Study on earthquake resistance behaviors of Taihe Palace by simulation

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Abstract. Taihe Palace in the Forbidden City in Beijing is the largest scale as well as highest level of Chinese ancient palace buildings. To effectively protect Chinese ancient buildings, the Taihe Palace is taken as example to study its earthquake resistance performances. Simulation means is considered for analysis. Based on typical constitutions of Taihe Palace such as free-standing column root, tenon-mortise connection between beam and column, bracket sets (tou-kung), heavy roof, filler wall and so on, its finite element model is built by ANSYS program. By modal analysis, response spectrum analysis and time-history analysis, its dynamic characteristic and seismic performances are discussed. Results show the basic frequency of Taihe Palace is 0.85 Hz, its main modes are of translation in level directions. There is little relation among main modes. Under 8 degree intensity of of frequently occurred earthquakes, internal forces of the building are within permission scopes, which means it is not destroyed. Under 8-degree intensity of rare occurred earthquakes, its maximum deformation value is within the permission scope, reflecting it does not collapse. The constitutions such as free-standing column root, tenon-mortise joint, bracket sets and so on are helpful for earthquake resistance. Thus the Taihe Palace has good aseismic performances.

1. Introduction
Taihe Palace, locating in the front part of the Forbidden City (Palace Museum) in Beijing, is the largest as well highest level of ancient palace buildings in China. It was built in 1697. Before serving as a part of museum, it was used as the emperor’s office in ancient time. The building has 2 eaves and is of hip type of roof. Its size is $4.0 \times 37.2 \times 24.4$ m (length $\times$ width $\times$ height). By constitution, the building is composed of the following parts: column, beam, tou-kung (bracket sets), roof truss, roof and filler wall. The column root of the building free stands on stone base, the beam and column are connected by tenon-mortise joint, the tou-kung is assembled by many small timber blocks, and the roof truss is made up of many beams and small columns. Figure 1 shows photo and sketches of Taihe Palace.
Beijing belongs to 8-degree intensity of seismic fortification area. It is necessary to carry out evaluation on seismic performances of Taihe Palace, not only because of the historical and cultural values of the ancient building, but also because of the threaten of earthquake. Some scholars have carried out researches on seismic performances of Chinese ancient buildings (including Taihe Palace). In recent years, main achievements include Zhou et al [1-2] have studied the seismic performances of tenon-mortise joint of Taihe Palace and thought that the joint can consume part of earthquake energy. Xie et al [3] studied seismic behavior of tou-kung by low cyclic-reversed tests. They thought that the tou-kung has good seismic performances. He et al [4] studied mechanical property of column footing joint in traditional wooden structure by quasi-static tests. They thought that the restoring moment, rotation stiffness and strain of edge point have a rising trend with the increase of vertical load. Xue et al [5] studied the damage rules for the initial stiffness and yielding stiffness of tenon-mortise joint based on shaking table tests. They thought that the initial stiffness damage of tenon-mortise joint increased first and then decreased. Based on researches above, finite element model of Taihe Palace is built in this paper. Modal, spectrum and time history analysis are carried out to study its vibration characteristics and seismic performances, results will benefit protection of the ancient building.

2. Simulation Model
ANSYS program is considered to carry out simulation of seismic performances of Taihe Palace. As typical constitutions of the building include free-standing column bottom, tenon-mortise joint, tou-kung and so on, their mechanical model can be simulated by the following hypotheses:
(1) Tenon-mortise connection: beam and column of the building is connected by tenon-mortise joint, which means end of the beam is made as tenon and inserted into the mortise of top of the column, as shown in Figure 2 (a) and Figure 2 (b). The tenon-mortise joint has good rotation performances. Under earthquakes, the relative rotation and compression between tenon and mortise can consume part of earthquake energy and mitigate the damage of the structure. According to achieved research results, restoring force curve of bending moment ($M$) and rotation angle ($\theta$) of the tenon-mortise joint is shown in Figure 2 (c). Here $k_1$, $k_2$, $k_3$ separately represents rotational stiffness of initial stage, elastic stage and hardening stage of the joint, $\theta = (0-0.005)$ rad, $k_1 = 3.602$ kN·m/rad; $\theta = (0.005-0.07)$ rad, $k_2 = 5.755$ kN·m/rad; $\theta = (0.07-0.1)$ rad, $k_3 = 1.781$ kN·m/rad [1].

