Analysis on Dynamic Characteristics and Seismic Response of Wooden Structure of South Gate Building in Jiangzhang Town

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Abstract. In order to study the seismic performance of ancient wooden structures with single eaves and beam lifting in China, the finite element model of the upper floor of the south gate of Jiangzhang town in Shangxi Province was established by using ANSYS. Through modal analysis, the main frequencies and modes of the south gate of Jiangduan were obtained. Through the seismic response analysis of the south gate tower model, the displacement and acceleration response curves of the top nodes of the outer eaves column, golden column and through column under various working conditions of the South gate tower are obtained. The results show that the first and second order frequencies of the South Gate tower model are 1.830Hz and 1.855Hz, and the first two order modes are mainly transitional. With the increase of seismic excitation, the displacement and acceleration response of the top joints of the outer eave column, golden column and through column increase.

Keywords. South Gate Tower; Dynamic characteristics; Seismic response.

1. Introduction

The South Gate Tower in Jiangzhang Town, Shaanxi Province is a masonry high platform structure with a wooden structure "Sanyi Temple" on it. It is a key cultural relic protection object in my country and has important research significance.

In recent years, scholars at home and abroad have done a lot of research on the dynamic characteristics and seismic response of ancient timber structures. Zhaobo Meng [1] conducted field measurement of traffic vibration of Xi'an bell tower, used ITD method to obtain the main dynamic parameters of the bell tower, and performed the stiffness of mortise-and-tenon joints of the wooden structure of the bell tower. Suzuki [2] made the overall model of Japanese traditional wood structure and conducted shaking table test, and the study showed that wood structure had good seismic performance. In the aspect of numerical simulation, the whole finite element model of wooden structure is established by large finite element software, and its seismic performance is analyzed. Xueqi Chen [3] studied the influence of external rammed earth wall and internal wood frame on the overall seismic performance of Fujian earth buildings by using the method of finite element numerical simulation, and discussed the difference between square and round earth buildings in seismic performance.

In order to accurately evaluate the seismic performance of ancient wooden structure with single eaves and beam, this paper takes shanxi province town south gate upstairs born of wood structure as the research object, is firstly established by ANSYS finite element software of south gate upstairs
wood structure finite element model for modal analysis for model fundamental frequency compared with standard formula to prove the validity of the model, finally carries on the seismic response analysis, The results can provide theoretical basis for earthquake protection of the south Gate building and the ancient buildings in the same area.

2. Numerical Model Establishment

2.1. Introduction To South Gate Tower
Nanmen Tower was built in the twelfth year of Daoguang in the Qing Dynasty and rebuilt in 1998. It is located in Jiangzhang Town, Fufeng County, Shaanxi Province. The south gate building is a masonry high platform base structure, on which there is a wooden structure "Sanyi Temple". The "Sanyi Temple" is a single-eave raised beam wooden structure, the size is 13.3m×8.2m. There are 18 outer eaves columns, inner gold There are 10 columns with a diameter of 0.4m and a height of 4.1m. The main beams are evenly distributed, and the wooden structure is divided into three.

2.2. Unit and Material Parameter Selection
The beam-column frame is simulated by BEAM188 beam element. Tenon and tenon joints and bucket arch joints are simulated by COMBIN14 and COMBIN39 spring elements. With reference to related researches on ancient buildings in similar areas, the stiffness values of tenon-mortise joints and bucket arch joints are based on the existing research results in literature [5]. The roof is simulated by mass unit MASS21. Column foot COMBIN39 unit to simulate, it stiffness value refers to the data of the study on the mechanical model of the column foot joints by Yi Pan [6]. The wood used in this paper is poplar, and the density of the wood is 410kg/m3. Refer to Professor Maohong Yu [7] the measured values of Xi'an Jianlou wood as the material parameters of the upper timber structure of the South Gate Tower. The specific wood material parameters are shown in table 1.

| Elastic Modulus (MPa) | Poisson's ratio | Shear modulus (MPa) |
|-----------------------|----------------|---------------------|
| $E_L$                 | $E_R$          | $E_T$               | $\mu_{LR}$ | $\mu_{LT}$ | $\mu_{RT}$ | $G_{LR}$ | $G_{LT}$ | $G_{RT}$ |
| 8301                  | 538            | 269                 | 0.25       | 0.035      | 0.02       | 623      | 498      | 149      |

3. Dynamic Characteristics and Seismic Response Analysis

3.1. Dynamic Characteristics
The Block Lanczos algorithm is used to extract the first 6-order natural frequency and natural vibration period of the upper wooden structure model of the South Gate Tower, as shown in table 2. In this analysis, the x-direction is horizontal, y-direction is vertical, and z-direction is vertical.

