Experimental Study on the Reinforcement Methods and Lateral Resistance of Mortise-Tenon Jointed Traditional Timber Frames

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In order to study the lateral resistance of reinforced traditional Chinese timber frames with mortise-tenon connections, three cyclic tests were conducted on one-bay mortise-tenon jointed traditional timber frames. Three reinforcement methods, *i.e.*, steel angle strengthening, wood brace, and Timu, were studied. Seismic performances were evaluated according to the experimental phenomena and the test results. The failure mode, hysteresis curves, skeleton curves, curves of stiffness degradation, and energy dissipation capacity of the three specimens were analyzed based on the tests. The test results showed that the wood frames had good deformability. The stiffness degradation of the timber frame was severe at the initial loading stage; however, the degradation rate tended to decrease after the initial stage. In addition, the energy dissipation increased as the lateral displacement increased. The wooden frames with mortise tenon joints strengthened by steel angle, wood brace, and Timu can achieve good aseismic results. The study can provide a theoretical basis for seismic design and reinforcing methods of traditional timber structures.

Keywords: Mortise-tenon jointed timber frames; Seismic strengthening; Steel angle; Wood brace; Timu; Low-cyclic reversed loading test

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INTRODUCTION

Timber structure systems are a unique structure system in ancient Chinese architecture, which has a long history and is spread over a vast area. Chinese timber architecture is as old as Chinese civilization. Tenon and mortise connections are the most prominent features of ancient wooden structures, which combine numerous wooden components into a solid and reliable structure. All the nodes work together, so that the wooden frame has good elasticity and semi-rigid characteristics. However, when subjected to an earthquake, the failure of the mortise and tenon joints will lead to building tilt or even collapse. Therefore, it is necessary to conduct in-depth research on the reinforcement of mortise and tenon joints.

In recent decades, many scholars have carried out experimental research and finite element analysis on ancient wood structures. The flexural behaviour of mortise–tenon joints of timber structures have been studied. The main failure mode of the dovetail joints is the pull-out of the tenon. The gaps within the joint have a great influence on the flexural behavior. The relationship of the moment and rotation is divided into a nonlinear initial stage, a yield stage, and a descending stage. The relationship of the moment and rotation can be simplified using a trilinear model (Chen *et al*. 2014, 2015, 2016; Chen 2016).

To study the impact of damage to the mortise-tenon joints in terms of the seismic performance of wooden frames, an artificial damage simulation method was used (Luo 2019; Li *et al*. 2020). Using a low reversed cyclic loading test, a comparative analysis of the different influence of the damage depth and the degree of surface damage of the tenon was performed. The hysteresis curves of the wooden frame showed the "Z" type, which experienced two stages, *i.e.*, sliding and rising. The curve of the sliding stage is longer; it shows that the timber frame has large displacement and small internal force characteristics. It is not comprehensive to judge the degree of declination of the seismic performance of the timber frame directly by the damage degree expressed *via* the volume loss ratio. Compared with the degree of tenon surface damage, the tenon damage depth had a greater impact on the seismic performance of the wood frame, which should be noted during the maintenance and reinforcement of ancient buildings. In addition, damaging the column bottom will also cause a decrease in seismic performance in the wood frame, and the reinforcement method used during repairs can effectively improve the seismic performance of the damaged wood frame.

Unreinforced wood frames and shape memory alloy (SMA) strengthened wood frames were tested. The failure mode, envelope curve, stiffness degradation, and energy consumption of these specimens were analyzed. The P-Δ effect, SMA enhancement efficiency, and coupling mechanism were also evaluated. An analytical model was proposed, and the model was tested by comparing the lateral load displacement responses of the strengthened and unreinforced specimens. In addition, an appropriate calculation method was established. Based on the excellent reinforcement effect of the wood structure, a future research focus is to establish reasonable design criteria (Zhou 2016; Xie *et al*. 2019, 2020). Experimental research, theoretical analysis, and finite element simulation methods have been used to make damage assessments and perform finite element analysis on dovetail joints (Li *et al.* 2016). The shape of the hysteretic curves of all specimens is an inverted Z shape, and they all have obvious pinching and sliding effects. As the loosening degree increases, the pinching and slippage effect of the hysteretic loop becomes more and more obvious. ABAQUS software was used to establish the finite element model of the dovetail joints with different degrees of looseness. The simulation results were compared with the experimental results, and on this basis, the parameters were analyzed. The results showed that the hysteresis curves simulated by ABAQUS were in good agreement with the measured results. At the initial loading stage, there was a difference between the ABAQUS simulated hysteretic skeleton curve and the measured skeleton curve. However, at the later loading stage, the curve was in good agreement (Li 2015; Li *et al*. 2016).

