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Mechanical properties of monodirectional Gutou mortise-tenon joints of the traditional timber buildings in the Yangtze River region

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Abstract: The mechanical properties of the monodirectional Gutou mortise-tenon joints of the ancient Chinese traditional timber buildings in the Yangtze River region were studied using the experimental method. Three monodirectional Gutou mortise-tenon joints were designed according to the actual configurations. The failure modes, the hysteretic curves, the skeleton curves, the rotation rigidities, and the energy dissipation capacity of this type of mortise-tenon joints under the low cyclic reversed loading were obtained. The results show that the hysteretic curves of the monodirectional Gutou mortise-tenon joints appear to be Z shape and have obvious pinch effects. During the process of the test, these mortise-tenon joints pass orderly through the elastic stage, the yield stage and the failure stage. The energy dissipation capacity of these mortise-tenon joints generally decreases with the increase in the rotation angle. The equivalent viscous damping coefficients of the monodirectional Gutou mortise-tenon joints are between 0. 161 and 0. 193. The results can provide the theoretical base for the computing analysis and repair design of Chinese traditional timber buildings in the Yangtze River region.

Key words: traditional timber building; monodirectional Gutou mortise-tenon joint; mechanical property; energy dissipation capacity

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Chinese traditional timber structure is the main structural type of Chinese ancient buildings, which is one of the most famous ancient building systems in the world. Chinese traditional timber buildings are mainly divided into the type of post-and-lintel construction and the type of column-and-tie construction. Mortise-tenon joints are the core of Chinese traditional timber buildings. The monodirectional Gutou mortise-tenon joint is one type of the main joints of column-and-tie construction, and this type of mortise-tenon joints are widely used in the traditional timber buildings of the Yangtze River region. Study on the mechanical properties of mortise-tenon joints is the foundation of the structural analysis and scientific conservation of the Chinese traditional timber buildings.

In China, Gao et al. [1-2] studied the mechanical performance of the traditional timber frame models designed according to "building formulas of Song dynasty" under low cyclic horizontal loading and presented the relevant structural calculation method. Xie et al. [3] studied the hall-style timber frame models with the dovetail mortise-tenon joints under the low cyclic horizontal loading, and the mechanical performance of this kind of timber frame was obtained. Zhou et al. [4-5] studied the aseismic performance of the Hall of Supreme Harmony in the Forbidden City with the finite element simulation method. Li[6] studied the mechanical properties of the typical mortise-tenon joints of Tibetan traditional timber buildings with the finite element method. Xiao et al. [7] studied the structural performance of the typical mortise-tenon joints of the traditional timber buildings in Guangdong Province. Chun et al. [8-9] studied the seismic behavior of the typical mortise-tenon joints of Chinese southern traditional timber buildings, including the dovetail mortise-tenon joint, the half mortise-tenon joint, the Mantou mortise-tenon joint, the Tou mortise-tenon joint, and the straight mortise-tenon joint.

Abroad, Villar et al. [10] carried out the finite element simulation of the timber frame joints. The results showed that the friction between contact surfaces was very important to the seismic performance of the structure. D'Ayala et al. [11] carried out the finite element analysis of the Dieh-Dou timber frame structure in Taiwan, China. The results showed that joint stiffness had great influence on the displacement response of the whole structure during earthquakes, while the vertical load affected the rotational stiffness of the joint. Pang et al. [12] carried out the study on the bending capacity of Korean traditional dovetail mortise-tenon joints with/without the beam shoulders, and pointed out that the beam shoulder can greatly improve the bending capacity of this kind of dovetail mortise-tenon joint. Isaksson et al. [13] established a logistic dose-response model that primarily focused on describing the relationship between the exposure and decay rating for moisture traps with long periods of high moisture con-

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tents. Ogawa et al.[14] studied the mechanical behavior of traditional Japanese "Watari-ago" joints with experimental and theoretical methods.

To sum up, Chinese research was mainly aimed at the northern mortise-tenon joints such as the dovetail mortise-tenon joints and the straight mortise-tenon joints, but the study on the monodirectional Gutou mortise-tenon joint mortise-tenon joint is still in infancy. Foreign research mainly focused on the local traditional timber joints, which are very different from the Chinese traditional timber joints. The mechanical properties of the monodirectional Gutou mortise-tenon joint of Chinese traditional timber buildings in the Yangtze River region is studied in this paper.

