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Experimental Study on the Synergistic Lateral Resistance of CLT Walls and Tension-only Braced Frames

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ABSTRACT: This paper proposed a novel structural system—Beam-through steel-timber hybrid structure—leveraging the high ductility of tension-only braces and the ease of installation inherent to floor-by-floor construction methods. To investigate the collaborative lateral resistance between CLT walls and tension-only braces within this system, two full-scale specimens consisting of a combination of the CLT wall and the tension-only braced frame were designed and subjected to low-cycle repeated loading tests. The experimental results demonstrated that the tension-only brace contributed over 70% of the initial lateral stiffness in the elastic stage of the structure. When the inter-story drift ratio reached 1/50, the shear force contributed by the CLT wall exceeded 50% in both specimens.

KEYWORDS: CLT wall; Tension-only braced frame; Full-scale quasi-static test; Collaborative lateral resistance

1 – INTRODUCTION

With the increasing prominence of resource and environmental concerns, the construction industry has shifted towards green construction practices and the use of sustainable building materials. Wood, as a recyclable and negative carbon building material, presents inherent advantages in prefabrication, leading to its expanding application in building structures.

Glulam frame structures typically exhibit limited lateral resistance due to low rotational stiffness of bolted beam-column connections. Consequently, additional braces are often necessary to enhance lateral performance. Conventional glulam braces, however, are susceptible to compressive buckling [1-3]. Previous studies introduced buckling-restrained braces (BRBs) [4-6] and energy dissipation devices [7] to improve the performance of the frames, though challenges such as the failures of connections and adjacent components remain unresolved. Tension-only braces, fabricated from slender steel elements, have been shown to be able to effectively increase lateral stiffness [8-10], demonstrating excellent ductility and ease of installation. These tension-only braces have been employed in multi-story steel buildings in China and Japan [11-15], yet their application in timber structures is still limited.

Compared to glulam frame structures, Cross-Laminated Timber (CLT) structures have higher lateral stiffness but are less flexible in structural layout. Research integrating CLT panels with glulam frames [16] demonstrated that CLT panels can significantly enhance the lateral stiffness and load-bearing capacity of glulam frames. However, this came at the cost of reduced ductility and potential failure at beam-column connections. Additionally, studies on steel-timber hybrid structures with CLT panels as frame infill [17] showed that increasing the proportion of CLT panels can markedly reduce the seismic vulnerability of the structure.

To improve the lateral performance of glulam frame structures, this paper proposed a novel beam-through steel-timber hybrid structure, which integrates CLT walls with tension-only braced glulam frames. The CLT walls are connected to the glulam columns using steel coupling beams, which are further connected within each floor by end-plate bolts, as illustrated in Figure 1.

To assess the synergistic lateral performance of CLT walls combined with tension-only braced glulam frames, two full-scale composite frames were designed and tested under low-cycle reversed loading. The test results were analyzed for the load-bearing mechanisms and the failure modes of the composite frames under horizontal loading.

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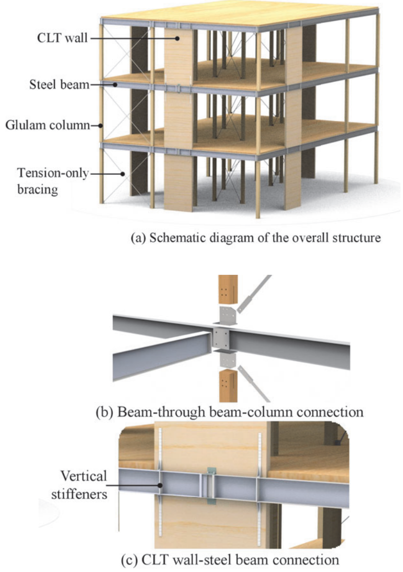


