manufactured into prefabricated plane members (e.g., walls or floors). Recently, CLT has gained increased popularity in both residential and non-residential applications due to its desirable dimensional stability, fire resistance, and sound insulation [2][3][4].

Various connection techniques have been developed to connect CLT panels, involving the use of metal connectors [5][6], dowel-type fasteners [7][8], glued-in steel rods or plates [9], etc. Metal connectors are usually employed in accompany with steel-to-CLT screwed connections. They are extensively used in CLT construction, such as typical hold-downs and angle brackets in CLT shear walls [10][11][12]. Compared to metal connectors, steel-to-CLT screwed connections exhibit more complicated nonlinear behaviors when deformation occurs. In previous analytical studies [13][14], the mechanical behavior of steel-to-CLT screwed connections was commonly evaluated using the formulas given in Eurocode 5 [15]. These formulas, however, were derived for the screwed connections between steel plates and unidirectional layered timber products. Considering that the perpendicular-to-grain embedment strength of wood members is only about 0.5 time parallel-to-grain embedment strength, the formulas in Eurocode 5 may fail to give reasonable results when predicting the capacity of steel-to-CLT screwed connections. On the other hand, the narrow faces of the boards in CLT are usually not glued together. This could have certain impact on the mechanical performance of steel-to-CLT screwed connections and it is difficult to control the distance between narrow faces and screws in

[1] Xijun WANG, Postdoctoral research fellow, Department of Structural Engineering, Tongji University, Shanghai, China, xijunwang@tongji.edu.cn

[2] Minjuan HE, Professor, Department of Structural Engineering, Tongji University, Shanghai, China, hemj@tongji.edu.cn

[3] Zheng LI, Professor, Department of Structural Engineering, Tongji University, Shanghai, China, zhengli@tongji.edu.cn

[4] Hanlin DONG, Assistant professor, College of Civil Engineering, Shanghai Normal University, Shanghai, China, hanlin.dong@shnu.edu.cn

https://doi.org/10.52202/080513-0707

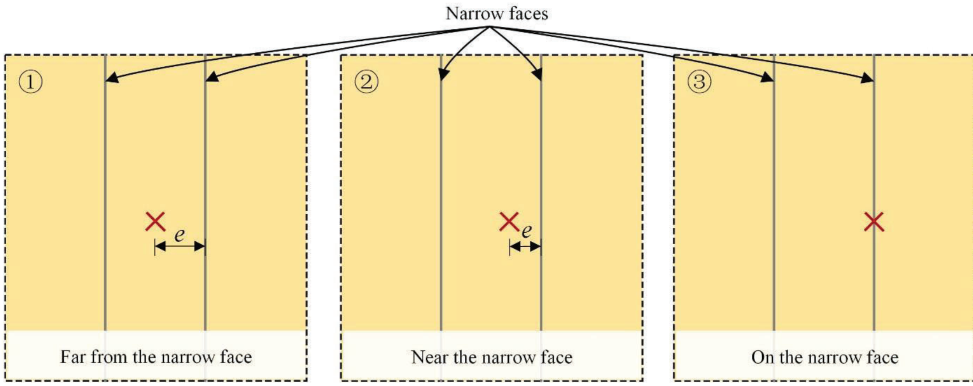

Figure 1. Possible distance between narrow faces and screws in practical engineering.

practical engineering (Figure 1). So far, limited study was conducted to explore the influence of narrow faces on the mechanical performance of these connections.

In this study, a series of experimental tests are conducted on steel-to-CLT screwed connections. The mechanical properties of the specimens were compared in terms of failure modes, load-displacement responses, capacities, stiffnesses, and deformability. The influence of distance between narrow faces and screws on the mechanical behavior of screwed connections was evaluated.

