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EXPERIMENTAL STUDY ON THE MECHANICAL PERFORMANCE OF DOUGONG IN MAHAVIRA HALL OF HUISHAN TEMPLE

YY. Liu(1), ZX. Han(2), XZ. Nie(3), TQ. Zhang(4)

(1) *Lecturer, Zhengzhou University, yingyang_liu@163.com*
(2) *Master student, Zhengzhou University, hanzhixuu@qq.com*
(3) *Master student, Central South University, 1316032095@qq.com*
(4) *Master student, Central South University, 1138637429@qq.com*

Abstract

Mahavira Hall of Huishan Temple was built in the Yuan Dynasty of China. It is a traditional timber beam-lifting structure and its architectural form and structural technology are of great significance for study. Based on the component characteristics of the Dougong in Mahavira Hall, six full-scale specimens were designed; two of them were tested under vertical monotonic loading and the other four were tested under cyclic loading. Failure modes and mechanical performance were studied on the basis of the experimental phenomena and the test results. Results showed that the Dougong were of good vertical bearing capacity; the intersection joints of Ludou, Touang, and Nidaogong were the weak parts. Under the horizontal cyclic tests, failure modes were the loose of the connections between components; stiffness degradation was observed while deformation capacity, energy dissipation, and ductility were very decent.

Keywords: Mahavira Hall of Huishan Temple, Dougong, vertical loading, cyclic test, mechanical performance

1. Introduction

Huishan Temple, located in Dengfeng City, Henan Province, China, is a national key cultural relic protection unit. It was listed in the World Heritage List in 2010 as one of the historical buildings "in the middle of heaven and earth". Mahavira Hall is the main building of Huishan Temple, which was firstly built in the Yuan Dynasty and the traditional beam-lifting wooden structure building.

Dougong is a unique component of ancient architecture in China, which is located at the intersection of columns and beams [1]. It is a structure installed under the eaves of ancient buildings or between girders that consist of two members, namely Dous (wooden block) and Gongs (bow-shaped brackets) [2]. Gong is the arch-shaped load-bearing member protruding from the column top layer by layer located at the intersection of the column and the beam and Dou is the square wood block padded between the arches. The Gong Frame is pulled out from Dou, and then Dou is installed on the top of the Gong end. In this way, it is staggered and stacked layer by layer to form a bracket with large upper and small lower parts. Dougong can transfer the roof load to the column frame to improve the seismic performance of the column frame, which has the function of architectural aesthetics [3]. As an important part of the ancient timber structure, the mechanical performance of Dougong directly affects the vertical bearing capacity and seismic performance of the whole structure. Thus scholars have carried out relevant theoretical and experimental research work. Sui et al. [4] studied the degradation of the lateral stiffness of Dougong through low cyclic loadings of single Dougong, two Dougongs, and four Dougongs. According to the test, the hysteresis curve and skeleton curve of load-displacement were obtained and the formula of the resilience model and mechanical model were established. It was by all appearances that slippage was the main deformation of Dougong and plump area of the hysteretic loop accounted for its excellent ability of energy dissipation performance. Xie et al. [5-6] took Dougong built by floor forked columns of Guanyin Pavilion in Dule Temple as the research object. They adopted the horizontal and low cyclic reversed loading method and they compared the seismic performance of intact and damaged Dougong joints. The results showed that though the bearing capacity and stiffness of damaged Dougong joints were reduced to some degree, their energy dissipation capacity was improved. Que et al. [7] took Dougong in Tianwang Hall of Luzhibaosheng Temple as the research object. They obtained the displacement response of each component of Dougong under earthquake action through shaking table tests and discussed the change law of Dougong's acceleration and dynamic amplification coefficient. Zhou et al. [8-9] conducted a systematic study on the first floor and the second floor of the hall of supreme peace of the imperial palace. They made a 1:2 scale model and carried out a vertical loading test and horizontal cyclic reversed loading test respectively. They analyzed the transmission mechanism and failure mode of the brackets and proposed a simplified mechanical model. Yuan et al. [10] took Dougong of the wooden tower in Yingxian County as the research object and simplified the Dougong structure through experiments. They proposed a numerical model based on frictional shear energy dissipation. Xie et al. [11] established a friction-based mechanical model for mortise and tenon joints and carried out a numerical simulation on the lateral force resistance of wood frames connected by mortise and tenon joints in ancient China, which was in good consistency with the experimental results.

