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Anti-seismic Effect of Lattice Grid Structure with Friction Pendulum Bearings Under the Earthquake Impact of Various Dimensions

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Abstract

As a typical base isolation device, the friction pendulum bearing (FPB) was applied to the lattice grid structures in this paper. The isolation mechanism of FPBs was analyzed from two aspects of force and energy consumption, while the static and dynamic mechanical properties of lattice grid structures with FPBs were numerically investigated using two models of regular and oblique quadrangular pyramid framed structures. The physical models of FPBs with fictional coefficient of 0.1 and a curvature radius of 1.0 m was established and applied to the lattice grid structures. Moreover, the mechanical properties of these structures with FPBs ware studied. Numerical results indicate that the seismic response of structures is remarkably weakened by using FPBs, which means FPBs can be used to effectively control structural vibration.

Keywords: lattice grid structures, friction pendulum bearing (FPB), isolation mechanism, mechanical properties, structural vibration

1. Introduction

With more and more lattice grid structures used on such various building structures, such as railway stations, airport terminal buildings, conference centers, exhibition halls, and many other public buildings, the requirements for safety, reliability, durability, and serviceability of the lattice grid structure are becoming increasingly stringent and vibration control technology has drawn much attention of the civil engineering community.

By now, the vibration control methods of truss structures mainly include active, semi-active, and passive control. In the past, some active and semi-active control methods were proposed and applied to the truss structures, and their rationality and validity have been verified by lots of experiments and numerical analyses (Dunn, 1992; Schotze and Goetting, 1996; Yan and Yam, 2002; Gao *et al.*, 2003; Onoda *et al.*, 1997; Oh and Onoda, 2002; Gaul *et al.*, 2002; Park and Kim, 2011). Generally, the active and semi-active hybrid systems can offer improved performance over passive systems in a wider range of earthquakes, but obstacles related to implementation and questions regarding reliability still persist. Three main passive control technologies, the tuned mass dampers (TMD) (Yamada, 1995; Lin *et al.*, 1999; Guo and Chen, 2007), energy dissipation (DesRoches, 2000; Lai *et al.*, 1995; Yang *et al.*, 2013), and base isolation, have been developed and researched to overcome these limitations. As a typical base isolation device, a friction pendulum bearing (FPB) consisting of a concave sliding surface and an articulated slider was proposed (Zayas *et al.*, 1987). The efficiency of FPB isolator with self-limit and self-reset capability for reducing the seismic responses of structures had been verified through extensive experiments and numerical investigations (Mokha *et al.*, 1991; Tsai, 1997; Wang *et al.*, 1998; Eröz and DesRoches, 2008; Tsai *et al.*, 2002). These FPB isolators are widely used in many buildings in the world (EPS, 2014) because of their favorable isolation performance. However, little work is done on large-scale spatial lattice structures with the FPBs. The seismic performance of spatial lattice shell structures with FPBs was discussed in 2010 through SAP2000 software, and the results showed that seismic responses of structures with FPBs were obviously weakened (Kim *et al.*, 2010).

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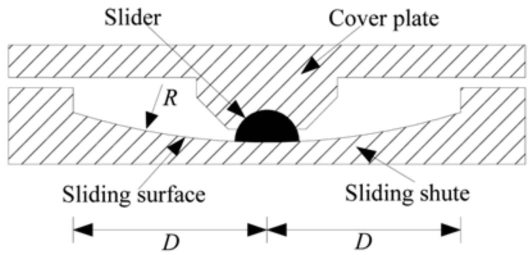


Figure 1. FPB.

