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USING ORTHOGONAL PAIRS OF RODS ON CONCAVE BEDS (OPRCB) AS A BASE ISOLATION DEVICE – PART (I): ANALYTICAL, EXPERIMENTAL AND NUMERICAL STUDIES OF OPRCB ISOLATORS

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ABSTRACT

A newly developed low-cost isolating system, not needing high technology for producing, and easily installable, is introduced for short- to mid-rise buildings, in which each isolator consists of two Orthogonal Pairs of Rods on Concave Beds (OPRCB). Rolling rods installed in two orthogonal directions make possible the movement of the superstructure in all horizontal directions. The concave beds give the system both restoring and re-centering capabilities. This paper presents the analytical formulations base, and the results of experimental and numerical studies of the system's mechanical feature. The effectiveness of the proposed isolation system in seismic response reduction of low- to mid-rise buildings is also shown by using an equivalent SDOF system. The lateral load displacement relationship of the rollers pair under various vertical loads has been obtained by both finite element analyses and laboratory tests of a prototype sample. The equivalent isolated SDOF systems and their fixed-base counterparts have been analyzed subjected to simultaneous effect of horizontal and vertical ground motions and their responses have been compared. Numerical results show that the amount of absolute acceleration in equivalent isolated SDOF systems, with equivalent mass of multistory buildings up to 14 stories can be reduced drastically in comparison with the fixed-base systems.

Introduction

Just very few cases of practical use of isolators in buildings before the 80s have been reported, of which one relates to construction of two buildings by using isolation layer consisting of top and bottom steel plates (plane or curved) with rollers between them in central China between 1968 and 1978 (Zhou 2001). Kelly (1983) discussed the economic feasibility of rehabilitation by seismic isolation technique, however, the first professional effort within the engineering community for developing the base-isolated buildings design provisions was started by Dr. Ron Mayes in California in late 80s, that resulted in the first set of design provisions for base-isolated buildings in the 1991 Uniform Building Code (Hart and Wong 2000).

As one of the first seismic isolators the Friction Pendulum System (FPS) can be mentioned, which is the first manufactured seismic isolation device to rely on a spherical sliding surface as a

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restoring mechanism (Zayas et al. 1987). Using rollers as seismic isolators is not also a new idea, however, very few academic studies has been performed in this regard prior to 1990. In early 90s the use of free rolling rods under basement has been studied for a one-story frame (Lin and Hone 1993). Jangid (1995) has also studied a sliding isolation system in the form of circular rolling rods. In those works the rolling rods were considered without any restoring force. As a result, there were more peak and residual base displacements. To overcome this difficulty the use of elliptical rods instead of the circular rods was suggested (Jangid and Londhe 1998). However, the elliptical rolling rods may induce some vertical acceleration into the superstructure. The other alternative was to use some re-centering device along with circular rolling rods to provide the restoring force for controlling the base displacement (Jangid 2000). Jangid has shown that the rolling rods are quite effective in reducing the earthquake response of the superstructure, and that the presence of a re-centering device significantly reduces the relative base displacement without transmitting additional accelerations into the superstructure. Another study has been done also on sloping surface roller bearing and its lateral stiffness measurement (Lee and Liang 2003). Recently, a similar isolator has been used in seismic isolation tests of a bridge model (Tsai et al. 2007).

In continuation of studies on rollers as isolators Hosseini and Kangarloo (2007) have introduced a somehow new isolating system which does not need high technology for construction, and is not costly as other existing systems like lead-rubber bearing, or friction pendulum bearing systems. That system consists of two pairs of orthogonal steel rollers, making possible the movement of the superstructure in all horizontal directions. Rollers move on a cylindrical steel bed, which gives a restoring capability to the system. The two rollers of each pair are connected together at both ends with two plates with hinges. This makes the two rollers of each pair to move together and have the same elevation in the cylindrical bed at any instant during the earthquake. The natural period of the system is almost independent of the superstructure mass, and is basically a function of r/R ratio in which r is the radius of the rollers and R is the radius of the cylindrical beds. In that study to obtain the appropriate values of r and R to reach a specific value of the natural period of the isolated system, in addition to analytical hand calculations, some numerical Finite Element calculations have been performed, and verified by laboratory tests. Following Hosseini and Kangarloo' studies, recently Hosseini and Soroor (2009), calling the system "Orthogonal Pairs of Rods on Concave Beds (OPRCB)" have continued studies on this type of isolating system. This paper presents very briefly the a part of that study, containing the analytical, experimental and numerical investigations on OPRCB isolators.