The Dougong in Mahavira Hall of Huishan Temple has obvious characteristics of the Yuan Dynasty. The existing researches mainly focus on the architectural style and cultural inheritance of the temple and do not involve the mechanical performance of the Dougong and other key structural components. Based on the related research results, this paper takes the Dougong in Mahavira Hall of Huishan Temple as the research object. Through the vertical monotonic load test and horizontal low cyclic reversed loading test, the force transmission mechanism, failure mode, stiffness, deformation, energy dissipation and other mechanical performance parameters were studied, to enrich the research content of the mechanical performance on the ancient timber artwork, Dougong.

2. Test program

2.1 Specimen design

Under the eaves of the Dougong in Mahavira Hall of Huishan Temple, there are three kinds of Dougong, between the columns, on the top of the columns, and at the corners, respectively. There are 16 Dougongs between the columns, 12 Dougongs on the top of the columns and 4 Dougongs at the corners. The practice of Dougong between columns and Dougong on the top of the columns, are the same. The tests in this paper are based on those kinds of Dougongs.

(a) Side photo of the Dougong (b) Front photo of the Dougong

Fig. 1 – Dougong in Mahavira Hall of Huishan Temple

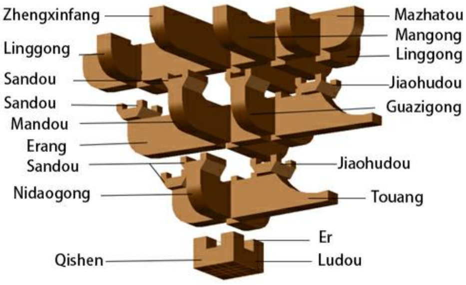


Fig. 2 –Detail sketch of the Dougong

Table 1 – Configuration of the components

Components	**Length / mm**	**Width / mm**	**Height / mm**
Touang	1360	138	282
Erang	2010	138	282
Mazhatou	2445	138	282
Nidaogong	986	138	282
Guazigong	986	138	282
Linggong	1000	138	282
Mangong	1496	138	282
Zhengxinfang	1996	138	282

The example of Dougong in Huishan temple is shown in Figure 1. ①Ludou, ②Touang, ③Erang, ④Mazhatou, ⑤Nidaogong, ⑥Guazigong, ⑦Linggong, ⑧⑨Mangong. The detailed construction of Dougong is shown in Figure 2. The sizes of main components are shown in Table 1.

The test is based on Dougong in Mahavira Hall of Huishan Temple and uses a 1:1 full-scale model. The overall sizes of the specimen are 991mm (H), 2445mm (L) and 1996mm (W). A total of 6 specimens of Dougong are designed. 2 of them are for vertical loading and the remaining 4 are for horizontal loading. Horizontal loading contains 2 directions that the longitudinal is that the direction parallel to the Gong and Fang of the specimen and the transverse is that the direction perpendicular to the Gong and Fang of the specimen. Each test piece is made with domestic hardwood pine. The density is 454kg/m^3; the tensile strength parallel to the grain 56.3MPa; the compressive strength parallel to the grain 27.5MPa; the elastic modulus perpendicular to the grain is 9215MPa; the compressive strength perpendicular to the grain is 10.2MPa. Each component is prefabricated in the factory and assembled in the laboratory. During the test, the moisture content of the specimens is between 12% and 14%.

2.2 Test setup and procedure

The experiment was conducted in the structural laboratory of Henan University of Technology. Vertical loading was carried out with a hydraulic servo jack with a range of 500kN, and horizontal loading was carried out by MTS loading system. The design thrust of the actuator was ±250kN and the displacement range was ±375mm.

During the vertical loading, the Dougong was placed on the steel structure grade beam and the load was applied in the way of displacement control (Fig. 3). The preloading was carried out first in order to reduce the system error. The experiment adopted continuous uniform loading mode. The displacement increment speed was 2mm/min. Until the Dougong appeared obvious damage to stop loading, the force was unloaded to 0, and the experiment was over. The load-displacement curve of the test piece was measured by the pressure sensor (connected to the jack) and the thimble displacement meter (set at the Mazhatou).

