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EXPERIMENTAL AND THEORETICAL ANALYSIS ON THE PRB BASE ISOLATION SYSTEM

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ABSTRACT

Using base isolators for the aseismic design of structures has attracted considerable attention in recent years. The authors have proposed in previous papers the PRB (Pendulum Rubber Bearing) base-isolation system. The main objective of the present paper is to summarize the experimental and theoretical study on this system. Extensive experimental research has been carried out on a full scale model. The model consists of two rigid R/C platforms of a triangular shape. Each platform has three bearings for the columns. In the clearances between the pendulum and bearing, a rubber gasket was introduced. At the ends of the pendulum, two steel plates (calottes), spherically shaped, were mounted. The parameters of the system are the radius of the steel spherical calottes and the dimensions of the rubber gaskets. Static loading tests, free vibration tests and forced vibration tests on the PRB system mounted on the shaking table were performed. Analytical studies were carried out to determine the seismic response of the structures on the PRB base-isolation system. The paper describes major results: the measured hysteresis loops of the system for different values of the parameters, the dissipated energy, the response of the isolated structure to a harmonic excitation and the response of the isolated structure at El Centro earthquake input data.

KEYWORDS

Earthquake engineering, seismic isolation, passive control, base isolation, response control, dynamic response.

STRUCTURAL RESPONSE CONTROL

There are two ways of protecting structures from the effects of earthquake ground motions. The first one is based on the conventional design philosophy, and the second - on the structural response-control. In accordance with the traditional design philosophy of earthquake resistant design for buildings, based on economic considerations, structures should be able to resist minor earthquakes without damages, resist moderate earthquakes without structural damages but with some nonstructural damages, and resist major earthquakes with some structural as well as nonstructural damages, but without collapse. The structures designed for the seismic loads normally recommended by codes can survive strong ground shakings only if they have sufficient ability to dissipate seismic energy. The energy dissipated by inelastic deformations requires adequate ductility of the elements in the structure. A good traditional design, that assumes several yielding lines, may assure these demands. Economically it is not feasible to continue this designing tradition. We are convinced that in the future the conventional technique will be considered as a starting point for the earthquake-resistant structures design. The use of structural response-control to create earthquake-resistant structures is a radical departure from the traditional approaches used by structural engineers. Although the first patent was conferred in 1870, the structural response-control has been developed in the last two decades. There have been made many propositions in this respect.

The principle of the seismic response-control may be put into evidence by the differential equation of motion:

$$my + f(y, y) + ky = -mu \tag{1}$$

The seismic force is given by:

$$S = m(u + y) = -m(\frac{f(y, y)}{m} + \omega^2 y) \tag{2}$$

So that for zero seismic force, the following relations must be satisfied:

$$\omega = 0 \tag{3}$$

$$f(y, y) = 0 \tag{4}$$

The first one is easy to accomplish by mounting the base of the structure on balls or rolls (Olariu, 1994a). But in this way the building would be irreversibly displaced. To accomplish the second requirement there must be produced a force equal and opposite to that given by (4). This force may be active, case in which a feedback system may be achieved, or may be passive, the system being nonfeedback.

THE PENDULUM RUBBER BEARING (PRB) SYSTEM

The most common method of seismically isolating structure is by mounting them on laminated-rubber bearings. The insulating material plays both rolls of supporting the vertical loads of the building and of dissipating energy.

a.   b.

Fig. 1. The PRB System. a. View of the pendulum unit. b. The column mounted in the platform

This fact situates the statical equillibrium position of the system always in the inelastic range, having the disadvantage of a small life duration on account of fatigue considerations. The authors have proposed in previous papers (Pocanschi and Olariu, 1980, Olariu *at al.*, 1982, Olariu and Olariu, 1992, Olariu *at al.*, 1994b) the PRB (Pendulum Rubber Bearing) base-isolation system. The main objective of the present paper is to summarize the experimental and theoretical study on this system.

The system consists of a series of short pendular R/C columns fixed on the top in the superstructure and at the bottom in the foundation, laterally embedded in a mass of rubber (neopren). The steel calottes fixed at the ends of the columns are spherically shaped. The force needed to produce displacement of the PRB bearing consists of the combination of restoring force during the induced rising of the structure along the spherical surface and of elastic reversible force accumulated by rubber. The kinetic energy absorbed by the system from the ground motion is partly dissipated by inner friction. The system combines the advantages of kinematic systems with those of the LRB ones. Unlike other systems, the new type of isolator has the possibility to ensure the general stability of the structure against the overturning moments. As the rubber is not subjected to compression except during earthquakes, its "aging" danger is diminished.