General Features of the OPRCB Devices

Main parts of the proposed isolator, called Orthogonal Pairs of Rods on Concave Beds (OPRCB) and its prototype sample are shown in Figs. 1 and 2, and the specifications of its manufacturing steel material in Table 1.

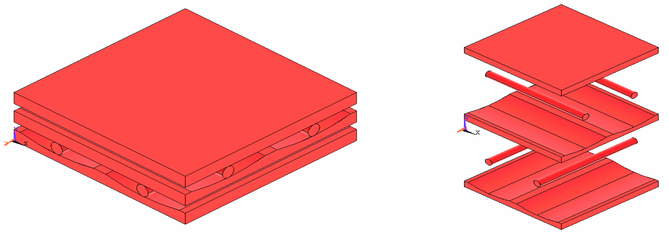


Figure 1. The components of OPRCB isolator

(a) (b)

Figure 2. The proposed isolation system: (a) A set of the prototype sample under test, and (b) One pair of rolling rods on their concave beds

Table 1. Assigned names and usage of the used steel alloy for making the OPRCB parts, and the specifications of the steel material of the OPRCB isolators (Ref: Key to steel 1995)

Steel group	Assigned name in different standards							Application
Hot forming and heat treatment (high quality alloyed)	IASC MARK	SYMBOL DIN	DIN	SARSTAHL ROCHLING	B.S	SWEDEN	A.I.S.I SAE/ASTM	For automotive and aircraft components with high toughness as axle journals, gears, tyres, push rods,rollers in concrete and steel industies, high resistance bolts.
	IASC7225	42CrMo4	1.7225	MO40	708M40	42CrMo4	4140(SAE)	

chemical composition (%)													
C		Cr		Mn		Mo		P		S		Si	
from	t0	from	to	from	to	from	to	from	to	from	to	from	to
0.38	0.45	0.8	1.2	0.6	1	0.2	0.3	0	0.02	0	0.015	0	0.6
yielding stress is 900 N/mm^2 based on Key to steel 1995													

Analytical Study of the OPRCB Isolators

To derive the equation of motion of a SDOF system, isolated by OPRCB isolators, it is noted that because of the curved beds any horizontal motion, u_b, as shown in Fig. 3, leads to a vertical motion, v_b, which creates a vertical acceleration as well, as shown in Fig. 4.

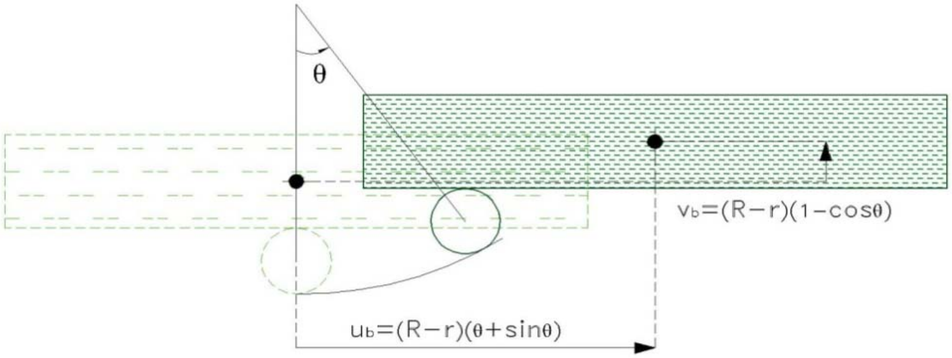
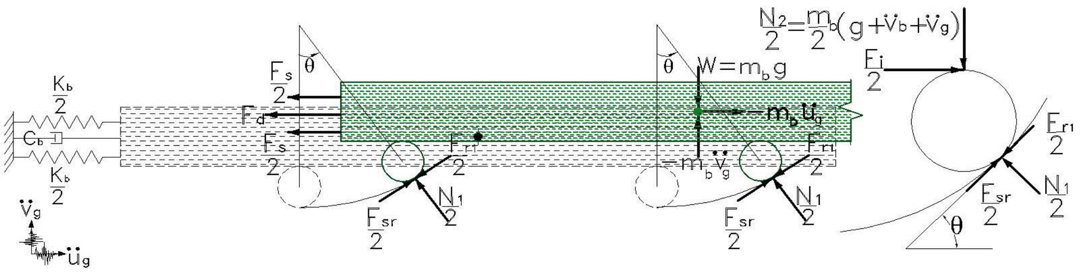


