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EARTHQUAKE DAMAGE ESTIMATION OF FOUR PALACE BUILDINGS AND MEASUREMENTS OF VIBRATION DECREASING FOR CULTURAL RELICS CABINET IN BEIJING FORBIDDEN CITY

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Abstract. *In order to research the seismic performance of Taihe, Zhonghe, Baohe and Wenhua Palace, nonlinear dynamic time response analyses under different earthquakes and PGA levels are carried out. ANSYS/LS-DYNA is used to conduct the finite element analysis. Moreover, in order to select more effective seismic protection measurements for the storage cabinets of cultural relics in the existing underground storehouse of the Palace Museum, seismic responses of storage cabinets with different spring-dampers connected between each other are calculated. Corresponding acceleration and displacement responses are compared. Suggestions on parameter settings of spring dampers which maximum the damping efficiency are finally given.*

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1 INTRODUCTION

Beijing is located in 8-degree seismic fortification district, it's beneficial to research the seismic performance of some typical structures in The Forbidden City. Four typical buildings, Taihe Palace, Zhonghe Palace, Baohe Palace and Wenhua Palace are chosen and relevant nonlinear dynamic time response analyses are conducted. Based on the existing research, selecting 1999 Chi-Chi earthquake and 1976 Tangshan earthquake respectively those durations are 40 seconds from four PGA levels, i.e. 0.05g, 0.1g, 0.2g and 0.4g, corresponding to the local seismic risk level of Beijing area. Peak acceleration ratio among the three directions is $a_{PGx}:a_{PGy}:a_{PGz}=1:0.85:0.65$, x and z is horizontal, y for vertical. The finite elements used are as follows, BEAM161 for beams and columns, SHELL163 for roofs and walls and COMNI165 for mortise-tenon joints.

Consulting the documents and reference [2], wooden beam itself has little energy dissipation capacity, energy dissipation is mainly relied on the mortise-tenon joint. The mortise-tenon joint energy dissipation is generated through extrusion and rotation. According to the results of related experiments[1] bending moment and corner restoring force curve chart of mortis-tenon joint is plotted in figure 1, for the value of relevant parameters: $k_1=3.602kN\cdot m/rad$ when θ=0~0.005rad, $k_2=5.755kN\cdot m/rad$ when θ=0.005~0.07rad, $k_3=1.781kN\cdot m/rad$ when θ=0.070~0.100rad.

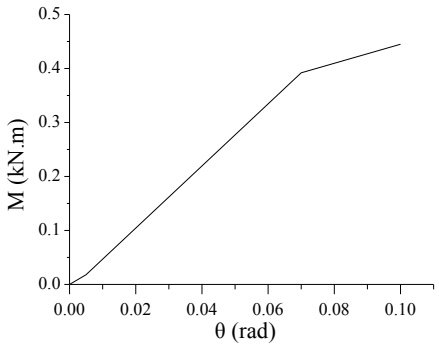

Figure 1:Bending moment and corner restoring force curve of mortis-tenon joint

Acceleration histories of ground motion records used in this paper are plotted in figure 2 and figure 3.