The period of vibration of the kinematic system is independent of the supported mass of the structure and depends only on the radius of the spherical calottes. The properties of flexibility and energy absorbtion capability are not interrelated. The former is entirely controlled by geometry of the calottes and the latter is controlled by the volume of the insulated rubber. This property allows for optimum design of the PRB isolation system.

TESTS DESCRIPTION

Experimental Elements

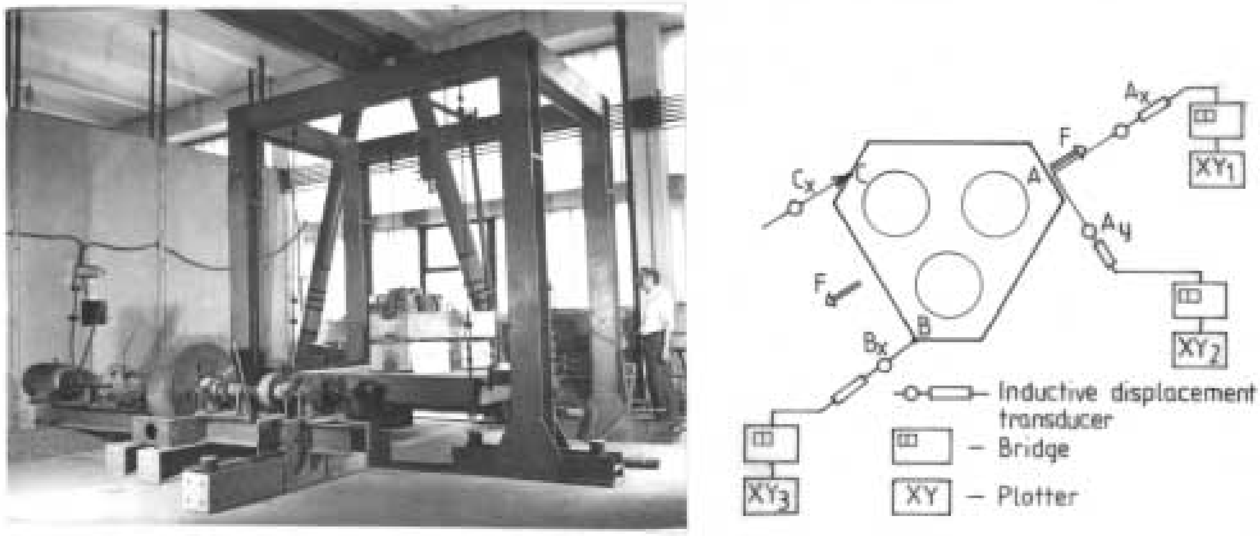
Extensive experimental research has been carried out on a full scale model. The model consists of two rigid R/C platforms of a triangular shape (Fig.1b). Each platform has three bearings for the columns(Fig.1a). In the clearances between the pendulum and bearing, a rubber gasket was introduced. The gasket was vulcanized in a special matrix. At the ends of the pendulum, two steel plates (calottes), spherically shaped, were mounted. The parameters of the system are:
- the radius of the steel spherical calottes (three variants: 17.5, 21 and 28 cm.);
- the dimensions of the rubber gaskets (three variants: 5, 10 and 15 cm. at the base, named type A, B and C, respectively.

So that, nine different specimens of PRB system have been tested. The following tests were performed:
- static loading tests;
- free vibration tests on the PRB system;
- forced vibration tests on the system mounted on the shaking table (Fig.2a).

The tests have been conducted for all the values of the parameters.

Static Loading Tests

The dynamic response of an isolated structure is strongly influenced by the mechanical properties of the isolation system. To determine the hysteresis loops of a pendular unit, alternate reverse force cycles in five steps were applied the upper platform, in the direction of the mass center of gravity.