Fig. 3 –Vertical loading setup

Fig. 4 –Horizontal loading setup

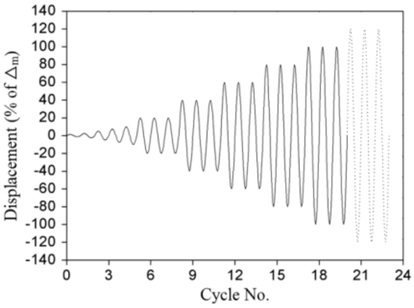


Fig. 5 – Test procedure

The horizontal loading contained the longitudinal and transverse directions. A steel tie rod system was set to realize the application of cyclic load (Fig. 4) when loading. When thrust was applied by the actuator, the force was transmitted directly to the specimen through a steel plate on the side close to the actuator. When the tension was applied, the force was first transferred to the steel plate on the other side through the steel tie rod, and then the force was transferred from the steel plate to the specimen, so as to avoid local tension of the specimen joints. According to the actual structure of Dougong in Mahavira Hall of Huishan Temple, The bottom of the beam was provided with a wooden beam. The middle of the beam extended the mortise and passed through the bottom of the Ludou to connect with the Dougong, and the wooden beam was firmly fixed with the laboratory cement pedestal. Displacement loading was used under low cyclic reversed loading, and the loading protocol referred to method B (ISO16670 standard) in ASTM E2126-11 standard [12]. As shown in Figure 5, the displacement amplitude Δ_m of low cyclic reversed loading was taken as 50 mm. The test was terminated when the carrying capacity dropped to 80% of the limit load or when the Dougong was visibly damaged. The load of the specimen was directly output by MTS loading system and the displacement was measured by a displacement meter connected with the top steel plate.

3. Experimental phenomenon and failure modes

3.1 Vertical loading test of Dougong

At the initial stage of loading, with the increase of load, the components of the Dougong were gradually squeezed, and there were frequent "squeaking" noises. When the Dougong was loaded to 8mm of vertical displacement, micro cracks were formed along the bottom of the Ludou Ear at the intersection of the Nidaogong and the bottom of Ludou. The cracks continued to develop with the loading. Horizontal cracks appeared on the Touang while the load displacement increased to 12mm (Fig. 6a). In this process, Micro-cracks began to form at the intersection of the Mangong and Fang in the upper part; the two ends of the Guazigong were slightly up and the rests of the test piece did not show the phenomenon of destruction.

During the loading to 24mm of vertical displacement, the specimen frequently made the sound of wood cracking. Horizontal cracks appeared at the Ludou, Nidaogong and Touang in the flat, and the gap gradually increased (Fig. 6b). The loose battle at the intersection of the upper Erang and the Linggong appeared oblique cracks (Fig. 6c); horizontal cracks formed at the intersection of the Linggong and Mazhatou, and gradually extended outwards (Fig. 6d). With the loading, horizontal cracks appeared in the tail of the Erang, the cracks in the Nidaogong increased, and the sound of wood cracking appeared low frequency and high sound. When the displacement was loaded to 34mm, horizontal cracks in each layer gradually formed a common seam. Then the Erang and the Touang had obvious warping; Sandous on both sides of Manggong were formed horizontal seam on the outer side of the Ear, and the intersection between Mangong and Mazhatou also began to appear cracks. The test was terminated at 42mm of vertical displacement, and most of the cracks in the Dougong were formed through the seams, which was regarded as the failure of the specimen.

(a) Horizontal crack of the Touang (b) Development of horizontal cracks at the bottom

(c) Oblique cracks of the Sandou (d) Development of upper horizontal cracks

Fig.6 – Failure mode of Dougong under vertical loading

Under the action of vertical load, the middle part of the Dougong passed through the force, so the specimen also showed high bearing capacity. The Gong, Fang and other components bore the bending moment, showing the warping at both ends. Components such as the Sandou and Jiaohudou were tilted under eccentric pressure.