| Mode shape | 1     | 2     | 3     | 4     | 5     | 6     |
|------------|-------|-------|-------|-------|-------|-------|
| Natural frequency (Hz) | 1.830 | 1.855 | 2.314 | 2.842 | 2.857 | 3.356 |
| Natural vibration period (S) | 0.546 | 0.539 | 0.432 | 0.352 | 0.350 | 0.298 |

As shown in figure 1, the first two modes of the upper wooden structure of the South Gate Tower are horizontal vibration in the X and Z directions; the third mode is torsional vibration around the Y axis. It can be seen from Table 2 that the basic period of the upper wooden structure of the South Gate Building obtained by finite element analysis is 0.546s, which is slightly higher than 0.44s calculated by the empirical formula provided by literature [8], but the error is within an acceptable range. It can be seen from the period calculation formula $T = \frac{2\pi}{\sqrt{\frac{k}{m}}}$, The main factor affecting the natural
vibration period of the structure is the stiffness and quality of the structure. The main reason is that the influence of the wall is not considered in the modeling process. In practice, the wall also provides a certain lateral stiffness to the wooden structure itself. It can be seen from figure 1 that the changes in the first three-order modes are in line with reality. Therefore, the above analysis shows that the finite element model is more reasonable and accurate, and the seismic time history analysis can be performed on it.

Figure 1. The first three-order mode of the Nanmen Tower.

3.2. Seismic Wave Selection and Damping Determination
According to the "Code for Seismic Design of Buildings" (GB 5001-2010), the location of the South Gate Tower is located at an 8 degree seismic fortification, the basic acceleration is 0.2g, the site category is Class II, the design earthquake is divided into the second group, and the characteristic period is 0.40s. In this paper, EL-Centro waves, Taft waves and artificial waves are selected as the ground motion input. During the time history analysis, adjust the peak acceleration of the seismic wave to 70gal (for frequent earthquakes), 200gal (fortified earthquakes), and 400gal (rare earthquakes).

Using Rayleigh damping as the structural damping of the finite element model of the South Gate Tower [1]. Because the low-order mode shape contributes a lot, it is generally confirmed by the first two modes. In the seismic analysis of the structure, often take $\xi_i = \xi_j = 0.05$, determine the constant $\alpha$, $\beta$ according to the first two-order natural circular frequency of the structure, get $\alpha = 0.576$, $\beta = 0.00434$.

3.3. Acceleration Response Analysis
The seismic response of the upper wooden structure of the South Gate Building can be obtained by inputting the three kinds of seismic wave excitations with different acceleration peaks into the finite element model. Figure 2 shows the acceleration response time history curves of the outer eave pillar top, the gold pillar top, and the through pillar top under the excitation of EL-Centro wave. See Table 3 for the acceleration peaks and dynamic amplification coefficients of the outer eave pillar tops, gold pillar tops, and through pillar tops under different acceleration peak seismic waves. In Table 3, E, T, and R correspond to EL-Centro waves, Taft waves, and artificial waves, respectively. 70, 200, and 400 correspond to seismic waves with acceleration peaks of 70 gal, 200 gal, and 400 gal.
Figure 2. Acceleration response of outer eave pillar top, gold pillar top, and through pillar top under the excitation of EL-Centro wave.

Table 3. Acceleration response peak values and dynamic amplification factors of outer eave pillar tops, gold pillar tops, and through pillar tops under different seismic waves.

|                      | E70 | E200 | E400 | T70 | T200 | T400 | R70 | R200 | R400 |
|----------------------|-----|------|------|-----|------|------|-----|------|------|
| Outer eaves column top |     |      |      |     |      |      |     |      |      |
| Acceleration(cm/s^2)  | 220.84 | 546.15 | 181.31 | 410.73 | 736.21 | 187.36 | 306.58 | 666.1 |
| amplification factor  | 3.16 | 1.61 | 1.37 | 2.59 | 2.05 | 2.68 | 1.53 | 1.67 |
| Golden pillar top     |     |      |      |     |      |      |     |      |      |
| Acceleration(cm/s^2)  | 247.90 | 757.23 | 236.56 | 530.92 | 974.41 | 228.44 | 399.20 | 869.1 |
| amplification factor  | 3.54 | 2.19 | 1.89 | 3.38 | 2.65 | 2.44 | 3.26 | 1.99 | 2.17 |
| Column top            |     |      |      |     |      |      |     |      |      |
| Acceleration(cm/s^2)  | 260.83 | 551.30 | 996.25 | 634.17 | 1210.23 | 233.47 | 479.30 | 1037.9 |
| amplification factor  | 3.73 | 2.76 | 2.49 | 3.87 | 3.17 | 3.03 | 3.34 | 2.40 | 2.60 |

