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SEISMIC PERFORMANCE OF ROCKING BASE-ISOLATED STRUCTURES SUBJECTED TO BIAXIAL EARTHQUAKE LOADS

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Abstract

Literatures have showed that traditional sliding base-isolated systems may have long-period resonant-like response induced by a ground motion containing strong long-period frequency spectra. In this paper, a new type of isolator called variable-frequency rocking bearing is proposed. The system allows the bearing remain still under a moderate seismic load but start to rock back-and-forth during severe earthquakes. And the vibration is damped throughout each impact of the bearing on structural footing or foundation surfaces. Based on the force-displacement relation and analytical damping of the system, seismic response of the structure may be estimated through a modified elastic response spectrum. The objective of the paper is to investigate seismic performance of this base-isolated structure subjected to bi-axial earthquake loads. To validate proposed idea, a one-bay-one-story spaced structure base-isolated with rocking bearings was constructed. In total, 236 shaking table tests were conducted with various investigated parameters including aspect ratio of bearings, the shape of rocking plates (plane or polynomial), bi-directional earthquakes and waveforms of ground motion. Test results indicate that vibration behavior was nonlinear with respect to rocking amplitude. And structural response of the structure excited by bi-horizontal earthquakes is the largest, followed by uni-axial and then bi-directional with horizontal plus vertical earthquakes. Due to the restrain of spring force at rocking interface, seismic response of structures excited by bi-directional with horizontal plus vertical earthquakes is found similar to those excited by uni-axial earthquakes. It is also found that seismic response is increased with the increase of aspect ratio of bearings, while the effect of rocking surface is marginal. Without any damage incurred under earthquakes, radiation damping of rocking systems is found less than 4% for all tests.

Keywords: Rocking Bearing; Base-isolation; Damping Ratio; Shaking Table Tests.

1. Introduction

Literatures have shown that seismic isolation is an effective technology to protect structures from earthquake attacks [1]. Seismic isolation is achieved through the installation of a soft layer below the protected structures, so that seismic energy transmitted up to the super-structure due to a ground motion is isolated. The flexibility required in isolation system to reduce seismic response may be alternatively obtained by allowing part of structure to uplift, rocking or stepping during large horizontal motions [2]. For example, bridges with insufficient tensile pile capacity at footings allow the uplift of structures during strong earthquakes. This rocking behavior dominates the pier response and minimizes the damage to the footing and columns. More recently, control of rocking behavior of steel braced frames has been investigated by researchers (3-4). The system consists of three main components: a steel braced frame that remains essentially elastic by uplifting at the column bases during ground motions, vertical post-tensioning (PT) that provides resistance to overturning and provides self-centering forces, and replaceable energy-dissipating elements that resist overturning and act as structural fuses that yield, effectively limiting the forces imposed on the rest of the structure (3). The system is capable of preventing major structural damage and residual drift when subjected to severe maximum considered earthquake (MCE) level ground motion intensities.

In general, the isolated structure is designed to exhibit a fixed long-period vibration and constant damping ratio under earthquakes. Consequently, seismic response of structures such as roof acceleration (inertial loads), inter story drift etc. will be significantly reduced due to this lengthened vibrating period. However, long-period resonant-like response of isolated structure may be induced by a ground motion containing strong long-period frequency spectra [5]. To mitigate the resonant-like response that conventional isolation system may encounter in long-period earthquakes, researchers have proposed using isolation systems with variable mechanical properties, so that the isolation system can be more adaptive to a wider range of earthquakes with various spectral compositions [6]. Based on current research, Lu and Hsu [7] have classified six categories of isolation systems with variable mechanical properties, such as multiple friction pendulum isolators (MFPIs) [8-10], sliding isolators with variable curvature (SIVC) [11-12], sliding isolators with variable friction (SIVF) [13], rocking pier isolation (RPI) [14-18], rolling bearings (RB) [19-20] and eccentric rolling bearings (ERB) [21-22].

In order to advance the technology of isolators with variable mechanical properties, a new type of rocking isolator is proposed in this paper. Similar to the concept in literature of control rocking of steel braced frames, the system consists of two main components: a moment-resistant frame that remains essentially elastic base-isolated by rocking bearings at the column bases during ground motions, and disc spring that provides resistance to overturning and provides self-centering forces. If it is necessary, supplementary damping devices may be added at rocking interface. The designer can choose appropriate aspect ratio of the bearing based on seismic hazards at engineering site, such that the rocking motion of the bearings will remain still under a moderate seismic load but start to rock back-and-forth during severe earthquakes. The superstructure will move in a rigid body motion to release ductility demand on the plastic hinge of superstructure.

The objective of this research is to investigate seismic performance of base-isolated structure subjected to bi-axial earthquake loads. To validate proposed idea, a one-bay-one-story spaced structure base-isolated with rocking bearings was constructed and tested by a shaking table. Seismic response of structures varied with investigating parameters is evaluated to investigate the effect of bi-directional earthquakes.