Zhou and Yan (2015) studied the mechanical properties and strengthening methods of mortise-tenon joints in ancient Chinese architecture. After the steel member method was used to strengthen the joint, the stiffness and strength were improved. In addition, the ductility and energy dissipation capabilities of the strengthened joints were good.

By carrying out quasi-static tests, mortise and tenon joints with different degrees of looseness were analyzed (Xue *et al*. 2016, 2018a, 2019). Based on the finite element analysis program (ABAQUS), the effects of the tenon height, friction coefficient between the tenon and mortise, the wood material properties, and the axial compression ratio were studied. A shaking table test was carried out. After the tenon mortise joints of ancient wooden buildings were strengthened with CFRP, the structure still had good energy dissipation capacity (Xue *et al*. 2012, 2016, 2018a,b, 2019).

EXPERIMENTAL

Test Specimens

This experiment used a common straight tenon joint as the research object. Three full-scale frame specimens were prepared, and all specimens were subjected to in-plane lateral cyclic loading. The span of the frame was 2600 mm, and the total height was 3200 mm. Table 1 shows the dimensions of the full-scale specimens, and the geometric details are illustrated in Fig. 2. Material property tests were carried out according to Chinese standards for the compressive strength, tensile strength, and modulus of elasticity of wood GB/T standard 1935-2009 (2009), GB/T standard 15777-1995 (1995), and GB/T standard 1938-2009 (2009), respectively. The pictures showing the standard material tests are given in Fig. 1. The compressive strength, tensile strength, and modulus of elasticity of the wood in the parallel to grain direction were determined from small clear specimens at 32.0, 72.2, and 10040 MPa, respectively.

Table 1. Dimensions of the Straight-tenon Jointed Timber Frames

Member		Component Dimensions (mm)
Column	Diameter	200
	Height	3200
Beam	Length	2400
	Width	120
	Height	200
Tenon	Length	400
	Width	60
	Height	200