2 – EXPERIMENTAL PROGRAM

2.1 MATERIALS AND SPECIMENS

To investigate the effects of narrow faces and orthogonally placed layers on the behavior of steel-to-CLT screwed connections, a series of monotonic loading tests was conducted. Figure 2 shows the layouts of the specimens. The CLT blocks were five-ply 175 mm thick (35 + 35 + 35 + 35 + 35), made of graded No.2 and better [16] spruce-pine-fir (SPF) lumbers. Each CLT blocks had dimensions of 300 mm in height and 70 mm in width. The thickness of the C-shaped steel plates was 5 mm. They were fastened to the CLT blocks using 6.0 mm × 100 mm partially threaded countersunk screws, which were made in China. The screws were installed considering three distances between narrow faces and screws: 0 mm, 4 mm, and 15 mm. Each of the three distances corresponded to an independent test group, and each group had ten replicates. Table 1 lists the test matrix of the steel-to-CLT screwed connections.

2.2 TEST SETUP

The test setup of the specimens is also illustrated in Figure 2. The C-shaped steel plates were connected the actuator by a fixture with steel connectors and bolts. A steel beam and a pair of threaded rods were used to fix the CLT block to the testing machine. Considering that the load applied to the specimen was eccentric, a roller support was employed to constrain the out-of-plane deformation of the specimens. The shear force of the steel-to-CLT screwed connection was directly read from the loading cell. A pair of linear voltage displacement transducers (LVDTs) were installed on the two sides of the C-shaped steel plates, recording the relative displacement between CLT and steel.

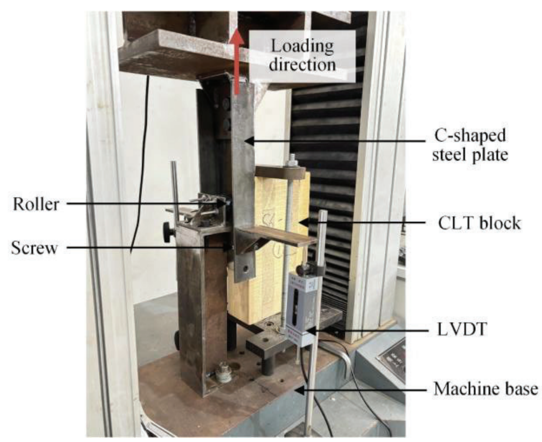

Figure 2. Specimen layouts.

Table 1: Test matrix

Group	e^{a}	No. of replicates
S-0	0 mm	10
S-4	4 mm	10
S-35	15 mm	10

[a] *e* stands for the distance between narrow faces and screws.

2.3 LOADING PROTOCOL

The actuator was displacement controlled with a loading rate of 3 mm/s according to ASTM D1762 [17]. The loading process was terminated when failure occurred or the load dropped to 80% of the maximum load.

https://doi.org/10.52202/080513-0707

3 – RESULTS AND DISCUSSION

3.1 EXPERIMENTAL OBSERVATIONS

Similar deformation and failure modes were observed among the three groups of specimens. During the loading procedure, no obvious observation was found except the tilting of the screw heads (Figure 3(a)), since the screw shanks inside the CLT block were invisible.

Two failure modes were observed for the steel-to-CLT screwed connection specimens: about half of the specimens failed in screw fracture (as shown in Figure 3(b)), and another half failed in screw yielding. Figure 3(c) illustrates the yielding deformation of a screw, which was driven out of the CLT block after the loading process. The screw fracture and yielding occurred in accompany with localized wood crushing, and the severer crushing was observed in the failure mode of screw yielding. The observed variation in failure modes may be attributed to the presence of wood knots within the CLT blocks. Note that the distance between narrow faces and screws did not have a significant impact on the failure modes of the screwed connections.

3.2 LOAD-DEFLECTION CURVE

The load-deflection curves of the steel-to-CLT screwed connection specimens are given in Figure 4. For the three groups S-0, S-4, and S-35, the load increased rapidly during the initial loading stage. It was because the surrounding wood was compressed when the screw was driven in. The load then increased at a lower rate until the screwed connections reached their peak shear capacities. After that, two load-deflection responses were observed for the three groups, corresponding to the two failure modes. If the specimen failed in screw fracture, a sudden load drop occurred at the end of the loading process, indicating a brittle failure mode. Most of the sudden decreases happened at the deflection around 10 mm. However, in the case of screw yielding, the load decreased more gradually, and the specimens could reach a larger deflection before failure.

