Journal of Southeast University (English Edition) Vol. 27, No. 2, pp. 192 – 195 June 2011 ISSN 1003—7985

Experimental study on aseismic behaviors of Chinese ancient tenon-mortise joint strengthened by CFRP

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Abstract: In order to well protect Chinese ancient buildings, aseismic behaviors of Chinese ancient tenon-mortise joints strengthened by carbon fibre reinforced plastic (CFRP) are studied by experiments. Based on the actual size of an ancient building, a wooden frame model with a scale of 1∶8 of the prototype structure is built considering the swallow-tail type of tenon-mortise connections. Low cyclic reversed loading tests are carried out including three groups of unstrengthened structures and two groups of structures strengthened with CFRP. Based on experimental data, moment-rotation angle hysteretic curves and skeleton curves for each joint are obtained. The energy dissipation capability, stiffness degradation and deformation performance of the joints before and after being strengthened are also analyzed. Results show that after being strengthened with CFRP, the tenon value pulled out of the mortise is reduced; the bending strength and the energy dissipation capabilities of the joint are enhanced; stiffness degradation of the joint is not obvious; and the deformation performance of the joint remains good. Thus, the CFRP has good effects on strengthening the tenon-mortise joints of Chinese ancient buildings.

Key words: tenon-mortise joint; aseismic strengthening; CFRP (carbon fibre reinforced plastic); wooden construction; Chinese ancient building

doi: 10.3969/j.issn.1003 – 7985.2011.02.016

Chinese ancient buildings are mainly made of wood whose beams and columns are connected by tenon-mortise joints. Under an earthquake, the friction between the tenon and the mortise produces energy dissipation and the tenon is pulled out of the mortise, which makes the connection between beams and columns weakened and lead to instability of the whole structure[1-4]. So the tenon-mortise joint has to be strengthened on time for the protection of Chinese ancient buildings. In previous studies, steel components were considered to strengthen the tenon-mortise joint[5-7]. However, steel is not a very good material for strengthening the tenon-mortise joint due to the fact that it has heavy weight and corrodes easily. Xie et al.[8-9] considered using carbon fibre reinforced plastic (CFRP) to strengthen the tenon-mortise joint on a plane wooden frame due to its light weight and high strength. Based on achievements above, a spatial wooden frame model with a scale of 1∶8 of an actual Chinese ancient building is built considering swallow-tail types of tenon-mortise connections in this paper. By low cyclic reversed loading tests, aseismic behaviors of the tenon-mortise joint strengthened by CFRP are studied. Experimental results show that CFRP has good effects on strengthening the tenon-mortise joint of Chinese ancient buildings.

Received 2010-10-13.

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Foundation items: The Cultural Ministry Foundation of China (No. 17-2009), the Research Foundation of Palace Museum (No. 2007-4).

Citation: Zhou Qian, Yan Weiming. Experimental study on aseismic behaviors of Chinese ancient tenon-mortise joint strengthened by CFRP[J]. Journal of Southeast University (English Edition), 2011, 27(2): 192 – 195. [doi: 10.3969/j.issn.1003 – 7985.2011.02.016]

1 Experiment

1.1 Experimental model

Based on the actual size of an ancient Chinese building and building techniques in the Qing dynasty[10], a wooden frame model with a scale of 1∶8 of the prototype structure is built considering the swallow-tail type of tenon-mortise connections. Detailed sizes of beams, columns and tenon-mortise joints are shown in Fig. 1. For convenience of applying loads, the top of each column is 150 mm higher than that of each beam after installation[11]. The roof of the ancient building is simulated by a concrete slab with a weight of 1.03 t after calculation, and it is set free-standing on column tops. The base of each column is considered as a swivel type whose rotation direction is just the same as the loading direction.

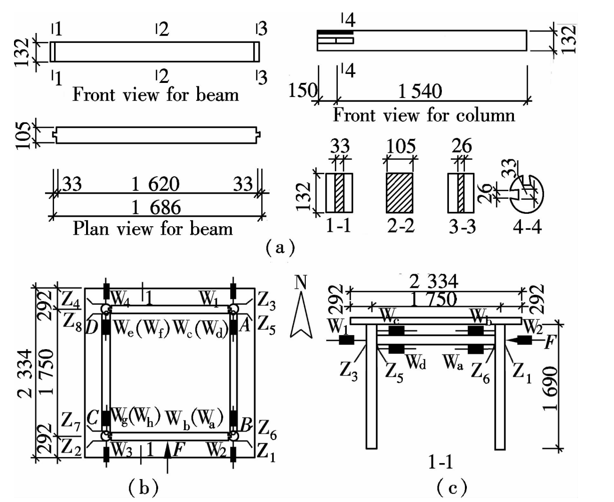

Fig. 1 Sizes for components and models (unit: mm). (a) Component sizes; (b) Plan view; (c) Section view