(2) Tou-kung: tou-kung (bracket sets) locates between the roof system and the top of beam. It is composed of many little parts in level and vertical directions, as shown in Figure 3 (a). The tou-kung parts connect each other by invisible timber bolt or tenon, thus under earthquakes the tou-kung can hardly be destroyed. What’s more, under earthquakes, the relative compress and friction among the little parts can also dissipate part of earthquake energy to mitigate damage of the structure. Mechanical model curve of the tou-kung is shown in Figure 3(b)[6], where $k_1$, $k_2$ separately represents elastic stage and hardening stage of its lateral stiffness, $\Delta$ represents the lateral displacement of the tou-kung, $P$ represents the restoring force; $\Delta = (0-0.0045)$ m, $k_1 = 1.0 \times 10^6$ N/m; $\Delta = (0.0045-0.0353)$ m, $k_2 = 0.05 \times 10^6$ N/m.
3. Free-standing column root: the column root stands on the stone base without any lateral support, as shown in Figure 4(a). Under earthquakes, the column roots move on the stone surface, which produces friction and consumes part of earthquake energy. As the diameter of the stone face is big enough, the column root will hardly fall down [7]. Under earthquakes, the force - displacement ($P-\Delta$) restoring curve of the column root is shown in Figure 4(b), where $P_0$ means initial sliding force, which also is the maximum static friction force value between the column bottom and the stone base surface; while $k''$ represents the initial sliding stiffness of the column root. Values of the parameters are [3]:

- $P_0 = 2.01 \times 10^5$ N, $\Delta = (0-0.005)$ m, $k'' = 5.2 \times 10^4$ N/m; $\Delta = (0.005-0.1)$ m, $k'' = 0$. 

![Figure 3. Mechanical model of the tou-kung.](image)

![Figure 4. Mechanical model of the column bottom.](image)
In ANSYS program, element MATRI27 is used to simulate tenon-mortise joint and tou-kung, element COMBIN40 is used to simulate free-standing column root, element BEAM189 is used to simulate the beam and column, element SHELL181 is used to simulate filler wall, and element Mass21 is used to simulate roof mass. By hypotheses above, the finite element model of Taihe Palace is built, as shown in Figure 5.

![Finite element model of Taihe Palace.](image)

**Figure 5. Finite element model of Taihe Palace.**

### 3. Modal Analysis

Modal analysis is a method to obtain the vibration status of the structure under earthquakes. By modal analysis, the natural frequencies as well as vibration modes of Taihe Palace are obtained, the top 5 of which are shown in Table 1. It indicates that its basic frequency value in x direction (lengthwise direction) is 0.85Hz; the vibration mode is translation, as shown in Figure 6(a). Its basic frequency value in z direction (transverse direction) is 1.58Hz, also the translation type of mode, as shown in Figure 6(b). Besides, mode 1 and mode 2 has little correlation, reflecting the structure does not twist under earthquakes, which mitigate damage of the structure. Figure 6 also shows that vibration of the timber structure near the filler walls is inconspicuous, the reason is that the filler wall restricts the vibration of the timber structure.

| No | $f$ (Hz) | Vibration characteristics                        |
|----|---------|--------------------------------------------------|
| 1  | 0.85    | Translation in x direction                       |
| 2  | 1.58    | Translation in z direction                       |
| 3  | 2.09    | Local translation in x direction of the timber structure |
| 4  | 2.61    | Local translation in z direction of the timber structure |
| 5  | 3.01    | Local translation in x direction of the timber structure |
4. Spectrum Response Analysis

The methods of spectrum response analysis is often used for seismic performance analysis, in which the earthquake force is simplified as static force. The virtue of the method is that it can quickly get the distribution of deformation as well as internal force of the whole structure. Under 8-degree intensity of frequently occurred earthquakes, the seismic performances of Taihe Palace are studied by this method.