1 Design of Experiment

The monodirectional Gutou mortise-tenon joints are widely used in the traditional timber buildings in the Yangtze River region, and they are used to connect timber beams and timber columns in the type of column-and-tie construction. The monodirectional Gutou mortise-tenon joints can be used in the middle frame and the side frame of the whole timber building, as shown in Fig. 1. They are very different from the bidirectional Gutou mortise-tenon joints which can be only used in the side frame of the timber building. The construction process of the monodirectional Gutou mortise-tenon joint is shown in Fig. 2.

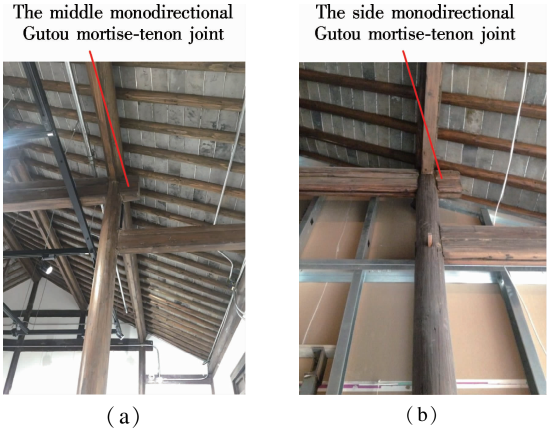


Fig. 1 Monodirectional Gutou mortise-tenon joints in the traditional timber building. (a) Middle frame; (b) Side frame

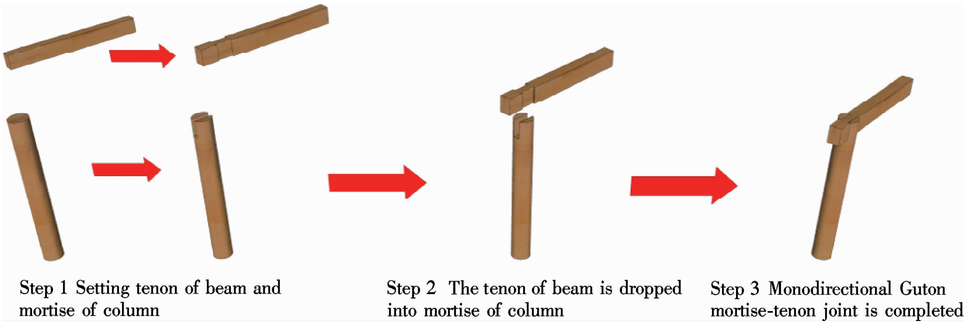


Fig. 2 Construction process of the monodirectional Gutou mortise-tenon joint

In order to understand the structural performance of the monodirectional Gutou mortise-tenon joints of Chinese traditional timber buildings in the Yangtze River region, the mechanical properties of the three monodirectional Gutou mortise-tenon joints were studied through the low cyclic loading test. The tested three monodirectional Gutou mortise-tenon joints were designed according to the actual configurations based on the investigation of some typical traditional timber buildings in the Yangtze River region, and the dimension scale of the three mortise-tenon joints was 1∶1.76. The three monodirectional Gutou mortise-tenon joints included two hold-shoulder type specimens (Figs. 3(a) and (c)), and a back-shoulder type specimen (Fig. 3(b)). The tenon's thickness of the two hold-shoulder type joints were different. All the test specimens were made of Chinese fir, which is the common material in Chinese traditional timber buildings in the Yangtze River region.

The mechanical parameters of the wood were obtained by the standard material test. The average parallel-to-grain tensile strength, compression strength, bending strength, shear strength, and bending elastic modulus are 91.4, 30.0, 50.0, 3.6 and 10 238.1 MPa, respectively. The average of the moisture content was 8.68%. The failure mode of the wood under parallel-to-grain tensile force is brittle fracture, and the failure mode of the wood under parallel-to-grain compressive force is yield failure. According to Ref. [15], the test wood can meet the requirements of TC11 which is the strength grade of Chinese fir.