2. Experimental Programs

Figure 1 depicts the structure base-isolated with four sets of rocking bearings and springs. The superstructure is a one-bay-one-story moment resistant spaced structure. The top and bottom floors of superstructure are assembled by steel beams and steel plate with 3000X2000X300 mm in size and steel block weighted 4 tons and 3 tons acting as inertial mass for the top and bottom floor, respectively. The columns are made of flange beam with 150X150X7X10 mm in size. The steel rocking bearing consists of top and bottom rocking plates and four 60 mm diameter rods in the middle, locked together by bolts as shown in Figure 2, where the bearings have aspect ratio of 2.0, having 187mm width of plane surface and 374 mm height. The middle rods can be replaced and lengthened to have aspect ratios of 2.5 and 3.0 with increasing height of 468mm and 561mm, respectively. The higher the aspect ratio of the bearing; the lower the ground acceleration can initiate the rocking of the bearing. The designer can choose appropriate aspect ratio of the bearing based on seismic hazards at engineering site. When the rocking of bearings initates, rocking plate rocks on top and bottom base plates, which are respectively fixed underneath the first floor or on top of shaking table. In order to force the bearing to rock without slip at the interface, a hemispherical steel ball (80 mm diameter), acting as a shear key, is bolted to the center of each base plate. The installation of shear key can also ensure the re-centering of the bearing after rocking.

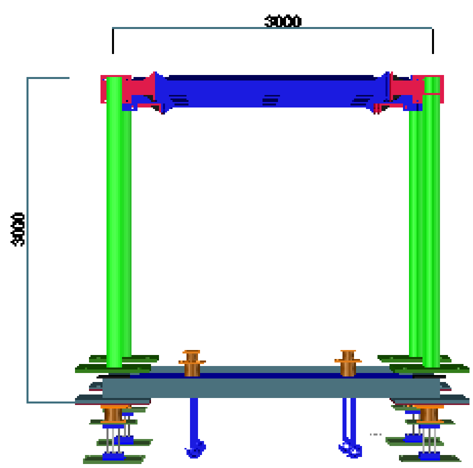
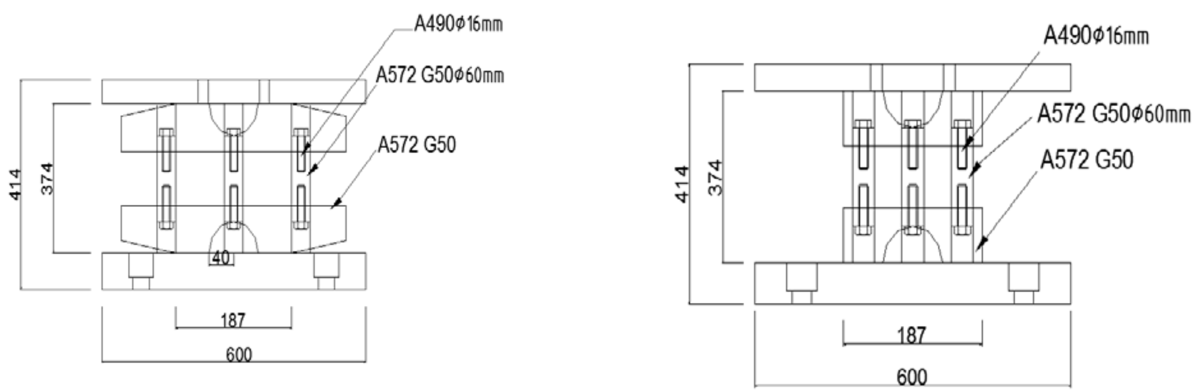


Figure 1 Drawings showing structures base-isolated with rocking bearings and springs (unit: mm)

As shown in Figure 2, rocking plates of the bearing are designed to have two shapes such as plane and polynomial surfaces. The curve for the polynomial rocking surface started from a plane portion is expressed as