(a) Schematic diagram of the overall structure

(b) Beam-through beam-column connection

(c) CLT wall-steel beam connection

Fig. 1 Diagrams of beam-through steel-timber hybrid structures

2 – Experiment design

2.1 – Specimen design

In accordance with Chinese Standard GB/T 51226-2017 Standard for Design of Timber Structures [18] and previous studies [19], two full-scale composite frames combining the CLT wall and the tension-only braced glulam frame were designed and labeled as specimens F1 and F2, respectively. Except for the cross-sectional area of the tension-only brace, the geometric and physical parameters of the two composite frames were identical. The cross-sectional area of the braces of specimen F1 was 200 mm², while that of specimen F2 was 400 mm². The CLT walls measured 1000 mm×2700 mm×105 mm (length × height × thickness). The glulam columns had a cross-sectional dimension of 200 mm×200 mm with a height of 2680 mm. The upper steel beam had a cross-section of H250×300 ×6×8, while the bottom steel beam had a cross-section of H350 ×350×12×19. The frame with tension-only bracing featured a span of 1200 mm. More dimensions of the specimens were detailed in Figure 2.

The CLT walls were connected to the upper and bottom steel beams using hold-down and bracket connections, as depicted in Figure 3. The glulam columns, steel beams, and tension-only braces were connected through metal connectors, as illustrated in Figure 4.

According to Chinese Standard GB 50005-2017 Standard for Design of Timber Structures [20], the end and edge distances of the bolt holes of the glulam column were 130 mm and 65 mm, respectively. The glulam columns were fastened using grade 10.9 hex bolts with a nominal diameter of 18 mm, while the tension-only braces were secured to adjacent members with grade 10.9 M24 bolts.

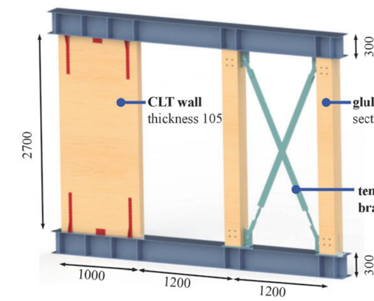


Fig.2 Dimensions of the specimen

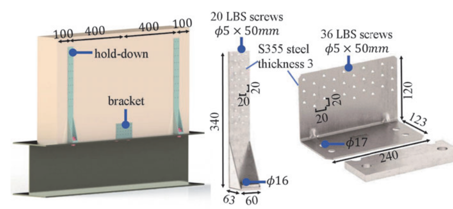
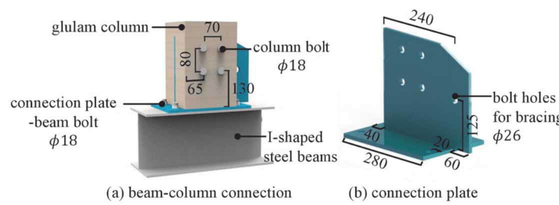


Fig.3 CLT connections design



(a) beam-column connection (b) connection plate

Fig.4 Beam-column connection design

The tension-only brace was tensioned through a sleeve, and its performance was primarily determined by the axial loading capacity of the flat steel, as shown in Figure 5. In specimen F1, the flat steel section of the tension-only brace had a thickness of 5 mm and a width of 40 mm (area 200 mm²). In specimen F2, the flat steel section had the same thickness of 5 mm but a width of 80 mm (area 400 mm²).

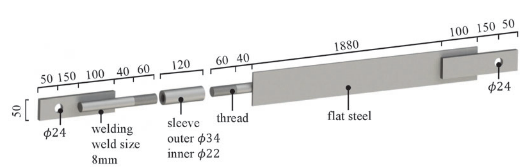


Fig.5 Design of tension-only bracing

The CLT wall comprised three layers of No. 1 grade Spruce-Pine-Fir (S-P-F) lumber, laminated orthogonally. Each lumber piece had a cross-sectional dimension of 140 mm×35 mm. The glulam columns were made from horizontally laminated Douglas fir, with a material strength grade of TCT32. The upper and bottom steel beams, as well as the flat steel used for the braces, were fabricated from Q235B steel with a nominal yielding strength of 235 MPa, while Q345B steel with a nominal yielding strength of 345 MPa was used for the beam-column connection plates and other components.