The test method was the low cyclic reversed loading test. The vertical force acting on the top was applied by a jack, and the value of vertical load was constantly 10 kN. According to the theory of similarity, $S_P = S_\sigma \times S_L^2$, where S_P is the similarity constant of concentrated load; S_σ is the stress similarity constant and $S_\sigma = 1$ in this experiment; S_L is the size similarity constant and $S_L = 1/1.76$ in this experiment. In the actual Chinese traditional timber buildings with the type of column-and-tie construction, the vertical load on the top of the column transferred from the purlins commonly ranges from 22 to 42 kN based on different purlin spans and purlin distances, and the average actual vertical load is 32 kN, so the vertical load on

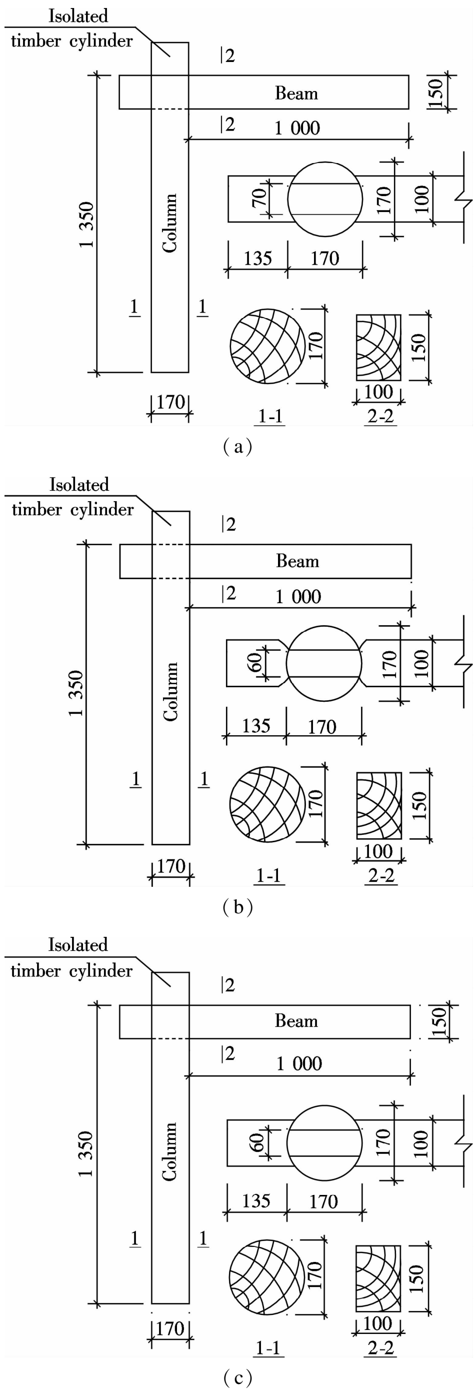


Fig. 3 Design of the three monodirectional Gutou mortise-tenon joints (unit: mm). (a) Monodirectional Gutou mortise-tenon joint 1; (b) Monodirectional Gutou mortise-tenon joint 2; (c) Monodirectional Gutou mortise-tenon joint 3

the top of the column in the experiment is 10 kN, which is calculated by $32S_p$. The method of loading was the displacement control method, and the displacement step was 10 mm. The low cyclic reversed load was generated by the screw rod loading device. The joint's rotation angle was obtained by the test of the two displacement gauges fixed on the top side and the bottom side of the joint separately, and it was calculated by the displacement difference of the two displacement gauges divided by the height of beam. The loading is not over until the specimen finally fails. The test devices are shown in Fig. 4. The loading sequence is shown in Fig. 5.