Comparing the curves plotted for groups S-0, S-4, and S-35, the steel-to-CLT screwed connection specimens with smaller distance between narrow faces and screws tended to exhibit enhanced deformability prior to failure. For the specimens that failed in screw yielding in group S-35, the ultimate displacement was smaller than 30 mm. However, some of the specimens in groups S-0 and S-4 could reach displacement of 40 mm, and the specimens in group S-0 showed higher deformability compared to those in group S-4. It was because the presence of narrow faces reduced the lateral constraint for the screws, by which the connection could accommodate greater deformation prior to failure.

3.3 MECHANICAL PROPERTIES

Figure 5 gives the mechanical properties of the three test groups. Two properties were compared: ultimate shear capacity (F_{max}) and initial stiffness ($K_{initial}$). Note that, although the ductility ratio (μ) serves as a critical indicator of the mechanical performance for wood connections, it was not investigated in this study. It was because the two failure modes led to pronounced variability in ductility ratios within each test group. The calculation of $K_{initial}$ follows Eq. (1) according to EN 26891 [18].

$$K_{initial} = (0.4F_{max}-0.1F_{max})/(D_{0.4Fmax}-D_{0.1Fmax}) \quad (1)$$

where F_{max} is the maximum absolute shear force resisted by the connection; $D_{0.1Fmax}$ and $D_{0.4Fmax}$ are the displacement of the connection at $0.1F_{max}$ and $0.4F_{max}$, respectively. Note that, for each group, the values of F_{max} and $K_{initial}$ presented in Figure 5 are the average of ten replicates.

(a) Tilting of screw head (b) Screw fracture (c) Screw yielding

Figure 3 Test observations.

The results show that the distance between narrow faces and screws greatly influenced the ultimate shear capacity of connections, but had little effect on their initial stiffness. The ultimate shear capacity of group S-35 was 7.27 kN, 31.5% and 34.9 % larger than those of groups S-4 and S-0, respectively. The narrow faces not only reduced the load-bearing capacity of connections directly fastened to them but also compromises the capacity of adjacent connections.

4 – CONCLUSION

This paper presents experimental investigations on the behavior of steel-to-CLT screwed connections. Experimental tests were conducted on a series of steel-to-CLT screwed connections designed with different distances between narrow faces and screws. Failure modes, load-displacement responses, capacities, stiffnesses, and deformability of the specimens were obtained and compared. The effects of narrow faces and orthogonally placed layers on the connection behavior were studied. The primary conclusions are listed as follows:

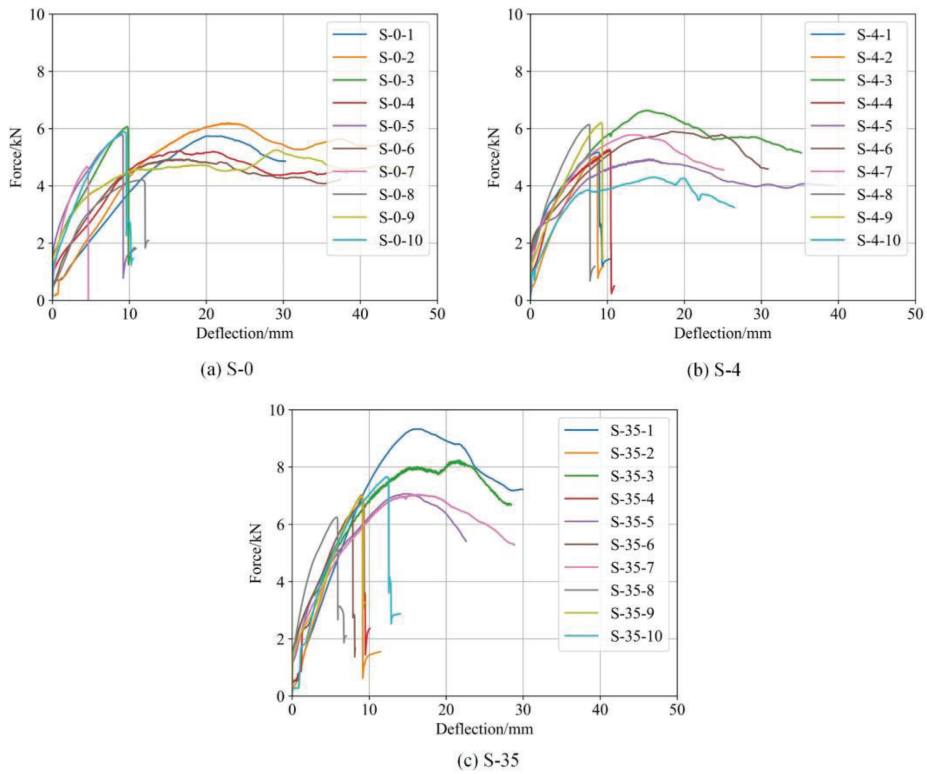

Figure 4 Load-deflection curve of the steel-to-CLT screwed connection specimens.

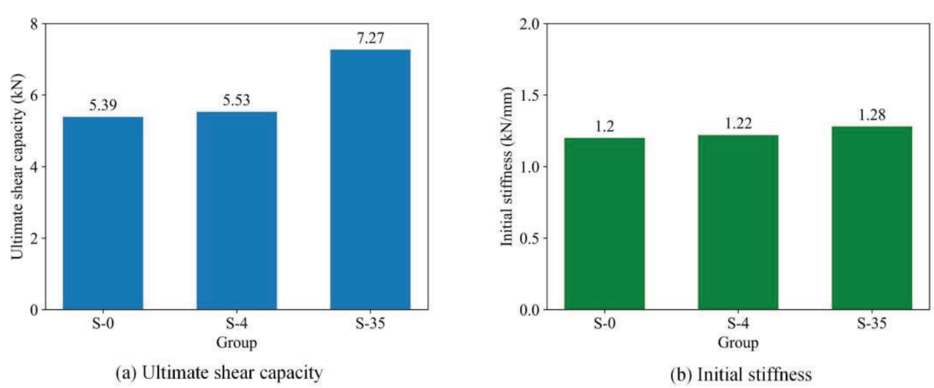

Figure 5 Mechanical properties of the specimens.

https://doi.org/10.52202/080513-0707

(1) Two failure modes were observed for the steel-to-CLT screwed connection specimens: screw fracture and screw yielding. The screw fracture and yielding occurred in accompany with localized wood crushing, and the severer crushing was observed in the failure mode of screw yielding.

(2) Compared to screw fracture, the specimens could reach a larger deflection if they failed in screw yielding. The connection nearer the narrow faces could accommodate greater deformation prior to failure.

(3) The distance between narrow faces and screws greatly influenced the ultimate shear capacity of connections, but had little effect on their initial stiffness. The ultimate shear capacity of the connections with screws far from the narrow face was 34.9 % larger than that of the connections directly fastened to the narrow face.

(4) Although these works shed some light on the analyses and design of steel-to-CLT screwed connection, further studies are needed due to certain limitations in this study. For example, the reason why the connections failed in different modes was unclear. Future works are required to comprehensively understand the failure mechanism of the connection. Besides, the mechanical performance of the steel-to-CLT screwed connection was investigated through monotonic loading tests. Future works could focus on the cyclic behavior of the connection.

5 – ACKNOWLEDGMENT

The authors gratefully acknowledge the National Natural Science Foundation of China (Grant Nos. 52408207, 52208270) and China Postdoctoral Science Foundation (Grant No. 2023M742665) for supporting this research.

6 – REFERENCES

[1] X. Sun, M. He, and Z. Li. “Novel engineered wood and bamboo composites for structural applications: state-of-art of manufacturing technology and mechanical performance evaluation.” In: Construction and Building Materials 249 (2020), pp. 118751.

[2] S. Navaratnam, P. B. Christopher, T. Ngo, and T. V. Le. “Bending and shear performance of Australian Radiata pine cross-laminated timber.” In: Construction and Building Materials 232 (2020), pp. 117215.