3.2 Horizontal and longitudinal loading test of Dougong

Vertical loading is that the load is parallel to the direction of Gong and Fang of the specimen, and the resistance performance of the Dougong in the wall plane is studied. In the early stage of loading, the parts of the test piece gradually squeezed out, making a slight squeak. Then there was a smaller slip between the Fang and the Mazhatou. There was a squeeze sound between the Guazigong and the Erang at the crucified connection. When horizontal displacement was 5mm, a slight slip appeared between the Fang and the Sandou. Along the Ear of the Ludou, the Nidaogong and the Touang connection appeared small oblique cracks. In the process of loading to 10mm, the cracks continued to develop in the early stage, and the Mangong and the Erang appeared cracks at the intersection. Components such as the Sandou and Guazigong were tilted under eccentric pressure.

When the displacement was loaded to 30mm, the Ear of the Ludou split (Fig. 7a); the gap between the horizontal components increased, and Mazhatou appeared the phenomenon that it was out of tenoning (Fig. 7b). When the displacement was loaded to 60mm, there was a large cracking sound in the Dougong; there was a clear slip between the horizontal components; the Dougong overall tilted (Fig. 7c), and the bottom had the phenomenon of warping (Fig. 7d). During subsequent loading, the friction between the horizontal layers slipped back and forth. The wood cross-pattern pressure damage appeared at the intersection. Some components were seriously out of tenoning, but the Dougong showed good deformation ability and ductility.

(a) Split in the ear of the Ludou

(b) Tenon at the Mazhatou

(c) The overall tilt of the Dougong

(d) Bottom cock up

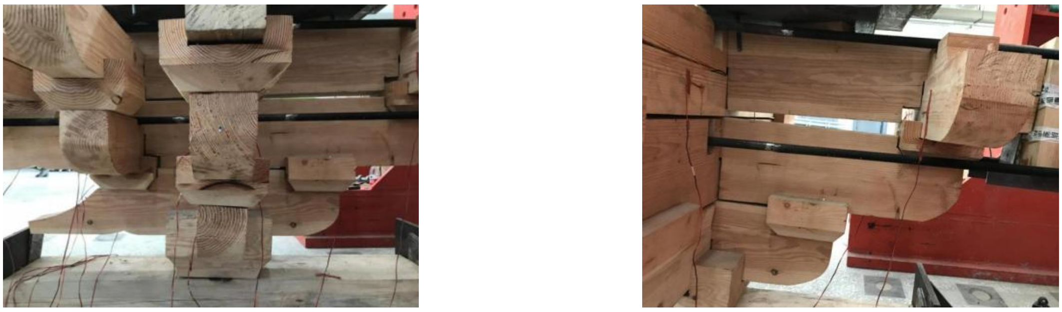
Fig.7 – Failure mode of Dougong under longitudinal loading

Under the action of vertical horizontal loading, the Dougong drove the Mazhatou by Zhengxinfang, and then transmitted force to the upper Mangong and the Linggong. The upper structure transmitted the force to the second layer's Guazigong and Erang through the Sandou and the Jiaohudou. Then the second layer of components was transmitted by the Sandou and the Jiaohudou to the third layer of Nidaogong and Touang, and finally to the beam frame through the Ludou.

3.3 Horizontal transverse loading test of Dougong

The lateral loading is that the load is perpendicular to the direction of the arch and Fang of the specimen, and the Anti-side force performance outside the wall plane is studied. In the early stage of loading, the parts of the test piece gradually squeezed out, making a slight squeak. When the displacement was loaded to 5 mm, there was a slight slip between Mazhatou and Erang. The Mazhatou and Guazigong; the Touang and Nidaogong were squeezed tightly. When the displacement was loaded to 10mm, there was a more obvious slip between the horizontal components and a micro-crack appears at the bottom of the Ludou.

In the process of loading to 20mm, there was a large friction between the Sandou and the Gong, and there was occasional cracking sound in the components. In the process of loading to 40mm, the Dougong was inclined obviously, and there was an obvious gap between the horizontal layers (Fig. 8a). In the process of loading to 50mm, the splitting sound was frequent; there was obvious slip between layers, and the phenomenon was out of tenoning at the Sandou (Fig. 8b). After loading to failure, the Dougong still showed good deformation ability and ductility in this direction.