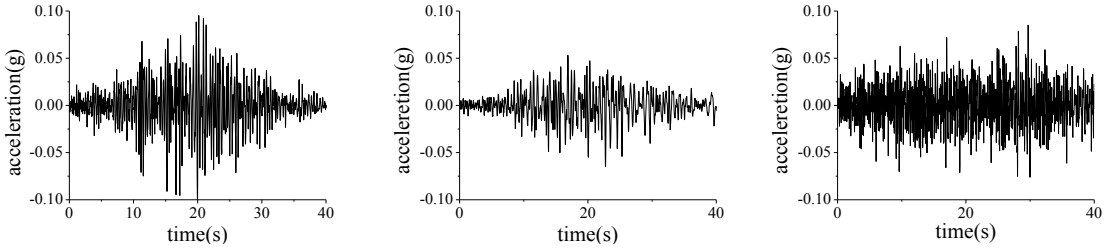

Figure 2:Three direction time history of Tangshan earthquake

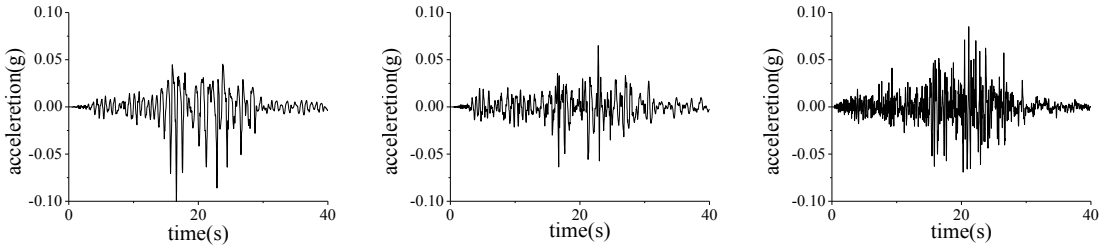

Figure 3: Three direction time history of Chichi earthquake

Simplified measures as follows are used in the process of establishing the finite element models: (1) Low walls, doors and windows are not considered. (2) Roof weight is set as $4.1kN/m^2$ according to the reference[3]. (3) The weight of building ridge beast is not considered. (4) The details of tiles are not established. (5) The influence of the steps is not involved.

2 SEISMIC PERFORMANCE OF CULTURAL RELIC BUILDINGS

2.1 The seismic performance of Taihe palace

Taihe Palace is located in the central axis of the Forbidden City. It is the largest existing wood structure of Chinese timberwork temple and commonly known as the essence of the ancient Chinese palace buildings. It is 64m long, 37m wide and 26.92m high. Two nodes of the numerical model at the center of the roof (Node 40026) and outer pillars point (Node802) is selected to study its acceleration and displacement responses. Realistic picture and finite element model of Taihe palace are shown in figure 4.

Figure 4: Realistic picture and finite element model of Taihe palace

Based on the numerical simulation result, the acceleration amplification factors and maximum displacements under different earthquakes (Chichi and Tangshan) and different PGA levels (0.05g, 0.10g, 0.02g and 0.40g) are plotted in figure 5 and 6. Acceleration amplification factors represent the ratio between the maximum acceleration response of selected node and corresponding PGA.