Firstly, the parameter $\alpha$ (means seismic influence coefficient) is determined according to Figure 7 [8], where $\alpha_{\text{max}}$ means the maximum value of $\alpha$, under the condition of frequently occurred earthquake with the intensity of 8-degree, $\alpha_{\text{max}}=0.16$; $T$ means the natural period of Taihe Palace; $T_g$ means the characteristic period of Taihe Palace, $T_g=0.35s$; $\gamma$ means the attenuation ratio of the declining part of the curve, $\gamma=0.9$; $\eta_1$ means the adjustment ratio of the slope of the curve, $\eta_1=0.02$; $\eta_2$ means the adjustment ratio of the damping value of the curve, $\eta_2=1$.

\[
\alpha = \begin{cases} 
0.45 + (10\eta_2 - 4.5)T & (0 \leq T < 0.1) \\
\eta_2 \alpha_{\text{max}} & (0.1 \leq T \leq T_g) \\
(T_g / T) \eta_2 \alpha_{\text{max}} & (T_g < T \leq 5T_g) \\
\eta_2 0.2 - \eta_2 (T - 5T_g) \alpha_{\text{max}} & (5T_g < T \leq 6.0) 
\end{cases}
\]

Figure 7. $\alpha$ curve.

Then according to Figure 7, equation (1) can be obtained, which includes the following 4 parts:

By equation (1) as well as the condition of 8-degree of frequently occurred earthquake intensity in level directions, the seismic forces are determined. Single-point Response Spectrum (SPRS) is carried out. The responses of internal forces of Taihe Palace are studied. To justify the safety state of the structure, some permission values are given [9]: maximum tension stress, $[f_t] = 8.5\text{MPa}$; maximum compression stress, $[f_c] = 12\text{MPa}$; maximum bending stress, $[f_m] = 13\text{MPa}$, maximum shearing stress, $[f_s] = 1.5\text{MPa}$.

Some typical nodes of beam system 1 and beam system 2 (see Figure 1(c)) are selected for analysis, as shown in Figure 8, where the nodes in brackets belong to system 2. Internal force values such as bending moment ($M$), shearing force ($V$), axial force ($N$) and the corresponding stress values are shown in Table 2 and Table 3. Results indicate that all the internal forces are within the permission scopes, reflecting the good performance of the structure under 8-degree intensity of free occurred earthquakes. The reasons lie not only the tenon-mortise connection means of beam and column, but also the enough size of each beam. For example, the maximum bending moment value of node 5711 of a beam reaches 76979N·m, however the corresponding bending stress is only 1.37MPa, which is far lower than the permission value. The reason is that its section size is 0.72 x 1.52 m (width x height), which is big enough to resist bending. Besides the internal force values of beam system 1 are smaller than those of beam system 2. This is because the location of beam system 2 is closer to the side wall than beam system 1, while the side wall may bear part of earthquake force to mitigate damage of beam system 1.
The deformation value is 0.075m in the deformation response, reflecting the vibration of the column root. It is found that its maximum acceleration value in 3 directions are: node No. 1536 (the position of mortise joint), node No. 280 (the position of stone base [10]), and node No. 11718 (the position of tenon-mortise joint), node No. 1536 (the position of tenon-mortise joint), and node No. 11718 (the position of tenon-mortise joint) are considered to apply to the model. For each earthquake wave, action time space is 0.02s, and the total duration time is 30s. The ratio of peak acceleration value in 3 directions are: $a_x, a_y, a_z = 1 \cdot 0.65 \cdot 0.85$, where $x, y, z$ represent longitudinal, vertical, and transverse directions. The maximum acceleration value in $x$ direction is 0.4g ($1g = 9.8 m / s^2$). Some typical nodes (see Figure 5) are selected to reflect the deformation of the structure under the rare occurred earthquakes: node No. 280 (the position of column root), node No. 1536 (the position of tenon-mortise joint), and node No. 11718 (the position of middle of roof).

Deformation response curves of the nodes above are shown in Figure 6. For node No. 280, its deformation response reflects the vibration of the column root. It is found that its maximum deformation value is 0.075m in $z$ direction, reflecting its slide motion on stone base [10].