$$f(x) = C_1x^6 + C_2x^4 + C_3x^2 \tag{1}$$

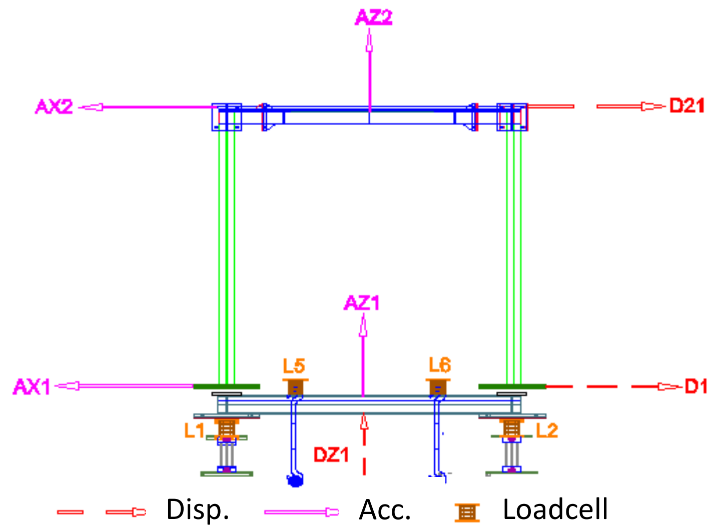
where C_1=603.5 (1/m^5), C_2=45.14 (1/m^3)and C_3=1.31 (1/m), based on the research of Lu and Hsu [6], x is the distance away from the edge of plane surface, and $f(x)$ the increasing height on a concave or convex surface along with *x*. It is also noted that, when the bearing rocks, rocking plate of plane bearing will stand up in line contact with the base plate; while it becomes point contact at rocking interface for polynomial rocking bearing. In addition to the self-weight of superstructure, the spring force provides restoring force for the isolated structure during earthquakes. The higher spring stiffness gets the benefit of higher restoring force, but pays the price of more acceleration transmitted to upper floors. And, the spring stiffness should be soft enough so that bearing can rock on desired ground motion. Based on this idea, four springs were installed between the base floors and shaking table, force transfer of each spring relies on a 25mm diameter threaded bar passing through the center hole of disc springs. The bottom end of each threaded bar was connected to the shaking table by a turn-bucky that keeps steel bar upright and moves parallel relative to the table without bend. Each steel disc spring has properties of 125 mm outside diameter, 64 mm inside diameter, 5 mm thickness, 3.5 mm compressive displacement and stiffness of 12250 KN/m. Each set of the ten-disc spring can be stacked in composition of Kelvin, Maxwell or mixed series, having a resultant total stiffness of 4900 kN/m and 35 mm compressive displacement.



Polynomial rocking bearing Plane rocking bearing

Figure 2 Drawings showing two rocking bearing with aspect ratio of 2 (unit: mm)

Figure 3 shows the test measurements, including ten 500 mm displacement transducers to measure the lateral displacement and vertical uplift of superstructure with respect to shaking table, nine 3G accelerometers to monitor the accelerations of superstructure and the table, and eight 200 kN load cells to measure spring force and column axial loads. The shaking table is 5000X5000mm in size with maximum 500 kN loads, and 500 mm stroke capacity in x direction, while 200 mm in y direction. In total, 236 tests were successively conducted by the composition of various investigating parameters, including aspect ratio of the bearings, shape of the rocking plates (plane or polynomial surface), bi-directional earthquakes and waveforms of ground motion. The first character "X", "Y", and "Z" in test numbering represents aspect ratio of the bearings in 2, 2.5 and 3.0, respectively. The second character "P" and "S" stands for polynomial and plane rocking bearings, respectively. The third character "U", "B" and "V" indicates the structure subjected to uni-axial (longitudinal), bi-horizontal (longitudinal and transverse) and horizontal plus vertical earthquakes, respectively. The number 0.3 and 0.7 after the third character means the ratio of intensity level of transverse or vertical earthquakes with respect to longitudinal direction. The fourth character "E" , "K" and "T" indicates the exciting waveforms in 1940 El Centro, 1995 Kobe earthquakes, and 1999 TCU-129 earthquakes, respectively. The last group number means intensity level of table excitations, such as 100 gal horizontal acceleration.



Fgiure 3 Schematic drawing showing measurement of the specimen

3. Test Results

In order to understand the dynamic characteristic of base-isolated structure, a Fast Fourier Transform (FFT) analysis was applied on roof acceleration for some typical tests. Figure 4 shows the effect of intensity level of Kobe earthquake on vibrating frequency for structures isolated by polynomial rocking bearings with aspect ratio of 3.0. It can be seen that its primary frequency tends to decrease with the increase of ground accelerations, showing nonlinear rocking behavior of the bearing. It manifests that rocking-isolated structure exhibits variable frequency under excitations to avoid resonant-like response that conventional isolators may encounter in long-period earthquakes.