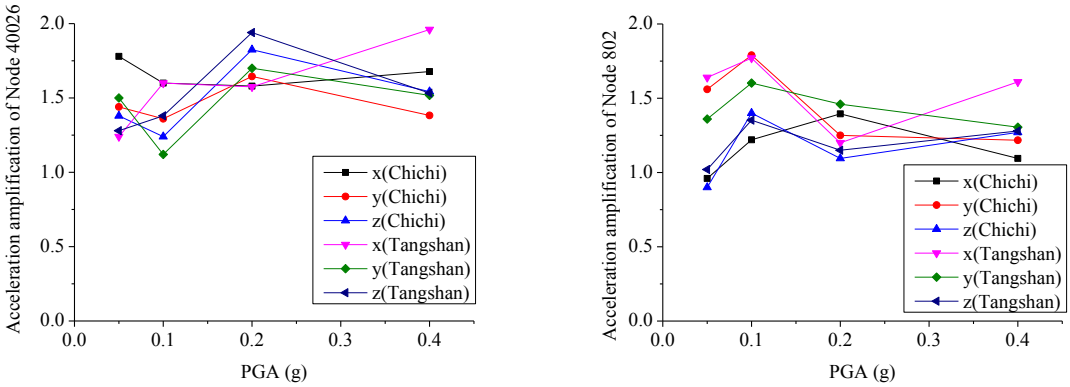

Figure 5:Acceleration amplification of Node 40026 node and Node 802

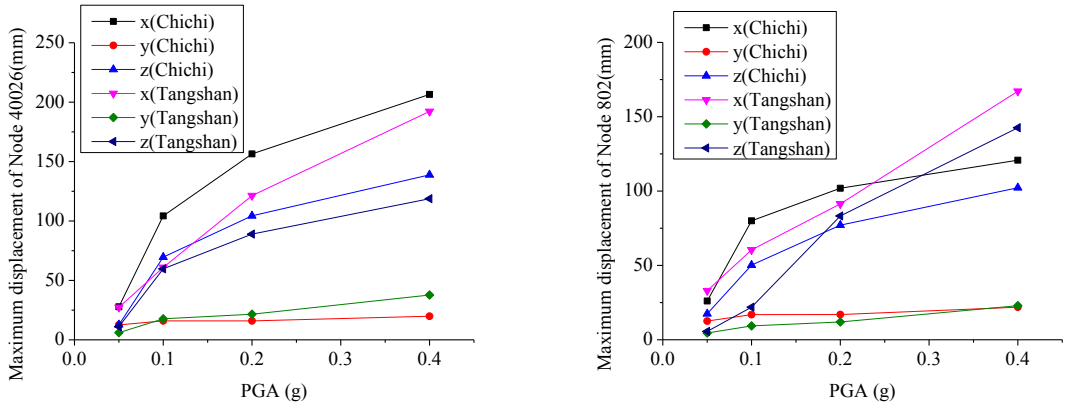

Figure 6: displacement response of Node 40026 node and Node 802

2.2 The seismic performance of Zhonghe Palace

Zhonghe Palace is one of the three main halls in The Forbidden City. It is 22m long, 22m wide and 19m high. Two nodes of the numerical model at roof top (Node 6517) and outer pillars point (Node 328) are selected to study its acceleration and displacement responses. Realistic picture and finite element model of Zhonghe Palace are shown at figure 7. In the peak of 0.05g, 0.1g, 0.2 g ,0.4 g Chichi and Tangshan ground motion, the acceleration amplification and displacement reaction of Node 6517, Node 328 is shown at figure 8 to figure 9.

