Lateral performance of timber shear walls reinforced by prestressed diagonal cross bars

Hongliang Zuo*, Yishi Li, Jing Di, Nan Guo

School of Civil Engineering, Northeast Forestry University, Harbin 150040, China

ZHL9163@163.com

ABSTRACT. This paper investigates the lateral performance of a new type of steel-wood composite walls, namely, timber shear walls reinforced by prestressed diagonal cross bars. A total of ten such walls with different features were subjected to monotonic in-plane horizontal loading tests, aiming to disclose the effects of these features on the failure mode, bearing capacity and ultimate displacement. The test results show that the walls reinforced by diagonal cross bars had better lateral performance than the traditional shear walls. The displacement of the walls decreased significantly with the growth in prestress, indicating that prestressing can reduce the ultimate displacement of the walls. However, the walls' bearing capacity had nothing to do with the prestress level. In addition, the enhancement effects of the bars were specified through the analysis on mechanical behaviors. The research findings provide new insights into the mechanical performance of steel-wood composite walls.

RÉSUMÉ. Cet article examine les performances latérales d'un nouveau type de murs composites acier-bois, à savoir les murs de cisaillement en bois renforcés par des barres transversales diagonales précontraintes. Au total, dix murs présentant des caractéristiques différentes ont été soumis à des tests monotoniques de chargement horizontal dans le plan afin de révéler les effets de ces caractéristiques sur le mode de défaillance, la capacité portante et le déplacement ultime. Les résultats des tests montrent que les murs renforcés par des barres transversales diagonales ont une meilleure performance latérale que les murs à cisaillement traditionnels. Le déplacement des murs a été diminué de manière significative avec la croissance de la précontrainte, ce qui indique que la précontrainte peut réduire le déplacement ultime des murs. Cependant, la capacité portante des murs n'a rien à voir avec le niveau de précontrainte. De plus, les effets d'amélioration des barres ont été spécifiés par l'analyse des comportements mécaniques. Les résultats de la recherche fournissent de nouvelles informations sur les performances mécaniques des murs composites acier-bois.

KEYWORDS: diagonal cross-bar, prestress, monotonic loading test, lateral performance, deformation behavior.

MOTS-CLÉS: barre transversale diagonale, précontrainte, test de chargement monotonique, performance latérale, comportement à la déformation.

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1. Introduction

Light wood frame construction is a type of structural system composed of dimensional lumber and wood-based panels. Due to its advantages in environmental friendliness, better seismic performance and construction flexibility, it is widely used in North America, Canada, Japan, and European countries (Awad *et al.*, 2014; Yin & Li, 2010; Tarabia & Itani, 1997). Timber shear walls are the primary components of light wood structural systems, which mainly resist the lateral forces from earthquakes and wind loads (Li & Ellingwood, 2007).

Extensive experimental programs and numerical research studies are conducted to study the lateral performance of timber shear walls (Cheung, 1988; Winkel & Smith, 2010; Memari *et al.*, 2008; Michael & Ian, 2010). These studies suggest that weak links between the framing and sheathing panel result in lower utilization of the wall material's strength, which decreases the lateral performance of traditional timber shear walls. In addition, several experimental campaigns focus on the lateral performance of timber shear walls composed of different materials (Correal & Varela, 2012; Guo & Jiang, 2016). These results suggest that the failure modes of timber shear walls that use different materials are still the uplift of the end stud, nail withdrawal and pull through the panels (Premrov & Dobrila, 2012; Seim *et al.*, 2016).

Therefore, a new type of prestressed diagonal cross-bar-reinforced timber shear wall is developed, which is intended to improve the failure mode of timber shear walls and further enhance their bearing capacity and ductility. The weak parts of the walls are expected to be strengthened during the shearing process by setting a diagonal cross reinforcement, and a new type of corner anchoring member is designed to enhance the behavior of the connection in the wall and affix the steel bar. The bars are pretensioned to further enhance the lateral performance of the timber shear walls.