Figure 3. The horizontal and vertical motions of a SDOF system on OPRCB isolators



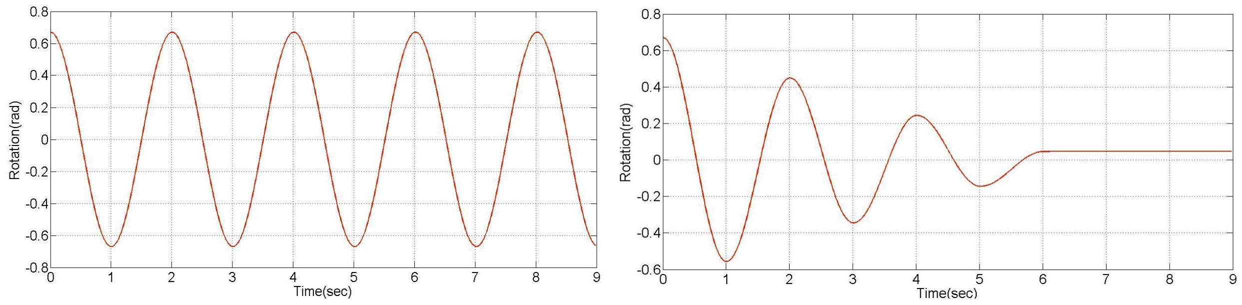
(a) (b)

Figure 4. The forces engaged in: (a) the motion of the SDOF system on OPRCB isolator subjected to horizontal and vertical components of ground acceleration, and (b) the forces engaged in the instantaneous equilibrium of each roller

As it is seen in Fig. 4, the acting forces on the isolated SDOF are the spring force, F_s, the damping force, F_d, the sliding friction force, F_{sr}, required for preventing the rollers from slippage during their motion, the rolling resistance force, F_{r1}, between the rollers and their beds, and F_i is the internal horizontal force between the rollers and the mass above them. The value of rolling resistance force, F_{r1}, is dependent on the coefficient of rolling resistance and the forces normal to the surfaces in contact. The coefficient of rolling resistance is itself a function of the normal force as explained in the main report of the study (Hosseini 2009). Considering the nonlinear nature of the problem, the most appropriate method for deriving the equation of motion is using the Lagrange equation, which results in (Hosseini 2009; Soroor 2009):

$$2\ddot{\theta}\cot\frac{\theta}{2}-\dot{\theta}^2+\frac{g}{R-r}+\frac{k_b}{m_b}\frac{(1+\cos\theta)(\theta+\sin\theta)}{\sin\theta}=\left[-\frac{\ddot{u}_g}{(R-r)\sin\theta}-\frac{c_b\dot{\theta}\cot\frac{\theta}{2}}{m_b}\right](1+\cos\theta)-\frac{\mathrm{sign}(\dot{\theta})\,F_r}{m_b(R-r)\sin\theta}-\frac{\ddot{v}_g}{R-r} \tag{1}$$

By solving Eq. (1) the response time histories of the SDOF system isolated by OPRCB devices can be obtained. It is seen that Eq. (1) is a nonlinear equation and does not have a classical solution. An appropriate approach for solving this equation is using the fourth order Runge-Kutta numerical method. To calculate the seismic response of the system by this method a program has been developed in MALTB environment (Soroor 2009). A very interesting finding from response calculations of SDOF system on OPRCB isolator is the independency of the free vibration response period of the system from the initial values of vibration amplitude, and also of the value of rolling resistance, in spite of its nonlinear behavior. To show this independency, the response histories of the prototype sample for the case of θ_0= 0.67rad, the maximum value for which rotation of rollers can happen without sliding (assuming a value of 0.35 for coefficient of sliding friction), are shown in Fig. 5 in two states of without and with rolling friction.