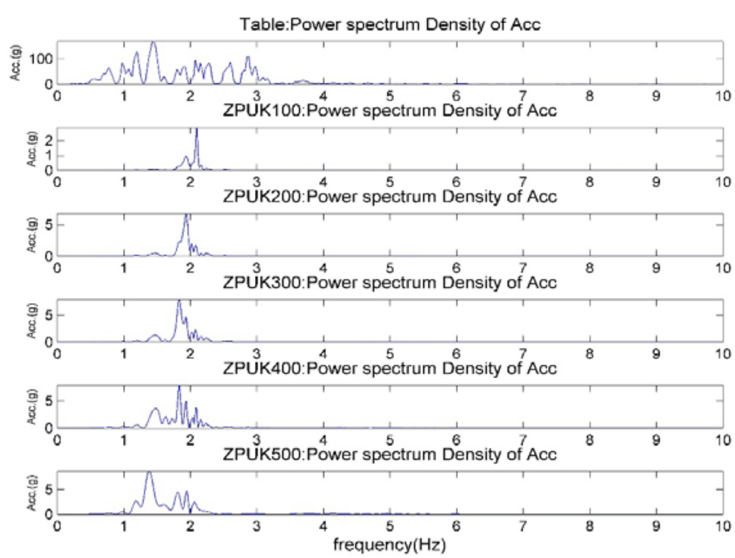
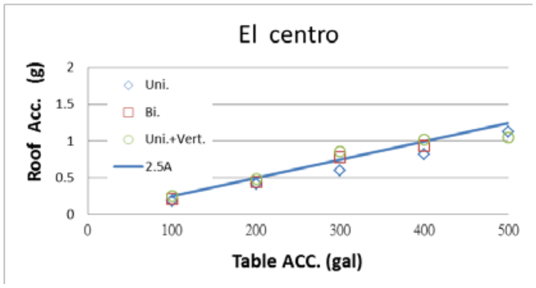
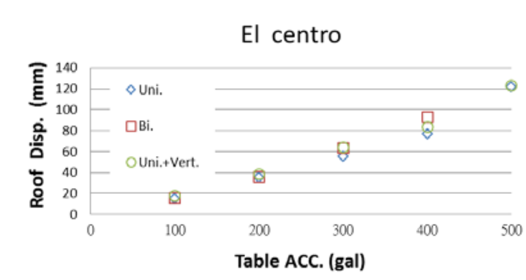


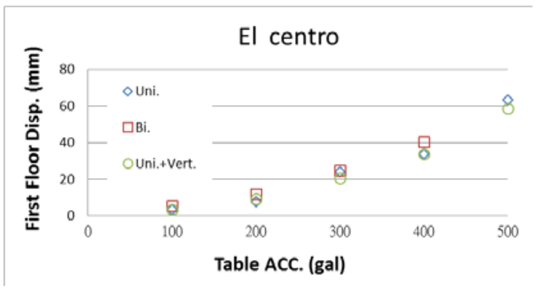
Figure 4 Effect of intensity level of Kobe Earthquake on vibrating frequency



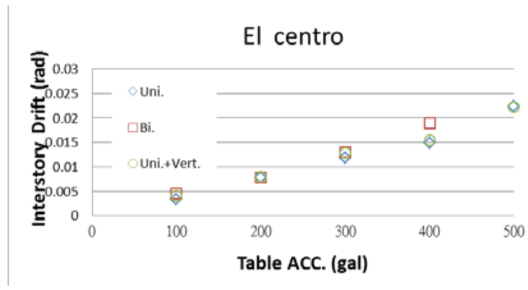
a) roof acceleration



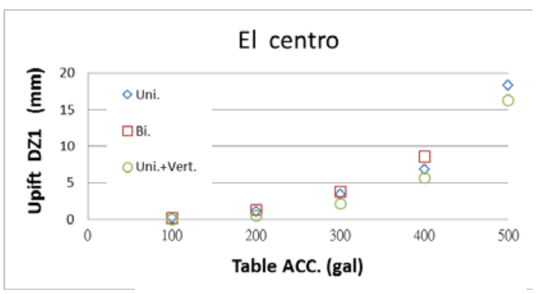
b) roof displacement



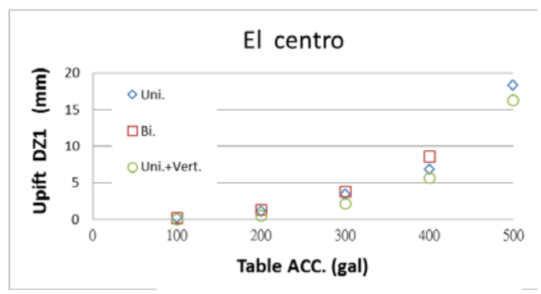
c) isolator displacement



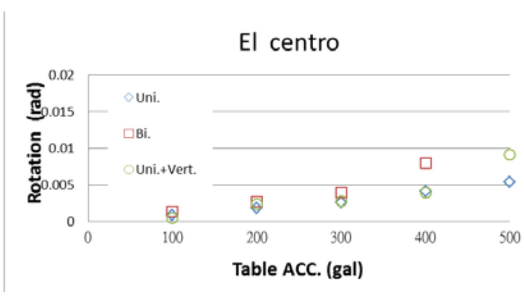
d) interstory drift



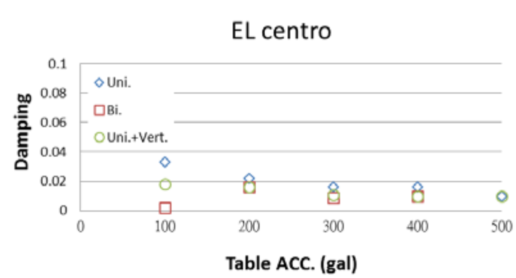
e) uplift of floor DZ1



f) uplift of floor DZ2



g) plane rotation



h) damping of structures

Figure 5 Effect of bi-axial El Centro Earthquake on seismic response for structures base-isolated by polynomial rocking bearing with aspect ratio of 3

