

EXPERIMENTAL STUDY ON A NEW VERTICAL ISOLATION BEARING

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Abstract

In the near fault area or epicenter, significant vertical ground motion had been recorded frequently and lots of damage was found on the buildings caused by the vertical earthquakes. The vertical component of the earthquake impact can not be ignored. Nowadays various horizontal isolation bearings have been put into use to protect buildings from earthquake damage. They can work well in seismic reduction in the horizontal direction, but not so good in the vertical direction. Therefore, it is necessary to develop proper vertical isolation bearing. This paper proposes a creative vertical isolation bearing which has the advantage of simple configuration, low price and stable performance. It can be used as not only the vertical isolation bearing. Factors affecting the mechanical properties of the bearing have been investigated. Furthermore, shaking table tests have been realized in the frame model including vertical base isolation, three-dimensional base isolation, horizontal base isolation and the normal fix supporting. Sine waves and earthquake motions have been input to the shaking table. The test results show that the proposed vertical isolation bearing possesses high and steady vertical supporting ability, proper stiffness and good energy dissipation ability. The frame model in the case of three-dimensional isolation supporting using the proposed vertical isolation bearing displayed more remarkable seismic isolation performance than in the other supporting cases.

Keywords: Vertical Isolation; Three-Dimensional Isolation; Bearing; Seismic Control

1. Introduction

In near few decades, seismic isolation has been developed rapidly in many countries. Some of the base isolated buildings experienced real earthquake attacks and behaved excellent seismic reduction. However, most of the isolation bearings, such as laminated rubber bearing, can isolate the horizontal shaking very well but can hardly isolate the vertical shaking. In the near fault area or epicenter, significant vertical ground motion had been recorded frequently and lots of damage induced by the vertical component of earthquakes had been found on the buildings. Therefore, in recent years, many scholars and experts have worked on developing new vertical isolation bearings or three-dimensional ('3D' in short in the following statements) isolation bearings. Typically four kinds of vertical isolation bearings have been researched, including thick rubber bearing[1~6], air pressure spring[7~10], hydraulic cylinder[11~14], and disk spring system[15~18]. They can work well in vertical isolation or 3D isolation. But they have one weakness or another, such as high cost, complicated in structure, or hard to be maintained. Until now, vertical isolation bearing or 3D isolation bearing is still under developing.

This paper proposes a new vertical isolation bearing which has the advantage of simple in structure, low cost and long durability. It has been obtained China patent. It can be used as a vertical isolation bearing or combined with a horizontal isolation bearing to form a 3D isolation bearing.



2. The new vertical isolation bearing

The new vertical isolation bearing consists of five parts as shown in Fig.1(a): inferior barrel(1), up barrel(2), balls made of rubber or similar material(3), division plate(4), and silicon oil(5). Fig.1(a) instructs the assembling of the bearing. Fig.1(b) shows the bearing ready for use, outside of which is the shield sleeve(6) made of rubber or other flexible material. Fig.1(c) indicates the status when the bearing is used for vertical isolating. Fig.1(d) indicates the status when the bearing to form the 3D isolation bearing.



Fig.1 – Sectional view and the instruction of the new vertical isolation bearing

The operational principle of this new vertical isolation bearing is simple. When loaded the superstructure, the aggregated rubber balls are always in 3D compressed state owing to the constraint of the inferior barrel and up barrel. This makes the new vertical isolation bearing possesses high vertical loading capacity and low vertical stiffness at the same time, which is the key for vertical seismic isolation. When vertical earthquake takes place, the up barrel of the bearing will move up and down relatively to the inferior barrel. When the superstructure jumps up, the up barrel of the bearing can go up freely with the superstructure, which can release the pull force in building structure induced by the vertical earthquake. When the superstructure goes down, the up barrel of the bearing dashes the aggregated balls through the division plate, which makes the balls compressed furthermore and the silicon oil extruded from the gap of the rubber balls. With the up barrel moving relatively to the inferior barrel, the balls rub and squeeze each other and the silicon oil flow in the gap of the balls, which dissipates lots of energy and plays the role of a damper.