Figure 7: Realistic picture and finite element model of Zhonghe palace

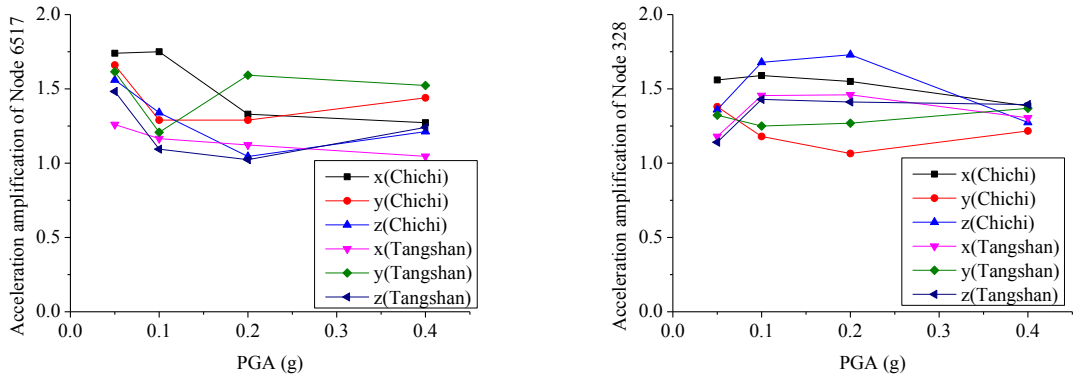

Figure 8:Acceleration amplification of Node 6517, Node 328

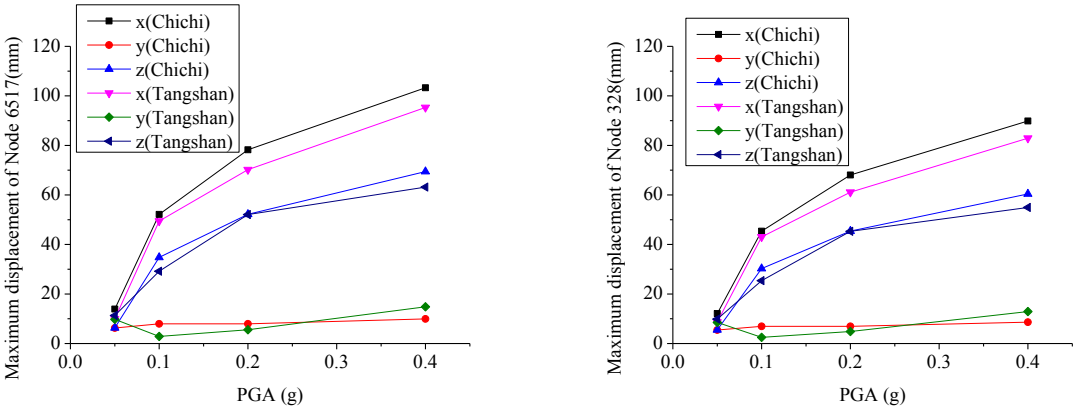

Figure 9:Displacement response of Node 6517, Node 328

2.3 The seismic performance of Baohe Palace

Baohe Palace is one of the three main halls in The Forbidden City. It is 42m long, 21.66m wide and 29.50m high. Two nodes of the numerical model at the center of the roof (Node 2602) and outer pillars point (Node 107) is selected to study its acceleration and displacement responses. Finite element model of Baohe Palace is shown in figure10.

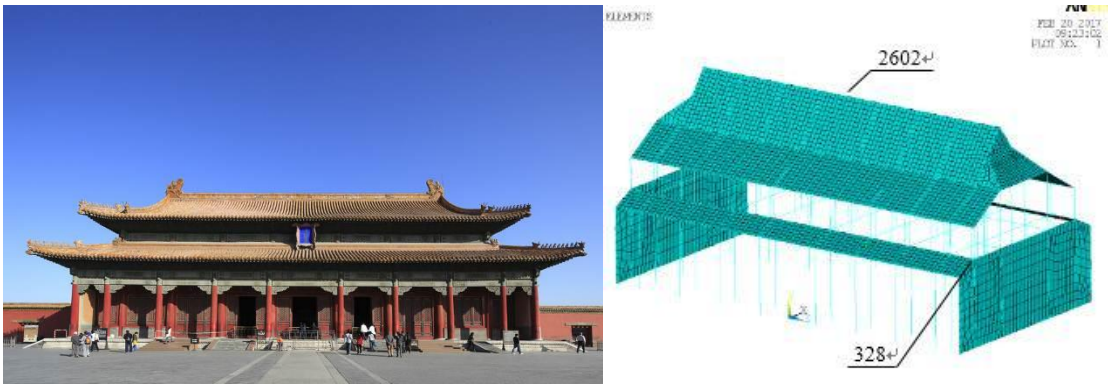

Figure 10: Realistic picture and finite element model of Baohe palace

The acceleration amplification factors and maximum displacements under Chichi and Tangshan earthquakes at 4 PGA levels are plotted in figure 11 and 12.

