A numerical investigation on the seismic isolation effect of flexible wooden cushion

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Abstract. This paper proposes a finite element simulation of wooden structures with flexible cushion. Applied with different loads, the seismic isolation effect of the cushion is analyzed. By changing the thickness and elastic modulus of the cushion, the dynamic effect of the cushion under various conditions was analyzed. The Pi theorem is used to obtain the non-constant parameter that affects the vibration isolation result.

1. Introduction.
Wood structure building is an important part of traditional Chinese architecture and has unique seismic characteristics. Existing seismic studies on wooden structures mainly focus on the analysis of the joint performance of the beam-column connection, or the overall swing of the frame and the slippage of the column foot, and there is little research on the dynamic magnification of the column foot.

In his research on the seismic effect of the column base of the Palace of Supreme Harmony in the Forbidden City, Zhou Qian found that the column base would have a significant dynamic amplification effect on the superstructure [1]. Junxiao He and Qingshan Yang proposed that under low-cycle repeated loads, the joints of the column base will gradually enter the plastic zone along with the rotation, resulting in stiffness degradation [2]. Shengcai Li found that the energy dissipation capacity of the structure has been significantly reduced with the development of damage in the seismic research of the damaged wooden structure with column feet [3].

The above studies have shown that the bottom cushion of the wooden structure has a significant dynamic effect on the upper structure. Based on this, this paper proposes a finite element simulation to reduce the elastic modulus of the bottom cushion of the frame column to comprehensively characterize the damage or stiffness degradation. This simulation result can be used to characterize the dynamic effect of the column bottom cushion in the overall structure.

2. Establishment of finite element model.
With reference to Yingzao Fashi, a finite element model of Song-style third grade timber frame is established [4].
The beam-column joints are connected by dovetail tenon. The load of the column is controlled by two rigid masses, which size suit to the size of the bottom of the cap block. A cushion of certain thickness is set at the foot of the column. The column feet are placed horizontally on a large rigid floor. The wood used in the model is Pinus koraiensis. The material properties are shown in the followed table:

Table 2. Property constants of Pinus koraiensis

| Elastic Modulus (N/mm²) | Poisson's ratio | Shear modulus (N/mm²) |
|-------------------------|-----------------|-----------------------|
| $E_1$                   | $E_2$           | $E_3$     | $v_{12}$ | $v_{13}$ | $v_{23}$ | $G_{12}$ | $G_{13}$ | $G_{23}$ |
| 10000                   | 650             | 275       | 0.02     | 0.035    | 0.02     | 650      | 275      | 210      |
The thickness of the cushion is set to five levels: 10mm, 40mm, 80mm, and 120mm. In order to comprehensively simulate the material property attenuation caused by damage or partial plasticization, the elastic modulus of the underlayer of the column is set to a certain reduction relative to the column modulus, which is 10%, 20%, 40%, 60%, 80%, 100% of the column modulus.

3. Loading system.
Since the wooden structure is a highly nonlinear dynamic system, its dynamic response will change with the loading load. So the change of load and dynamic boundary conditions is very important for research.

3.1. Sinusoidal excitation
Nicos Makris discovered the characteristic length that characterizes the excitation intensity of rectangular loading pulses in dynamic response study of nonlinear systems: \( L_e \approx \frac{1}{2} a_p T_p^2 \), \( a_p \) and \( T_p \) are the amplitude and the cycle of the loading pulse wave respectively, and the characteristic length is 288mm as half of the column diameter[5]. In this paper, through the compare of the loading history of the sinusoidal excitation with the rectangular wave in one cycle, the reduction coefficient \( \lambda_e \) can be calculated:

\[
\lambda_e = \frac{\int_0^{T_p} a_p \sin \frac{2\pi}{T_p} t dt}{\frac{1}{2} a_p T_p^2} = \frac{1}{\pi}
\]

When the loading frequency is 0.5hz, the loading amplitude \( a_p = \frac{2\lambda_e}{\lambda_e T_p^2} = 452\text{mm/s}^2 \)

The sine excitation is loaded on the rigid floor to simulate the seismic excitation, and the vibration isolation effect of the cushion under different power inputs can be studied by changing the frequency and amplitude of the loading excitation.