(a) Significant clearance of horizontal layer

(b) Tenon at the Mazhatou

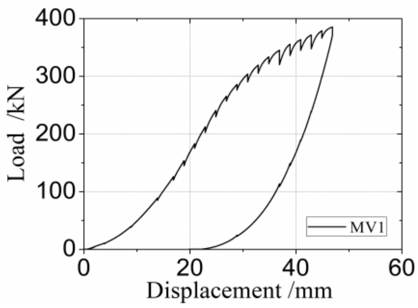
Fig.8 – Failure mode of Dougong under transversal loading

Under the action of transverse horizontal load, the Mazhatou drove the Zhengxinfang, the Mangong and the Linggpong. The upper structure transmitted the force to the Guazigong and Erang through the Sandou and the Jiaohudou, then to the Nidaogong and Touang, and finally to the beam frame through the Ludou.

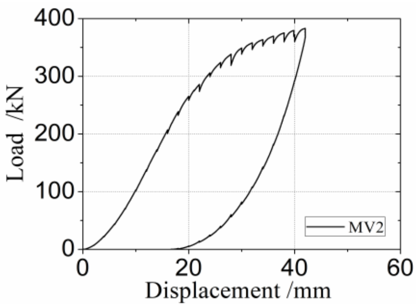
4. Experimental results and analysis

4.1 Load–displacement curve and main mechanical performance parameters

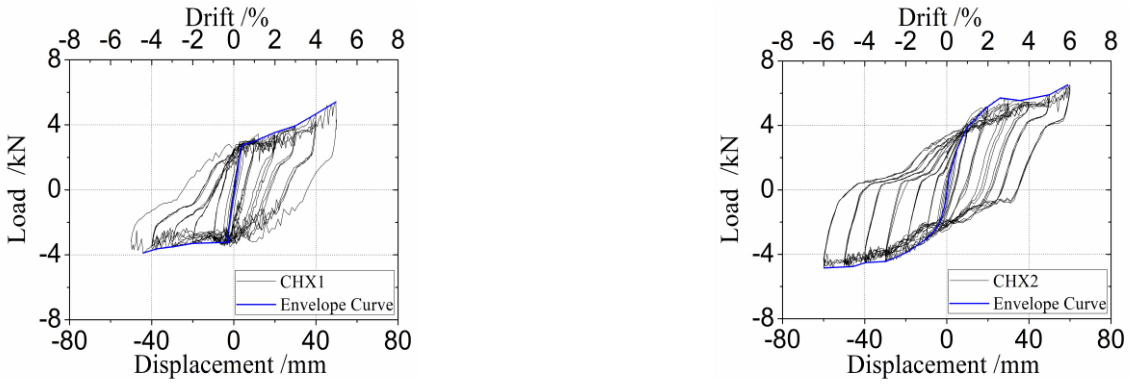
The load–displacement curves of Dougong under vertical monotonic load and horizontal cyclic load are shown in Figure 9.