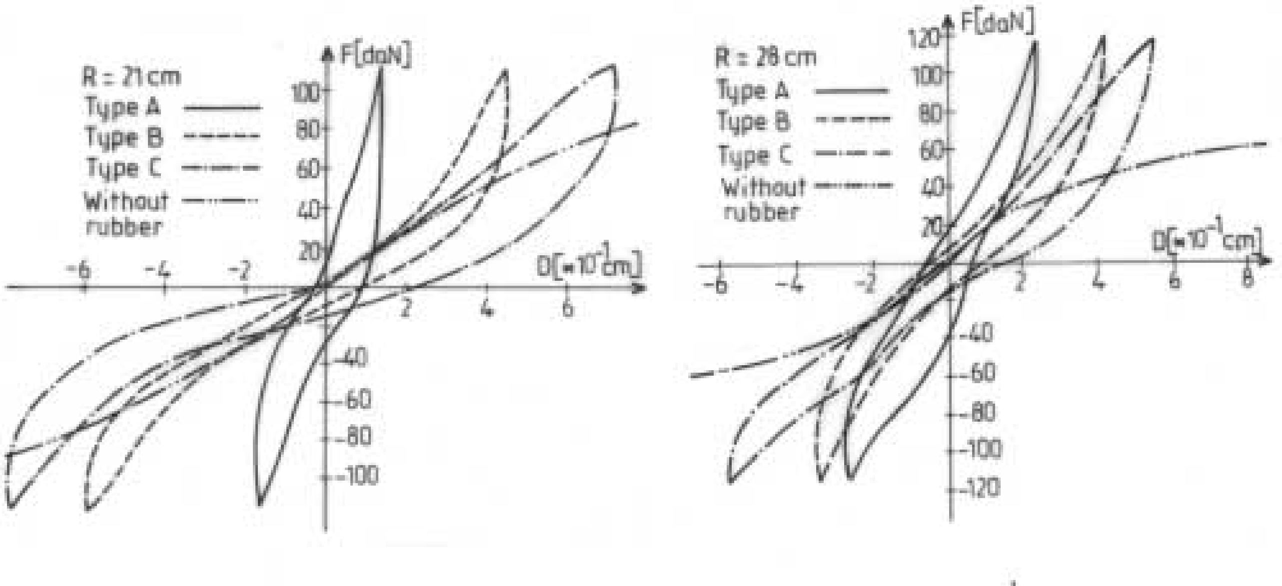


a. b.

Fig. 2. The mock-up on the shaking table. a. General view. b. The instrumentation network.

Free Vibration Tests

Snap-back tests were performed with the shaking table kept steady. The mock-up was pulled toward a fixed stiff frame located outside the table by means of a hydraulic jack acting in the direction of the mass center of gravity. After reaching the imposed displacement, the mass was released using a mechanical uncoupling device. The initial displacement was equal to 72 mm. The instrumentation network installed to record the mock-up response during the snap-back tests and the location of the transducers was designed so as to be able to describe completely the 2D motion of the upper plate, considered as a rigid body. Three networks composed by an inductive displacement transducers, a bridge and an XY plotter were used, as it may be seen in Fig.2b.



a. b.

Fig. 3. The hysteresis loops. a. R=21 cm. b. R=28 cm.

Forced Vibration Tests

Sinusoidal forced vibrations, as usually requested for an accurate dynamic structural characterization, were applied to the 1D shaking table. The applied oscillations have variable frequencies (from 0 to 4,70 Hz.) and amplitudes (0,35 to 0,80), so that the accelerations are also variable (0 to 0.5g).