In this paper, monotonic tests of 10 full-scale walls are carried out under in-plane horizontal loads. The paper investigates the effects of the corner anchors, diagonal cross-bars and prestress level on the lateral performance of the timber shear walls. Based on the test data, the bearing calculation formula of the prestressed diagonal cross-bar-reinforced timber shear wall is derived.

2. Overview of the experiment

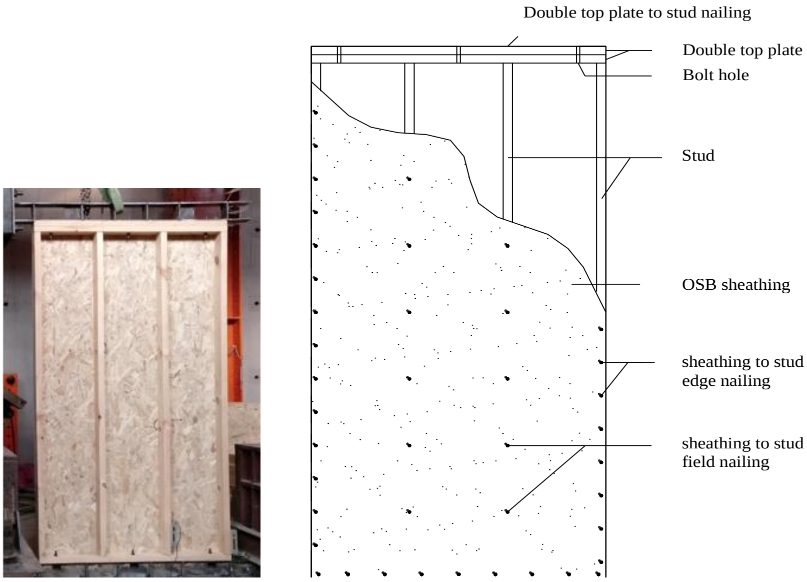
2.1. Material specifications and properties

The material specifications used in the elements of the specimens are selected according to GB5005-2003. The details of these specimens are shown in Table 1.

Table 1. Material specifications of the test wall

Element	Material	Specifications
Stud	Mongolian Scots pine	Cross-sectional dimensions: 38 mm×89 mm
Top and ground plate		
Sheathing panel	Oriented strand board	b=1200mm, h=2400mm, t_1=9.5 mm
Framing nail	Iron nail made in China	d_n=3.5 mm, l=85 mm
Sheathing nail	Iron nail made in China	d_n=3.5 mm, l=65 mm
Bolt	High strength bolts	d_b=12 mm
Corner anchor	Steel	t_2=8 mm
Bar	HPB300	D=10 mm

2.2. Design and fabrication of specimens

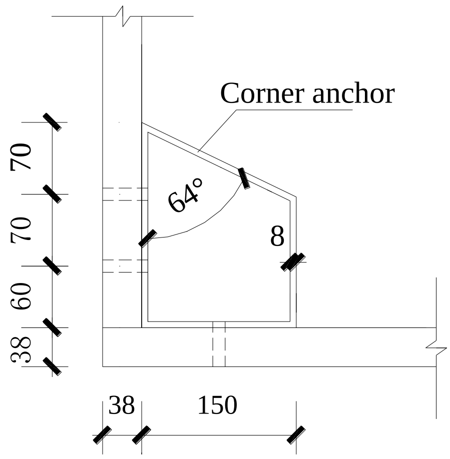


(a) Front view *(b) Rear elevation*

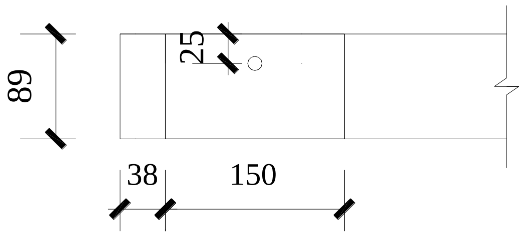
Figure 1. Details of the test specimens in group T