The selected CFRP is 0.11 mm in thickness and it is used to strengthen the tenon-mortise joint by adhering to it with special glue. When strengthening the joint, two CFRP sheets (The width of each is 80 mm) are stuck to the side faces of the beams with 250 mm exceeding the column sides in a level direction. To enhance the sticking force between the CFRP and the joint, 6 CFRP sheets (The width of each is 50 mm) are used to wrap the beams with glue in a vertical direction. Detailed sizes of the CFRP for strengthening the tenon-mortise joint are shown in Fig. 2.

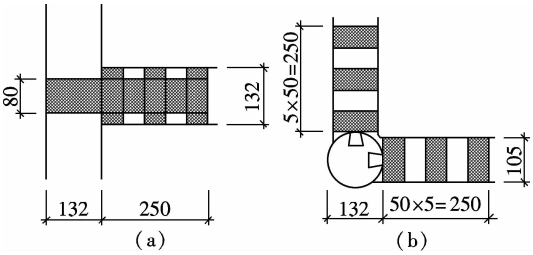

Fig. 2 Sizes of CFRP (unit: mm). (a) Plan view; (b) Front view

1.2 Measuring and loading rules

In order to obtain lateral displacement values of the model, the displacement gauges with the range of ±200 mm are set on each column top along the loading direction (Numbering: W_1 to W_4). To obtain bending moment of each joint, the resistance strain gauges are set on both the outside and the inside of each column top (Numbering: Z_1 to Z_8). To obtain the rotation angle of each joint, the displacement gauges with the range of ±100 mm are set on both the upside and the underside of each beam along the loading direction (Numbering: W_a to W_h). Measuring positions are shown in Fig. 1. As the required load is not so large, manual loading means are considered; the force sensor with the scope of 0 to 1 t is selected for the experiment. Besides, considering the large displacement values of the model during the experiment, the variable amplitude displacement load is considered as the loading method. Based on obtained achievements[7], the controlled displacement load values are: 0, ±30, ±60, ±90, ±120 and ±150 mm, with one cycle at each controlled level.

2 Experimental Phenomena

Experiments including three groups of unstrengthened models and two groups of CFRP strengthened models are carried out. During the experiments, the phenomena of joints and models appear as follows:

Whether the joint is strengthened or not, when the model is pulled or pushed at a small displacement, compression and friction between tenon of beam and mortise of column occur. The eccentricity moment from the roof is small; the structure can restore itself to balance location automatically by restoring force; and there is a squeeze sound from the joint position. When the displacement of the model becomes large, the internal force between tenon and mortise increases, and the eccentricity moment from the roof becomes large, which makes the model unable to restore itself to a balance location automatically. The squeeze sound also becomes obvious. Besides, when the load exceeds the internal force between tenon and mortise, the tenon will be pulled out of the mortise, as shown in Fig. 3.

Compared to the unstrengthened model, for the CFRP-strengthening model besides the squeeze sound, there is a crack sound from the joint location during the experiment, which means that some glue has become disengaged from the joint. With the increase in the structure displacement, the crack sound becomes obvious, and part of the CFRP sheet is destroyed because of tensile failure (see Fig. 3(b)). However, by the restriction effect of the CFRP, the value of the tenon pulled out of the mortise decreases, and the bearing capacity of the joint is also enhanced.

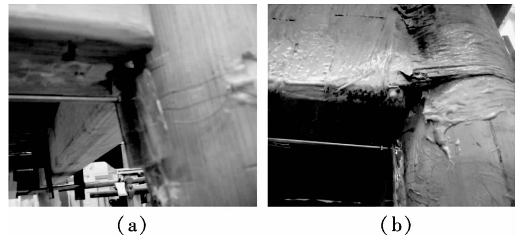

Fig. 3 Photos of deformation for joint ($\Delta = 150$ mm). (a) Before strengthening; (b) After strengthening

3 Experiment Analysis

During experiments, each tenon-mortise joint of the model shows similar aseismic behaviors. Due to the limitation of space, joint *C* in Fig. 1(b) is taken as an example to study the aseismic parameters before and after strengthening by CFRP.