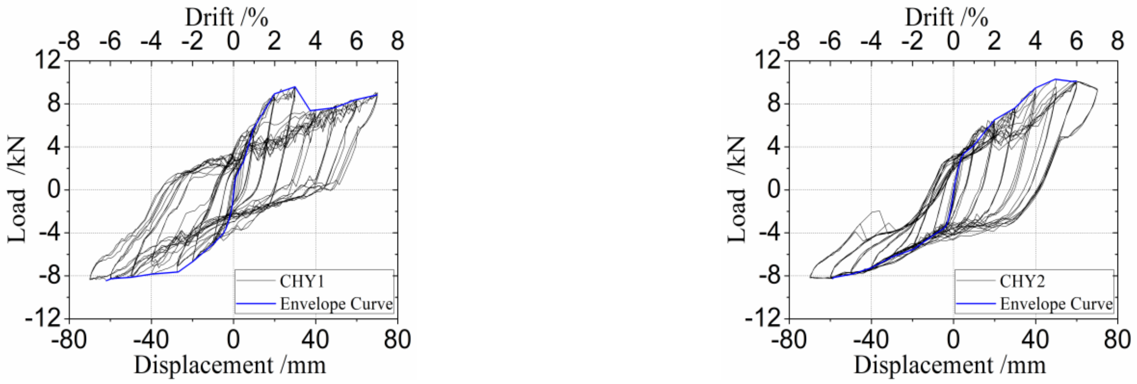
(a) MV1 Specimen



(b) MV2 Specimen



(c) CHX1 Specimen (d) CHX2 Specimen



(e) CHY1 Specimen (f) CHY2 Specimen

Fig.9 – Load-displacement relationship curves

The peak load P_{peak}, the corresponding peak displacement Δ_{peak}, the limit displacement of the structural damage Δ_{u} and the corresponding limit load P_{u} are determined by the load–displacement curve under the monotonic load and the average skeleton curve under the cyclic load (the absolute values of the positive and negative skeleton curves are averaged). The yield point under the monotonic load is defined as the point corresponding to the $0.4P_{\mathrm{peak}}$ load value of the rising segment, and the yield point under the cyclic load is determined by the ideal elastic-plastic method based on energy equivalence (EEEP). The yield load P_{yield}, the yield displacement Δ_{yield}, the stiffness of elasticity stage $K_{\mathrm{e}} = P_{\mathrm{yield}} / \Delta_{\mathrm{yield}}$ and the elongation coefficient $D = \Delta_{\mathrm{u}} / \Delta_{\mathrm{yield}}$ are defined. The main mechanical performance parameters of each test specimen are shown in Table 2.

Table 2 – Mechanical performance parameters

Specimen	**P_{peak}/kN**	**Δ_{peak}/mm**	**P_{u}/kN**	**Δ_{u}/mm**	**P_{yield}/kN**	**Δ_{yield} /mm**	**K_{e}/(kN/mm)**	**D**
MV1	385.56	46.89	385.56	46.89	154.22	19.76	7.80	2.37
MV2	383.06	42.00	383.06	42.00	153.22	16.58	9.24	2.53
CHX1	4.65	46.96	4.65	46.96	3.68	4.44	0.83	10.57
CHX2	5.69	59.41	5.69	59.41	4.88	9.72	0.50	6.11
CHY1	8.64	65.94	8.64	65.94	7.85	11.90	0.66	5.54
CHY2	9.19	59.39	9.19	59.39	7.47	12.71	0.59	4.67

The mechanical performance parameters in Table 2 are evaluated by taking the average of each group of test specimen, and they can be seen from the graph and table:

1. The peak load and the limit load of each test piece are equal that the bearing capacity of each specimen does not decrease during the loading process, indicating that after the components of Dougong have a large displacement, they can still maintain their overall carrying capacities though the parts have damaged. On the other hand, it also shows that the deformation ability of the wooden structure is strong and the method of displacement control should be adopted in the design.

2. Under the action of vertical load, the stiffness of the curve has increased in the initial loading with the parts of the Dougong tight; In the middle and late stages of loading, the stage of curve appears "serrated" because parts of the wood are cracked by pressure. The carrying capacity of the Dougong component reaches 384.31kN, which shows good carrying capacity.

3. The carrying capacity of the horizontal vertically loaded Dougong specimen is 5.17kN, which is 58% of the carrying capacity of the horizontal loading under the Dougong specimen, because the Dougong bites more in the horizontal card slot, showing better carrying capacity. The longitudinal and lateral elastic phases are equally rigid at 0.67kN/mm and 0.63kN/mm respectively. The limit displacement of the Dougong under the vertical load effect is 53.19mm (the angle of displacement is 5.37%), and the limit displacement under the effect of the horizontal load is 62.67mm (the angle of displacement is 6.32%), both of which reach more than 1/20 of the angle of displacement, which shows the good deformation ability of the Dougong.

4. The hysteresis curve of the Dougong specimen under the effect of the low cyclic reversed loading is full and shows good ability of energy dissipation. The ductility coefficient of the Dougong components under vertical load is 8.34 and the ductility coefficient under the horizontal load is 5.11, which shows good ductility.

4.2 Stiffness degradation

In order to reflect the stiffness of the Dougong under cyclic load, the effective stiffness of the test specimen is represented by the cutting line stiffness. The effective stiffness can be defined

$$k_i = \frac{|F_i^+| + |F_i^-|}{|X_i^+| + |X_i^-|} \tag{1}$$

Where: F_i^+ and F_i^- are the positive and negative peak load of every cycle. X_i^+ and X_i^- are the positive and negative peak displacement of every cycle.