Ten timber shear walls are divided into four groups based on the different steel components, including T, C, CB and CBP. The test specimens in group T are traditional timber shear walls. The specimens are fabricated according to the requirements of the code ASTM E564. The top plate consists of two members, whereas the bottom plate and studs consist of a single member. The timber frame is connected by two framing nails with a spacing of 30 mm. The sheathing panel is connected to the framing members with nails at spacings of 150 mm along the panel edges and 300 mm for the interior studs. The details of the test specimens in T are shown in Fig. 1. The test specimens in C are set up with four corner anchors based on the specimens of group T, and the corner anchors are affixed to the timber frame by bolts. The details of the test specimens in C are shown in Fig. 2. The specimens in group CB include two bars along the diagonal of the panel based on the specimens in group C and affix the diagonal cross-bars to the inclined plate of the corner anchor. Group CBP is further divided into group CBP-30 and CBP-90 based on the prestress level. The specimens in CBP-30 had a pretension of 30 MPa in the diagonal cross-bars, and the specimens in CBP-90 of 90 MPa. The details of the test specimens in CB and CBP are shown in Fig. 3.

(a) Front view



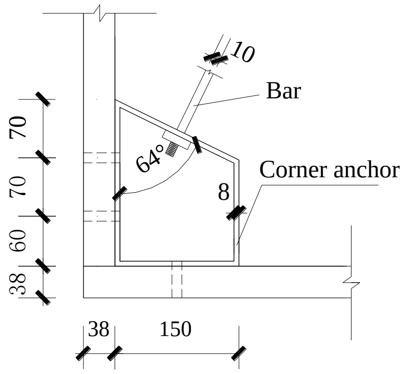
(b) Front view of timber frame joint in the corner



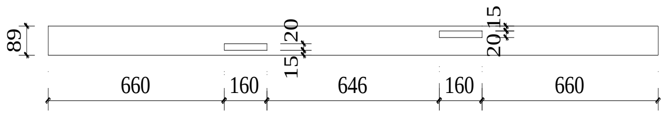
(c) Top view of timber frame joint in the corner

Figure 2. Details of the test specimens in group C

(a)Front view



(b)Front view of timber frame joint in the corner



(c) Details of the interior studs

Figure 3. Details of the test specimens in groups CB and CBP

2.3. Test setups, instrumentions, and procedures

A 250-kN actuator is applied to the lateral load. This actuator is connected to the wall by a steel load transfer beam. The ground plate of the specimens is affixed to the base steel beam to ensure that no horizontal displacement is produced at the bottom of the wall. The experimental setups and locations of the transducers are shown in Fig. 4.

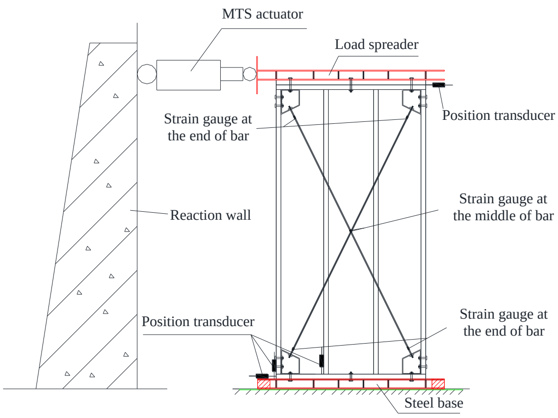


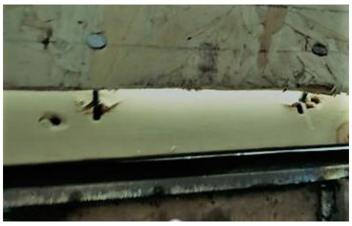
Figure 4. Experimental setups and locations of the transducers

The displacement-controlled loading mechanism follows ASTM E564. The horizontal loading rate is 7.5 mm per minute. Failure of a specimen is considered to occur when the load carrying capacity degraded to 80% of its maximum.