3.1 Hysteretic curve

According to experimental data, M-θ hysteretic curves of joint *C* for different cases are shown in Fig. 4, where M represents the bending moment of the joint, θ represents the rotation angle of the joint, B represents before strengthening, A represents after strengthening. It is found that before strengthening the hysteretic curve appears as an S shape at first and then changes to a Z shape. Near the balance location, the hysteretic loop shrinks obviously. As the rotation angle increases, the hysteretic loop tends to be chubby. When the θ value is large, the slope of the curve is great, which reflects restoring characteristic of the joint is poor.

After being strengthened with CFRP, the M-θ hysteretic curve of joint *C* remains in a Z shape. At first, the bending capacity of the joint is provided by the CFRP, then by both the relative friction between the tenon and the mortise and the CFRP, and the CFRP plays a more important role. Because of CFRP's restriction, the hysteretic loop of the joint shrinks little at the balance location, and its restoring force is enhanced.

3.2 Skeleton curve

By connecting peak points of all the M-θ hysteretic cycles, the skeleton curve of joint *C* is obtained for each case, as shown in Fig. 5. It is found that after strengthening, the slope of the skeleton curve of the joint is enhanced, which reflects that the rotation stiffness of the joint is enhanced by CFRP. From the peak values of all the skeleton curves, it is found that the bending capacity of the joint can be enhanced about two times after it is strengthened by CFRP. Besides, all the skeleton curves in Fig. 5 are relatively flat, which shows that the joint maintains good ductility after being strengthened.

3.3 Energy dissipation

Here, the equivalent viscous damping coefficient h_e is used to represent energy dissipation[12]. By calculation, h_e-θ curves for different cases of joint *C* are shown in Fig. 6. It is found that: 1) Whether the joint is strengthened or not, with the increase in its rotation angle, the h_e value decreases and tends to be constant. This is because the energy dissipation of the joint is provided mainly by the relative friction between tenon and mortise. As the rotation angle of the joint increases, the tenon is gradually pulled out of the mortise,

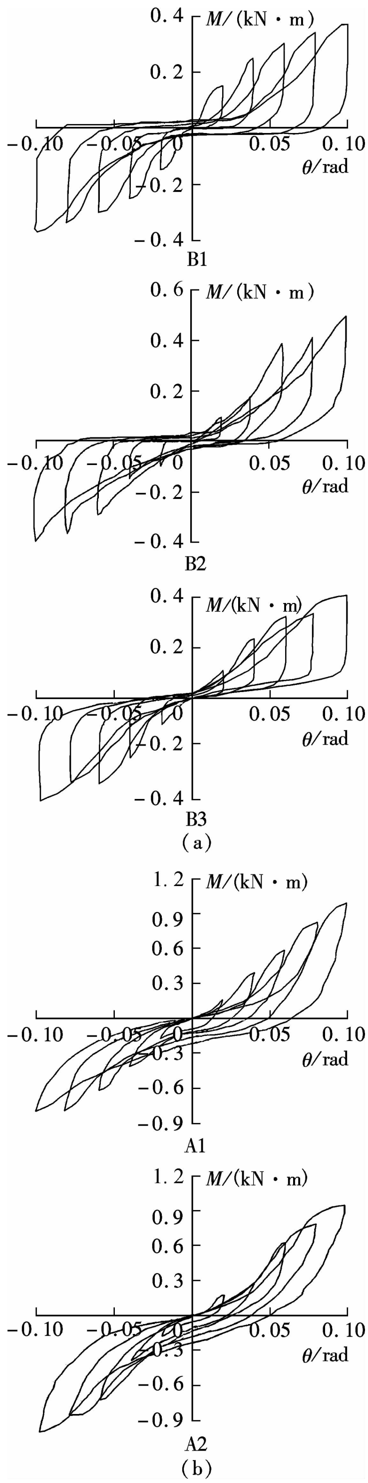

Fig. 4 M-θ hysteretic curves of joint C. (a) Before strengthening; (b) After strengthening

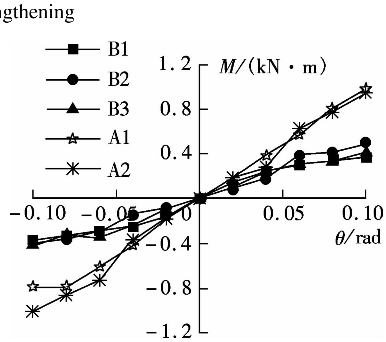

Fig. 5 M-θ skeleton curves of joint C

which weakens the friction. Before the tenon is completely pulled out, energy dissipation tends to be stable. 2) After being strengthened by CFRP, the energy dissipation of the joint is enhanced. This is because the rotation of the joint is restricted by the CFRP, which strengthens the relative friction between the tenon and the mortise.