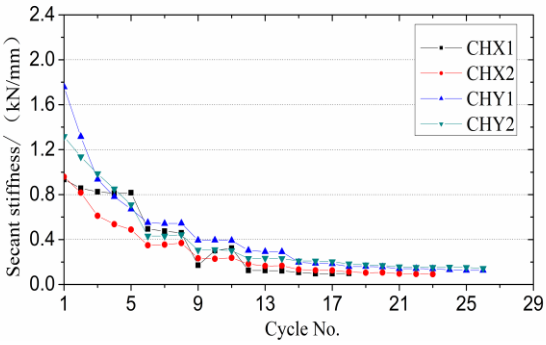


Fig.10 – Secant stiffness curves

The effective stiffness curve of each test specimen under cyclic load is shown in Figure 10, which can be seen:

1. With loading, the bite of the parts of the Dougong gradually looses, and even appears the phenomenon that it is out of tenoning. In the curve of effective stiffness, the stiffness shows a significant decrease and eventually remains at a low level, which is consistent.

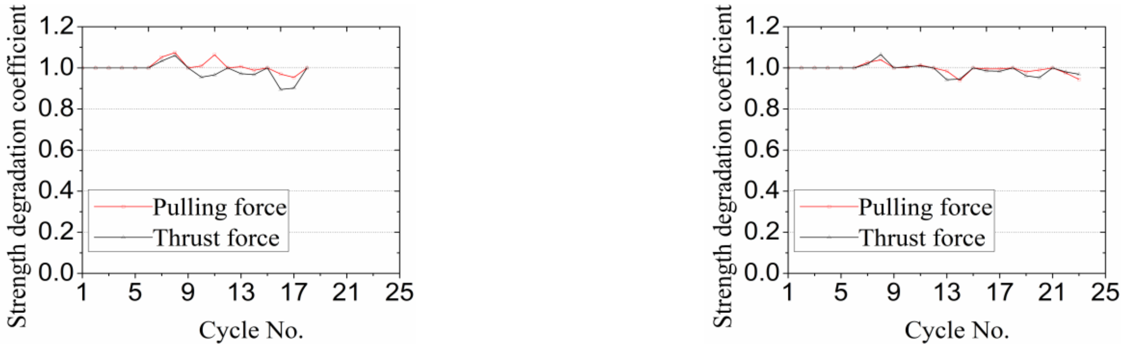
2. The stiffness level of the Dougong is always slightly in the horizontal direction higher than that in the vertical direction because the part of the Dougong is connected more in the horizontal card slot than that in the vertical card slot and the integrity of the specimen in the horizontal direction is slightly better than that in the vertical direction.

4.3 Strength degradation

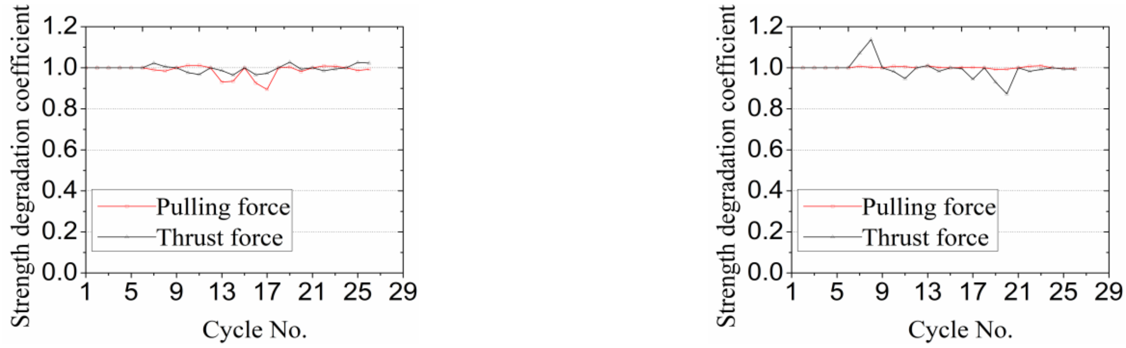
Strength degradation refers to the characteristic that the bearing capacity of Dougong decreases with the increase of cyclic loading times under the condition of constant displacement amplitude. In terms of the degradation coefficient of the same load strength, the degradation coefficient of the same load strength is defined.

$$\lambda = \frac{F_{\min}}{F_{\max}} \tag{2}$$

Where $F_{\min}$ is the peak load of the last cycle under the same displacement amplitude and $F_{\max}$ is the peak load of the first cycle under the same displacement amplitude.