### Table 3. Calculation results of beam system 2

| No | $M/(N\cdot m)$ | $f_{cd}/(MPa)$ | $f_{y}/(MPa)$ | $V/(N)$ | $f_{ct}/(MPa)$ | $f_{ct}/(MPa)$ | $N/(N)$ | $f_{ct}/(MPa)$ | $f_{ct}/(MPa)$ |
|----|----------------|----------------|--------------|--------|----------------|--------------|--------|----------------|--------------|
| 94 | 0              | 0              | Y            | 10498  | 0.025          | Y            | 7084   | 0.015          | Y            |
| 1057 | 0           | 0              | Y            | 16547  | 0.027          | Y            | 10586  | 0.014          | Y            |
| 1618 | 0            | 0              | Y            | 8660   | 0.016          | Y            | 22637  | 0.037          | Y            |
| 5137 | 53577       | 2.05           | Y            | 15881  | 0.146          | Y            | 23418  | 0.144          | Y            |
| 6030 | 11435       | 0.11           | Y            | 6613   | 0.015          | Y            | 7724   | 0.015          | Y            |
| 5172 | 36440       | 1.39           | Y            | 6276   | 0.055          | Y            | 7901   | 0.048          | Y            |
| 9023 | 2137        | 0              | Y            | 2115   | 0              | Y            | 9670   | 0.011          | Y            |
| 9032 | 11521       | 0.20           | Y            | 6629   | 0.044          | Y            | 18900  | 0.084          | Y            |
| 9775 | 18463       | 0.31           | Y            | 3634   | 0              | Y            | 38737  | 0.186          | Y            |
| 5894 | 19169       | 0.13           | Y            | 13224  | 0.029          | Y            | 4560   | 0.011          | Y            |
| 6166 | 10405       | 0.07           | Y            | 9778   | 0.016          | Y            | 5823   | 0.021          | Y            |
also within the boundary of the stone base, reflecting that the column root will not fall off. Maximum deformation values of node No. 1536 in 3 directions are all bigger than those of node No. 280, reflecting the more obviously vibration status of the tenon-mortise joint. However, the vibration curves in 3 directions are all stable and even, reflecting the timber structure are stable under the 8-degree intensity of rare occurred earthquakes. For node No. 11718, its vibration curves in 3 directions are all unstable, reflecting the roof vibrates obviously. The maximum values in level directions ($x$: 0.15m, $z$: 0.09m) are within the permission value 0.81m ($H/\theta=24.42/30=0.81$, here “$H$” and “$\theta$” represent height and permitted ratio of story drift) [11]. Thus the roof of the Taihe Palace will not collapse under the rare occurred earthquakes, and the building retains safety.

![Figure 9. Curves of deformation of typical nodes.](image)

The maximum acceleration values of the selected nodes above are shown in Table 4. It indicates that the values of node No.280 are lower than those of input peak values, reflecting that the slide
motion of column root on the stone base can consume part of earthquake energy. The peak values of node No. 1536 are lower than those of node No. 280, reflecting that the relative rotation between tenon and mortise can further consume part of earthquake energy and mitigate damage of the structure. Peak values of node No. 11718 are a litter larger than those of node No. 1536, reflecting the earthquake forces are magnified on the roof position. However, the constitution of tou-kung make it absorbs part of earthquake energy, thus the peak acceleration values of node No. 11718 are not too large, which avoids serious damage of the roof.

| Table 4. Maximum value of acceleration (Unit: m·s⁻²) |
|-----------------------------------------------|
|     |   aₓ  |   aᵧ  |   a₂  |
| Input | 3.92  | 2.55  | 3.33  |
| 280   | 3.89  | 1.75  | 2.96  |
| 1536  | 3.80  | 1.46  | 2.44  |
| 11718 | 3.81  | 2.50  | 2.20  |

6. Conclusions
(1) Basic frequency values of Taihe Palace are 0.85Hz in x direction and 1.58Hz in z direction, the modes are of translation in level directions, which have little co-relation between each other.

(2) Under the action of 8-degree intensity of frequently occurred earthquakes, internal force values of Taihe Palace are less the the permission values, reflecting the structure will not be damaged.

(3) Under the action of 8-degree intensity of rare occurred earthquakes, peak deformation value of the timber structure is within the permission scope, reflecting the structure will not collapse.

(4) The free-standing column root, tenon-mortise joint, tou-kung, filler wall and so on constitutions of Taihe Palace are all helpful to mitigate damage of the structure under earthquakes

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