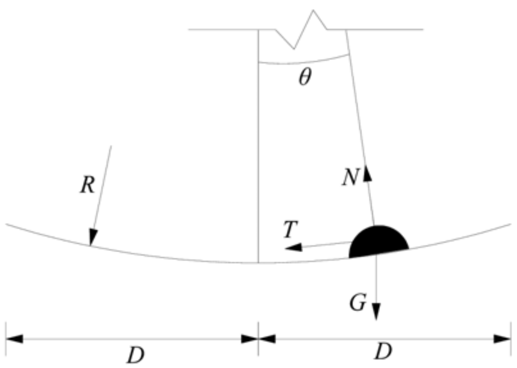


Figure 2. Forces acting on slider.

Therefore, a simplified physical finite element model of FPBs is used and applied to the lattice grid structures, regular and oblique quadrangular pyramid framed structures in finite element software LS-DYNA. The correctness and rationality of this modeling method were verified (Kong *et al*., 2012). The impact of FPBs on the seismic performance is then proved to be the favorable for lattice grid structures in this paper.

2. Isolation Mechanism of a FPB

The compositions of a FPB include a spherical sliding surface, a slider and a cover plate, and the curvature radius of sliding surface is R as shown in Fig. 1. Here, D is the limiting displacement of the sliding surface. The isolation mechanism of a FPB is analyzed from the two aspects of isolation and friction damping energy consumption in this section.

Firstly, Fig. 2 shows the two-dimensional force of the slider. The slider slides on the sliding surface when the external excitation is more than the maximum static friction force.

As shown in Fig. 2, for equilibriums in horizontal and vertical directions, the following relationships are obtained as

$$\sum F_h = 0 \quad G\cos\theta + F\sin\theta - N = 0 \tag{1}$$

$$\sum F_v = 0 \quad G\sin\theta - F\cos\theta + T = 0 \tag{2}$$

where G is the gravity of superstructures, N is the normal force, T is the friction force between slider and sliding surface, θ is the angle between the normal direction and vertical plane, and F is the horizontal force. Combining Eqs. (1) and (2), the horizontal force F can be given by

$$F = G\tan\theta + T/\cos\theta \tag{3}$$

The motion equation of the superstructure with FPBs can be given by

$$\begin{bmatrix} M & m_{12} \\ m_{21} & m \end{bmatrix}\ddot{x} + \begin{bmatrix} C & c_{12} \\ c_{21} & c \end{bmatrix}\dot{x} + \begin{bmatrix} K & k_{12} \\ k_{21} & k \end{bmatrix}x = p \tag{4}$$

where, M, C and K are the mass matrix, friction damping and stiffness matrix of the structure, respectively. And, m, c and k are the mass matrix, damping matrix and stiffness matrix of FPB, respectively. m_{12}, m_{21}, c_{12}, c_{21}, k_{12} and k_{21} are the correction matrices, and p is the external excitation to the structure.

In addition, when the slider slides on the sliding surface, a part of earthquake energy is consumed through mutual friction. Assuming that R=100 cm and μ=0.1, the hysteresis curve of a FPB was given in Fig. 3. Here, μ is the coefficient of friction between the slider and the sliding surface. Figure 3 shows that the stiffness of hysteresis curve of a FPB has no influence on the external load and time, so it remains unchanged when the curvature radius and coefficient of friction are constants.

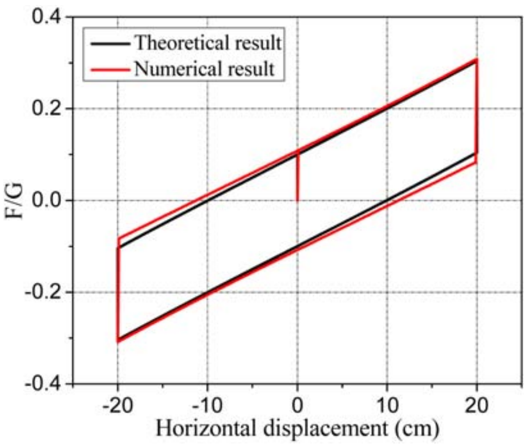
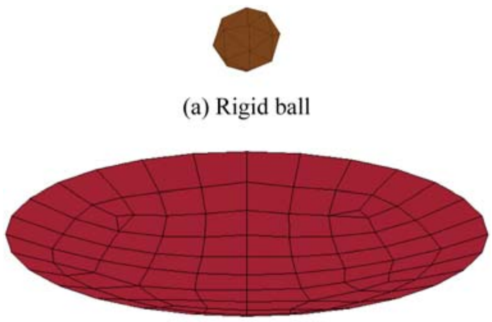


Figure 3. Hysteresis curve of FPB.