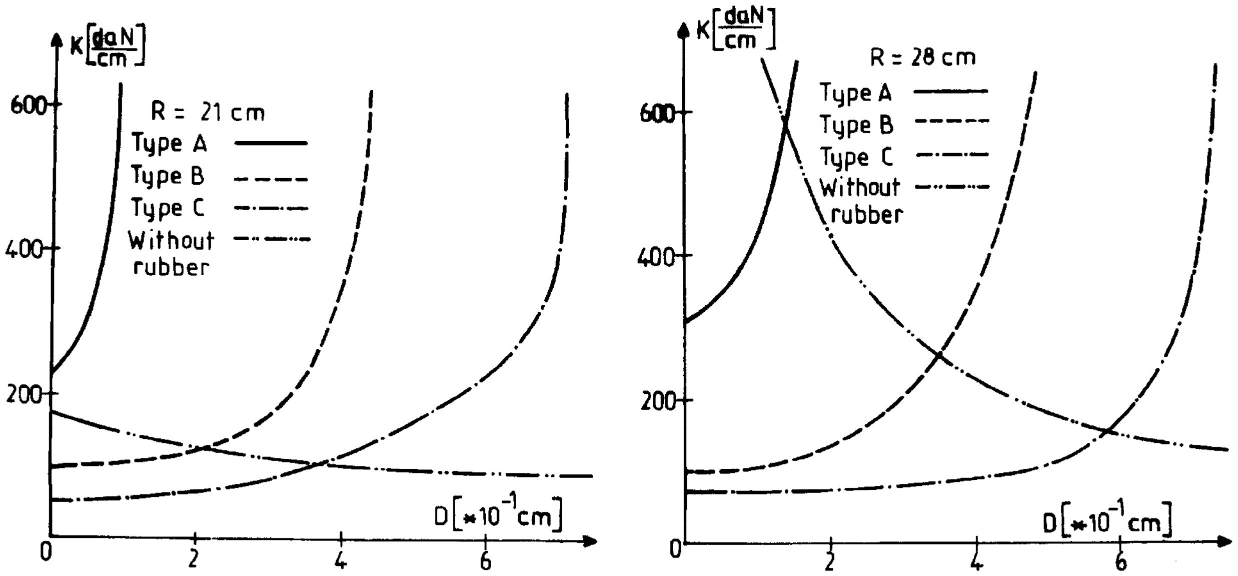
EXPERIMENTAL RESULTS

Hysteresis Loops

Figure 3 shows the hysteresis loops, obtained during the static loading tests for the model with R=21 cm. (Fig.3a) and with R=28 cm. (Fig.3b). Each figure is plotted for all the three types of rubber gaskets.

Stiffnes Variation

The stiffness variation of the isolation system may be seen in Fig. 4a (for R=21 cm.) and in Fig. 4b(for R=28 cm.). All types af pendular units are considered.

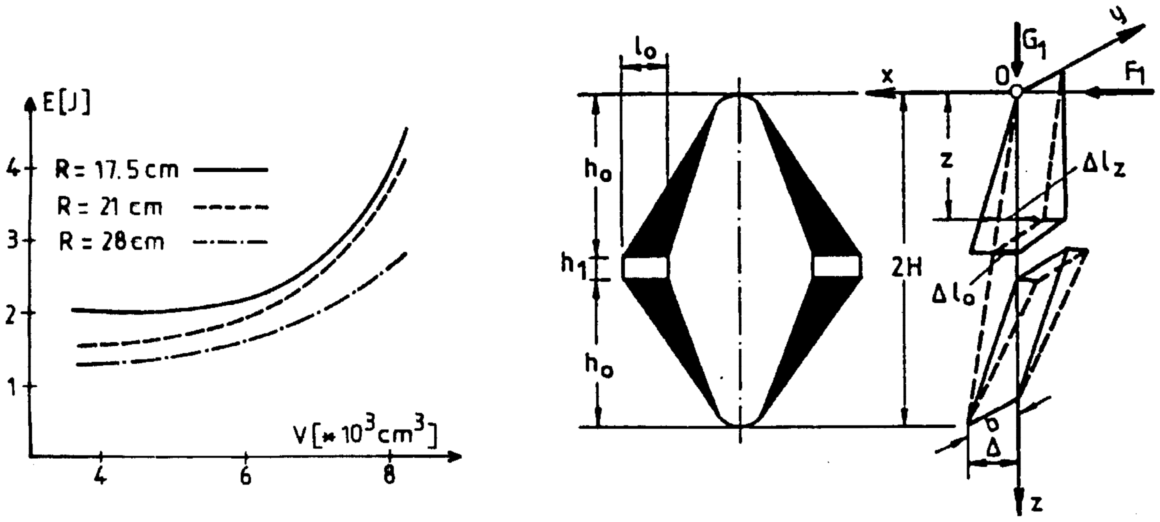


a. b.

Fig. 4. The stiffness variation. a. R=21 cm. b. R=28 cm.

Energy Dissipation Capacity

Figure 5a indicates the energy dissipation capacity of the model in different configurations as a function of the rubber volume.