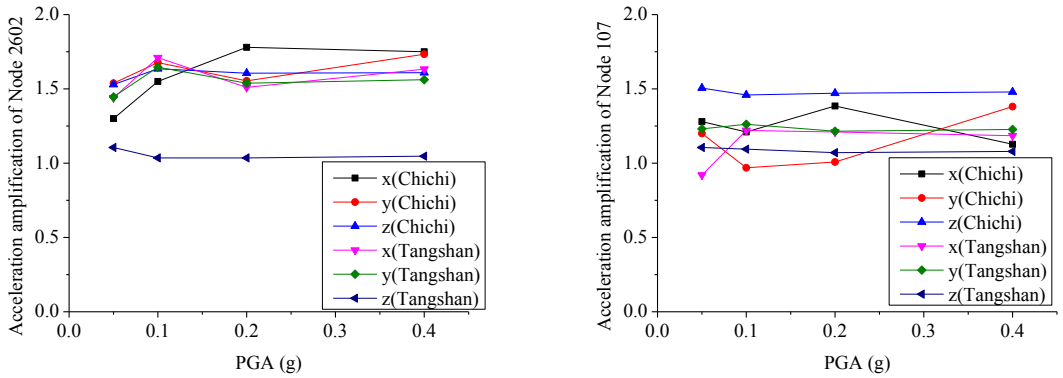

Figure 11:Acceleration amplification of Node 2602 and Node107

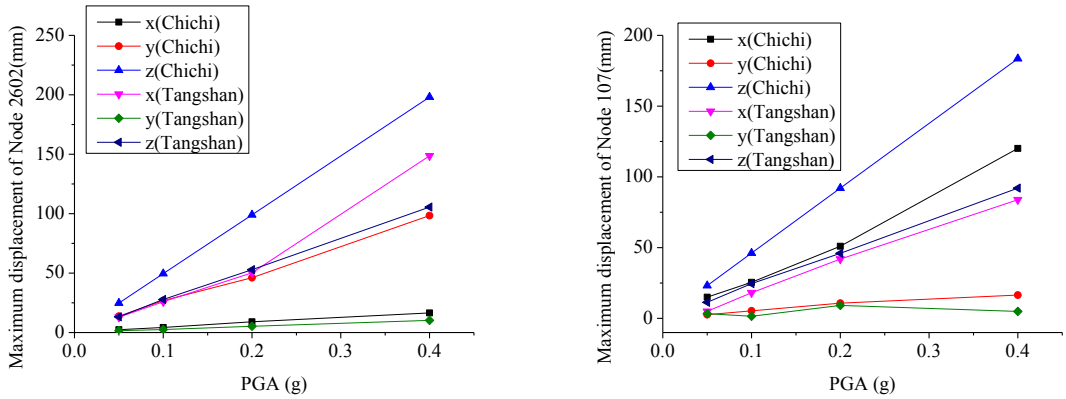

Figure 12: displacement response of Node 2602 and Node107

2.4 The seismic performance of Wenhua Palace

The horizontal shape of the Main Palace is I-section. As shown in figure 13. The Front Hall is similar as the Rear Hall but a little shallower. The two halls are connected by corridor. select 4 nodes at the center of the roof (Node 11240, Node 1140) and outer pillars point (Node 601, Node 5737) are selected to study the palace's acceleration and displacement response. Finite element model of Wenhua Palace is shown in figure 13. In the peak of 0.05g ,0.1g, 0.2g ,0.4 g Chichi and Tangshan ground motion, the maximum acceleration and displacement reaction of Node 11240, Node 601, Node 11140 and Node 5737 is shown at figure 14 to figure15.

