SIMULATION AND EXPERIMENTAL RESEARCH ON ENERGY DISSIPATION BEHAVIOR OF DOU-GONG

Yuan Jianli¹, Shi Ying²

ABSTRACT

Dou-Gong (bracket set) is a unique timber component in traditional Chinese building. In this research the representative bracket sets in Yingxian timber pagoda are selected as the investigating object, and physical model testing method is adopted to ascertain the load transfer mechanism and deformation character of Dou-Gong. By means of horizontal low cyclic loading test under the vertical load action, the hysteresis curves and skeleton curves of the bracket set models have been obtained. The research result indicated the lateral displacement stiffness of the bracket set is increase with the vertical load increase, the friction and shear on interface between members of the bracket set is a main means to energy dissipation.

According as the mechanical and geometrical parameters extracted from physical model, a finite element model based on energy dissipation of Dou-Gong has been proposed. In this FE model the dimensional bracket layer substructure is adopted to incarnate the connecting rule of structural configurations of Dou-Gong, and “contact-target” pair is set on the interface between Dou (bracket block) and Gong (bracket arm) to carry out the function of energy dissipation by friction and shear. A typical FE model of Dou-Gong has been constructed by program ANSYS, and the whole loading processes of the corresponding physical model test have been simulated and analyzed. The analysis result proved that this FE model with perfect simulation function for friction-shear action, and can be applied to seismic behavior study for the traditional Chinese timber building.

Keywords: Dou-Gong (bracket set), Model test, Load transfer mechanism, Friction-shear function, Energy dissipation, Traditional Chinese timber building

1. INTRODUCTION

Dou-Gong (bracket set) is a unique structural component in traditional Chinese timber building. According to the historical literatures [1], Dou-Gong had been set up the top of column to bear overhanging roof in ancient building as early as the initial stage of Xi-Zhou Dynasty (around 1066 B.C.). Because of the various functions on prettified building’s appearance, transferred overhanging load, and dissipated earthquake energy, Dou-Gong was widely used in ancient significant Chinese buildings, such as palaces, pagodas, and temples.

Yingxian timber pagoda built in A.D.1056 is the highest wooden pavilion style structure in China. The exquisite bracket sets totaled 440 are the most remarkable components of the pagoda (Fig. 1) [2]. Undergone numerous strong earthquakes and weather erosion nearly a thousand years, Yingxian timber pagoda is severely damaged and needs to be repaired urgently [3].

In this research the representative bracket sets in Yingxian timber pagoda are selected as the investigating object, and physical model testing method is adopted to ascertain the load transfer mechanism and deformation character of Dou-Gong. And combined with the application of program ANSYS, the practical generation method of finite element model of Dou-Gong based on energy dissipation by friction and shear is discussed.

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2. CONFIGURATION CHARACTER OF DOU-GONG

2.1. Main types of Dou-Gong
Dou-Gong is usually set between column and floor or roof in ancient wooden structures. Dou is a quadrate block member with groove, and Gong is a bowed cantilever arm member. Based on the construction rule these block members and cantilever arm members are tiered vertically and horizontally to form a bracket system. The number of layers of the bracket system is depended on the overhanging length of the roof, and is restricted by the feudalistic grade of the traditional buildings. According to the Construction Rule in Song Dynasty [4], Dou-Gong is mainly classed to three types based on the positions of bracket set and columns, that is, Bracket set on column, Bracket set between columns, and Bracket set on corner column. The representative bracket sets in Yingxian timber pagoda are showed in Figure 2 [2].

![Fig. 1 Bracket sets in Yingxian timber pagoda](image1)

2.2. Basic configuration of Dou-Gong
Figure 3 shows the basic configuration and member denomination [4] of Dou-Gong based on the Construction Rule in Song Dynasty. The big block located underlayer of Dou-Gong is Cap block, the Cap block with cross groove for placement of Axial arm and Flower arm. From bottom layer to top layer, Axial arm, Long arm, Oval arm, and Regular arm are arranged along the vertical ordinate of building. Correspondingly, Flower arm, Second flower arm, Nose arm, Angled arm, and Small tie-beam are arranged along the horizontal ordinate of building. The bracket arm layers are supported and fixed by blocks such as Connection block, Center block, and End block. In the one layer of Dou-Gong, two crossed bracket arms are connected by means of mortise and tenon, and the blocks are fixed on the bracket arms by wooden dowel.
3. MECHANICAL PROPERTY TEST OF DOU-GONG

3.1. Test scheme of physical model of Dou-Gong

3.1.1. Design and fabrication of physical model

Three typical bracket sets at the key positions of Yingxian timber pagoda, that is, Bracket set on column, Bracket set between columns, and Bracket set on corner column (Fig. 2), are made into the physical models on the scale of 1:3 (Fig. 4). Each physical model is 690 mm tall, the detailed dimensions can be find in the literatures [6, 7]. The timber of model is red pine, and the assembled units are listed in the Table 1.