3. Finite Element Model

3.1. Finite element model of FPB

A simplified physical model of FPB was established using finite element software LS-DYNA in this section. According to the results on isolation mechanisms of a FPB in Section 2, the isolation could be mainly completed through the mutual sliding and friction between the slider and the sliding surface. With the assumption that the deformation of FPBs is very small under external loads,



(a) Rigid ball

(b) Rigid sliding surface

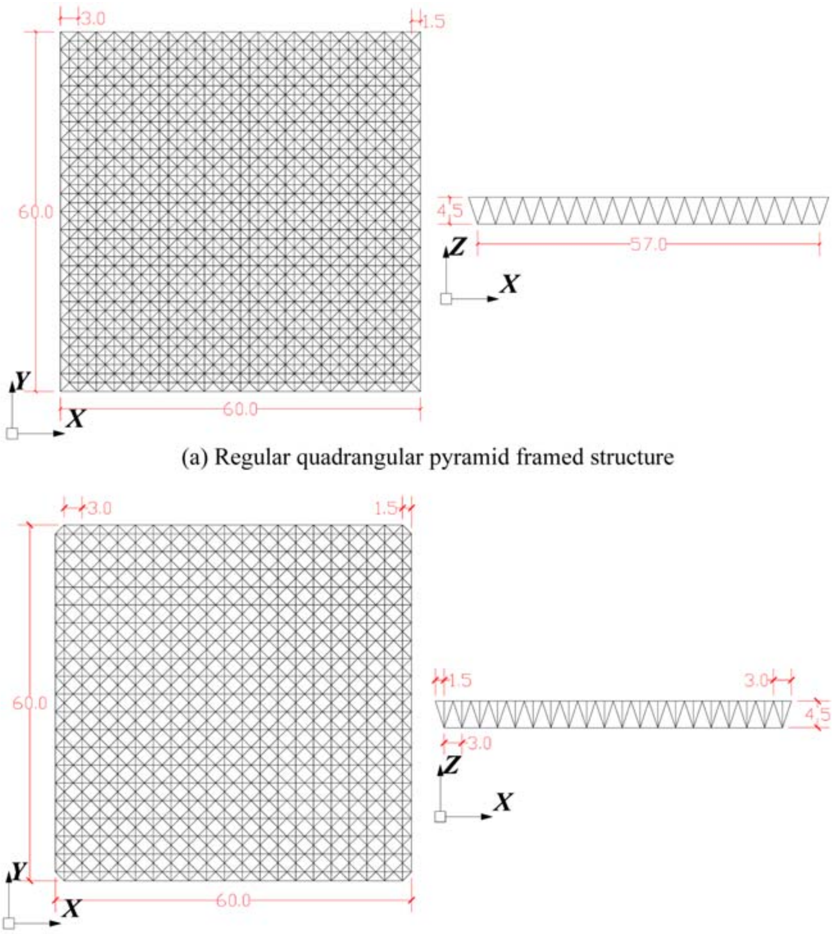
Figure 4. Finite element model of FPB.

the sliding chute and the slider can be replaced by a grid sliding surface and a rigid ball respectively, while the cover plate was ignored in the finite element model, as shown in Fig. 4. Furthermore, in order to stop rotation and deformation of the little ball on the sliding surface, all nodes of ball coupled with the corresponding node of the superstructure, and the little rigid ball was connected to the sliding surface through contact elements. Under the dynamic loads, the little ball slides on the rigid sliding surface, which causes superstructure vibration. Here, T shown in Fig. 2 represents the friction force between the ball and the rigid sliding surface. The grid little ball and the rigid surface were modeled SOLID164 and SHELL163 elements in software LS-DYNA, respectively. The rationality and validity of this modeling method of FPBs has been proved by Kong *et al.* (2012). In addition, the material elasticity modulus is 206GPa, while Poisson ratio is 0.33 and the material density is 7850 kg/m^3.