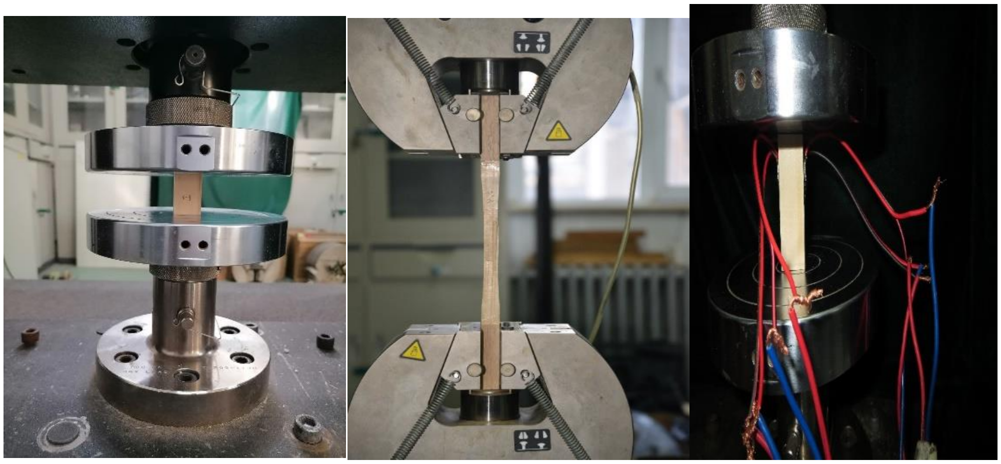
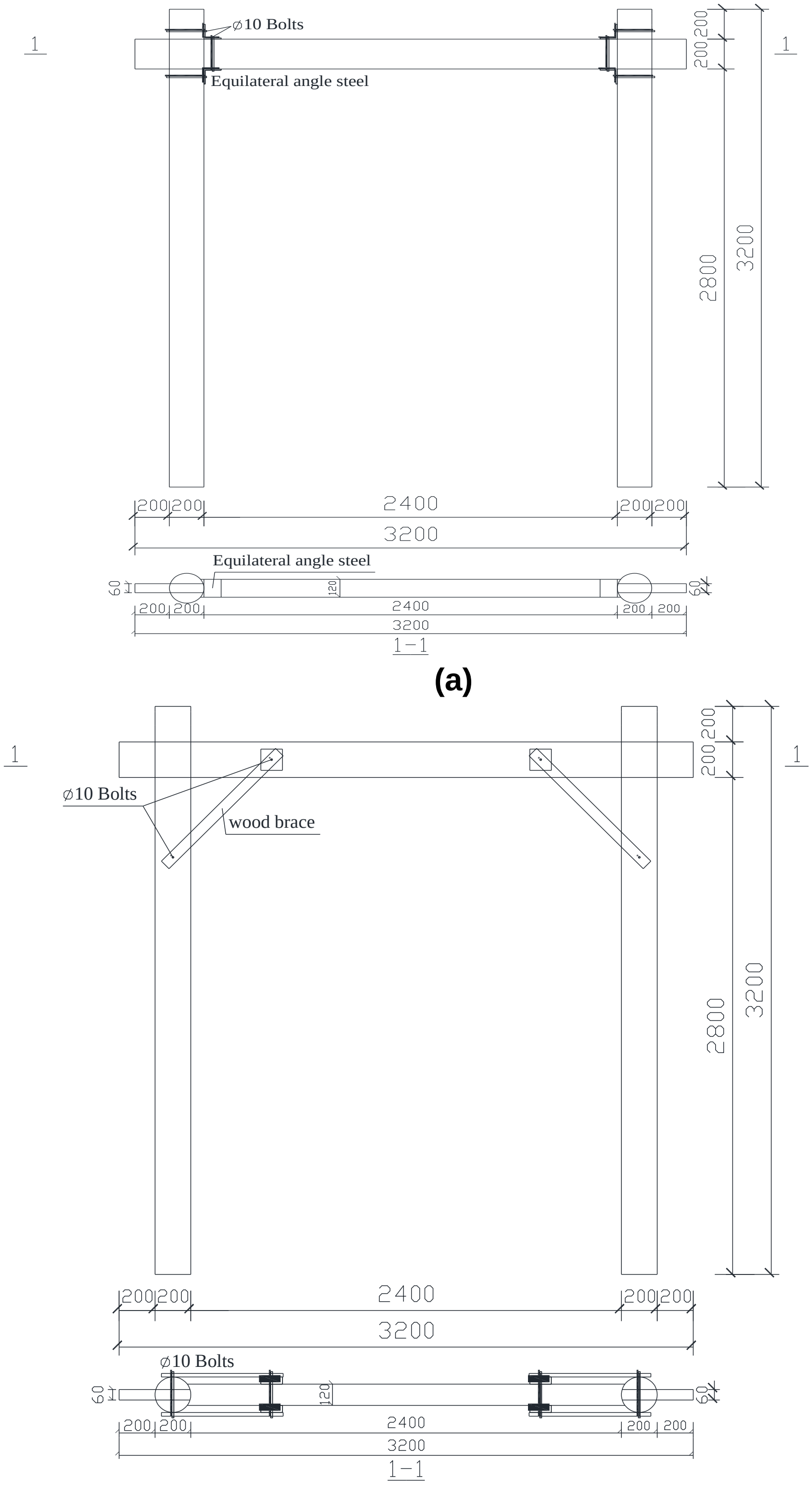

(a) (b) (c)