![Fig. 3 Basic configuration of Dou-Gong](image1)


![Fig. 4 Physical model of Dou-Gong](image2)

Fig. 4 Physical model of Dou-Gong

![Bracket set on column](image3)

(a) Bracket set on column

![Bracket set between columns](image4)

(b) Bracket set between columns

![Bracket set on corner column](image5)

(c) Bracket set on corner column

Table 1 Assembled units of physical models

<table>
<thead>
<tr>
<th>Member number</th>
<th>DOU (block member)</th>
<th>GONG (arm member)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cap block</td>
<td>Flower arm</td>
</tr>
<tr>
<td></td>
<td>Center block</td>
<td>Axial arm</td>
</tr>
<tr>
<td></td>
<td>End block</td>
<td>Long arm</td>
</tr>
<tr>
<td></td>
<td>Connection block</td>
<td>Oval arm</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>Regular arm</td>
</tr>
<tr>
<td>Bracket set on column</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Bracket set between columns</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Bracket set on corner column</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

3.1.2. Loading scheme

To understand the load transfer mechanism and energy dissipation behavior of Dou-Gong, the horizontal low cyclic loading test with the vertical load action is adopted. According to the FE analysis
to deadweight load of main floors of the pagoda [6], three vertical loads, 15 kN, 22.5 kN, and 30 kN, are put on the physical model, which are corresponding to the deadweight loads act on the top of columns at fourth floor, third floor, and second floor, respectively. Horizontal low cyclic test is controlled by displacement act on the Cap block of the model. The initial value of the displacement is 3mm, then an increment of 3 mm each step is applied up to 18mm. The cyclic load repeats 3 times at each step of displacements, and the loading speed is 0.15 mm/s.

3.1.3. Loading equipment and measure method
Test equipment and instruments consist of FTS servo loading test system, hydraulic pressure jack, and displacement sensors (Fig. 5). In the test process the physical model is upended, that is the Cap block is located on the top layer, which is convenient for loading and fixation of the model. The vertical load \( N \) is acted on the geometric center of bottom side of Cap block and loaded by hydraulic pressure jack. The vertical displacement \( \Delta y \), is measured by displacement sensors put on the upside of every layer. The horizontal load \( P \) is acted on the lateral side of Cap block and loaded by FTS servo loading test system along the horizontal ordinate of model. The horizontal displacement, \( \Delta H \), is measured by displacement meters put on the lateral side of every layer (Fig. 5).

![Fig. 5 Load and experiment equipment](image)

3.2. Test result of physical model of DOU-GONG

3.2.1. Deformation and damage process of physical model
During the horizontal low cyclic test, the block members of the model, such as Connection blocks and End blocks, are sliding along the direction of horizontal load. Along with the increase of horizontal load, the slippage of block members are increase, some flexual deformations and small cracks can be found in the arm members, and the model has a whole turn deformation. When the control horizontal displacement \( \Delta H \) is around 15mm, the obvious cracks can be found in arm members located the upper layer of the models. The test is stopped with the horizontal split at the weak internal groove of Axial arm (Fig. 6) when the control horizontal displacement \( \Delta H \) reached 18 mm.

The Axial arm is a severe damaged member in each physical model during the test. Because the Axial arm borne the vertical pressure \( N \) and horizontal shearing force \( P \) transferred from Cap block, and the extrusion force \( P \) transferred from Flower arm. The complicated stress condition (Fig. 7) induced the failure that horizontal split along the weak internal groove of Axial arm.

![Fig. 6 Horizontal split of Axial arm](image)

3.2.2. Hysteresis curve and skeleton curve of physical model
The \( N - P - \Delta y \) hysteresis curves of each physical model under three vertical loads are showed in figure 8. The energy dissipation property of Dou-Gong can be concluded from Fig. 8:1) under the each
step of horizontal displacement $\Delta_{H}$, the decreases of bear capacity of the model are not obvious along with the increase of cyclic times, which indicated Dou-Gong has a steady capability for energy dissipation. 2) under the same step of horizontal displacement $\Delta_{H}$, the friction-shear force is increase with the vertical load, so the horizontal load $P$ acted on the DOU-GONG is increase correspondingly. Figure 9 shows the skeleton curves of models at three vertical load conditions, which are drawn according as the outline of corresponding hysteresis curve in figure 8. By comparison of these skeleton curves in figure 9, it can be found the lateral displacement stiffness of Dou-Gong is increase with the vertical load. In addition, the lateral displacement stiffness is proportional to the total member number of Dou-Gong (see also from Table 1), in stiffness ascending sequence is Bracket set on column, Bracket set between columns, and Bracket set on corner column.

