Analysis of the Force Characteristics of the Chinese Wooden Dou-Gong Brackets in the Ming Dynasty

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Abstract. The Dou-Gong bracket is the most unique part of Chinese wooden architecture. It has an exquisite structure and complex stress. It bears the important force-bearing components between the beam and the column. Different Dou-Gong in different historical periods has different structures and characteristics. This article takes the Jinci Mirror Terrace in the Ming Dynasty as an example and uses the Abaqus to simulate the vertical force to analyze its force characteristics and force transmission path. At the same time, comparing the actual damage of the ancient buildings, it is found that they are consistent with the simulation phenomenon, which proves that the stress simulation of the Dou-Gong has certain guiding significance, and thus summarizes the weak points of the Gou-Gong in the Ming Dynasty, to provide a basis for the daily protection and reinforcement of the Gou-Gong brackets.

Keywords: Dou-Gong Brackets, Abaqus, Force Transmission Path, Protection Of Ancient Buildings

1. Introduction

Figure 1. The Duo-Gong bracket of Mirror Terrace:(a) Perspective;(b) Front view;(c) Side view;(d) Top view

The most remarkable and unique feature of the Chinese wooden frame is the traditional Dou-Gong brackets between the roof and the columns. The Dou-Gong brackets have obvious damping effects on
both horizontal and vertical earthquakes\[1-3\]. The Dou-Gong brackets are the most critical node between the horizontal structure and the column. The research on the mechanical properties of the Dou-Gong bracket mainly focuses on the numerical simulation, finite element simulation and test simulation of the construction of YingZaoFaShi and the key nodes of Yingxian wooden tower. The test cannot explain the 1000-year history of the use of Dou-gong. Time will change the mechanical, physical and chemical characteristics of wood, which affects the performance of wood. A series of comprehensive tests and analyses are required to develop methods to study the performance of Dou-gong brackets supports under long-term loads\[4\]. In this paper, through the analysis of the mechanical performance and force transmission path of the non-official buildings of the Ming Dynasty Dou-Gong brackets, and reference to the actual situation of the local Dou-Gong damage for comparison, so as to enrich the research on the mechanical performance of the Dou-Gong, and provide a basis for the analysis of the mechanical performance of the Dou-Gong brackets and the protection of ancient buildings.

The object of this research is the Ming Dynasty opera stage architecture Jinci Mirror Terrace, one-layer Dou-gong bracket is shown in Fig.1. The names and abbreviations of components of the Dou-Gong bracket are shown in Fig.2. The detailed dimensions of the Dou-gong brackets are obtained from actual surveying, and the dimensions of some hidden parts refer to the example of QingGongChengZuoFaZeLi\[5\], as well as asking local craftsmen to obtain.

In this paper, the finite element analysis software ABAQUS was used to simulate the monotonous loading process of the Dou-Gong brackets and the deformation state and stress distribution were observed. Compared with the example of ancient architecture, it verifies the feasibility of ABAQUS analysis and provides a basis for the protection and maintenance of ancient architecture in the Ming Dynasty based on the finite element simulation results.

![Figure 2. The names and abbreviations of components of Dou-Gong bracket](image)

2. Method
In this paper, an eight-node hexahedral linear reduction element (C3D8R) is used to simulate wood components. When the wood properties are used in the finite element simulation, the wood is simplified into orthotropic materials. The joints between the tenon and the mortise are simulated with normal hard contacts ("hard contact"). The tangential direction is simulated by a dynamic friction model. Under the action of a certain pressure N, when the tangential force \( f \) of the contact surface is less than the critical value \( f_{\text{crit}} \), as shown in the equation 1, there will be no relative slip (bonding state) between the two contact surfaces, otherwise tangential slip will occur. After the relative sliding of the contact surface occurs, the friction coefficient and the sliding speed \( V \) has an exponential decay relationship. As shown in the equation 2, the friction coefficient of the two relative contact surfaces from the sticking state to the initial relative slip is greater than the friction coefficient during sliding. The average static and dynamic friction coefficients between woods are 0.35 and 0.28, respectively, with significant differences. \( dc \) takes 3.0.
Figure 3. Three-dimensional solid model of the Dou-Gong bracket

The column Dou-Gong considers the boundary conditions in its actual building structure. The column head has a fixed constraint on it under the Dou-Gong bracket to restrict the movement in the up-down, left-right, front-rear direction, and the tail beam is inserted into the wall and becomes the fixed end. Therefore, in the finite element simulation and actual experiment, it is similar to the actual situation, and fixed constraints are adopted for the column end and the beam end. Through the load calculation, the load on the Dou-Gong bracket is 36 KN\(^{[6]}\), which is loaded on the reference point of the coupling constraint of the purlin loading surface. Through the ABAQUS CAE pre-processing module, a three-dimensional solid model of the Dou-Gong bracket is established. As shown in fig.3, the size and structure of all components are taken from the measured data of the first-stage Dou-Gong of the Mirror Terrace. In order to improve the calculation accuracy and consider the calculation time, the grid size of all parts is 6mm. This model is modeled and solved in the ABAQUS / Standard module, and the general method (Static, General) is selected for calculation.