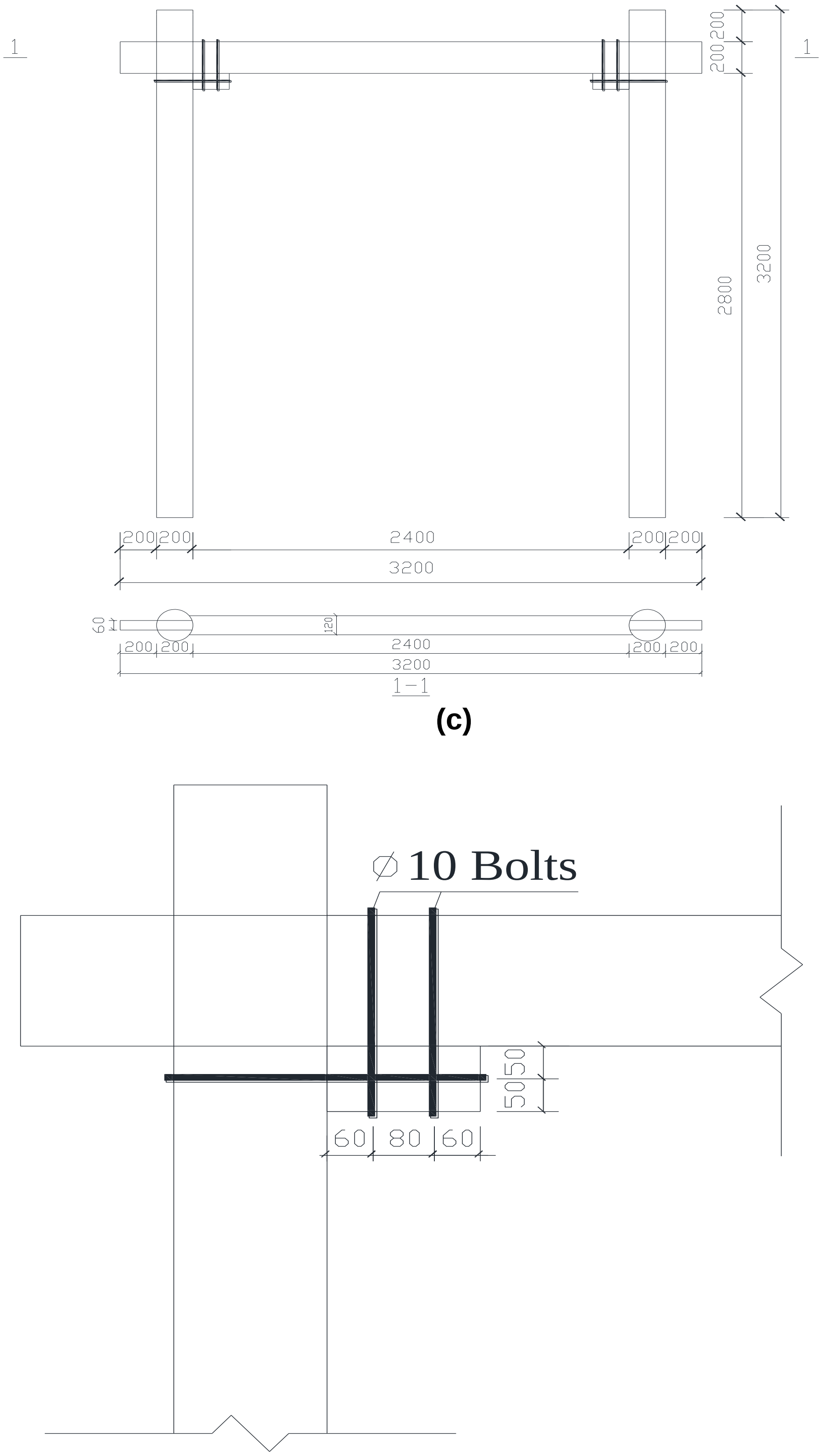
Fig. 1. Standard material testing: (a) parallel-to-grain compressive strength test; (b) parallel-to-grain tensile strength test; and (c) parallel-to-grain elastic modulus test

The frames consisted of beams and columns that were connected using straight tenon joints, as illustrated in Fig. 2 (the column diameter is 200 mm). Three methods were considered to strengthen the tenon and mortise joints of the models: steel angle, wood brace, and Timu. Figure 2 shows the following three methods: R1, where the angle steel was 100 × 8 angle steel (Q235), the length of the two flanges was 100 mm, the thickness was 8 mm, and the diameter of bolts was 10 mm; R2, where the wood brace was 60 mm wide, 20 mm thick, and 900 mm long; and R3, where the Timu was made of wood block with a thickness is 100 mm, a length of 200 mm, and a width of 120 mm.



(a)

(b)



(c)

(d)

Fig. 2. Three reinforcement methods: (a) R1: steel angle reinforcement; (b) R2: wood brace reinforcement; and (c) R3: Timu reinforcement (note: (d) shows a detailed drawing of the reinforcing joints with Timu in mm)

Test Setup and Loading Program

The electron-hydraulic servo loading system was made by MTS Co. Ltd. The traditional Chinese wooden columns were directly installed on the natural foundation stone. This connection cannot bear bending moment, so it can be simplified as a hinge joint. The horizontal actuator was hinge connected to the reaction wall and the loading position on the test model. The hinge between the hydraulic actuator and the specimen was used to eliminate the bending moment generated by the gravity of the actuator. The two jigs on both columns were connected by four steel rods on both sides of the frame to transfer the horizontal force. Two vertical loads, in line with the columns, were applied on top of the column by using two hydraulic jacks. The concentrated vertical loads were taken at 10 kN. Lateral restraint made of angle steel shapes was used to prevent out of plane deformation.

A schematic drawing of the test setup is shown in Fig. 3, and the overview of the specimen is shown in Fig. 4. The horizontal cyclic load was applied under displacement control. Three cycles of lateral loadings were attempted for the displacement of 10 mm, 20 mm, 30 mm, 40 mm, *etc*.