Fig. 8 $N-P - \Delta_{H}$ hysteresis curves of bracket sets under horizontal low cyclic loading

Fig. 9 Skeleton curves of bracket sets
4. RESEARCH AND GENERATION OF FE MODEL OF DOU-GONG

4.1. Simplification of structure of Dou-Gong
The structural configuration of Dou-Gong is comparative complex. In order to generate a practicable FE analysis model, it is necessary to simplify the structure of Dou-Gong based on the mechanical property and connection configuration of the structural members.

According to the mechanical character of Dou-Gong that vertical load transfer by the cantilever brackets, the Dou-Gong can be regarded to a dimensional multilayer bracket set (Fig. 10a). In this bracket set, Cap block and Center blocks located on the vertical central axis as the central standing-piller, the arm member as the cantilever fixed the central standing-pillar, and Connection block and End block as the stow-wood fixed on the cantilevers.

Based on the assembling rule of Dou-Gong tiered the block and arm members layer by layer, each bracket layer can be regarded as a substructure of the dimensional multilayer bracket set. The ledge joints are set between two substructures on the position of blocks to incarnate the function of energy dissipation by friction and shear (Fig. 10b). The ledge joint can transfer the vertical pressure, shearing force and horizontal friction, but can not transfer the pull force and bending moment.

![image](image1.png)  ![image](image2.png)

(a) Dimensional structure of bracket set  (b) Layer substructure of bracket set

Fig. 10 Sketch map of simplified structural model of bracket set

4.2. Material parameter of FE model
To obtain reasonable material parameter of the FE model of Dou-Gong, it is important to consider that the timber is a typical anisotropic material. The main material parameters to be ascertained are as follows: 1) Density and Poisson ratio of the timber. 2) The compressive strength and elastic modulus at across grain direction of timber. 3) The compressive strength and elastic modulus at parallel grain direction of timber. 4) Friction coefficient between the wooden members, such as static friction coefficient and dynamic friction coefficient.

The timber of physical model is red pine, with the density of 548 kg/m$^3$, and the Poisson ratio is 0.17. The compressive strength and elastic modulus is measured by axial compression test. Figure 11 shows the $\sigma - \varepsilon$ curve of timber samples. To simplify the hysteresis behavior analysis of FE model, the stress – strain behavior of the timber is described by bilinear kinematic hardening model. At across grain direction of timber, the yield stress is 1.67 MPa, elastic modulus is 216 MPa, and hardening modulus is 3.8 MPa. At parallel grain direction of timber, the yield stress is 23.08 MPa, elastic modulus is 907 MPa, and hardening modulus is 44.7 MPa.

![image](image3.png)  ![image](image4.png)

(a) Axial compression to across grain  (b) Axial compression to parallel grain

Fig. 11 $\sigma - \varepsilon$ curve of timber under axial compression
PVN=  

The friction coefficient of timber is an important parameter to the FE model based on energy dissipation by friction-shear. Considering the relative displacement between members engendered by the practical horizontal load is small, as well as the contact interface of members is not carefully made, the static friction coefficient is adopted in the FE model for structural analysis. The static friction coefficient of timber used in the physical models is measured based on two practical contact conditions of interfaces [6], for the contact condition of across grain to parallel grain is $\mu = 0.519$, and for the contact condition of parallel grain to parallel grain is $\mu = 0.455$.

4.3. Element type of FE model  

In order to simulate the character of energy dissipation by friction and shear, it is necessary to adopt three dimension solid element and set “contact-target” pair on the contact interface between members for the generation of FE model of Dou-Gong. In this simulation and analysis investigation, the program ANSYS is adopted, three dimension solid element SOLID45 is used to generate block members and arm members, and contact element CONTA173 and target element TARGE170 are set on every contact interface between block member and arm member (Fig. 12).  

The contact element CONTA173 should be set along inner surface of block member. The target element TARGE170 can be set on the possible slip area of arm member to reduce the total element number of the model and increase the analysis efficiency. According to the observation value from physical model test and considering a moderate slippage increment, the double covered length of block (2L), that is a covered length (L) superadd the respective half length (L/2) at foreside and backside of block, is adopted as the length of slid area.

![Fig. 12 Setting of contact element and target element](image)

5. APPLICATION OF FE MODEL OF DOU-GONG  

5.1. General situation of FE model of Dou-Gong  

In this research the Bracket set on column is selected as the example to generate FE model, and program ANSYS is adopted to simulate the mechanical behavior according as the progress of physical model test introduced in above paragraphs. The FE model of Bracket set is composed of four substructure layers (Fig. 13). It is generated by three dimension solid element SOLID45, with total 142,693 mesh elements when the mesh size level of 6 is set. The contact-target pair, composed of contact element CONTA173 and target element TARGE170, is defined on the every contact interface between block member and arm member, with total 5,624 mesh elements in the FE model.