2.2 – Measurements and loading schemes

The tests were conducted at the Key Laboratory of Disaster Reduction in Civil Engineering of China, Tongji University. The loading setup involved a 500 kN hydraulic jack and an electro-hydraulic servo loading system. The bottom beam of the specimen was welded to two rectangular steel beams, which were anchored to the ground using bolts. The upper steel beam was connected to the actuator via bolts. Additionally, external portal frames were used to restrict the out-of-plane deformation of the specimen, as shown in Figure 6.

The loading was applied via displacement control. Referencing Krawinkler et al.'s suggestion [21], six cycles of 6 mm constant amplitude loading were initially applied. Subsequently, a loading protocol combining primary cycles with trailing cycles was implemented, as shown in Figure 7. The amplitudes of the primary cycles were sequentially set to 9, 12, 24, 36, 48, 84, 120 mm, and 180 mm, with trailing amplitudes at 75% of the amplitude of the preceding primary cycle. After the 9 mm and 12 mm primary cycles, six trailing cycles were performed; following the 24 mm and 36 mm primary cycles, three trailing cycles were executed; and for the remaining primary cycles, two trailing cycles were conducted after each. The loading rate was set to 20mm/min.

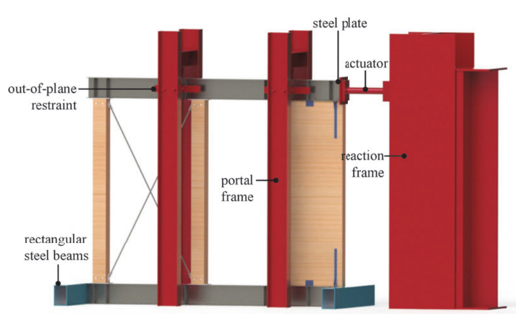


Fig.6 Loading schematic diagram

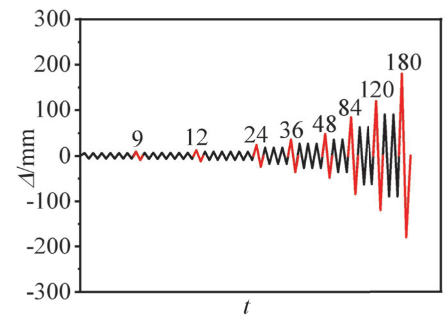


Fig.7 CUREE displacement loading system

The arrangement of the measuring points of the experiment is illustrated in Figure 8. Eight displacement gauges were placed at the CLT connections to record the relative horizontal and vertical displacements between the CLT wall and the steel beam. Additionally, sixteen strain gauges (resistance 120 Ω±0.2%, grid length 3 mm, sensitivity factor 2.06) were positioned at one-third the height from the bottom (Sections S5 and S8) and one-third the height from the top (Sections S6 and S7) of the glulam columns to measure axial strains. Finally, eight strain gauges were installed on the brace flat steel and the sleeve to monitor the axial strain of the brace.

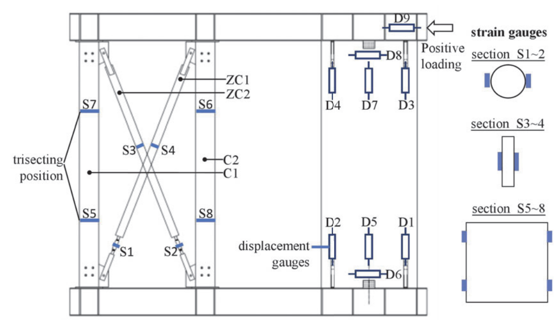


Fig.8 Layout diagram of measurements

3 – Main damage phenomena

Both composite frames failed during the negative loading cycle with a displacement amplitude of 180.0 mm. The failure mode of specimen F1 is shown in Figure 9. The timber at the hold-down connection near the loading end on the upper side of the CLT wall was completely pulled out, while the timber at the hold-down connection on the lower side, away from the loading end, suffered bearing failure at the dowel holes. Additionally, transverse splitting occurred around the bolt holes near the top and bottom ends of the column, away from the loading end (the one on the left of Figure 9). For specimen F2, the hold-down connector on the