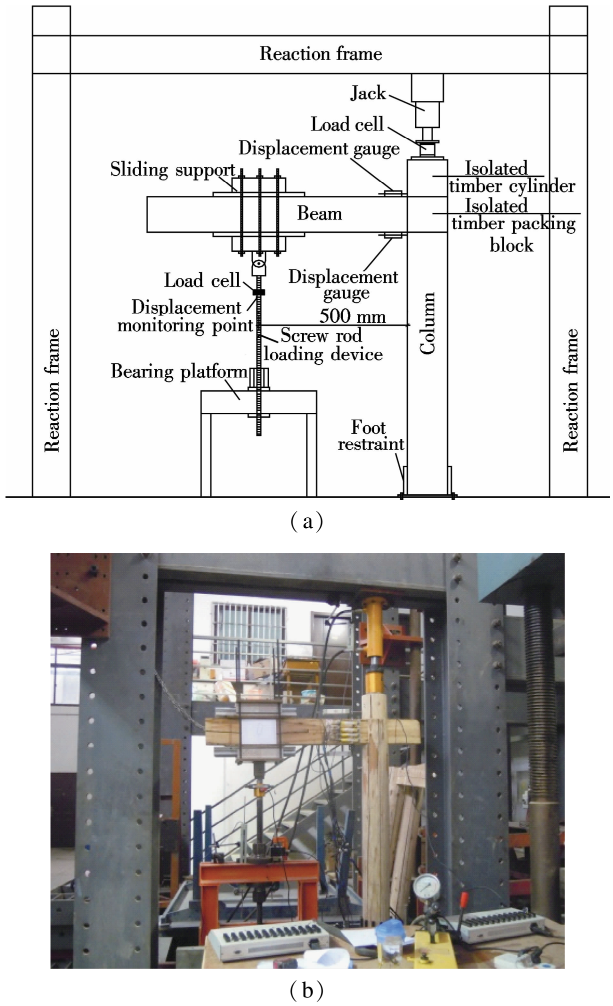


Fig. 4 Test device of the three monodirectional Gutou mortise-tenon joints. (a) Design of test method; (b) Actual test device

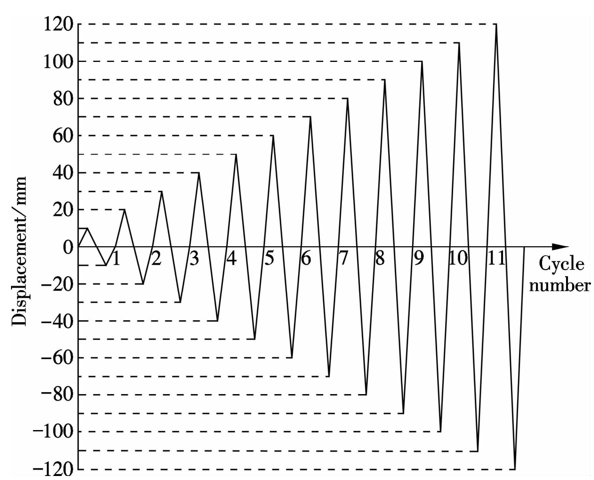
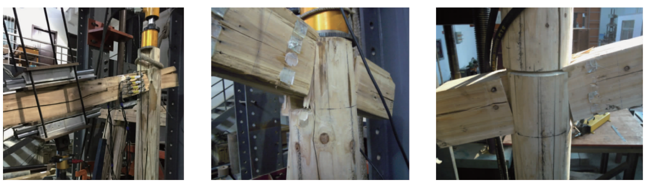


Fig. 5 Loading sequence

2 Results and Discussion

2.1 Experimental phenomenon

The tested monodirectional Gutou mortise-tenon joints included three specimens, a back-shoulder type specimen and two hold-shoulder type specimens. Through the analysis of the experimental phenomenon, the test process is generally as follows: when the loading is increased to make the rotation angle be 0.04 to 0.06 rad, the mortise and tenon squeeze each other and make a squeaking noise. As the load is increased, continuous splitting sounds are heard, and then the splitting crack occurs at the end of beam and the contact surface of mortise has an obvious compressive deformation. When the loading is increased to make the rotation angle be 0.110 to 0.167 rad, the end of the beam is embedded into the mortise, the mortise loses the restriction on the end of beam, and the joint finally fails. Through the comparative analysis of the test data, the specimen with the deeper tenon failed later. In the case of the same tenon's depth, the hold-shoulder type specimen fails later than the back-shoulder type specimen. The failure mode of this type of mortise-tenon joints is that the mortise loses the restriction on the end of beam, as shown in Fig. 6.



(a) (b) (c)

Fig. 6 Failure modes of the monodirectional Gutou mortise-tenon joints. (a) Gutou mortise-tenon joint 1; (b) Gutou mortise-tenon joint 2; (c) Gutou mortise-tenon joint 3

2.2 Moment-rotation angle hysteretic curves and skeleton curves

Through the analysis of the load-displacement hysteretic curves of this type of mortise-tenon joints, the moment-rotation angle (M-θ) hysteretic curves and the M-θ skeleton curves of these joints are obtained, as shown in Fig. 7, Fig. 8 and Fig. 9.