5.2. FE analysis and simulation to physical model test  

In order to simulate the practical loading condition of physical model test (Fig. 5), the FE model is still upended and the freedoms of fourth layer at x, y and z direction are restricted. The vertical load and horizontal load are acted on the Cap block, and the concentrated load is converted into the uniform load to avoid the occurrence of stress singularity point.  

Three vertical load conditions, (1) $N = 15$ kN, (2) $N = 22.5$ kN and (3) $N = 30$ kN, are used in FE analysis and simulation by ANSYS. Under each condition the horizontal load is increased step by step to the scheduled displacement, and the corresponding horizontal load and energy dissipation area of the FE model at each control displacement $\Delta H$ are checked. Figure 14a-14c show the hysteresis curves of FE model under three loading conditions. Along with the increase of vertical load $N$, the horizontal load $P$ acted on the model to reach the control
displacement $\Delta_{H}$ is increase, and plump degree of hysteresis curve of the model is also increase, which indicates this FE model is similar to the physical model of Dou-Gong on the function of energy dissipation by friction and shear. The horizontal loads need to be acted on the FE model and physical model to reach the same control displacement are listed in Table 2 respectively, and the calculated energy dissipation values according as the area of hysteresis curve are listed in Table 3. The comparison of analysis value and test value is demonstrated that this FE model can be effectively used to analyze and simulate the mechanical behavior of Dou-Gong.

![Model of Bracket set on column](image)

**Fig. 13** Model of Bracket set on column

![Hysteresis curves of FE model of Bracket set on column](image)

**Fig. 14** Hysteresis curves of FE model of Bracket set on column

**Table 2** Horizontal loads acted on Bracket set on column at control displacements, kN

<table>
<thead>
<tr>
<th>Load condition</th>
<th>Control displacement, $\Delta_{H}$</th>
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<tbody>
<tr>
<td></td>
<td>6 mm</td>
</tr>
<tr>
<td>Physical model (Horizontal load / kN)</td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>5.14</td>
</tr>
<tr>
<td>(2)</td>
<td>5.44</td>
</tr>
<tr>
<td>(3)</td>
<td>6.22</td>
</tr>
<tr>
<td>FE model (Horizontal load / kN)</td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>4.74</td>
</tr>
<tr>
<td>(2)</td>
<td>5.71</td>
</tr>
<tr>
<td>(3)</td>
<td>6.37</td>
</tr>
</tbody>
</table>

**Table 3** Energy dissipation value of Bracket set on column at control displacements, kN-mm

<table>
<thead>
<tr>
<th>Load condition</th>
<th>Control displacement, $\Delta_{H}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 mm</td>
</tr>
<tr>
<td>Physical model (Energy dissipation / kN-mm)</td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>153.55</td>
</tr>
<tr>
<td>(2)</td>
<td>159.10</td>
</tr>
<tr>
<td>(3)</td>
<td>160.95</td>
</tr>
<tr>
<td>FE model (Energy dissipation / kN-mm)</td>
<td></td>
</tr>
<tr>
<td>(1)</td>
<td>48.10</td>
</tr>
<tr>
<td>(2)</td>
<td>51.80</td>
</tr>
<tr>
<td>(3)</td>
<td>56.43</td>
</tr>
</tbody>
</table>
6. CONCLUSION

This research ascertained the load transfer mechanism and deformation character of Dou-Gong by physical model test. Under the action of horizontal low cyclic load and vertical load, the lateral displacement stiffness of the Dou-Gong is increase with the vertical load, the combination of whole turn and relative slide between layers is the main deformation character of Dou-Gong, and the friction and shear on interface between members of Dou-Gong is an important means to energy dissipation. According as the mechanical character and construction rule of Dou-Gong, this research proposed the practical generation method of FE model of Dou-Gong. In this FE model the dimensional bracket layer substructure is adopted to incarnate the basic character of loads transfer of Dou-Gong, and “contact-target” pair is set on the interface between block member and arm member to carry out the function of energy dissipation. A typical FE model of Bracket set on column has been generated by program ANSYS, and the whole loading processes of corresponding physical model test have been simulated and analyzed. The analysis result indicated that this FE model with perfect simulation function for friction-shear action, it is effectively to describe the mechanics behavior of the Dou-Gong under the action of vertical load together with horizontal cyclic load, and can be applied to seismic behavior study for the timber structure of traditional Chinese building.

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