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upper side of the CLT wall near the loading end fractured, and the other connections of the CLT wall exhibited significant deformation, with some steel components torn. Transverse splitting was also observed around the bolt holes at the top and bottom ends of the timber column, away from the loading end, as depicted in Figure 10.

4 – Load-displacement hysteresis curves

The lateral displacement-horizontal reaction force (Δ-F) hysteresis curves of the composite frames are illustrated in Figure 11. During the initial loading stage (Δ<12.0 mm), the composite frames behaved within the elastic range, and the loading and unloading curves almost overlapped. Specimen F2 exhibited slightly higher initial lateral stiffness compared to specimen F1. Once Δ exceeded 12.0 mm, the tension-only braces began to yield, resulting in a noticeable reduction in the lateral stiffness of the composite frames. In the later stages of loading, damages to the CLT wall connections further decreased the lateral stiffness of the frames.

During the positive loading cycles, the load increased consistently until failure occurred during the negative loading cycle at a displacement amplitude of 180.0 mm. Additionally, the load-displacement curves in the positive and negative directions were asymmetrical. The the load-bearing capacity during the negative loading cycles was greater than those during the positive loading cycles, attributed to the stronger constraint imposed by the upper steel beam on the CLT wall during negative loading.

As the loading increased, the plastic deformation accumulated in the tension-only braces, causing non-stressed state of the braces during small displacement cycles. Consequently, the corresponding slopes of the loading and unloading curves were small. The slope of the loading curves increased only after the braces regained tension. Consequently, the hysteresis curves exhibited a pronounced pinching effect, indicating that the performance of the tension-only braces significantly influenced the energy dissipation capacity of the composite frames.

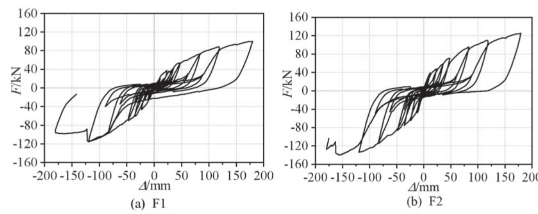

Fig.11 Hysteresis curves

5 – Distribution of horizontal force

Figures 12a and 13a illustrate the horizontal force carried by the tension-only braces, glulam columns, and CLT walls of the composite frames. Figures 12b and 13b depict the proportion (η) of these horizontal forces of the total horizontal force. At the inter-story drift