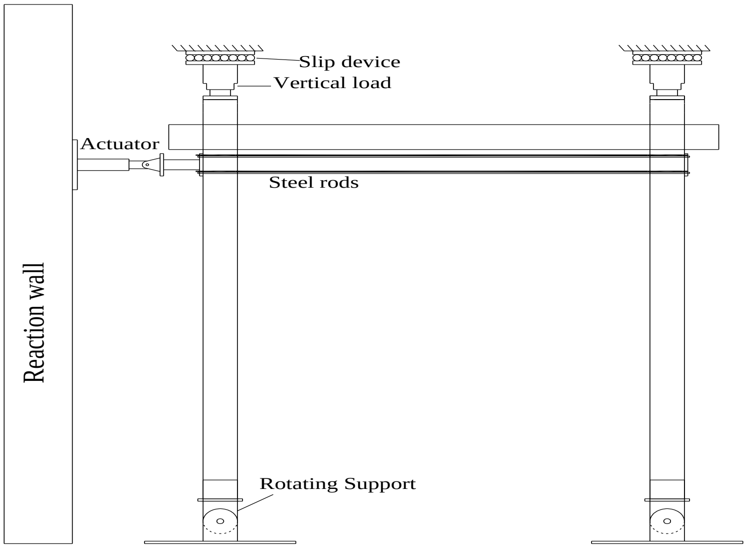


Fig. 3. Test setup

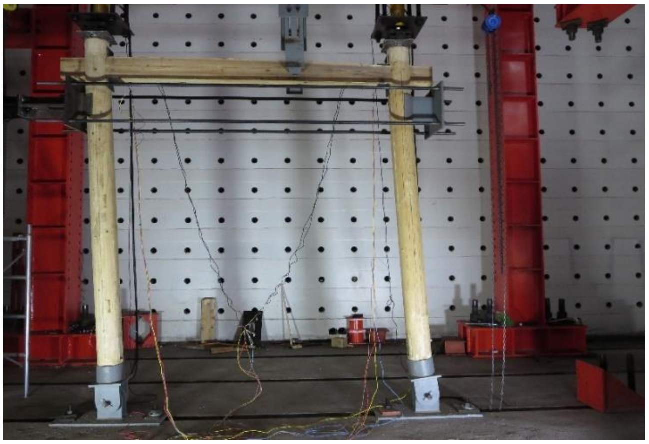


Fig. 4. The overview of the test

RESULTS AND DISCUSSION

Under a low cyclic load, a hysteresis curve is a comprehensive performance that measures the seismic performance of the timber frame. The larger the area of the hysteretic loop, the stronger the energy consumption ability and the better the seismic performance. Figure 5 shows the hysteretic curves obtained for the R1, R2, and R3 specimens, respectively. The pinching effect can be obviously observed in the hysteresis loops, which indicates that the timber frames had different degrees of slip.