Figure 5 shows the effect of bi-directional earthquakes on seismic response for structures isolated by polynomial rocking bearings with aspect ratio of 3.0. The line marked with 2.5A in upper Figure 5(a) means 2.5 times amplification in roof acceleration by a ground acceleration, A, for structures with short or medium vibrating period. And the test damping was evaluated by a modified elastic response spectra procedure [23]. It is also noted that the intensity level of transverse or vertical earthquakes is 30% of longitudinal earthquake. It can be seen that structural response of base-isolated structure excited by bi-horizontal earthquakes is the largest, followed by uni-axial, and then bi-directional with horizontal plus vertical earthquakes. As shown in Figure 6, the loads in spring for structures excited by horizontal plus vertical earthquakes are larger than those excited by uni-axial earthquakes. Due to the restrain of spring force at rocking interface, seismic response for structures excited by horizontal plus vetical earthquakes is found similar to those excitede by uni-axial earthquakes.

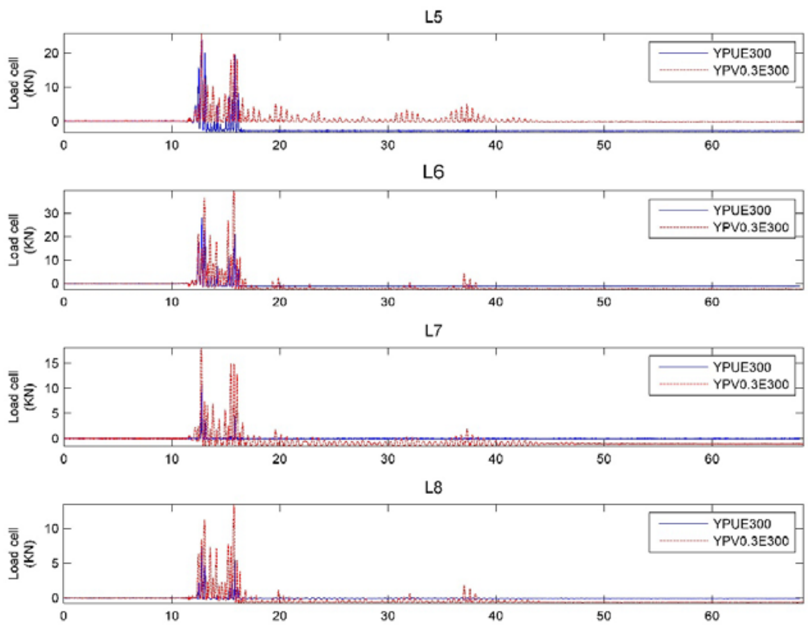
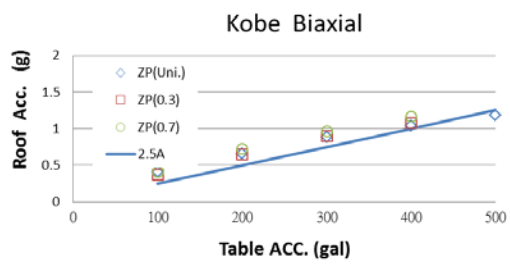
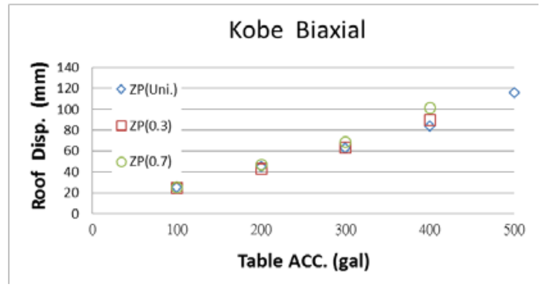


Figure 6 Effect of vertical excitation on spring force for structures base-isolated by polynomial rocking bearing with aspect ratio of 2.5 under excitations of El Centro Erarthquakes