In this paper, it is assumed that R =1.0 m, μ =0.1 and D =0.5 m.

3.2. Model of Lattice Grid Structure

In this paper, two typical lattice grid structures including the regular and oblique quadrangular pyramid framed structures were selected for the present study on seismic performance. The width and length of two kinds of structures is 60 m and the height is 4.5 m, and the other size parameters were given as shown in Fig. 5. Several types of steel tubes, ϕ120×3.5, ϕ152×5, ϕ172×4, ϕ206×4.5, ϕ228×5, ϕ318×6, were selected as the members of the structures, which were modeled as bar elements in the



(a) Regular quadrangular pyramid framed structure

(b) Oblique quadrangular pyramid framed structure

Figure 5. Model of lattice grid structures.

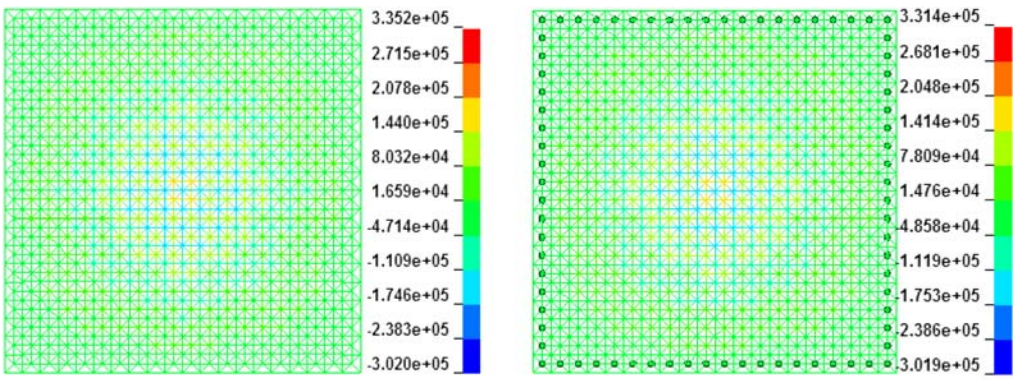
analysis. In addition, the material elasticity modulus is 206 GPa, while Poisson ratio is 0.33 and the material density is 7850 kg/m^3. It was assumed that the roof permanent and snow weight is 80 and 40 kg/m^2 respectively. The combination value coefficient of snow load was 0.5 for the representative of gravity load in the nonlinear time-history analysis (GB 50011, 2010). Therefore, the roof weight was taken as 100 kg/m^2. All the external loads of the structure are treated as lumped masses concentrated at the nodes of the structures. Here, the lumped masses could be obtained according to the tributary area of each node. In the analysis process, the roof load and bar members were simulated respectively by MASS166 and BEAM160 elements in the finite element software LS-DYNA. In this paper, it was assumed that the structure kept in the completely elastic state.

4. Static Analysis

When FPBs were selected as the supports of a lattice grid structure, the maximum horizontal support force is equal to the maximum static friction force between the slider and the sliding surface. So, compared with a hinged support structure, the horizontal supports of a structure with FPBs are weakened. However, compared with a Z-direction supported structure, the horizontal supports of a structure with FPBs are enhanced. The Z-direction support means that only the displacement in Z-direction is restrained, while the in the other two directions (X and Y) have been released. Take the regular quadrangular pyramid framed structure with only Z-direction supports or FPBs as examples, and the static mechanical properties of structure, including the axial force of bars and the deformation of structure, were researched and discussed in this section. The parameters of FPBs and structure were given in Section 3.