According to the analysis of Fig. 7 to Fig. 9, the M-θ hysteretic curves of the monodirectional Gutou mortise-tenon joints appear to be Z shape and have obvious pinch effects. For this type of mortise-tenon joint, in the elastic stage, the rotational rigidity remains unchanged, basically. As the rotation angle increases, the joint is in the yield stage and the rotational rigidity begins to decrease. As the rotation angle increases continually, the bearing capacity of the joint begins to decrease and the deformation continues to increase until the final failure. The whole test process of the joints shows a certain ductility.

2.3 Computing eigenvalue of M-θ skeleton curve

Through the analysis of the M-θ skeleton curves of this type of mortise-tenon joints, the curves can be approximately simplified to the trilinear model, as shown

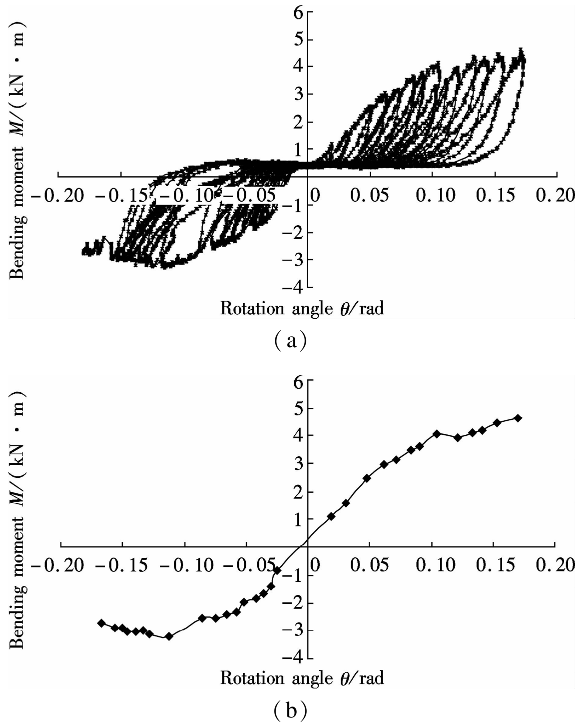


Fig. 7 M-θ hysteretic curves and skeleton curve of the monodirectional Gutou mortise-tenon joint 1. (a) Hysteretic curves; (b) Skeleton curve

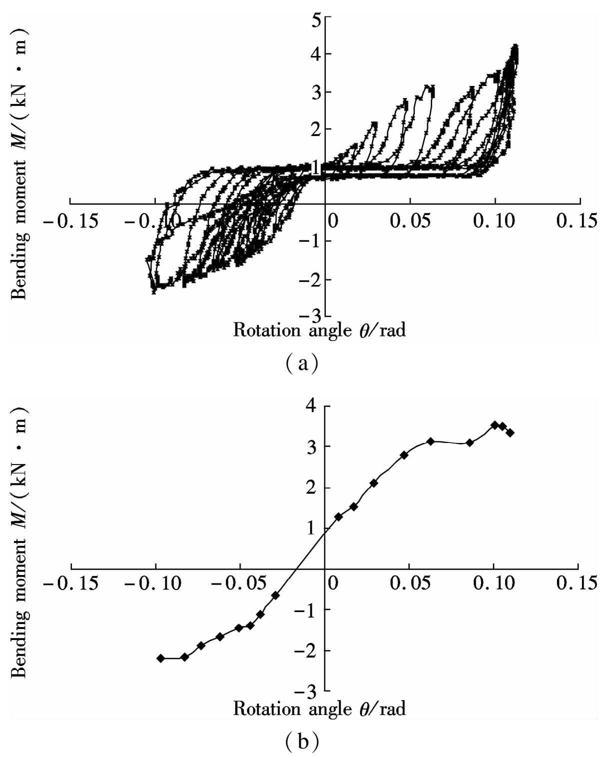


Fig. 8 M-θ hysteretic curves and skeleton curve of the monodirectional Gutou mortise-tenon joint 2. (a) Hysteretic curves; (b) Skeleton curve

in Fig. 10. The rotational rigidity of this type of mortise-tenon joints at different stages is shown in Tab. 1, the value of the rotation angle θ in Tab. 1 is from the M-θ skeleton curves of Figs. 7 to 9.