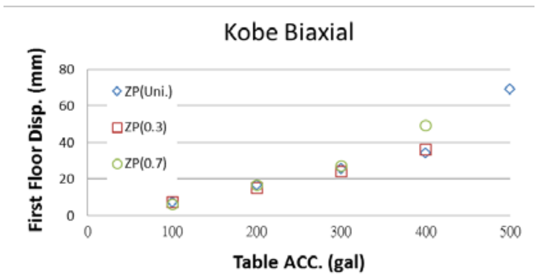
Figure 7 shows the effect of intensity level of transverse earthquakes on seismic response for structures base-isolated by polynomial rocking bearings with aspect ratio of 3. It can be seen that structural response of base-isolated structure excited by 100% intensity level of longitudinal plus 70% of transverse earthquakes is the largest, followed by 100% intensity level of longitudinal plus 30% transverse, and then uni-axial earthquakes. The higher intensity of transverse earthquakes excited, the larger the structural response was. Figure 8 shows the effect of various aspect ratio of the bearing on seismic response for structures base-isolated with polynomial rocking bearing. It is found that structural response except damping is increased with the increase of aspect ratio of the bearing. Figure 9 shows the effect of rocking surface on seismic response for base-isolated structures. It is found that structures isolated with polynomial bearings may have lower uplift and damping, but similar roof acceleration and displacement with plane bearings. Compared with negative stiffness after rocking exhibited in plane bearings, lateral stiffness of polynomial bearings is increased by rocking on concave or convex surfaces to lengthen its moment-resistant lever arm. This extending lever arm provides additional safety of overturning for polynomial bearings. Based on the test results as shown in Figures 5-9, the radiation damping of rocking systems is found less than 4% for all tests, without any damage incurred under earthquakes.