2.1 The influence factors of the new bearing

To investigate the influence factors of the energy dissipation and vertical stiffness for the new vertical isolation bearing, pseudo static tests have been done by use of the universal testing machine. The capacity of the testing machine is 10 Tons. Ten different influence factors (material of the ball, diameter gradation of the balls, hardness of the ball, filling rate of balls, viscosity of the silicon oil, filling rate of silicon oil, open porosity of the division plate, preloading value, loading rate and loading amplitude) have been considered. Pseudo static tests on 32 working conditions from orthogonal test design have been carried out. Fig.2 is the photo of under testing. Fig.3 shows part of the balls with different diameter, material and hardness used in the tests. Fig.4 shows the division plates with different open porosity.

It is found from the pseudo static tests that the influence factor affecting the energy dissipation coefficient of the bearing can be ranked from strong to weak as: whether or not having silicon oil, hardness of the ball, material of the ball, diameter gradation of the balls, viscosity of the silicon oil, loading rate, open porosity of the division plate, preloading value, loading rate and loading amplitude. It also is found that the influence factor affecting the stiffness of the bearing can be ranked from strong to weak as: whether or not having silicon oil,



preloading value, loading amplitude, hardness of the ball, viscosity of the silicon oil, diameter gradation of the balls, material of the ball, loading rate, open porosity of the division plate.

Low viscosity of the silicon oil, no holes or only 4mm holes in the division plate, medium diameter of the balls (about 60~70mm) and higher hardness of the ball can benefit to the high energy dissipation and low stiffness of the bearing. Rubber is better than silicon to be used as the material of the balls. Loading rate hardly affects the energy dissipation and stiffness of the bearing. The higher the preloading value, the larger the stiffness of the bearing was.



Fig. 2 – Pseudo static test of the new bearing



Fig. 3 - Part of the Balls used in the tests of the new bearing



Fig. 4 – Division plates with different open porosity

2.2 The hysteretic characteristics of the new bearing

The vertical isolation bearing was designed for the shaking table test. The inferior barrel is 390mm high and has 195mm internal diameter. The diameters of rubber balls were 80, 50 and 30mm respectively. Number of the balls was 24, 5 and 18 respectively. The pseudo static tests have been done under displacement control. The controlled displacement was $\pm 2\text{mm} \ \pm 5\text{mm} \ \pm 10\text{mm}$ and $\pm 15\text{mm}$ respectively. Each of the controlled displacement had been carried out for 6 cycles. The hysteretic curves under the four controlled displacements are listed in Fig.5. The equivalent damping ratio and stiffness of the bearing are calculated by the hysteretic loop of the fifth cycle. The equivalent damping ratio under the four controlled displacements was obtained as 10.48%, 11.66%, 14.17% and 7.31% respectively. The stiffness was 1.888 kN/mm, 1.451 kN/mm, 1.141 kN/mm and 0.977 kN/mm respectively.



Fig. 5 – The hysteresis curves of the proposed new bearing obtained by the pseudo static tests



Fig. 6 – The laminated rubber bearing for horizontal isolation of the frame model



3. Shaking table test on the new vertical bearing

To verify the function of the new vertical bearing, shaking table tests have been done by using a 3-storey steel frame model. Four kinds of supporting condition for the frame have been realized including fix, horizontal isolation, vertical isolation and 3D isolation by differently combining the new vertical bearing and the hollow laminated rubber bearing.

The hollow laminated rubber bearing shown in Fig.6 has been used as the horizontal isolation bearing. The new vertical isolation bearing has been combined with the laminated rubber bearing to form the 3D isolation bearing. Four hollow laminated rubber bearings have been tested to obtain their vertical and horizontal stiffness. The average vertical stiffness is 107.2kN/mm. The average equivalent horizontal stiffness is 150.7 N/mm.