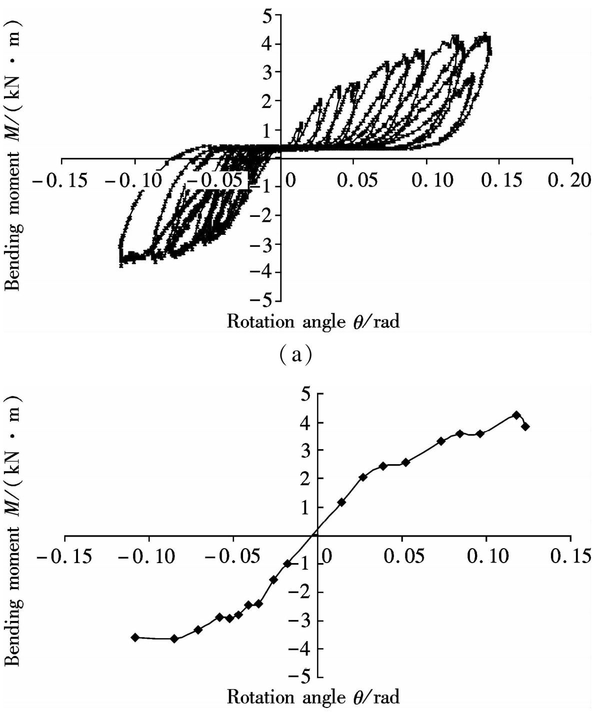


Fig. 9 M-θ hysteretic curves and skeleton curve of the monodirectional Gutou mortise-tenon joint 3. (a) Hysteretic curves; (b) Skeleton curve

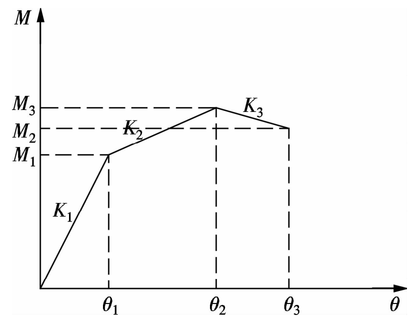


Fig. 10 Simplified M-θ skeleton curve

The semi-rigid calculation models of this type of mortise-tenon joints can be written as the following formula:

$$M=\begin{cases} K_1\theta & \theta\leqslant\theta_1 \\ K_1\theta_1+K_2(\theta-\theta_1) & \theta_1\leqslant\theta\leqslant\theta_2 \\ K_1\theta_1+K_2(\theta_2-\theta_1)+K_3(\theta-\theta_2) & \theta_2<\theta\leqslant\theta_3 \end{cases} \quad (1)$$

where the values of K_1, K_2, K_3, θ_1, θ_2, and θ_3 of this type of mortise-tenon joints in different stages are obtained from Tab. 1.

Tab. 1 shows that the elastic rotational rigidity of the hold-shoulder type joint is higher than that of the back-shoulder type joint in the case that they have the same mortise and tenon dimension. The elastic rotational rigidity of the joint with the deep tenon is smaller than that of the joint with the thin tenon in the case of same configuration.

Tab. 1 Computing eigenvalue results of simplified M-θ skeleton curves of the mortise-tenon joints

Number	Elastic stage		Yield stage		Failure stage		Ductility factor	Rotational rigidity/ (kN · m · rad^{-1})		
	M_1/(kN · m)	θ_1/rad	M_2/(kN · m)	θ_2/rad	M_3/(kN · m)	θ_3/rad	θ_3/θ_1	K_1	K_2	K_3
Gutou joint 1	2.321	0.058	3.198	0.112	2.708	0.167	2.879	40.02	28.55	-16.22
Gutou joint 2	1.933	0.047	2.668	0.101	2.492	0.110	2.340	41.13	19.34	-19.56
Gutou joint 3	2.452	0.039	4.272	0.118	3.838	0.123	3.154	62.87	23.04	-86.80

Note: The data of the rotational rigidity and the rotation angle in the table are both from the 1∶1.76 scale model.

2.4 Energy dissipation capacity

For mortise and tenon joints, the energy dissipation capacity is an important indicator of the structural aseismic performance. Strong energy dissipation capacity can ensure that the vibration amplitude of the structure under earthquake weakens rapidly. In this paper, the equivalent viscous damping coefficient is used to evaluate the energy dissipation capacity of the joints[16]. The energy dissipation capacity of the joints increases while the equivalent viscous damping coefficient increases. The equivalent viscous damping coefficient h_e can be calculated according to Fig. 11 by the following equation:

$$h_e=(S_{ABC}+S_{CDA})/[2\pi(S_{OBE}+S_{ODF})] \quad (2)$$

where S_{ABC} is the area of ABC hysteresis loop; S_{CDA} is the area of CDA hysteresis loop; S_{OBE} is the area of OBE triangle; S_{ODF} is the area of ODF triangle.

