Dynamic Analysis of Seventh-Class ColumnFrame with Cushion

Songye Yang¹, Jianliang Wang¹, Yifan Wang¹, Tieying Li¹

¹College of Civil Engineering, Taiyuan University of Technology, Taiyuan, Shanxi, 030024, China

*litieying@tyut.edu.cn

*806069129@qq.com

Abstract. In accordance with the relevant regulations of "Building Method", this paper uses the finite element model to establish a two-column seven-grade dovetail column frame model. 4 kinds of thin cushions are designed with different elasticity and shear modulus at the bottom of the column. The elastic modulus of the cushion is 1/5, 1/10, 1/15, 1/30 of the column frame modulus. A simple harmonic wave with an amplitude of 50 gal and a frequency of 1Hz-2.5Hz was applied to the wooden frame model with cushion and without cushion. There are a total of 20 models and their natural vibration period is obtained and the relative displacement time history curve of the top of the column was extracted to obtain the displacement angle between each model. The results show that: the natural vibration period of the wooden frame with cushion is greater than that without cushion, and the period increases with the decrease of the elastic modulus of the cushion. As the harmonic frequency increases, the layer displacement angle of each wood frame model decreases, and as the cushion modulus decreases, the decreasing amplitude becomes more gentle, indicating that the cushioned wood structure has better resistance to deformation.

1. Introduction
One of the main features of the wood structure of many ancient Chinese buildings is the mortise and tenon structure[1], which can connect several components tightly without using iron nails. Experts such as Ge Hongpeng[2] and Xu Minggang[3] conducted experimental research on the seismic performance analysis of ancient building wooden structure mortise joints under repeated loads, and obtained the failure form, hysteresis curve, skeleton curve, deformation and other properties of each joint. Li Tieying [4-5] and other experts have made great progress in the dynamic structural analysis of the wooden structure of ancient buildings, taking Yingxian wooden tower as an example.

However, there are few records in the literature about the effect of adding cushion at the bottom of the column on the overall structural performance. The resting state of the column and the foundation makes the wooden structure have a certain risk of overturning under the action of an earthquake, and the cushion with different elasticity and shear modulus is added to the bottom of the column. Regarding whether the stability and balance of the wooden structure under the action of an earthquake are important, based on the above considerations, this paper uses the ABAQUS software to make a preliminary exploration of the dynamic performance of the three-pillar wooden structure with different elasticity and shear modulus.
2. Research content and finite element model

2.1. Research content
According to the material division system in "French Style" written by Li Jie of the Song Dynasty [6], the column frame model of seven-grade wood structure is adopted, and a cushion layer of height 50mm and diameter 403.2mm is added at the bottom of the column, and its density is consistent with that of Pinus sylvestris. Its elastic modulus and shear modulus are one-fifth, one-tenth, one-fifteenth and one-thirtieth of the modulus of Pinus sylvestris. The pattern is shown in Figure 1, and the size is shown in Table 1. According to the "Preliminary Study on the Static Force of Ancient Large Wooden Works", the vertical force caused by the roof system is mainly transmitted to the general painting frame through the bucket arch, and then transmitted to the foundation through the column. The architectural form of the seventh grade hall, Looking up the table shows that the front eaves column, the rear eaves column and the inner column have a real load of 9951.0 kg, 21262.5 kg and 16721 kg [7], namely 12.44t, 26.58t and 20.90t. This paper selects the column load 5t based on this data. In order to simplify the calculation, the mass block is used to simulate the load of the single column caused by the roof system. The size of the bottom surface of the mass block is selected according to the bottom surface of the bucket that acts on the general pat.

Table 1. Wooden frame size

| Types         | Column  | Lan-e  | Pupai-Fang | Dovetail tenon |
|---------------|---------|--------|------------|----------------|
| Songchi/fen   | 300     | 36     | 30         | 20             | 400 | 15 | 32 | 10 | 12 | 10 |
| Unit/mm       | 3360    | 403.2  | 336        | 3360           | 224 | 168 | 358 | 112 | 134.4 | 112 |

2.2 Material properties
Among them, the mechanical properties of wood in the longitudinal direction, the transverse direction and the chord direction are very different, and it is usually assumed to be a positive anisotropic material. The constitutive relationship is shown in Figure 2. Pinus sylvestris var. sylvestris was selected as the wood, and the density was determined to be 0.44g/cm3 according to experiments. The elastic modulus, Poisson's ratio and shear modulus are shown in Table 2. The elastic modulus of the mass and the bottom plate is taken as infinite, assuming a rigid body, and the density of the mass is determined by the vertical load.
Table 2. Elastic constants of Pinus sylvestris var. mongolica (Unit: MPa)

| E1  | E2   | E3   | V12 | V13 | V23 | G12 | G13 | G23 |
|-----|------|------|-----|-----|-----|-----|-----|-----|
| 3178 | 372.72 | 185.99 | 0.3 | 0.02 | 0.035 | 652 | 345 | 231 |

Note: The subscripts 1, 2 and 3 indicate the longitudinal direction along the grain, the radial direction along the grain and the chord.

2.3 Contact and friction

The contact surface type of the component adopts standard contact, the normal behavior of the contact surface adopts "hard" contact, and the tangential behavior adopts penalty. According to the test results of Murase[8] and Inayama[9], the friction coefficient of wood surface is 0.1 to 0.6. In order to simplify the model setting and take into account that the surface of each member of the wooden structure is relatively rough, the friction coefficient between the contact surfaces is taken as 0.4.