It can be seen from figure 4 that under the action of the same seismic wave, the shape of the acceleration time history curve of each node is very close, and the time point of the acceleration peak is basically the same. It can be seen from Table 3 that with the increase of seismic excitation, the acceleration peak value of the same floor height becomes larger and larger; under the same intensity seismic excitation, as the height increases, the acceleration peak value and the amplification factor become larger and larger. The acceleration amplification factor of the top is between 1.37-3.16, the top of the gold column is between 1.89-3.54, and the top of the through column is between 2.40-3.87. Among them, the peak acceleration response of the top of the column under the action of the EL-Centro wave, the Taft wave and the artificial wave with the acceleration peak of 400gal are 996.70gal, 1210.53gal, 1037.96gal, and the amplification factors are 2.49, 3.03, and 2.60 respectively. Waves have the greatest impact on the South Gate Tower, followed by artificial waves, followed by EL-Centro waves, which may be related to the different spectral characteristics of seismic waves; under different seismic wave excitation, the acceleration amplification factor gradually decreases with the increase of the seismic wave peak value. Because the upper wooden structure of the South Gate Tower increases with the peak acceleration of the seismic wave, the energy consumption and shock absorption of the tenon and tenon joints and the bucket arch joints increase.

3.4. Displacement Response Analysis

Figure 3 shows the displacement time history curve of each node under the action of EL-Centro wave.
The peak displacement response and maximum inter-layer displacement angle of each node are shown in table 4.

Table 4. Displacement response peak values and inter-layer displacement angles of outer eave pillar tops, gold pillar tops, and through pillar tops under different seismic waves.

|                  | E70 | E200 | E400 | T70 | T200 | T400 | R70 | R200 | R400 |
|------------------|-----|------|------|-----|------|------|-----|------|------|
| Outer eave       |     |      |      |     |      |      |     |      |      |
| column top       |     |      |      |     |      |      |     |      |      |
| Displacement (mm)| 13.8| 37.9 | 77.3 | 19.1| 49.8 | 79.02| 16.4| 31.8 | 68.9 |
| Layer displacement angle | 1/217| 1/79 | 1/39 | 1/157| 1/60 | 1/38 | 1/183| 1/94 | 1/44 |
| Golden pillar    |     |      |      |     |      |      |     |      |      |
| top              |     |      |      |     |      |      |     |      |      |
| Displacement (mm)| 18.6| 50.3 | 102.1| 25.5| 66.1 | 104.87| 21.9 | 42.2 | 90.9 |
| Layer displacement angle | 1/231| 1/90 | 1/45 | 1/173| 1/68 | 1/43 | 1/202| 1/107| 1/51 |
| Column top       |     |      |      |     |      |      |     |      |      |
| Displacement (mm)| 22.3| 58.9 | 120.4| 29.7| 77.7 | 123.67| 25.4 | 49.4 | 107.9|
| Layer displacement angle | 1/299| 1/129| 1/60 | 1/263| 1/95 | 1/59 | 1/316| 1/153| 1/65 |

It can be seen from Figure 5 that under the action of the same seismic wave, the shape of the displacement time history curve of each node is very close, and the time point of the displacement peak is basically the same. It can be seen from table 4 that under the action of seismic waves of different amplitudes of the upper wooden structure of the South Gate Building, the displacement peaks generally show a gradually increasing trend from bottom to top. Under the action of 400gal rare earthquake, the maximum inter-story displacement angle of the upper wooden structure column frame of the South Gate Tower is 6/353, which meets GB 50165-2020, "Technical Specification for Maintenance and Reinforcement of Ancient Building Wood Structures" [12] for the maximum floor. The displacement angle does not exceed the limit of 1/30.

4. Conclusion
(1) The modal analysis of the numerical model of the Nanmen Tower is carried out, and it is determined that the main vibration modes of the Nanmen Tower are mainly transitional, and the first and second order frequencies are 1.830 Hz and 1.855 Hz.

(2) Under different seismic wave excitation, the acceleration amplification factor gradually decreases with the increase of the peak acceleration of the seismic wave, mainly because the upper
wood structure of the south gate building increases with the increase of the peak acceleration of the seismic wave, which increases the energy consumption and damping of the tenon-and-mortise joints and the bucket arch joints.

(3) Under the action of rare earthquakes, the maximum inter-story displacement angle of the upper wooden structure column frame of the South Gate Tower is 1/38, which meets the requirement of the code not exceeding 1/30.

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