(a) CHX1 Specimen (b) CHX2 Specimen



(c) CHY1 Specimen (d) CHY2 Specimen

Fig.11 – Strength degradation curves

The curve of the strength degradation coefficient under the displacement amplitude value at all levels can reflect the trend of strength degradation in the overall structure, and the strength degradation curve of each test specimen is shown in Figure 11, which can be seen.

1. In the loading process, the various parts of the Dougong show different degrees of damage with the increase of lateral displacement, including the cross-line plastic deformation and cracking of the wood at the intersection, which is also reflected in the strength degradation of the curve.

2. Each group of test specimen of has the strength degradation to less than 20% before the destruction occurs, indicating that under the effect of the earthquake, Dougong still can maintain a good collaborative characteristic and maintain the overall carrying capacity though the various parts of the slip and misalignment.

4.4 Energy dissipation

As an important index to measure the seismic performance of the Dougong, energy dissipation can be measured by the sum of the areas surrounded by the hysteresis curve, which reflects the stiffness, ductility and other factors. The energy dissipation of each load cycle is shown in Figure 12, which can be seen.

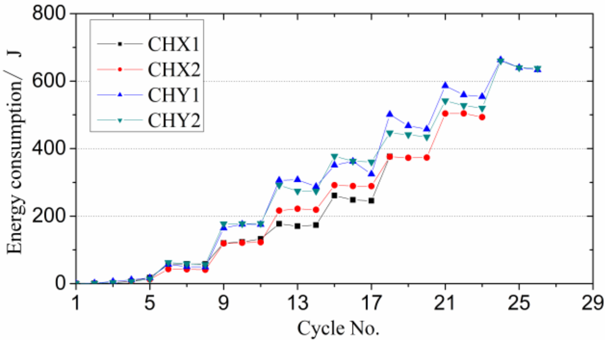


Fig.12 – Energy dissipation characteristics within each cycle group of specimens

1. The energy dissipation of the Dougong mainly comes from friction between the components and the crushing and cracking of the wood. During the loading process, the total stroke of friction increases, showing the increase of energy dissipation level with the increase of displacement amplitude. In the three cycles of the same displacement magnitude, the first cycle increases the deformation of the Dougong; there will be a new wood split and the release of elastic strain energy, showing the maximum energy dissipation level. At the 2nd and 3rd cycles, there is no new cleavage, so there is a degree of decrease in consumption.

2. The capacity of energy dissipation of the Dougong in the horizontal direction is always slightly higher than that in the vertical direction, because the effective stiffness of the Dougong in the horizontal direction. The reaction force under the same displacement amplitude value is larger, so the area of the hysteresis loop is also larger, which also shows consistency with the stiffness degradation curve in sections.

3. With the increase of displacement, the energy dissipation has always been increased and there is no decline in the phenomenon, which shows that the Dougong under the effect of earthquake can show good energy dissipation and ductility.

5. Conclusions

Based on the observation of experimental phenomena and the analysis of experimental data, the following conclusions can be drawn.

1. The failure modes of Dougong under vertical load and horizontal load were the local crushing and splitting of wood as well as the loose connection between various parts (such as tilting, warping and out of tenoning, etc.). In the process of horizontal loading, especially at the end of loading, the components of Dougong maintained the characteristics of good coordination and the overall bearing capacity, and showed a good ductility.

2. Dougong had a good bearing capacity under the vertical load. Under the action of horizontal load, it showed a good deformation capacity and reached the displacement angle of 1/20 or above in both longitudinal and transverse directions without obvious bearing capacity decline. In the design of Dougong, the method of displacement control should be adopted.

3. Dougong had a good energy dissipation capacity under cyclic loading. During the loading process, friction between components provided the main energy dissipation. As the lateral displacement increased, the energy dissipation was always increasing without any drop, which indicated the reliability of Dougong under earthquake action.

6. Acknowledgements

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7. Copyrights

8. References

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