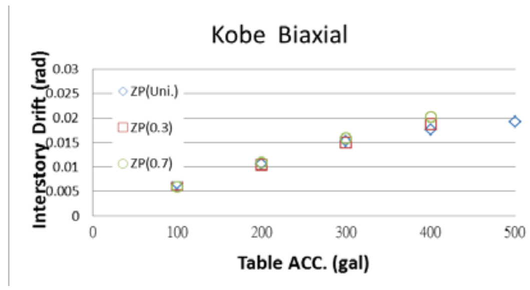
a) roof acceleration



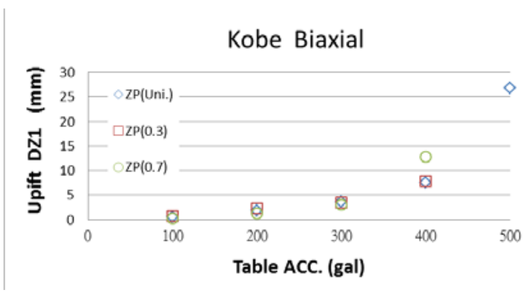
b) roof displacement



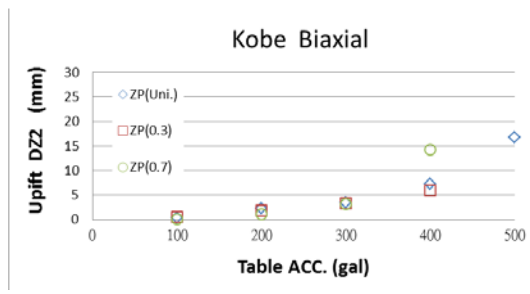
c) isolator displacement



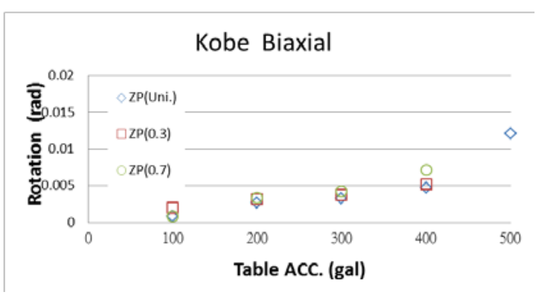
d) interstory drift



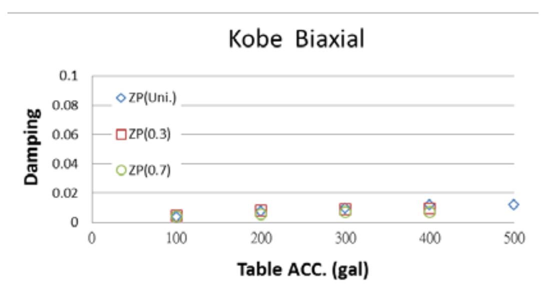
e) uplift of floor DZ1



f) uplift of floor DZ2

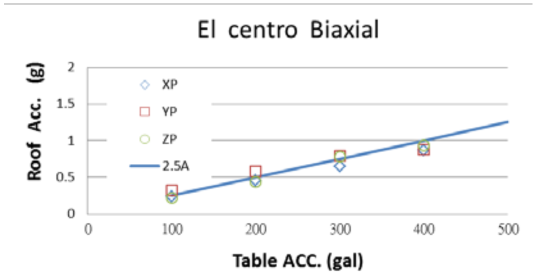


g) plane rotation

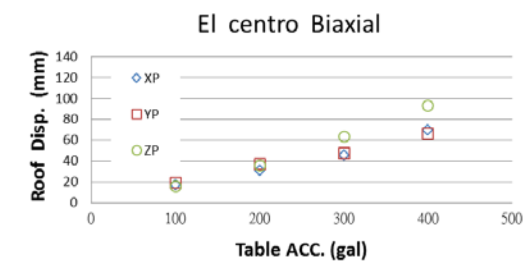


h) damping of structures

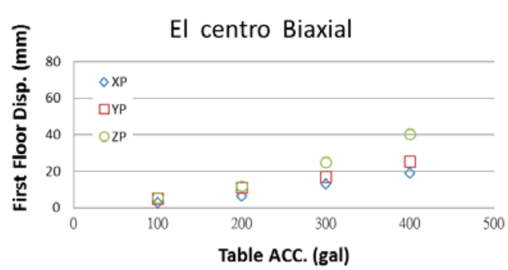
Figure 7 Effect of intensity level of transverse earthquake on seismic response for structures base-isolated by polynomial rocking bearing with aspect ratio of 3



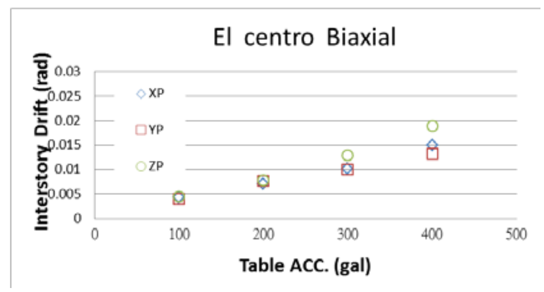
a) roof acceleration



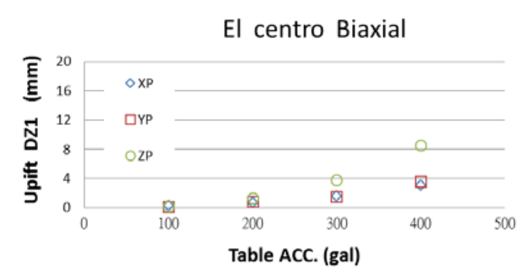
b) roof displacement



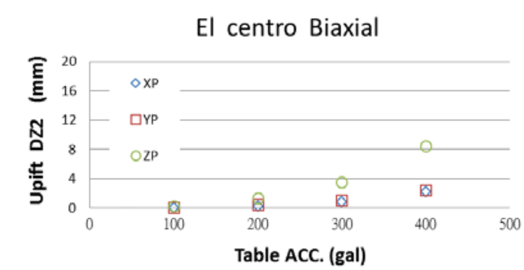
c) isolator displacement



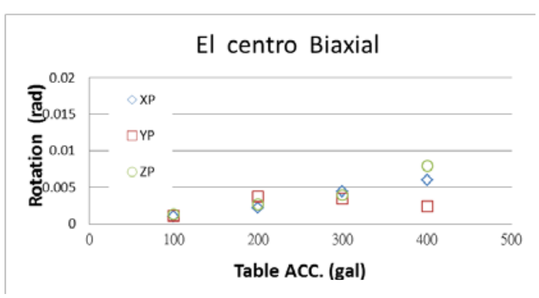
d) interstory drift



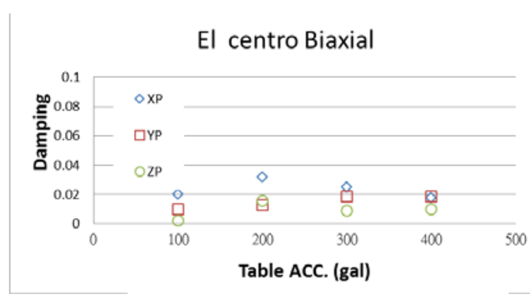
e) uplift of floor DZ1



f) uplift of floor DZ2

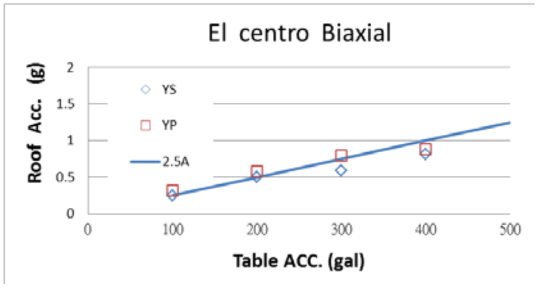


g) plane rotation

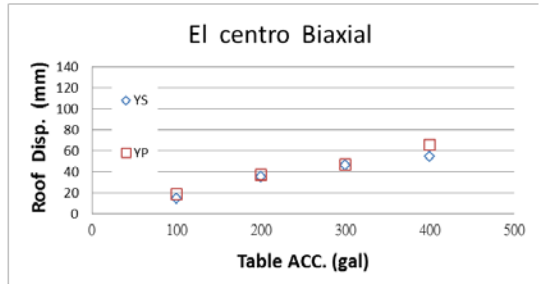


h) damping of structures

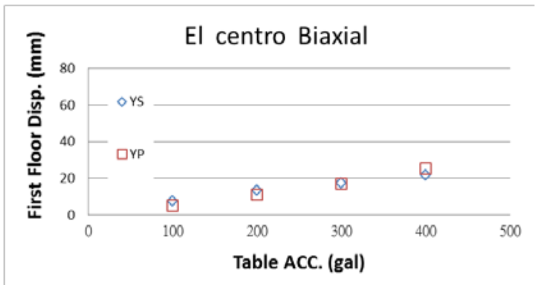
Figure 8 Effect of aspect ratio of the bearing on seismic response for structures base-isolated with polynomial rocking bearing