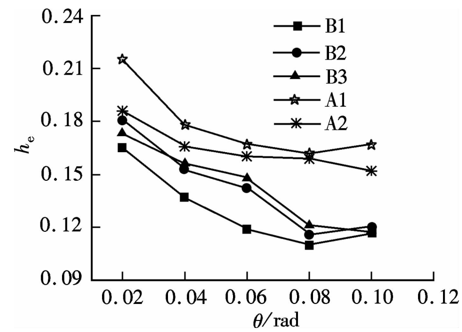

Fig. 6 h_e-θ curves of joint C

3.4 Stiffness degradation

Stiffness degradation of joint C is calculated according to the equation as follows:

$$k_i = \frac{|M_i| + |-M_i|}{|+\theta_i| + |-\theta_i|} \tag{1}$$

where k_i represents the joint rotation stiffness during the i-th cycle ($i = 1, 2, \ldots, 5$); M_i represents the peak bending moment during the i-th cycle; and θ_i represents the peak rotation angle during the i-th cycle.

By calculation, the k-θ curves of joint C for different cases are obtained, as shown in Fig. 7. It is found that: 1) Whether the joint is strengthened or not, with the increase in the rotation angle, the k value degrades; 2) After the joint is strengthened by CFRP, the k value is enhanced during each cycle due to the restriction effects from CFRP.

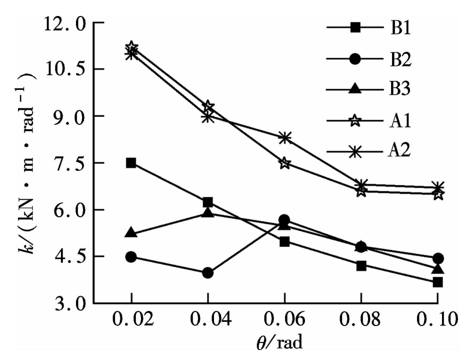

Fig. 7 k-θ curves of joint C

3.5 Ductility coefficient

For the tenon-mortise joint, as the rotation angle increases, it gradually yields but it can still bear loads, which shows its ductility. According to Ref. [9], the ductility coefficient of the tenon-mortise joint can be calculated as

$$\beta_L = (\delta_T + \delta_L)/L_S \tag{2}$$

where β_L represents the relative deformation of the joint; δ_T represents the value of the tenon pulled out; δ_L represents the value of the tenon embedded into the mortise; $L_S = 33$ mm is the length of the tenon. If the bearing capacity of the joint does not decrease obviously, the greater β_L is, the better ductility it will possess. By calculation, the β_L values of joint C for different cases are obtained, as shown in Tab. 1. It is clear that after being strengthened by CFRP, β_L value changes little, which reflects good ductility of the joint after strengthening.

Tab. 1 β_L values of joint C

B1	B2	B3	A1	A2
0. 507	0. 465	0. 538	0. 517	0. 497

4 Conclusion

By low cyclic reversed loading tests, aseismic behaviors of the tenon-mortise joint after being strengthened with CFRP are studied. Results show that after being strengthened, bearing capacity, rotation stiffness and energy dissipation capabilities of the joint are enhanced; the stiffness degradation of the joint is not obvious, and the deformation performance of the joint remains good, which reflect good strengthening results by CFRP.

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CFRP 加固古建筑榫卯节点抗震试验

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摘要:为了更好地保护古建筑,采用试验方法研究了 CFRP 加固古建筑榫卯节点后的抗震性能. 基于某古建筑实际尺寸,制作了 1∶8缩尺比例的木结构空间框架模型,并考虑梁柱连接为燕尾榫形式. 进行了低周反复加载试验,包括 3 组未加固构架试验和 2 组 CFRP 加固试验. 基于试验相关数据,获得了节点的弯矩-转角滞回曲线和骨架曲线,并对比分析了节点加固前后的耗能能力、刚度退化和延性等抗震指标. 结果表明:CFRP 加固榫卯节点后,节点拔榫量减小,抗弯承载力及耗能能力均有所提高,刚度退化不明显,且加固后的节点仍有良好的延性性能. 因此,CFRP 加固古建筑榫卯节点具有良好的效果.

关键词:榫卯节点;抗震加固;碳纤维布;木结构;中国古建筑
中图分类号:TU366. 2