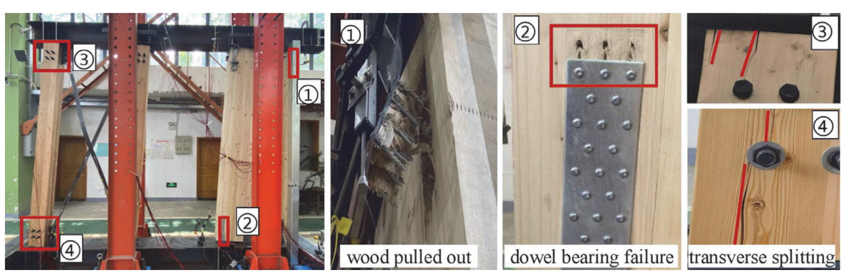

Fig.9 Failure mode of specimen F1

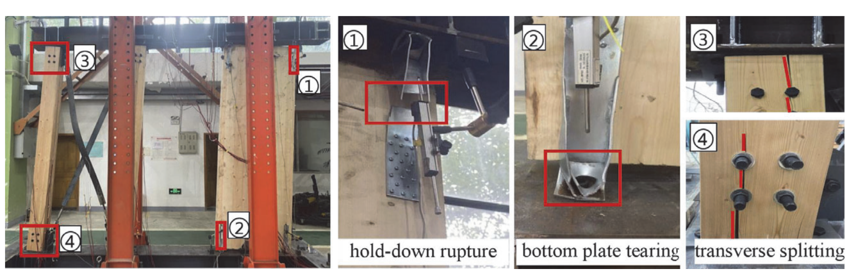

Fig.10 Failure mode of specimen F2

angle limit of 1/250 required by the Chinese Standard GB 50011-2010 Code for Seismic Design of Buildings [22] for steel structures under frequent earthquakes , the columns carried less than 3% of the horizontal force, while the tension-only braces carried approximately 70% and 90% of the horizontal force, respectively. This indicated that the tension-only braces provided the majority of the lateral resistance for the composite frames during the elastic phase.

After the tension-only braces yielded, the horizontal force carried by them did not increase any more while the applied load increased, and thus the proportion of the bracing force in the total force gradually decreased. When the inter-story drift angle reached the elastic-plastic limit of 1/50 as specified by Chinese Standard GB 50011-2010 [22] (Δ=60.0 mm), nearly 60% and 55% of the horizontal force were carried by the CLT wall in specimens F1 and F2, respectively, while the tension-only braces carried only 35% and 40%, respectively. This indicated that in the plastic phase, the CLT walls provided the majority of the lateral resistance for the composite frame.

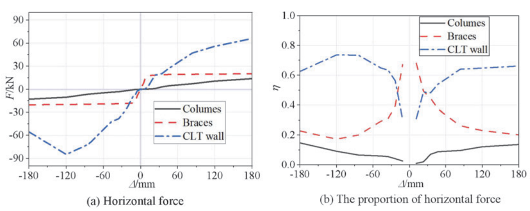

Fig.12 Horizontal force distribution of specimen F1

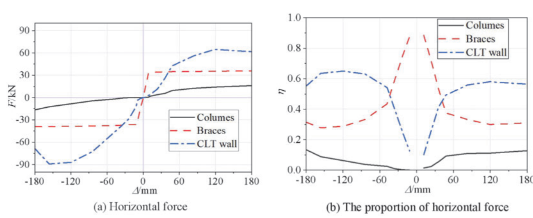

Fig.13 Horizontal force distribution of specimen F2

6 – Conclusions

To explore the synergistic lateral resistance of composite frames with CLT walls and tension-only braced frames, low-cycle reversed loading tests were carried out. The following conclusions can be drawn from the test results and discussion:

(1) The tension-only bracing yielded under tensile internal force, followed by the wood cracking at the ends of the glulam columns, and eventually the failure of the CLT wall's hold-down connections caused the decrease of the lateral resistance of the frames.

(2) The hysteretic curve of the frames showed a distinct pinching effect. After the yielding of the tension-only bracing, there was a significant reduction in the lateral stiffness of the frames.

(3) The tension-only bracing and the CLT wall contributed by different extent to the lateral resistance of the composite frame during different stages. Specifically, the tension-only bracing was mainly active during the elastic stage of the composite frame, providing at least 70% of the lateral resistance. Contrarily, the CLT wall became more critical in the elastic-plastic stage of the composite frame, contributing no less than 55% of the lateral resistance.

7 – REFERENCES

[1]Chen X, Leng Y, Xu Q. Experimental study on seismic behavior of braced glulam frames. Journal of Building Structures. 2020;41:122-30.

[2]Xiong H, Liu Y, Yang C, Qin H. Experimental Study on Lateral Resistance of Glued-laminated Timber Post and Beam Systems. Journal of Tongji University Natural Science. 2014;42:1167-75.