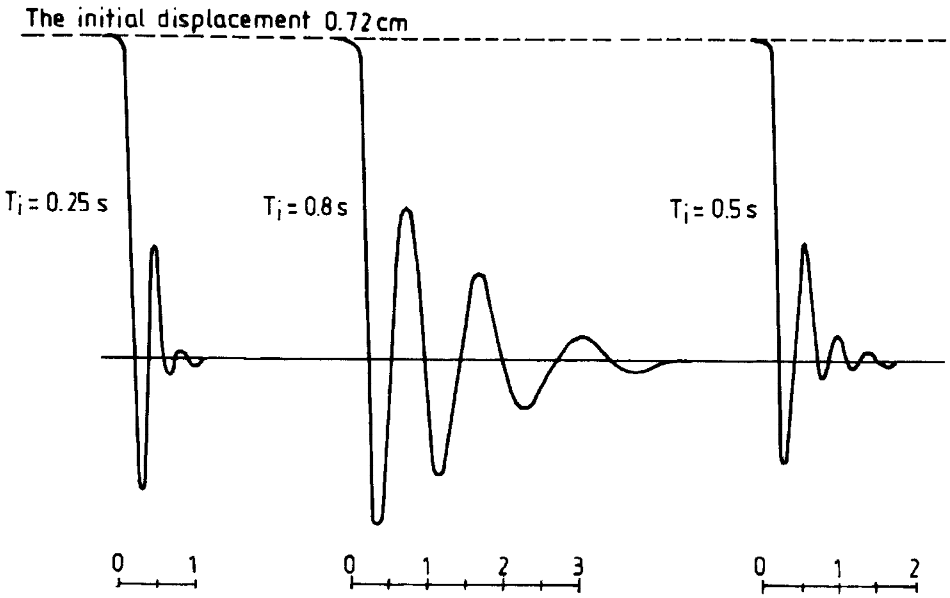
a.

b.

Fig. 5. The dissipated energy (a.) and the deformation pattern of a unit (b.)

Free vibrations

The displacement time history in the direction of the applied pulling force, recorded during the snap-back test, of the R=21 cm. model, is presented in Fig.6 for the type A (a), B (b) and C (c).



a.

b.

c.

Fig. 6. Free vibrations response

Forced Vibrations

Figure 7 shows the displacement time history of the shaking table (Fig. 7a) and of the model without rubber (Fig. 7b) during the forced vibrations tests.

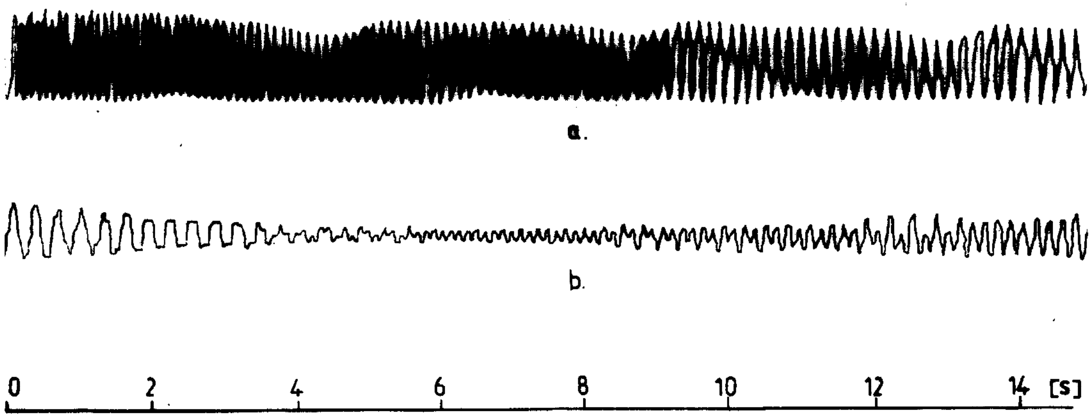
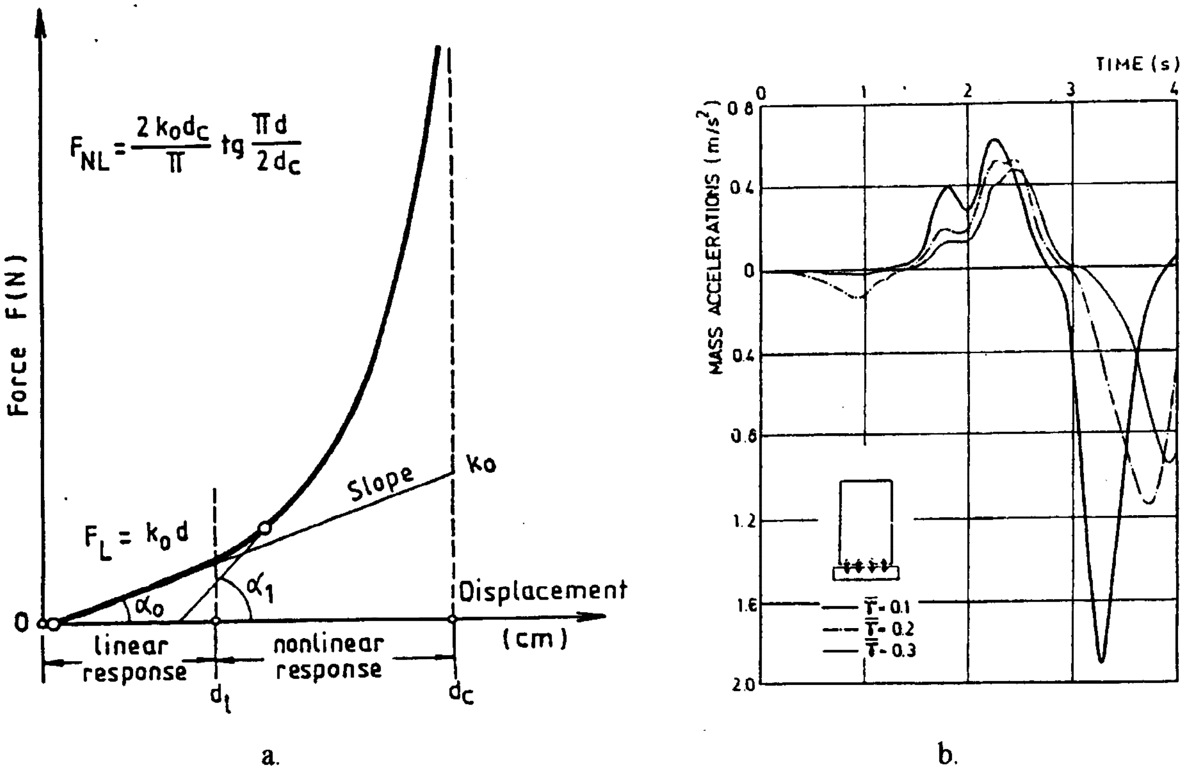