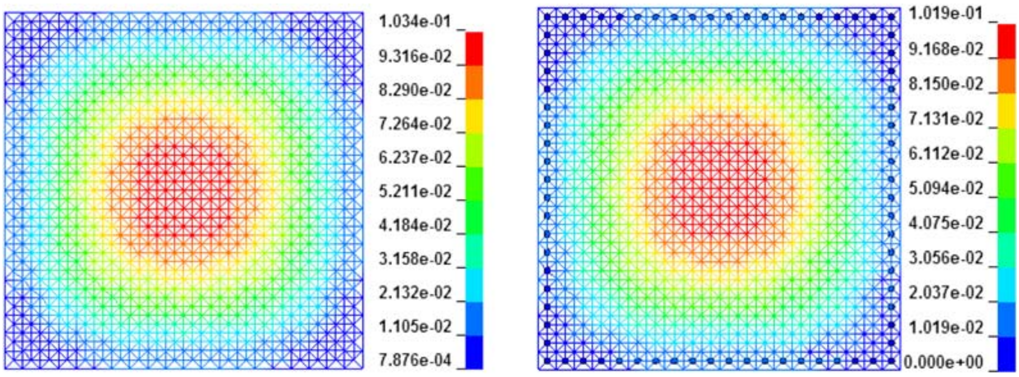
Figure 6 shows that the maximum axial forces of two type structures were 3.352×10^5 and 3.314×10^5 N, while the minimums of them were –3.020×10^5 and –3.019×10^5 N. Therefore, the axial forces are slightly reduced when the Z-direction supports were replaced by FPBs. However, the contour of bar axial forces of this structure with FPBs was similar to that of the structure with only Z-direction supports.

In addition, if the Z-direction supports were replaced by FPBs, the horizontal supporting forces were provided by the friction forces between the slider and the sliding surface in each of the supporting point. Because the normal force N was different for each supporting point, the value of the friction forces is different. In this example,



(a) Z-direction supports (b) FPBs

Figure 6. Axial forces of bars of regular quadrangular pyramid framed structure.



(a) Z-direction supports (b) FPBs

Figure 7. Displacement of regular quadrangular pyramid framed structure.

the friction forces located between 0.9×10^3 and 11.2×10^3 N. As shown in Fig. 7, the maximum displacement of the structure with FPBs reduces from 10.34 to 10.19 cm. The analysis and discussion of the structural deformation are similar with the axial force.

In comparison to the structure with only Z-direction supports, FPBs can strengthen the static properties of a lattice grid structure.

5. Seismic Response Analysis

In order to study the seismic performance of a lattice grid structure, two ground motion records, El-Centro wave and Taft Wave, were selected as seismic inputs in the X-, Z-, XY- and Tri- directions, while the seismic responses of these structures were analyzed under five kinds of peak ground accelerations (PGA), 70, 140, 220, 300 and 400 cm/s^2. The physical finite element models of FPBs in Fig. 4 were applied to the lattice grid structures. The displacement time history curves which time-step was 0.02s were imposed on the rigid sliding surface, and the dynamic responses of structures were analyzed by finite element software LS-DYNA. In this section, the parameters of FPBs are given in section 3.1.