Figure 13: Realistic picture and finite element model of Wenhua palace

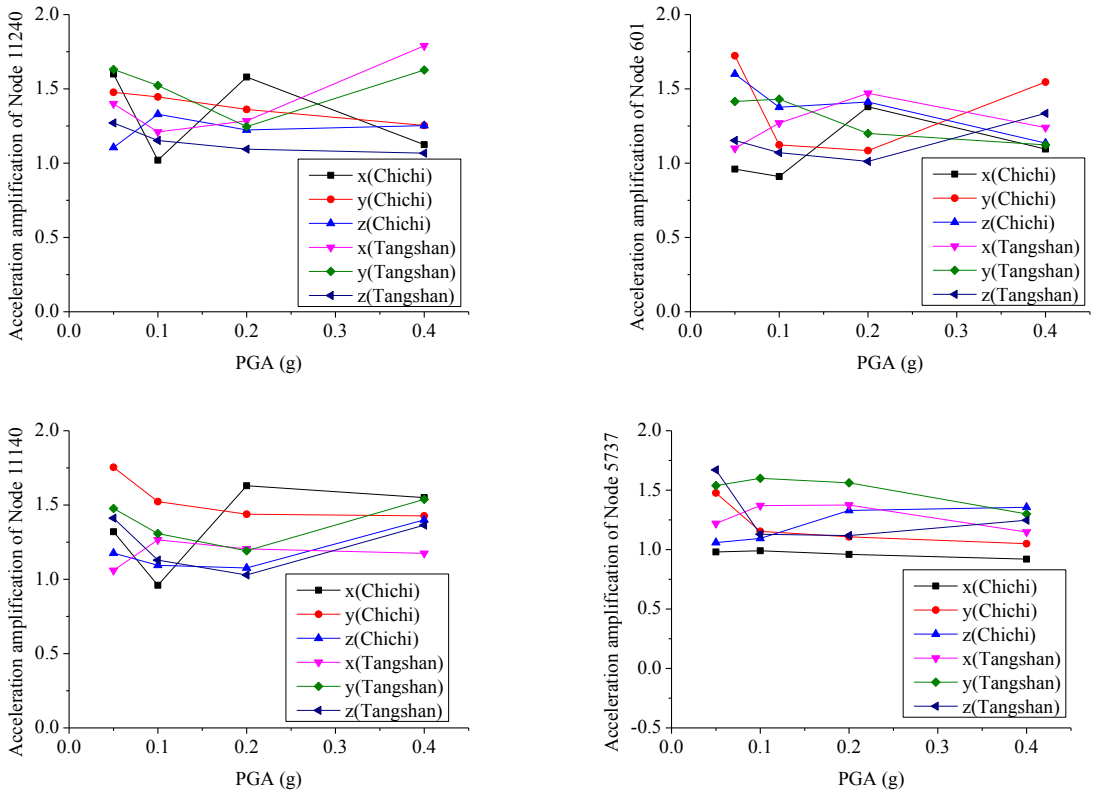

Figure 14:Acceleration amplification of Node 11240, Node 601, Node 11140 and Node 5737

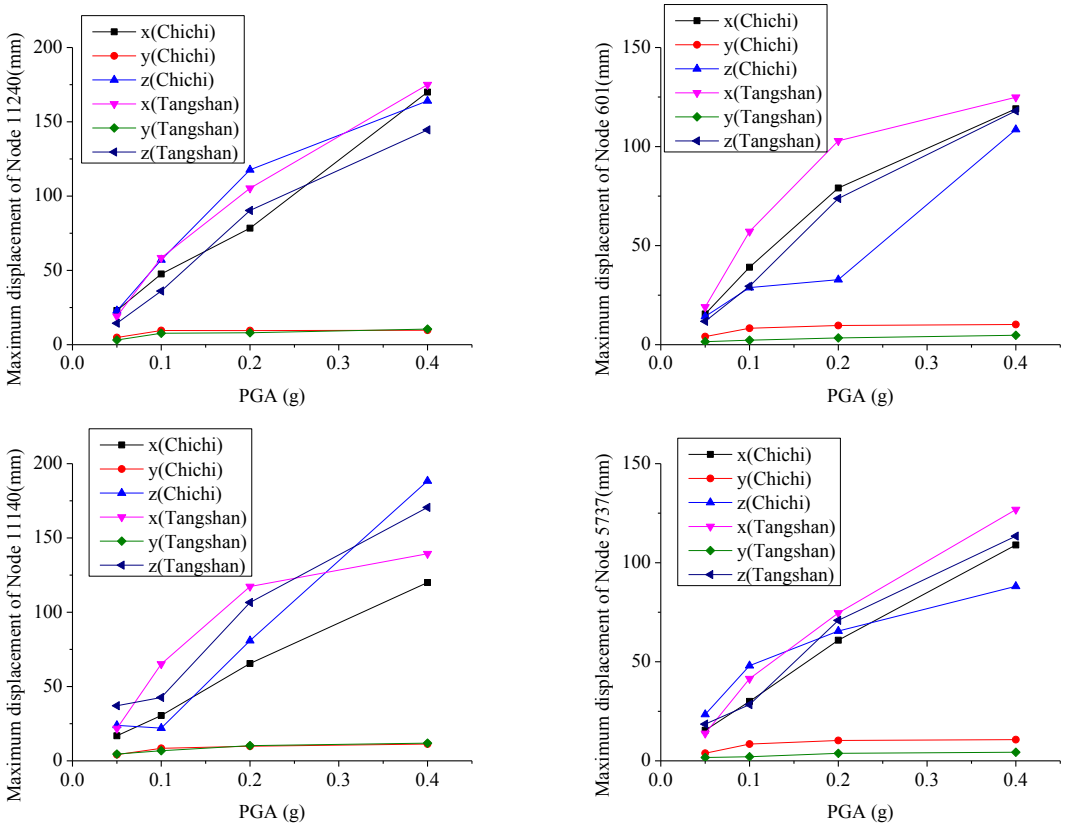

Figure 15: displacement responses of Node 11240, Node 601, Node 11140 and Node 5737

3 SEISMIC PROTECTION MEASUREMENTS FOR THE STORAGE CABINETS

All cultural relics cabinets are made by metal materials. According to the actual circumstance of cultural relics tank placed in the storehouse, the following three cases, listed as below, are numerically simulated to show damping effect:

Case 1: a set of cultural relics are placed against the wall while another group of cultural relics cabinet floated on the ground, no isolation or damping measures are used. The space between cultural relics tank is 1000 mm.