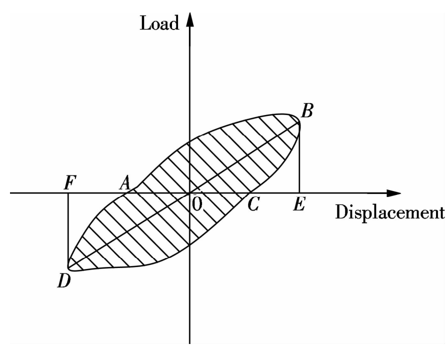


Fig. 11 Computing diagram of equivalent viscous damping coefficient

In this paper, the equivalent viscous damping coefficients in different stages were calculated by Origin 8 software. The computation results of the equivalent viscous damping coefficients of the monodirectional Gutou mortise-tenon joints are shown in Tab. 2.

The data in Tab. 2 show that the energy dissipation capacity of the monodirectional Gutou mortise-tenon joints generally decreases with the increase of the joint's rotation angle, and the equivalent viscous damping coefficients of

Tab. 2 Computation results of equivalent viscous damping coefficients of the mortise-tenon joints

Number	Equivalent viscous damping coefficient h_e		
	At the elastic stage θ_1	At the yield stage θ_2	At the failure stage θ_3
Gutou mortise-tenon joint 1	0.162	0.158	0.146
Gutou mortise-tenon joint 2	0.241	0.202	0.200
Gutou mortise-tenon joint 3	0.176	0.153	0.138
Average	0.193	0.171	0.161

the monodirectional Gutou mortise-tenon joints are be tween 0.161 and 0.193. In summary, the energy dissipation capacity of the back-shoulder type joint is better than that of the hold-shoulder type joint when the same size.

3 Conclusions

The mechanical properties of the monodirectional Gutou mortise-tenon joints of the Chinese traditional timber buildings in the Yangtze River region are studied through the low cyclic reversed loading test. Some mechanical properties including the failure modes, the hysteretic curves, the skeleton curves, the rotational rigidities, and the energy dissipation capacity of this type of mortise-tenon joints are presented, and the main conclusions are as follows:

1) The final failure of this type of mortise-tenon joints under the low cyclic reversed loading is that the mortise loses the restriction on the end of the beam, and the limit rotation of this type of the mortise-tenon joints is 0.110 to 0.167 rad.

2) The M-θ hysteretic curves of this type of mortise-tenon joints appear to be Z shape and have the obvious pinch effects during the whole test process. The slippage of mortise and tenon increases with the increase of the rotation angle. During the process of the test, this type of mortise-tenon joints pass orderly through the elastic stage, the yield stage and the failure stage.

3) The M-θ skeleton curves of this type of mortise-tenon joints are simplified as the trilinear model, and the rotational rigidity values in the elastic stage, the yield stage and the failure stage are presented. The test results can be used to analyze structural performance of Chinese traditional timber buildings in the Yangtze River region.

4) The energy dissipation capacity of this type of mortise-tenon joints decreases with the increase of the rotation angle, and the equivalent viscous damping coefficients of this type of mortise-tenon joints are between 0.161 and 0.193. The results need to be verified by more test data.

References

[1] Gao D F. A research on the structure and their aseismatic characteristics of ancient Chinese timber buildings[D]. Xi'an: School of Civil Engineering, Xi'an University of Architecture and Technology, 2007. (in Chinese)

[2] Gao D F, Zhao H T, Xue J Y, et al. The deformational and stress behavior of wooden frame of Chinese ancient buildings under horizontally reverse load [J]. *World Earthquake Engineering*, 2003, **19**(1): 9 − 14. (in Chinese)

[3] Xie Q F, Zhao H T, Xue J Y, et al. An experimental study on the strengthening of mortise-tenon joints in ancient Chinese wooden buildings[J]. *China Civil Engineering Journal*, 2008, **41**(1): 28 − 34. (in Chinese)