Fig.7 is the diagram of the frame model equipped with the 3D isolation bearing. 3D force sensor has been equipped under the bottom of the column to measure the base force of the frame model. Fig.8 shows the installing of the 3D isolation bearing on the shaking table. The frame model in the four kinds of supporting condition is shown in Fig.9 to Fig.12. To balance the height of the new vertical isolation bearing, the rigid steel column has been used in the fix support and horizontal isolation support situation.





Fig. 7 – Diagram of the frame model equipped with the 3D isolation bearing

Fig. 8 – Photo of installing the 3D isolation bearing on the shaking table



Fig. 9 – Photo of the frame model supported by the 3D isolation bearing



Fig. 10 – Photo of the frame model supported by the vertical isolation



Fig. 11 – Photo of the frame model supported by the horizontal isolation bearing



Fig. 12 – Photo of the frame model with fix supporting



3.1 The input waves and the test states

Sine wave and three earthquake records (El-centro, Taft and Chi-Chi) were input to the shaking table in horizontal (X, Y) direction and vertical (Z) direction separately or synchronously. Sine wave was tuned to the frequency as 0.25Hz, 0.5Hz, 1Hz, 3Hz and the peak displacement \pm 5mm, \pm 10mm, \pm 20mm respectively. The peak acceleration of the earthquake records has been tuned to 0.26g in Z direction, 0.4g in X+0.26g in Z direction respectively. To check the change of the dynamic characteristics of the frame model in each of the four supporting conditions, white noise was input before and after the tests of each level of peak acceleration. Totally 97 test states have been fulfilled.

3.2 Seismic response of the frame model

The seismic responses of the frame model in the four supporting conditions were compared under each of the input earthquake record. Table 1 lists the peak acceleration in Z direction on each floor of the frame when the earthquake records were input in Z direction. The peak accelerations of the input earthquake records were tuned to 0.26g. Table 2 lists the peak inter-storey displacements for the same cases as in Tabel1. By comparing the seismic responses of the frame with four different supporting conditions as listed in Tab.1 and Tab.2, we can find some phenomena for the frame vibrated in the vertical (Z) direction. Under the same seismic excitation, the lower floor of the frame got the larger acceleration and inter-storey displacement in the case of fix support and horizontal isolation. However in the case of 3D isolation and vertical isolation, every floor got almost the same small value of acceleration and inter-storey displacement, except the isolation layer got large inter-storey displacement. This implies that the proposed new bearing works well for the vertical seismic isolation.

Floor No.	El-centro				Taft				Chi-Chi			
	Fix	Horizontal	3D	Vertical	Fix	Horizontal	3D	Vertical	Fix	Horizontal	3D	Vertical
	support	isolation	isolation	isolation	support	isolation	isolation	isolation	support	isolation	isolation	isolation
4	0.82	0.48	0.16	0.15	0.85	0.66	0.22	0.24	0.77	0.46	0.35	0.29
3	0.77	0.53	0.14	0.15	0.60	0.48	0.21	0.23	0.67	0.50	0.32	0.28
2	0.82	0.57	0.14	0.16	1.07	0.26	0.21	0.24	0.81	0.60	0.32	0.27
Column bottom	1.26	0.81	0.14	0.17	1.73	1.03	0.22	0.21	1.35	0.78	0.34	0.28
Table	0.26	0.26	0.26	0.30	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.27

 Table 1 – The peak acceleration in Z direction of the frame with different support conditions under inputting earthquake records in Z direction (unit:g)

 Table 2 – The peak inter-storey displacement in Z direction of the frame with different support conditions under inputting earthquake records in Z direction (unit:mm)