3.2. Gravity load
The gravity load can be adjusted by changing the density of the mass blocks, with reference to Wang Tian's " Static analysis on ancient timber structures", it can be obtained that the single column load of the third-class hall column is 9.7t~16.2t [6]. Therefore, three-stage counterweights are selected, namely 10t, 15t, and 20t.

4. Results of dynamic analysis.

4.1. Parameters for evaluating structural seismic isolation effect
Analyze the ratio of the acceleration on the top of the column to the input acceleration through the \( \pi \) theorem, you can get the following relationship.

\[
TR = \frac{a_x}{a_p} = \Phi \left( \frac{m}{E a_p T_p^4} \right)
\]

\( a_x, a_p \) are the acceleration of the top of the column and the input respectively, \( m \) is the mass of the blocks on the top of the column, \( E \) is the elastic modulus of the entire column, \( T_p \) is the period of the input wave.

The above acceleration ratio is the power transmission ratio \( TR \) of the structure, which is used to characterize the strength of the vibration isolation effect of the structure. Therefore, the data of this simulation control is only related to these parameters. Due to the geometric similarity of Song-style wood structures, the conclusions drawn in this paper are not limited to third-grade materials, but are generally applicable to Song-style wood structures.
4.2. The relationship between loading frequency and $TR$

By changing the frequency of the input wave, it can be found that the transmission ratio is related to the frequency. When the loading frequency is 0.5hz, the conduction ratio decreases as the cushion modulus increases; When the loading frequency is greater than or equal to 1hz, the transmission ratio decreases as the elastic modulus of the cushion decreases, which is consistent with the seismic isolation theory in structural dynamics.

![Figure 2. Power transmission ratio under different input frequencies]

When the input frequency is less than 1.5hz, the acceleration of the column with or without cushion is greater than the input acceleration; when the input frequency is greater than 1.5hz, the acceleration of the column is less than the input acceleration.

4.3. Effect of the modulus and thickness change of the cushion on $TR$

From the data in the previous section, in order to better reflect the vibration isolation of the cushion, the data points under the loading frequency of 2hz are used. By adjusting the elastic modulus and thickness of the cushion part, we can get the change curve of the transmission ratio TR.

![Figure 3. The relationship between cushion elastic modulus and TR](image1)
![Figure 4. The relationship between cushion thickness and TR](image2)
It can be found from Figure 2 that when the elastic modulus of the cushion is small, the rise of TR is steeper, indicating that the cushion with higher flexibility has a good vibration isolation effect; when the elastic modulus of the cushion layer is greater than half of the column, the increase in the elastic modulus has less effect on TR.

The data in Figure 3 intuitively shows that TR decreases greatly as the thickness of the cushion layer increases, and the decrease rate increases with the decrease of the elastic modulus.

From the above two, it can be concluded that when the dynamic loading frequency is greater than or equal to 2hz, the thicker the cushion layer, the smaller the elastic modulus, the lower the power transmission ratio TR of the structure, and the better the vibration isolation effect.

4.4. Relationship between column top load and TR
By changing the mass of the mass block on the top of the column, the dynamic effects of the structure under different column top loads can be simulated.

It can be clearly found from the figure that regardless of the stiffness of the cushion, TR decreases with the increase of the load, which indicates that the wooden frame exhibits a good seismic isolation effect under the action of a large vertical load. This also explains the good seismic performance of traditional Chinese wooden structures with heavier roof trusses.

![Figure 5. The relationship between column top load and TR](image)

5. Conclusion.
1. It can be seen from the loading frequency-TR curve that when the structure is subjected to dynamic loading with a frequency less than or equal to 1hz, the more flexible of the cushion, the worse the vibration isolation effect; when subjected to a dynamic load greater than 1hz, the more flexible of the cushion, the better the vibration isolation effect.

2. The vibration isolation effect of the structural cushion layer increases significantly as its stiffness decreases, especially when the stiffness decreases more than 50%

3. Within a reasonable range, the seismic performance of the structure increases with the increase of the load.

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