5.1. Assessment criteria

Due to the number of nodes and bar members of structures are varying, it is difficult to analyze each node and bar element. Therefore, two evaluation indexes, β_f and β_a, are defined in this paper to study the overall seismic performance of lattice grid structures. They are the dynamic axial force and acceleration amplification coefficients as shown below

$$\beta_f = \frac{\max(F_{\max j})}{\max(\bar{F}_{\max j})} \quad (j=1,\ 2,\ \cdots,\ m) \tag{5}$$

$$\beta_a = \frac{\max(a_{\max i})}{\max(\bar{a}_{\max i})} \quad (j=1,\ 2,\ \cdots,\ n) \tag{6}$$

where m and n are the number of nodes and bar elements of a lattice grid structure, and $F_{\max j}$ and $a_{\max i}$ represent the maximum dynamic axial force of the jth beam element and the maximum acceleration of the ith node of structures with FPB, respectively. In addition, the denominators of equations represent the corresponding values of a structure with hinged supports. According to Eqs. (5) and (6), the dynamic responses of a lattice grid structure with FPBs can be remarkably alleviated when β is less than 1, while

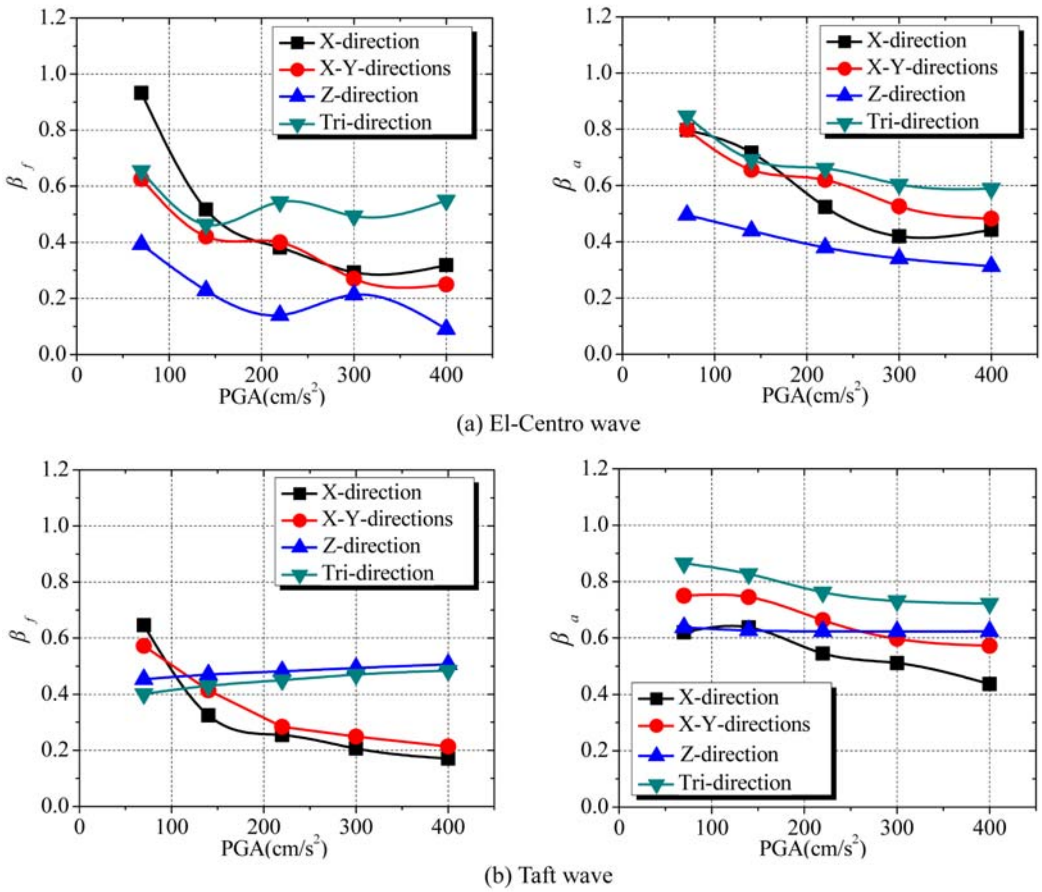


Figure 8. Seismic responses of regular quadrangular pyramid framed structure.

the isolation effect of FPBs increases as the value of β decreases.

5.2. Regular quadrangular pyramid framed structure

By nonlinear time history analysis for the regular quadrangular pyramid framed structure, the change curves of amplification coefficients are shown in Fig. 8.