Case 2: a set of cultural relics placed against the wall, another group of cultural relics cabinet floated on the ground, two groups of cultural relics are linked together by damper, cultural relics tank spacing is 1000 mm.

Case 3: Two groups of cultural relics were floating on the ground, a set of cultural relics are connected to the wall by dampers, also two groups of cultural relics are linked together by damper

Air dampers are recommended, the maximum stroke of the damper used in this paper is 130 mm, the load range is from 500 to 1500 N, the weight is 2.2 kg and the length is 460 mm. Air damper is connected by rod and connecting rod is fixed with cultural relics ark by the bolt. All 6 degrees at the connected node are coupled.

The shell element is adopted to establish the numerical FEA model of the standard storage cabinets. All models have the same size, W1000mm* T600mm* H1800mm. No anchorage is used between the cabinets and the floor. Solid elements are used to establish the floor and walls. The static friction coefficient between storage cabinets and ground is set as 0.2 while the dynamic friction coefficient is 0.34. The damping coefficient of the damper is $60N \cdot s / mm$ and the damping unit length is 460 mm according to the actual length and is connected with storage cabinets by beam unit. The three translational degrees of freedom and three rotational degrees of freedom are coupled in connected nodes, the finite element models of all the three groups cultural relics cabinets are shown in figure 17 to figure 19.

Spring-damping unit COMBI165 is used to simulate air damper. COMBI165 can be used for simple spring and damping system modeling, also can be used in some more complex system, this unit provides a series of discrete element method, thus can simulate complex force-displacement relationship. COMBI165 have two nodes of a one-dimensional units and support all the nonlinear characteristics of the software. Characteristics of the unit are shown in figure 16, it has 9 translational degree of freedom (UX, UY, UZ, VX, VY, VZ, AX, AY, AZ) and three rotary degrees of freedom (ROTX, ROTY, ROTZ).

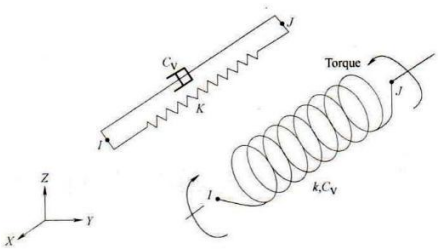

Figure 16 : Characteristics of the unit COMBI165

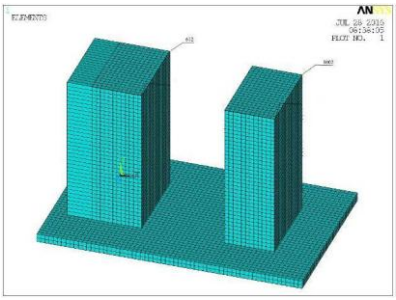

Figure 17 :First mode figure

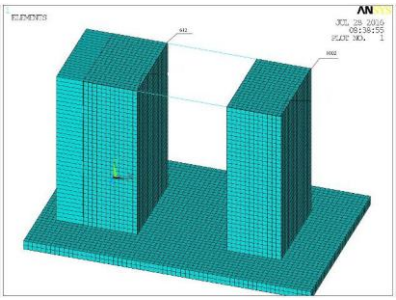

Figure 18:Second mode figure

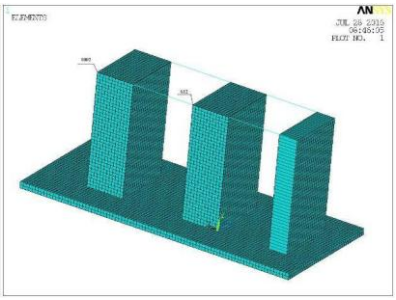

Figure 19:Third mode figure

From the case of Tangshan earthquake under PGA 0.40g, the displacement and acceleration responses of the two perpendicular horizontal direction at Node 612 and Node 1002 are extracted and shown in figure 20 to figure 23.