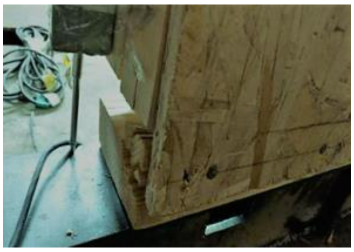
3. Failure modes

Fig. 5 shows the damage patterns of all specimens. In each group, stud uplift initially occurs at the bottom of the edge stud. As the load increased, the uplift increased, which causes the rotation of the sheathing panel. The framing nails are pulled out of the stud, and the sheathing panel is lifted away from the bottom plate. The heads of the sheathing nails are embedded into and pulled through the panels. With further loading, the edge of the panel is torn by nails, and splitting occurs at the middle of the bottom plate near the sheathing nails. In addition, in groups CB and CBP, cleavage of the end stud occurs at the edge of the bolt hole and develops along the wood fiber, which results in the final failure.


(a)Nail head embedding into the panel *(b)Nail tearing out of the edges of the panel*




(c)Nail pulling through the panel *(d) End stud lifted off the bottom plate*




(e) Nail splitting the bottom plate *(f) Bolt splitting the bottom plate*

Figure 5. Failure modes of walls

4. Results and analysis

4.1. Load-displacement relationship

The load-displacement curves obtained from the test are shown in Fig. 6. The ultimate bearing capacity and the limited displacement of group T are the lowest, and the curve of group T increases slowly. The ultimate load and displacement of group C are significantly higher than those of group T, and they have a greater slope in the ascending section of the curve than group T. The ultimate bearing capacities of groups CB and CBP are almost the same and much higher than that of group C. The ultimate displacement of group CB is the largest of the four groups. The ultimate displacement in group CBP decreases as the prestress level increases. When the prestress level reaches 90 MPa, the ultimate displacement of the wall is similar to that of group C. The slopes of the ascending sections in the load-displacement curves of groups CB and CBP rise with increasing prestress level. The parameters of the lateral behavior of the specimens are shown in Table 2.

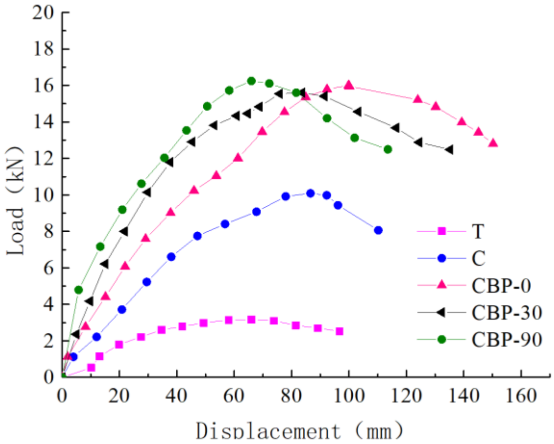


Figure 6. Load-displacement curves of test specimens

Table 2. Parameters of the lateral behavior of the specimens

Specimen NO.	Fmax/kN	Δfailure/mm
T	3.16	96.72
C	10.09	110.23
CB	16.01	150.23
CBP-30	15.61	135.24
CBP-90	16.25	113.56

4.2. Ultimate bearing capacity

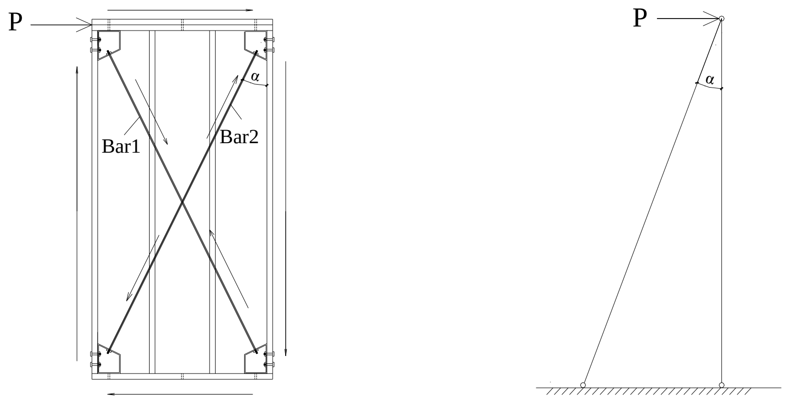
According to Table 2, the ultimate displacement of group C is 14% greater than that of group T, and the group CB 36% greater than that of group C. These results demonstrate that the corner anchors and bars enhance the deformation capacity of the walls. However, the ultimate displacements of group CBP for the prestress levels of 30 MPa and 90 MPa are 10% and 24% less than those of the group CB, respectively. A higher prestress level results in a greater reduction. The application of a prestress to the bars causes an initial displacement of the elements, which results in a restriction in the deformation capacity.