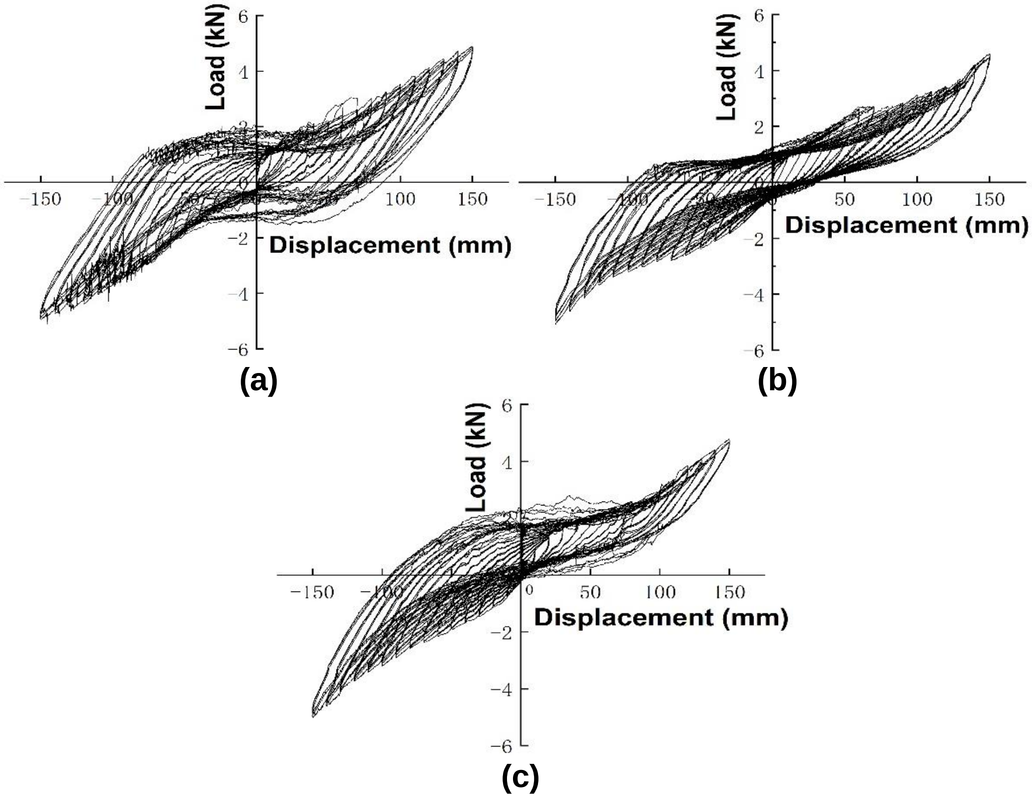


Fig. 5. Load-displacement hysteric curves: (a) R1; (b) R2; and (c) R3

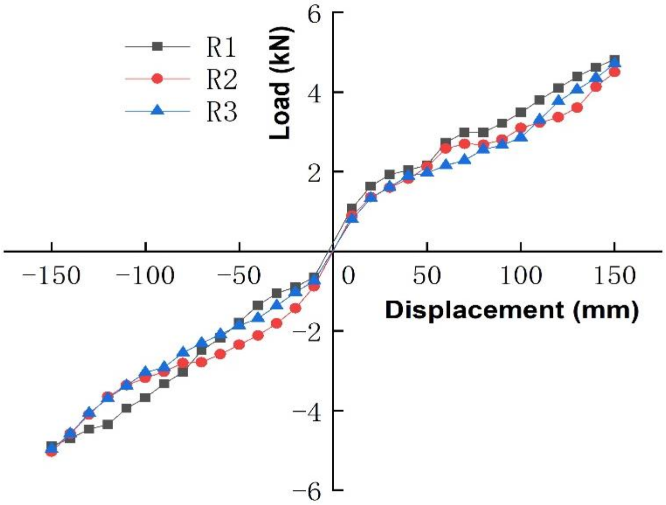


Fig. 6. Skeleton curves of the specimens

Skeleton Curves

A skeleton curve can reflect the ultimate bearing capacity and deformation capacity of the frames. The envelope curve was obtained in each case by connecting the extreme load points of all levels in the same direction is the skeleton curve. The skeleton curve is the track curve of the maximum peak value of force reached by each cyclic loading. The skeleton curves are shown in Fig. 6. During the loading process, the bearing capacity did not decrease; therefore, the reinforced frame showed good deformability.

Strength Degradation

Strength degradation corresponds to the strength decrease induced by subsequent cycles for a given displacement. The strength degradation factor is calculated by Eq. 1,

$$\boldsymbol{\lambda_{ji}} = \frac{\boldsymbol{F_{ji}}}{\boldsymbol{F_{j1}}} \tag{1}$$

where λ_{ji} is the strength degradation factor for the cycle "i", F_{j1} is the peak load of the first cycle of the j-stage displacement amplitude, and F_{ji} is the peak load of the i^th^ cycle of the j-stage displacement amplitude.

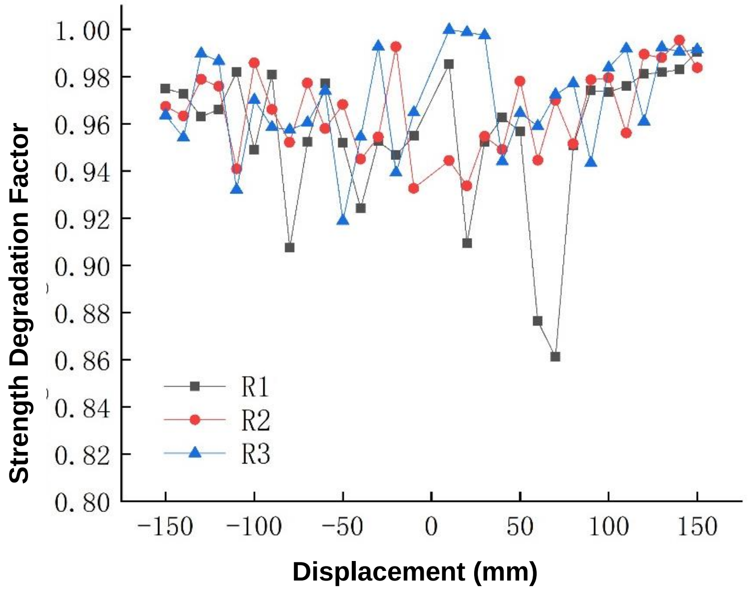


Fig. 7. Strength degradation of the tested frames

The curves of the strength degradation coefficient under different displacement amplitudes can reflect the overall strength degradation trend of the structure; the strength degradation curve of each specimen is shown in Fig. 7. The results showed that all specimens underwent the strength degradation phenomenon. This is because when the first excursion of the given cyclic amplitude was reached, the mortise and tenon squeezed each other tightly and were permanently deformed. During the loading process, the wood at the joint produced unrecoverable transverse deformation. The compression of the wooden frame joints primarily occurred during the first cycle, resulting in a strength degradation during the second cycle. As shown in Fig. 7, it can be seen that the strength degradation coefficients of the strengthened wooden frames were between 0.8 and 1.