[4] Zhou Q, Yan W M, Zhou X Y, et al. Aseismic behavior of Chinese ancient tenon-mortise joint[J]. *Journal of Vibration, Measurement & Diagnosis*, 2011, **31**(6): 679 − 684. (in Chinese)

[5] Zhou Q, Yan W M, Guan H Z, et al. Analysis of aseismic constitutions of Tai-He Palace in the Forbidden City [J]. *Journal of Fuzhou University*(*Natural Science Edition*), 2013, **41**(4): 652 − 657. (in Chinese)

[6] Li P. Mechanical performance of beam-column joints of Tibetan ancient timber buildings [D]. Beijing: School of Civil Engineering, Beijing Jiaotong University, 2009. (in Chinese)

[7] Xiao M, Chen Q J, Zhang Z Q, et al. Safety analysis of typical wood ancestral hall in Caton considering joint stiffness [J]. *Journal of Kunming University of Science and Technology*(*Natural Science Edition*), 2014, **39**(1): 40 − 47. (in Chinese)

[8] Chun Q, Yue Z, Pan J W. Experimental study on seismic characteristics of typical mortise-tenon joints of Chinese southern traditional timber frame buildings[J]. *Science China Technological Sciences*. 2011, **54**(9): 2404 − 2411. DOI: 10.1007/s11431-011-4448-3.

[9] Chun Q, Lü W, Wang J G, et al. Mechanical properties of typical mortise-tenon joints of post and lintel construction and column and tie construction of timber buildings in Jiangsu Province and Zhejiang Province[J]. *Journal of Southeast University*(*Natural Science Edition*), 2015, **45**(1): 151 − 158. (in Chinese)

[10] Villar J R, Guaita M, Vidal P, et al. Analysis of the stress state at the cogging joint in Timber structures[J]. *Biosystems Engineering*, 2007, **96**(1): 79 − 90. DOI: 10.1016/j.biosystemseng.2006.09.009.

[11] D'Ayala D F, Tsai P H. Seismic vulnerability of historic Dieh-Dou timber structures in Taiwan[J]. *Engineering Structures*, 2008, **30**(8): 2101 − 2113. DOI: 10.1016/j.engstruct.2007.11.007.

[12] Pang S J, Oh J K, Park J S, et al. Moment-carrying capacity of dovetailed mortise and tenon joints with or without beam shoulder[J]. *Journal of Structural Engineering*, 2011, **137**(7): 785 − 789. DOI: 10.1061/(asce)st.1943-541x.0000323.

[13] Isaksson T, Brischke C, Thelandersson S. Development of decay performance models for outdoor timber structures [J]. *Materials and Structures*, 2013, **46**(7): 1209 − 1225. DOI: 10.1617/s11527-012-9965-4.

[14] Ogawa K, Sasaki Y, Yamasaki M. Theoretical modeling and experimental study of Japanese "Watari-ago" joints [J]. *Journal of Wood Science*, 2015, **61**(6): 481 − 491. DOI: 10.1007/s10086-015-1498-3.

[15] Southwest Architectural Design & Research Institute of China. Code for design of timber structures GB50005—2003[S]. Beijing: China Architecture & Building Press, 2004. (in Chinese)

[16] Li Zhongxian. *Theory and technique of engineering structure*[M]. Tianjing: Tianjin University Press, 2003. DOI:10.1007/s10086-015-1498-3. (in Chinese)

江南地区传统木构建筑单向箍头榫节点受力性能

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摘要: 为研究江南地区传统木构建筑中常见的单向箍头榫节点的受力性能,基于真实构造设计了 3 个单向箍头榫节点试件并通过试验获取了该种榫卯节点在低周反复荷载作用下的破坏模式、滞回曲线、骨架曲线、转角刚度及耗能能力. 试验结果表明:该种榫卯节点的滞回曲线基本上都呈 Z 形,具有明显的捏拢特性. 该种榫卯节点在低周反复荷载作用下从开始到破坏均经历了弹性阶段、屈服阶段和破坏阶段,其耗能能力总体随着节点转角的增大而减小,该种榫卯节点的等效黏滞阻尼系数基本在 0.161 ~0.193 之间. 研究结果可为江南传统木构建筑的计算分析及保护修缮提供理论基础.

关键词: 传统木构建筑;单向箍头榫;受力性能;耗能能力

中图分类号: TU366.2