[3]Wang MQ, Chen X, Xu QF, Harries KA, Leng YB, Chen LZ. Numerical Simulation and Variability Analysis of Mechanical Behavior of Braced Glulam Frames. Journal of Structural Engineering. 2022;148.

[4]Dong WC, Li MH, Lee CL, MacRae G, Abu A. Experimental testing of full-scale glulam frames with buckling restrained braces. Engineering Structures. 2020;222.

[5]Wu Y, Song X, Jiang H, Gu X. Experimental study on lateral performance of glulam timber frames with timber-steel buckling-restrained bracings. Journal of Building Structures. 2021;42:38-46.

[6]Wang MQ, Zhou BC, Harries KA, Chen X, Zhang FW, Xu QF. Seismic performance evaluation of a five-story column-and-beam glulam frame with steel-timber buckling restrained braces. Journal of Building Engineering. 2023;80.

[7]Di Cesare, A., Ponzo, F.C., Lamarucciola, N. et al. Experimental seismic response of a resilient 3-storey post-tensioned timber framed building with dissipative braces. Bull Earthquake Eng 18, 2020;18:6825-6848.

[8]Papagiannopoulos GA. On the seismic behaviour of

https://doi.org/10.52202/080513-0527

tension-only concentrically braced steel structures. Soil Dynamics and Earthquake Engineering. 2018;115:27-35.

[9]Dong BP, Chen YS, Wang W. Self-centering mechanism and seismic response of steel tension-only concentrically braced beam-through frames. Structures. 2021;30:960-72.

[10]Liu D, Wang W, Baba M, Yu Y, Chen Y, Yang J. Development and behavior testing of innovative braces of floor-by-floor assembled steel structures. Building Structure. 2012;42:57.

[11]Wang W, Chen Y, Yu Y, Tong L, Yang J, Liu D et al. Floor-by-floor assembled steel braced structures for prefabricated buildings. Building Structure. 2012;42:48-52.

[12]Chen Y, Wang W, Chen Y. Full-scale shake table tests of the tension-only concentrically braced steel beam-through frame. Journal of Constructional Steel Research. 2018;148:611-26.

[13]Hu S, Wang W, Qu B. Enhancing seismic performance of tension-only concentrically braced beam-through frames through implementation of rocking cores. Engineering Structures. 2018;169:68-80.

[14]Li Y-W, Li G-Q, Jiang J, Wang Y-B. Seismic performance improvement of tension-only-braced frames with Energy-Dissipative Rocking Columns. Engineering Structures. 2019;196.

[15]Wu F-W, Li Y-Q. Large-scale shaking table tests of a six-story floor-by-floor assembled CFS frame-framing shear wall structure. Engineering Structures. 2023;293.

[16]Xue J, Ren G, Yuan Z, Wang P. Experimental study on seismic performance of glued-laminated timber frame infilled with CLT shear wall. Journal of Building Structures. 2022;43:140-50.

[17]Teweldebrhan BT, Tesfamariam S. Ductility-related seismic modification factor for CLT shear-wall and glulam moment-resisting frame dual system. Canadian Journal of Civil Engineering. 2024.

[18]Technical standard for multi-story and high rise timber buildings. Beijing, China: China Architecture and Building Press, 2017.

[19]Reynolds T, Foster R, Bregulla J, Chang WS, Harris R, Ramage M. Lateral-Load Resistance of Cross-Laminated Timber Shear Walls. Journal of Structural Engineering. 2017;143.

[20]Standard for Design of Timber Structures. Beijing, China: China Architecture and Building Press; 2017.

[21]Krawinkler H, Parisi F, Ibarra L, Ayoub A, Medina R. Development of a testing protocol for wood frame structures 2001.

[22]Code for Seismic Design of Buildings. Beijing, China: China Architecture and Building Press; 2016.