3. Result

Figure 4. Overall structure

3.1 Overall Structure

As shown in fig.4, the trend diagram of the deformation of the Dou-gong bracket model is enlarged. Because the pressure of the beam frame and the roof mainly acts on the Dou-gong through the purlins and the purlins are placed on the Gong-IV which is at the front of the entire Dou-Gong. Therefore, the Purlin Support, the Gong-IV, as well as the Dou-II under the Gong-IV, the front half of the Dou-Gong under the Dou-II, and the middle of the two ears on the front side of the Dou-B are under great pressure, so that the entire front of the Dou-Gong has a tendency to be deformed by pressure. This uneven compressive stress will cause compressive deformation on the compressed side of the Dou-Gong bracket, compressive deformation or cracking of the Dou-B, resulting in the uneven surface of the component.

3.2 Purlin
Fig. 5(a) shows the position of the Purlin before and after stress (the displacement magnification factor in the figure is 134). It can be seen that from the position before the stress to the final position after the stress, the movement in the Z direction and the Y direction occurs, and the rotation around the X-axis direction occurs. The state of the purlin is uniformly distributed as shown in the figure. The force analysis of the purlin is as follows: the top of the purlin is subjected to a uniform Y-direction downward force, and the part of the bottom that is in contact with the wood is subjected to a vertical upward Y-direction force; In addition to the vertical upward Y-direction force, the part where the bottom is in contact with the Beam is subjected to the X-direction force on the left side and the X-direction force on the right side. Since the Y-direction force of the Purlin is diagonally inward, the purlin tends to roll inward. The changing trend is similar to the actual situation (Fig. 5(b)).

Fig. 5(c) shows the S22 stress cloud diagram of Purlin and Purlin-Support. It can be seen from Fig. 5(c) that the top of purlin is subjected to downward Y-direction force, and the portion of the bottom of the timber that is in contact with the Beam and the sides that are in contact with the Gong-IV are subjected to vertically upward Y-direction force. The colored area in Fig. 5(c) is the compression area in the Y direction, and the gray area is the tension area in the Y direction. The black dotted arrow in the figure is the approximate transmission path for judging the pressure. From the S22 stress diagram, it can be seen that Purlin and Purlin-Support are affected compression in the most area; Purlin at the bottom and the Beam contact portion S22 direction compressive stress reaches the maximum, the bottom of the wood is in contact with the Beam S22 direction compressive stress reaches the maximum.

The force analysis of the Purlin-Support is as follows: the top of the Purlin-Support is subjected to the vertical downward Y-direction force, the part in the middle of the bottom that contacts the Beam, and the part that is in contact with the Gong-IV on both sides are subjected to the vertical upward Y-direction force.

3.3 Xiang-Gong (Gong-IV)

Fig. 6(a) shows the position of the Gong-IV before and after stress (the displacement magnification factor in the figure is 134), It can be seen that from the position before the load to the
final position after the load, the movement in the Z direction and the Y direction occurs, and the rotation around the X-axis direction occurs. The changing trend is similar to the actual situation (Fig. 6(b)).

As shown in Fig. 6(c), the stress cloud diagram of the Gong-IV S22 direction. As can be seen from the two sides of the top of the Gong-IV are subjected to the downward Y-direction force transmitted from the Purlin-Support. The groove in the middle of the Gong-IV is subjected to the downward Y-direction force transmitted from the Beam, and the bottom of the groove is supported by the upward Y-direction force from Gong-II.

In Fig. 6(c), the colored area is the compression area in the Y direction, and the gray area is the tension area in the Y direction. The black dotted arrow is the approximate transmission path of judgment. From the S22 stress diagram, it can be seen that the forces in the three directions of the top of the Gong-IV are basically directly transmitted to the bottom of the Gong-IV by pressure. The compressive stress of the area S22 outside the contact area between the Gong-IV groove and the Beam reaches the maximum.