2.4 Loads and boundary conditions

The bottom plate is consolidated, two mass blocks are placed on the normal beam and correspond to the center of the column, and the harmonics are directly added to the bottom plate to simulate the dynamic test.

2.5 Meshing

In order to avoid affecting the final calculation results of the model due to the difference in meshing, each model is meshed in the same way. The type of cell division for each component is C3D8R. The force transmission at the stud tenon and tenon joints is more complicated, so the mesh is refined at the nodes, while other places such as the bottom plate, the mass blocks are divided into larger sizes, which can improve computer operation speed.

3. Simulation results and analysis

3.1. Model natural vibration period analysis of different cushion modulus

Because the amplitude of the harmonics is too large, it will cause greater damage to the structure and cause collapse, while too small will result in a small self-amplitude of the structure and a large error. Therefore, this paper compares the natural frequency ranges obtained by the simple harmonics of different amplitudes, and finds that the simple harmonics with an amplitude of 50 gal have the best results. A simple harmonic is applied with an amplitude of 50gal and a frequency from 1Hz-2.5Hz to the bottom plate of the wooden frame model with a vertical load of 5t, and cushions of 1/5, 1/10, 1/15, 1/30 structural elastic modulus are added. The corresponding natural vibration period is shown in Figure 3. It can be seen from the figure that the natural vibration period of each model does not change significantly with the harmonic frequency, indicating that the natural vibration period is also an inherent property of the structure. The structure applies simple harmonics of different frequencies, and the stiffness of the cushion layer with different elastic modulus changes when vibrating, so the natural vibration period is different. Because the amplitude and frequency of simple harmonics are relatively small, the natural vibration period range of the structure is relatively close. Table 3 lists the natural vibration range of each wooden frame model.

It can be seen from the figure that the natural vibration period of the model with cushion and without cushion has the same change under the action of simple harmonics of different frequencies. When the harmonic frequency is 1Hz, the natural frequency of the wooden frame is the largest. And the period of the wooden frame with cushion under the same harmonic is larger than that without cushion, and as the elastic modulus of cushion decreases, the structure period increases. As the elastic modulus of the cushion decreases, the stiffness of the structure becomes smaller. When the vertical
load is constant, the period becomes larger, which verifies the calculation formula of the natural period of the structure that is $T = 2\pi\sqrt{\frac{m}{k}}$.

Figure 3. The natural vibration period of each model under different harmonic frequencies

Table 3. Natural vibration period of wood frame with different elastic modulus cushion

| cushion | no cushion | 1/5 modulus cushion | 1/10 modulus cushion | 1/15 modulus cushion | 1/30 modulus cushion |
|---------|------------|---------------------|----------------------|----------------------|----------------------|
| period  | 0.77s~1.004| 0.870s~1.112        | 1.001~1.252          | 1.054~1.334          | 1.252~1.335          |

3.2. Analysis of the displacement angle between model layers of cushions with different modulus

The relative displacement peak value of the wooden frame can be obtained by extracting the time history curve of each model in the action of the simple harmonics of different frequencies, and thus the maximum value of the interlayer displacement angle of each model. The data is shown in Table 4. The variation of cushioned and uncusped wood frame models with frequency is shown in Figure 4.

Table 4. Interlayer displacement angle of each model of wooden frame

| cushion modulus | no cushion | 1/5 | 1/10 | 1/15 | 1/30 | no cushion | 1/5 | 1/10 | 1/15 | 1/30 |
|-----------------|------------|-----|------|------|------|------------|-----|------|------|------|
| Layer displacement angle | 1/63 | 1/65 | 1/66 | 1/69 | 1/72 | 1/187 | 1/173 | 1/174 | 1/175 | 1/195 |
| frequency | 1 | 1.5 |
| Layer displacement angle | 1/352 | 1/360 | 1/363 | 1/337 | 1/299 | 1/630 | 1/535 | 1/483 | 1/454 | 1/410 |
Figure 4. Comparison of displacement angles between layers of each model of wooden frame

It can be seen from the figure that with the increase of the harmonic frequency, the inter-story displacement angle of each wooden frame model decreases rapidly, but the maximum value is still less than the limit of 1/16 of the limit displacement angle of the collapse of the wooden structure [10]. When the harmonic frequency is 1 Hz, the layer displacement angle of the model without cushion is larger than that with cushion, and the displacement angle between layers decreases with the decrease of cushion modulus. When the harmonic frequency of the simple harmonic is 2.5 Hz, the layer displacement angle of the model without cushion is smaller than that of the cushioned layer, and the displacement angle between layers increases with the decrease of the cushion modulus. In summary, with the simple harmonic As the frequency increases, the interlayer displacement angle of each model is decreasing, but it is obvious that the reduction amplitude of the cushion model is smaller, and the lower the cushion elastic modulus, the smoother the decrease, which indicates that the cushion wood The structure has better resistance to deformation.

4. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

(1) The natural vibration period of the wood frame with cushion layer at the bottom of the column is greater than the natural vibration period without cushion, and as the cushion elastic modulus decreases, its period increases, and as the cushion elastic modulus decreases, the structural stiffness changes. When the vertical load is constant, the period becomes larger, which verifies the calculation formula of the natural period of the structure that is $T = \frac{2\pi}{\sqrt{m/k}}$.

(2) Timber frame layer displacement angles are all small, and with the increase of harmonic frequency, the layer displacement angle of each wooden frame model decreases, and as the cushion modulus decreases, the decrease amplitude is more gentle, indicating that the cushion layer is added. The wooden structure has better resistance to deformation.

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