The following conclusions were observed from the analysis:

(1) The values of amplification coefficients are less than 1, which means that the seismic responses of this structure with FPB are effectively alleviated.

(2) Under X- and XY-direction ground motions, the amplification coefficients gradually reduce with the increase of PGA, so the isolation effect of FPB gradually enhances. Moreover, the amplification coefficients are similar under horizontal (X- and XY- direction) earthquake motions, which indicate that the seismic performance of this structure is similar.

(3) Under Z-direction ground motion of El-Centro wave, β_f<0.4 and β_a locates between 0.3 and 0.5, so the changes are very small. Amplification coefficients almost remain constants under different PGA of Taft wave. Therefore, the change of PGA has less effect on the seismic performance for this structure with FPBs.

(4) Under tri-dimension ground motions, the general change trends of β_f and β_a are gradually reduced with the increase of PGA. However, their changes of them are very small when PGA is more than 140 cm/s^2 which shows that the influence of PGA is diminished on isolation performance of FPBs. In addition, when PGA>140 cm/s^2, Fig. 8 shows that the amplification coefficients under tri-direction ground motions are more than horizontal ground motions. Therefore, the ability of isolating horizontal earthquakes (X- and XY- direction) of FPBs increases apparently with the increase of PGA compared with tri-direction ground motions.

In a word, the seismic responses of the structures were weakened by using FPBs. So, the isolation performance of FPBs was verified for a regular quadrangular pyramid framed structure.

5.3. Oblique quadrangular pyramid framed structure

In this part, the seismic performance of an oblique quadrangular pyramid framed structure with FPBs was researched, and the parameters of structure and a FPB were given in section 3. By the dynamic nonlinear history analysis, the changes of the amplification coefficients are shown in Fig. 9.