3.4 Qiao (Gong-II)

![Simulated and actual deformation of Gong-II: (a) The position before and after stress; (b) Actual deformation photo; (c) S22 direction cloud diagram of the Gong-II.](image)

Figure 7. Simulated and actual deformation of Gong-II: (a) The position before and after stress; (b) Actual deformation photo; (c) S22 direction cloud diagram of the Gong-II.

As shown in Fig. 7(a), the position of the Gong-II before and after the stress (the displacement magnification factor in the figure is 134), it can be seen that the Gong-II has bending deformation before and after being stressed and almost no rigid displacement occurs. The changing trend is similar to the actual situation (Fig. 7(b)).

The Gong-II S22 direction stress cloud is shown (Fig. 7(c)). The colored area in Fig. 7(c) is the Z-direction compression area, and the gray area is the Z-direction tension area. As can be seen from the S22 stress map, the left side of the Gong-II bottom S22 direction compressive stress reaches the maximum. The tensile stress of S22 in the middle of the top reaches the maximum value.

3.5 Dou-B

Fig. 8(a) shows the position of the Dou-B before and after the stress (the displacement magnification factor is 134). It can be seen that there is almost no rigid displacement before and after the stress of the Dou-B only local deformation occurs. The changing trend is similar to the actual situation (Fig. 8(b)).

As shown in Fig. 8(c), the stress cloud diagram of the Dou-B S33 direction, the left side of the Dou-B is affected by the downward Y-direction force from the bottom. The upward Y-direction force supported by the column at the bottom of the Dou-B, the colored area in Fig. 8(c) is the compression area in the Z direction, and the gray area is the tensile area in the Z direction. From the S33 direction stress figure, it can be seen that the compressive stress of the contact point between the Dou-B and the Gong-II reaches the maximum value in the S33 direction, and the tensile stress in the middle of the Dou-B reaches the maximum value in the S33 direction.
3.6 Main Aisle Exposed Tie beam (Beam)

As shown in Fig. 9(a), the position of the Beam before and after the stress (the displacement magnification factor in the figure is 134). It can be seen that the front part of the Beam is displaced downward in the Y direction, and the X-directional bending deformation occurs. The changing trend is similar to the actual situation (Fig. 9(b)).

As shown in fig. 9(c), the stress cloud diagram of the Beam S22 is shown. The colored area in Fig. 9(c) is the compression area in the Y direction, and the gray area is the tension area in the Y direction. From the S22 stress diagram, it can be seen that the Beam transfers the force of purlins and Purlin-Support from the top to the lower Gong-IV and Gong-II; the S22 compressive stress reaches the maximum in the area in contact with the Purlin-Support.

4. Conclusion

As shown in fig. 10(a) is the stress cloud diagram of the overall S22 direction of the Dou-Gong brackets; (b) Actual deformation photo

Figure 8. Simulated and actual deformation of Dou-B: (a) The position before and after stress; (b) Actual deformation photo; (c) S22 direction cloud diagram of the Dou-B

Figure 9. Simulated and actual deformation of Beam: (a) The position before and after stress; (b) Actual deformation photo; (c) S22 direction cloud diagram of the Beam

Figure 10. Simulated and actual deformation of Dou-Gong: (a) Stress cloud diagram of the overall S22 direction of the Dou-Gong brackets; (b) Actual deformation photo
brackets and actual Dou-Gong bracket picture. From the figure, it can be seen that the pressure is transmitted from the upper side of the purlin to the lower side of the big bucket along the black dotted arrow in the figure, and it affects the surrounding areas. As shown in Fig.10(b) the deformation of the Dou-Gong bracket is similar to the simulation which has a tendency to tilt forward.

- The overall strength of the Dou-Gong bracket is uneven. The members parallel to the roof, such as Gong, have the same stress on the left and right sides, and the weak point is in the middle. Components with a 90-degree angle to the roof, such as Gong-II and Beam, have large front-end stress and small rear-end stress, which can easily cause compression deformation of the front end of the component, causing the forward tilt of the Dou-Gong bracket. This forward tilt will exacerbate the front end pressure. The overall structure is out of balance;
- The stress of the component is uneven, and the contact parts of the construction and the joints of the tenon and mortise are concentrated, and the most vulnerable are most likely to deform, such as the middle of the Gong;
- Because the bucket is thin and small and has a large contact area with other members as a connecting member, the tenon and mortise structure is complex, so the stress it receives is relatively large, and it is more likely to deform and break.

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