The strength degradation of all specimens was less than 20%, which indicated that the reinforced mortise-tenon timber structure could provide reliable bearing capacity in subsequent aftershocks or small epicenters if the structure was not damaged after a large earthquake.

Stiffness Degradation

To assess the degradation rate of the lateral stiffness of the frames, the secant stiffness of the load-displacement hysteric curves was calculated for each primary cycle. The stiffness is evaluated according to the following relationship, shown in Eq. 2,

$$K_i = \frac{|+F_i|+|-F_i|}{|+\Delta_i|+|-\Delta_i|} \tag{2}$$

where Δ_i is the control displacement of the grade i and K_i and F_i are the lateral stiffness and lateral force of the specimens under the control displacement of the grade i, respectively.

The experimentally obtained stiffness degradation curve is shown in Fig. 8. As the lateral displacement increased, the stiffness of the model R1 reinforced with a steel angle dropped from 0.085 to 0.032 kN/mm. The stiffness of the model R2 reinforced with a wood brace ranged from 0.029 to 0.079 kN/mm, and the model R3 reinforced with Timu ranged from 0.029 to 0.069 kN/mm. At the beginning of the loading process, the stiffness of each wooden frame began to rapidly decrease when the displacement amplitude was small, and the degradation phenomenon was obvious. At the later loading stage, the degradation curve became relatively flat.

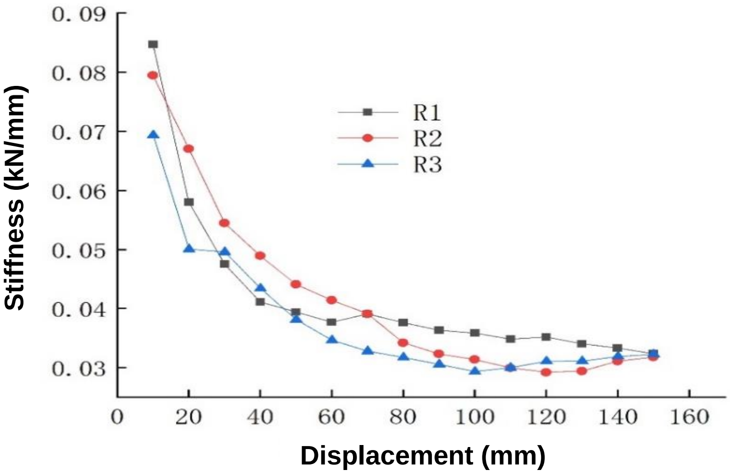


Fig. 8. Stiffness degradation curves of the frames

Energy Dissipation Capacity

Energy dissipation is measured by the area enclosed by the load–displacement hysteretic loop (as shown in Fig. 9). The accumulated area of the hysteretic loops reflects the amount of energy dissipation. The larger the hysteretic loop, the better the energy dissipation capacity of a structure. The energy dissipation capacity of the structure is usually expressed by the equivalent viscous damping coefficient h_e. The equivalent viscous damping factor is expressed by Eq. 3,

$$h_e = \frac{1}{2\pi}\frac{S_{CBA}+S_{ADC}}{S_{OBE}+S_{ODF}} \tag{3}$$

where h_e is the energy dissipation factor of a structure, S_{CBA} is the area enclosed by the curves of C–B–A, S_{ADC} is the area enclosed by the curves of A–D–C, S_{OBE} is the area enclosed by the polyline of O–B–E, and S_{ODF} is the area enclosed by the polyline of O–D–F.