From the numerical results, the followings could be

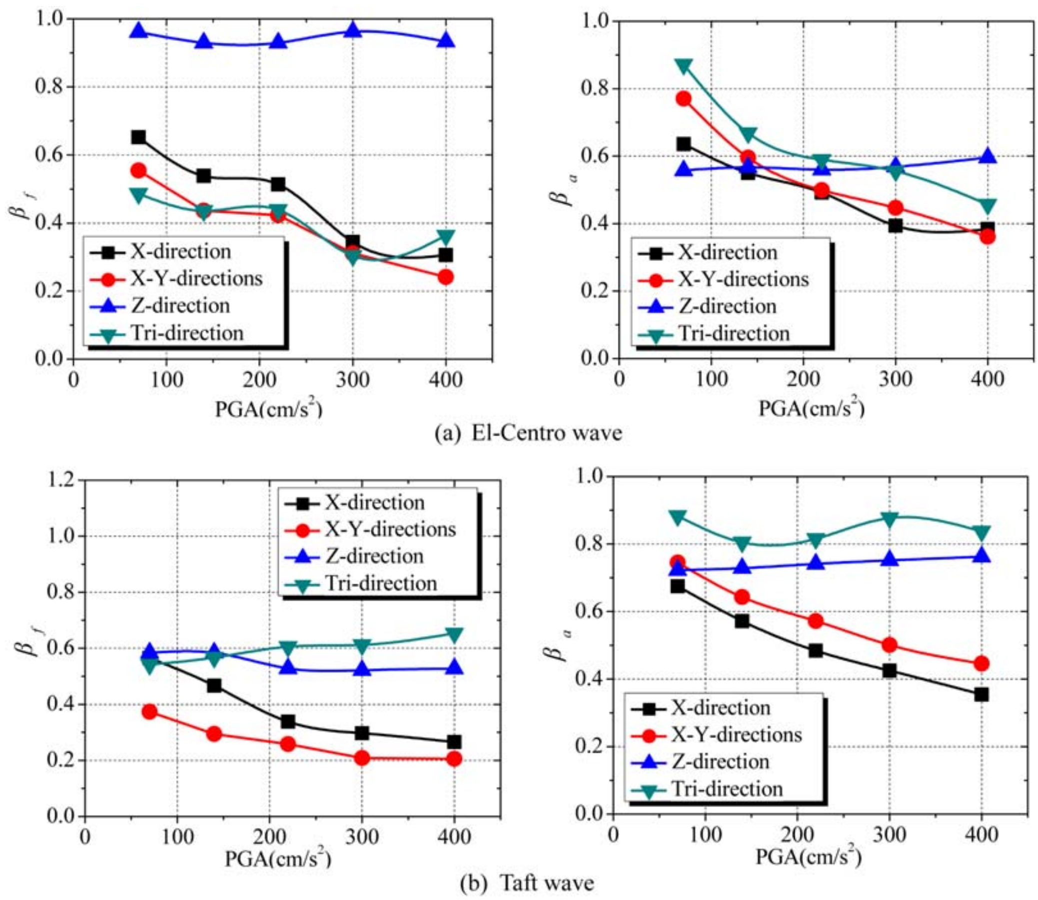


Figure 9. Seismic responses of the oblique quadrangular pyramid framed structure.

concluded:

(1) All of the amplification coefficients are less than 1, which means the maximums of the dynamic axial force and nodal acceleration of the structure are obviously reduced by using FPBs. Therefore, this structure with FPBs possesses favorable seismic performance.

(2) Under the X- and XY-direction inputs of earthquake waves, the amplification factors for the maximum dynamic axial force and nodal acceleration of the structure with FPBs gradually reduce with the enhancement of ground motion intensity. So, the seismic performance of this structure is gradually increased. Taking El-Centro wave as an example, when PGA=70 cm/s^2, β_f are 0.64 and 0.55 respectively under the X- and XY- direction inputs. However, β_f are decreased to 0.31 and 0.24 respectively when PGA increases to 400 cm/s^2, which means that the maximum bar dynamic axial forces are reduced by 69% and 76%, respectively.

(3) Under the Z-direction inputs of seismic waves, the amplification coefficients almost remain unchanged, which means that the seismic performance of this structure with FPBs remains unchanged. For example, under the input of Taft wave, β_f fluctuates by 0.58.

(4) Under the Tri-direction inputs of ground motions, the change trends of amplification coefficients differ under different seismic waves. But they are all less than 1. Therefore, it can be concluded that the seismic performance of this structure is enhanced by using FPBs.

In conclusion, the seismic responses of this type of structures can be notably reduced because of the FPBs.

6. Conclusion

The simplified physical models of FPBs were applied the lattice structures in this paper. The static mechanical properties of structures were analyzed from internal forces and deformation. Moreover, the dynamic mechanical properties of structures with FPBs were numerically investigated under different earthquake motions. Based on these studies, the following conclusions can be summarized.

(1) Compared with the grid structures with the Z-direction supports, the internal forces and deformation of structures with FPBs are slightly reduced due to the existence of the friction forces. Therefore, the static mechanical properties of the lattice grid structures with FPBs have no notable enhancement.

(2) Compared with a lattice grid structure with hinged supports, the seismic responses of a structure with FPBs are declined remarkably.

(3) Under X- and XY-direction earthquake waves, the seismic performance of the lattice grid structures with FPBs is enhanced as the ground motion intensity increases.

(4) Under Z-direction earthquake motion, the isolation effect of FPBs is apparently for the lattice grid structures, while the change of PGA has little influence on the seismic effect of structures with FPBs.

(5) FPBs can effectively control the dynamic responses of the lattice grid structures under tri-dimensional earthquake motions.

It can be seen from the conclusions above that the feasibility of applying FPB to a lattice grid structures is verified through numerical analyses. It can therefore be concluded that FPBs can be used as typical base isolation devices to effectively control the structural vibration.

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