4.3. Analysis of the load-bearing mechanism

In the test, the shear load of diagonal cross-bar reinforced timber shear walls were resisted not only by sheathing panel and nails, but also by timber frame and reinforcements. Therefore, addtion of those resisting force was the shear capacity of diagonal cross-bar reinforced timber shear walls. However, the sheathing panel and nails were the main load resisting elements in traditional timber shear walls, and the timber frame provided little to no resistance. Thus, the bearing capacity formula for prestressed diagonal cross-bar reinforced timber shear walls were presented as follows:

$$V = P + V_T$$

Where V is the shear resistance capacity of prestressed diagonal cross-bar reinforced timber shear wall, P is the shear resistance capacity of timber frame with prestressed diagonal cross-bars, V_T is the shear resistance capacity of traditional timber shear wall.



(a)The loading path of timber frame with prestressed diagonal cross-bar

(b)The calculating diagram of timber frame with prestressed diagonal cross-bar

Figure 6. Analysis of the load-bearing mechanism of timber frame with prestressed diagonal cross-bar

The loading path of timber frame with prestressed diagonal cross-bar in shear wall was presented in Fig. 7(a), for a fully anchored timber shear wall, the stud-to-beam connections can be assumed to behave as hinged joint. As the bars were limited by the nut in the direction of tension, and were free in direction of compression. Therefore, in the test process, the bar 1 no longer provided resistance when the presresssed value was reduced to 0, the bar 2 still resisted the tension on the basis of the prestressed value. The calculating diagram of timber frame with prestressed diagonal cross-bar was presented in Fig. 7(b).

The shear strength of the reinforced timber frame was mainly provided by tensile reinforcement. According to the principle of structural mechanics analysis, the shear capacity of the reinforced timber frame was presented as follow:

$$P = \frac{\pi d^2 \sigma_{\mathrm{con}} \sin \alpha}{4} + \frac{\pi d^2 \sigma_P \sin \alpha}{4}$$

Where P is the shear resistance capacity of timber frame with prestressed diagonal cross-bars, d is the diameter of the bars, σcon is the initial prestressed value of the bars, σp is the tensile stress of the bars in test process, α is the angle between the bar and the stud.

Accordingly, the cross-bar enhanced the shear capacity of timber shear walls. The prestressing force in the cross-bars caused the bar yield in advance. In elastic lateral displacement equal circumstances, increasing the prestrssed value improved shear capacity of diagonal cross-bar reinforced timber shear walls. Additionally, the initial compressive stress in stud and beam plate was applied by prestressed diagonal cross-bar, which effectively restrained the stud uplift and sufficiently used material strength. However, because of the prestressed force cannot improve the ultimate tensile strength of bars, the ultimate bearing capacity of diagonal cross-bar reinforced timber shear walls cannot be improved by increased prestressed value.

5. Conclusions

(1) The setting of corner anchors effectively restricts the uplift of the end stud in traditional timber shear walls, which improves the failure mode and enhances the integrity of the wall. Moreover, the ultimate bearing capacity of the walls with corner anchors is 219% higher than that of the walls without corner anchors.

(2) The presence of diagonal cross-bars in a timber shear wall is found to have significant effects on the bearing capacity and deformation performance. The ultimate bearing capacity of the walls with diagonal cross-bars is 65% higher than that of the walls without diagonal cross-bars.

(3) The ultimate bearing capacity of the timber shear walls with diagonal cross-bars is independent of the prestress level in the bar. However, the ultimate displacement of the timber shear walls is limited by the prestress in the bar. The ultimate displacement of the walls with diagonal cross-bars decreases by 10% and 24% for prestress levels of 30 MPa and 90 MPa, respectively, compared to walls

without prestressing.

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