Fig. 7. Forced vibrations response. a. Shaking table vibrations. b. Model response.

ANALYTICAL STUDY

Stiffness Characteristics of a Pendular Unit

The stiffness of the system is represented by a tangential function of the relative displacement (Fig.8a). On account of the nonlinearity in stiffness represented by a tangential function of the relative displacement, the response has an inherent stabilizing effect. The stiffness K_0 of a pendular unit for elastic linear range of



a. b.

Fig. 8. a. Force - displacement diagram. b. Acceleration response.

deformation results from the energetical equilibrium under a unit lateral base displacement. According to the notations from Fig. 5b, the strain energy of a damping unit may be written as (Pocanschi and Olariu, 1980):

$$L_i = \int_0^{l_0}\int_0^{b}\int_0^{h_0} \frac{1}{2}\frac{z^2 \Delta l_0^2 E_0}{h_0^2 l_0^2} dxdydz \tag{5}$$

For the unit displacement $\Delta = 1$:

$$K_0 = \frac{E_0 b h_0^3}{6 l_0 H^2} = \frac{E_0 b h_0^3}{12 H^3 \gamma} \tag{6}$$

DYNAMIC RESPONSE

Analytical studies were carried out to determine the seismic response of the structures on the PRB base-isolation system. An original computer program worked out by authors, based on a step-by-step algorithm (Newmark and Runge-Kutta methods) has been used to solve several cases. As an example, a structure with a gravity load of 200 tf. was supposed to be provided with four pendular units with the following characteristics: b=20 cm., E_0=5 daN/cm, $\gamma = 0.1$; 0.2 and 0.3. Fig. 8b shows the acceleration response of the isolated structure to El Centro earthquake acceleration input.

CONCLUSIONS

The comprehensive study of all available data of our experimental and theoretical results leads to some general conclusions. The PRB system combines the advantages of kinematic system with those of the LRB system. The experimental and parametric tests results demonstrated substantial reductions of the structural acceleration and drift in comparison to the response of a non-isolated model. The PRB system grants a uniform behaviour at an earthquake acting in any direction. The period of vibration is almost independent of the supported mass. As expected, the free vibration curves indicate a damped response with a significant high value of damping. The smallest damping and frequency response have been obtained for the type B of pendulum unit. The hysteresis loops of the model are very stable. The stiffness and the dissipated energy of the model depend on the volume of the rubber gasket. Permanent displacements were found to be very small and not cumulative in successive earthquakes. The PRB system grants a constant performance, without decay for a large number of cycles. An analytical model capable to describe the response of the isolated structure was presented. The properties of flexibility and energy absorbtion capability are not interrelated. The former is entirely controlled by geometry of the calottes and the latter is controlled by the volume of the insulated rubber. This property allows for an optimum design of the PRB isolation system.

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