[3] R. Emberley, C. G. Putynska, A. Bolanos, A. Lucherini, A. Solarte, D. Soriguer, M. G. Gonzalez, K. Humphreys, J. P. Hidalgo, C. Maluk, A. Law, and J. L. Torero. “Description of small and large-scale cross laminated timber fire tests.” In: Fire Safety Journal 91 (2017), pp. 327–335.

[4] R. Brandner. “Cross laminated timber (CLT) in compression perpendicular to plane: Testing, properties, design and recommendations for harmonizing design provisions for structural timber products.” In: Engineering Structures 171 (2018), pp. 944–960.

[5] Y. Shen, J. Schneider, S. Tesfamariam, S. F. Stiemer, and Z. Chen. “Cyclic behavior of bracket connections for cross-laminated timber (CLT): Assessment and comparison of experimental and numerical models studies.” In: Journal of Building Engineering 39 (2021), pp. 102197.

[6] I. Gavric, M. Fragiacomo, and A. Ceccotti. “Cyclic behaviour of typical metal connectors for cross-laminated (CLT) structures.” In: Materials and Structures 48 (2015), pp. 1841–1857.

[7] I. Gavric, M. Fragiacomo, and A. Ceccotti. “Cyclic behavior of typical screwed connections for cross-laminated (CLT) structures.” In: European Journal of Wood and Wood Products 73 (2015), pp. 179–191.

[8] J. R. Brown, M. Li, T. Tannert, and D. Moroder. “Experimental study on orthogonal joints in cross-laminated timber with self-tapping screws installed with mixed angles.” In: Engineering Structures 228 (2021), pp. 111560.

[9] X. Zhang, Y. Pan, and T. Tannert. “The influence of connection stiffness on the dynamic properties and seismic performance of tall cross-laminated timber buildings.” In: Engineering Structures 238 (2021), pp. 112261.

[10] A. Ceccotti, C. Sandhaas, M. Okabe, M. Yasumura, C. Minowa, and N. Kawai. “SOFIE project - 3D shaking table test on a seven-storey full-scale cross-laminated timber building.” In: Earthquake Engineering & Structural Dynamics 42.13 (2013), pp. 2003–2021.

[11] G. Rinaldin, C. Amadio, and M. Fragiacomo. “A component approach for the hysteretic behaviour of connections in cross-laminated wooden structures.” In: Earthquake Engineering & Structural Dynamics 42.13 (2013), pp. 2023–2042.

[12] M. Popovski, I. Gavric, and P. Scientist. “Performance of a 2-story CLT house subjected to lateral loads.” In: Journal of Structural Engineering 142.4 (2016), pp. E4015006.

https://doi.org/10.52202/080513-0707

[13] W. Dong, M. Li, L.-M. Ottenhaus, and H. Lim. "Ductility and overstrength of nailed CLT hold-down connections." In: Engineering Structures 215 (2020), pp. 110667.

[14] Z. Li, X. Wang, M. He, Z. Shu, Y. Huang, A. Wu, and Z. Ma. "Mechanical performance of pre-fabricated metal dovetail connections for Cross-Laminated Timber (CLT) structures." In: Construction and Building Materials 303 (2021), pp. 124468.

[15] European Committee for Standardization (CEN). "EN 1995-1-1 - Eurocode 5: Design of timber structures Part 1-1: General-common rules and rules for buildings." Brussels, Belgium 2008.

[16] National Lumber Grading Authority (NLGA). "Standard grading rules for Canadian lumber." Vancouver, BC, Canada 2014.

[17] American Society for Testing and Materials (ASTM). "D1761-12: Standard test methods for mechanical fasteners in wood." West Conshohocken, PA, United States 2012.

[18] European Committee for Standardization (CEN). "EN 26891-1991 - Timber structures - Joints made with mechanical fasteners - General principles for the determination of strength and deformation characteristics." Brussels, Belgium 1991.

 https://doi.org/10.52202/080513-0707