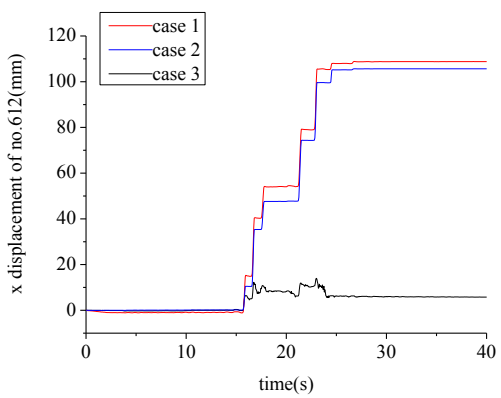

Figure 20: displacement response of Node 612

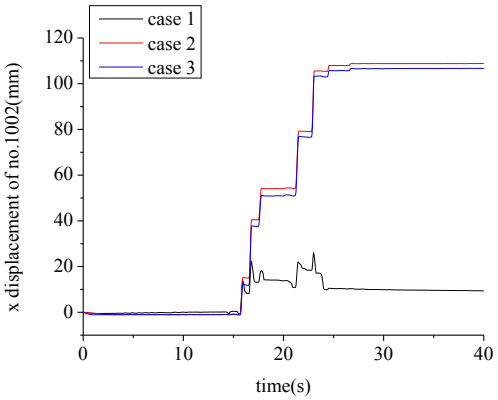

Figure 21: displacement response of Node 1002

According to the time history curves, it can be found that the maximum x and z acceleration of Node 612 and Node 1002 under 0.4 g ground motion in figure 22 to figure 23.

	Maximum x acceleration of Node 612 (g)	Maximum x acceleration of Node 1002 (g)
Case 1	1.03	0.97
Case 2	0.95	1.10
Case 3	0.74	0.88

Figure 22: Maximum x acceleration of Node 612 and Node 1002

	Maximum z acceleration of Node 612 (g)	Maximum z acceleration of Node 1002 (g)
Case 1	0.96	0.92
Case 2	0.90	0.93
Case 3	0.78	0.78

Figure 23: Maximum z acceleration of Node 612 and Node 1002

The maximum displacement response and acceleration of case 1 and case 2 are basically identical. When the cabinet close to the wall vibrate under the earthquake, the constraint of the cabinet disappear. For two cabinets floating on the ground, their seismic responses are the same and the relative speed between the two cultural relics is 0, so damper does not have any effect. We connect the cultural relics ark and the wall in case 3, maximum displacement of the cultural relics is 26 mm, but maximum displacement of the cultural relics is 107 mm in case 1. The maximum acceleration of the cultural relics is 0.88g in case 3, but maximum acceleration of the cultural relics is 0.97g in case 1.The simulation results show that the maximum displacement is reduced by 76% and the maximum acceleration is reduced by 10%.

4 CONCLUSION

1. Seismic hazards of The Forbidden City under different earthquake intensity are listed as follows:

(1) Under the influence of earthquakes at PGA 0.05 g (corresponding to the seismic intensity is 6 degree), few walls surface will spall, few slip tile may happen on roof.

(2) In the face of earthquake ground motion peak of 0.1 g (corresponding to the seismic intensity is 7 degree), walls crack slightly, a little slip tile may happen on roof.

(3) In the face of earthquake ground motion peak of 0.2 g (corresponding to the seismic intensity is 8 degree), the wall cracks seriously, the roof will collapse.

(4) In the face of earthquake ground motion peak of 0.4 g (corresponding to the seismic intensity is 9 degree), the wall roofs are totally damaged, some mortise-tenon joints will be pulled out.

2. It is recommended to use connection mode adopted by the working case 3. Two groups of cultural relics were floating on the ground, a set of cultural relics are connected to the wall by dampers, also two groups of cultural relics are linked together by damper. In these kind of cases, both acceleration and displacement responses are reduced effectively.

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