Floor	El-centro				Taft				Chi-Chi			
No.	Fix	Horizontal	3D	Vertical	Fix	Horizontal	3D	Vertical	Fix	Horizontal	3D	Vertical
	support	isolation	isolation	isolation	support	isolation	isolation	isolation	support	isolation	isolation	isolation
4	0.28	0.20	0.04	0.03	0.22	0.21	0.05	0.05	0.24	0.23	0.15	0.06
3	0.16	0.08	0.03	0.03	0.17	0.18	0.04	0.04	0.20	0.19	0.14	0.07
2	0.66	0.33	0.06	0.05	0.69	0.73	0.10	0.09	0.67	0.47	0.67	0.17
Column bottom	0.80	0.45	0.07	0.07	0.81	0.87	0.09	0.09	0.71	0.49	0.66	0.15
Isolation bearing	_	0.19	1.02	1.92	-	0.27	1.76	3.26	_	0.35	3.43	7.08
Table	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Among the four supporting cases, the frame with vertical isolation support got the smallest value of the peak acceleration and inter-storey displacement evenly on each floor. The frame with 3D isolation behaved similar to



the frame with vertical isolation support except the values of the acceleration and inter-storey displacement were a little larger. The frame with horizontal isolation support also behaved some extent of vertical isolation. The acceleration and the inter-storey displacement of the frame with horizontal isolation support were all smaller than those of the frame with fix support. Relative to the case of fix supporting, the acceleration average reduction rate is also 84% for the 3D isolation case and is only 39% for the horizontal isolation case. Relative to the case of fix supporting, the inter-storey displacement average reduction rate under the three earthquake inputs is 86% for the vertical isolation case, 62% for the 3D isolation case and 34% for the horizontal isolation case.

To compare the seismic response on top of the frame in three different support cases, the acceleration time history curves obtained by inputting the earthquake excitations to the shaking table in three directions are shown in Fig.13 to Fig.15. The input acceleration peak value was tuned to 0.4g in X direction, 0.34g in Y direction and 0.26g in Z direction. The acceleration time history curves of the frame in fix support, horizontal isolation support and 3D support are compared in X direction and Z direction separately. It can be seen that in X direction the acceleration in 3D isolation case is even smaller than that in horizontal isolation case and much small than that in fix support case along the time history, whatever earthquake record was input. In Z direction, the acceleration in 3D isolation case is a little smaller than that in fix support case when the earthquake wave was El-Centro and Taft, but much smaller when Chi-Chi wave was input.



Fig. 13– The acceleration time history curves of the top of flame model under the input of El-centro wave in three directions



Fig. 14 – The acceleration time history curves of the top of flame model under the input of Taft wave in three directions



Fig. 15– The acceleration time history curves of the top of flame model under the input of Chi-Chi wave in three directions

3.3 Hysteresis loops of the new vertical bearing under the earthquake excitations

Fig.16 shows the hysteresis loops of the proposed new bearing when the frame model was in vertical isolated supporting and earthquake excitations were input only in vertical (Z) direction. The peak accelerations of the input earthquake waves were tuned to 0.39g. It can be seen that the hysteresis loop of the bearing is full whatever earthquake excitation was input. The hysteresis loop obtained by Chi-Chi wave is the largest, and that obtained by El-Centro wave is the smallest.



Fig.16– Hysteresis loops of the proposed new bearing when the frame model was in vertical isolated supporting and the earthquake excitations were input only in vertical (Z) direction

Fig.17 shows the hysteresis loops of the proposed new bearing when the frame model was in 3D isolated supporting and earthquake excitations were input in three directions. The peak accelerations of the input earthquake waves were tuned to 0.6g in X direction, 0.51g in Y direction, and 0.39g in Z direction.



Fig.17– Hysteresis loops of the proposed new bearing when the frame model was in 3D isolated supporting and the earthquake excitations were input in three directions



Comparing Fig.16 and Fig.17, we can find that the hysteresis loops of the new bearing obtained by 3D excitation are much larger than those obtained by only vertical direction excitation.

4. Conclusion

The new vertical isolation bearing proposed in this paper is simple in structure, cheap in price and very effective in vertical seismic isolation. It can be used alone as the vertical seismic isolator or can be combined with the laminated rubber bearing to form the 3D isolator. It can provide enough vertical loading ability and small vertical stiffness at the same time. It has full and smooth hysterisis loop under the pseudo static test and shaking table tests. Shaking table tests on a 3-storey frame model with four kinds of support condition proved its excellent seismic isolation and reduction effects.

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6. References

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