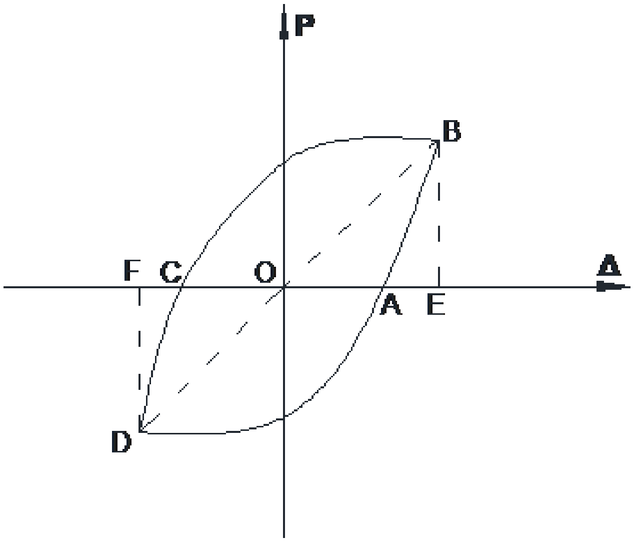


Fig. 9. Lateral force–displacement hysteretic loop

Figure 10 shows the relationship between the equivalent viscous damping coefficient and the displacement of the first cycle under different control displacements. The equivalent viscous damping coefficients of all the reinforced specimens ranged from 0.08 to 0.22.

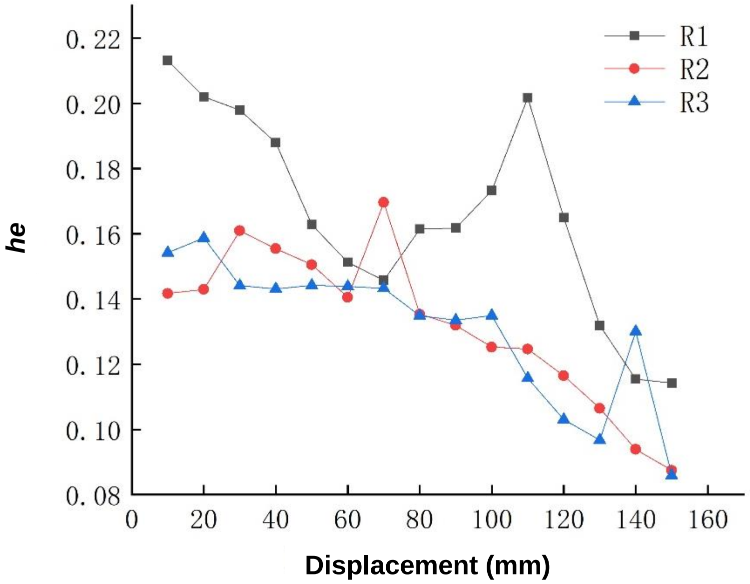


Fig. 10. Energy dissipation factors obtained *via* testing

All three models were laterally loaded up to 150 mm. No brittle failure was observed in any of the three models. The bearing capacity did not decrease, which indicated good deformation capacity of the mortise-tenon jointed timber frames. The energy dissipation mechanism primarily depended on joint deformation and the friction between the components. The mechanism especially depended on the friction energy dissipation effect, which can be used repeatedly in the loading process, therefore showing a good energy dissipation mechanism.

CONCLUSIONS

1. Through a quasi-static experimental study on three wooden frame models, the deformational behavior and the mortise-tenon joint mechanisms of three reinforced frame types in the corresponding state were analyzed. During the entire loading process, the whole frame was not damaged, the mortise and tenon joints underwent slight plastic extrusion deformation, *i.e.*, the tenon was compressed, and the mortise was enlarged.
2. Since the mortise and tenon joint has a certain amount of slip during the testing process, the hysteretic curve has an obvious pinching phenomenon. During the loading process, the bearing capacity did not decrease; therefore, the reinforced frame shows good deformability.
3. The strength degradation coefficients of the strengthened wooden frames were between 0.8 and 1. All specimens underwent the strength degradation phenomenon.
4. The stiffness degradation analysis shows that the stiffness degradation of the timber frame is severe during the initial loading stage, and then the degradation rate tends to decrease. Tenon and mortise joints are typical semi-rigid joints, whose mechanical properties are between rigid joints and articulated joints. The variation in stiffness has a strong influence on the stability of the entire wooden frame.
5. The equivalent viscous damping coefficients of all the reinforced specimens ranged from 0.08 to 0.22. The area of the hysteresis curve of each loading cycle tended to increase. The energy dissipation increases as the lateral displacement increases, which indicated the reinforced traditional frames provided good energy dissipation capacity during an earthquake.
6. This study analyzed the lateral load-resisting capacity and the energy-consuming capacity of the reinforced models, which can provide effective technical support for the seismic reinforcement of traditional timber structures. The proposed reinforcement method and construction technology can be used as a feasible choice for strengthening mortise-tenon jointed timber frames.

ACKNOWLEDGMENTS

This research was supported by the National Key R&D Program of China (No. 2018YFD1100402).

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Article submitted: February 14, 2021; Peer review completed: April 17, 2021; Revised version received and accepted: April 18, 2021; Published: April 20, 2021.
DOI: 10.15376/biores.16.2.4039-4051