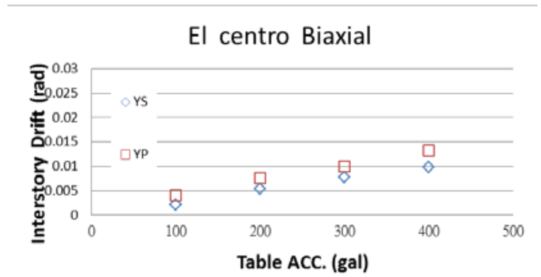
b) roof acceleration



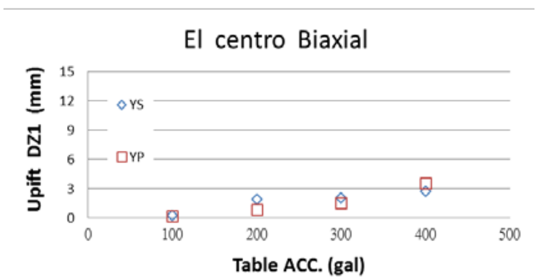
b) roof displacement



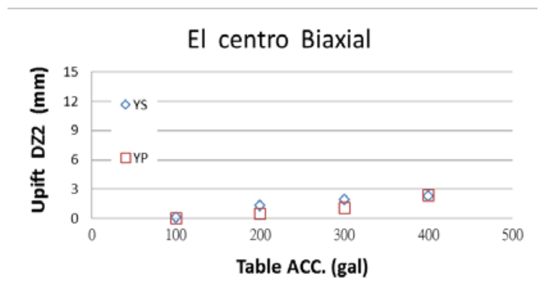
c) isolator displacement



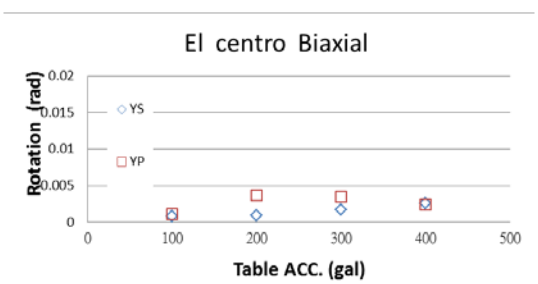
d) interstory drift



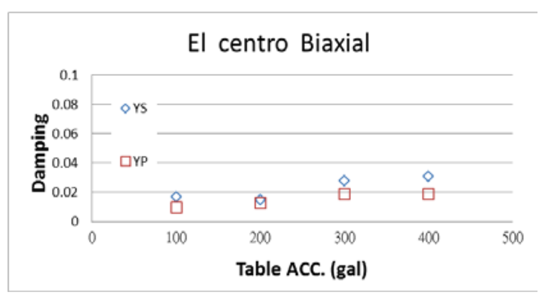
e) uplift of floor DZ1



f) uplift of floor DZ2



g) plane rotation



h) damping of structures

Figure 9 Effect of rocking interface on seismic response for base-isolated structures

4. Conclusions

Based on 236 shaking table tests, following conclusions can be drawn:

1. The vibrating frequency tends to decrease with the increase of ground acceleration, showing nonlinear rocking behavior of the bearing. It manifests that rocking-isolated structure exhibits variable frequency under

excitations to avoid resonant-like response that conventional isolators may encounter in long-period earthquakes.

2. Structural response of base-isolated structure excited by bi-horizontal earthquakes is the largest, followed by uni-axial, and then bi-directional with horizontal plus vertical earthquakes. Due to the restrain of spring force at rocking interface, seismic response for structures excited by horizontal plus vertical earthquakes is found similar to those excited by uni-axial earthquakes. Comparing with uni-axial earthquakes, the increase of intnsity level of additional transverse earthquake will increase its structural respsonse.
3. Without any damage incurred under earthquakes, the radiation damping of rocking system is found less than 4% for all tests.
4. It is found that structural response except damping is increased with the increase of aspect ratio of the bearing.
5. Compared with negative stiffness after rocking as exhibited in plane bearing, lateral stiffness of polynomial bearings is increased due to additional concave or convex surfaces. This extending part provides additional safety of overturning for polynomial bearings. While test results indicate that the effect of rocking surface is marginal, this may be attributed to not large enough rocking amplitudes.

5. Acknowledgements

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