(a) without rolling friction (b) with rolling friction

Figure 5. Free vibration response time history, $\theta(t)$, of the test sample with θ_0= 0.67rad

It is seen in Fig. 5 that the period of free vibration response of the SDOF system on the prototype sample of OPRCB isolator is 2.00sec regardless of the existence of rolling friction, however, this friction has an effect very similar to Coulomb damping, leading to linear decrease of free vibration amplitude.

The Experimental Studies of the OPRCB Isolators

For studying the performance of the OPRCB isolating devices in different directions and to find out the effect of superstructure's weight on the system performance, some shaking table and cyclic or pseudo-dynamic tests were carried out. At first, by using a sake table the prototype model, shown in Fig. 2-a, the behavior of the isolating system subjected to lateral excitations were studied. Response histories of the system in two orthogonal directions to the a series of harmonic excitations with frequencies of 0.25, 0.5, 1, 3, and 5Hz, and also to the El Centro earthquake all applied to the system at an angle of 45 degrees with respect to the main axes of the rollers were obtained. The masses used in this test were 50, 110, and 400kg, but no difference was observed in the value of natural period of the system, as expected. Results of these tests can be found in the preliminary report of the study (Kangarloo, 2007). As the second phase of experimental studies the lower half and the mid plate of the prototype sample were tested by using two actuators, as shown in Fig. 6, subjected to various values of vertical loads, starting from 10.0tonf, with an increment of 5.0tonf, reaching finally a value of 70.0tonf, which is around the average gravity load acting on the ground floor columns of a conventional 5-story building.

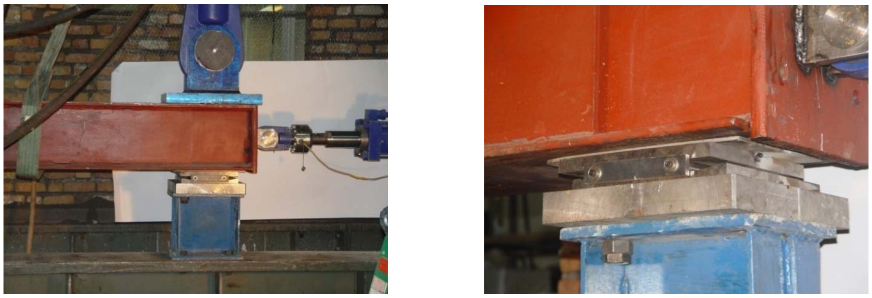


Figure 6. One pair of the OPRCB assembly in pseudo-dynamic test under vertical loads

Fig. 7 shows a sample of the results obtained by pseudo-dynamic tests for vertical load of 60.0tonf and 3.0cm lateral amplitude, showing the hysteretic behavior of the OPRCB device.

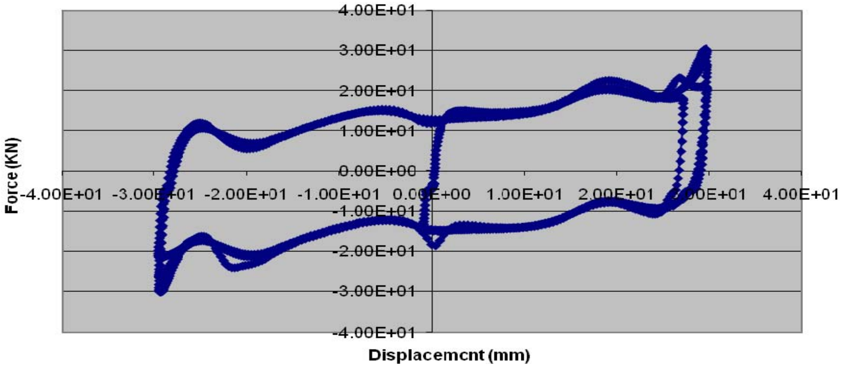


Figure 7. Hysteretic behavior of the sample isolator under 600kN vertical load in laboratory test

The rolling resistance as well as the lateral stiffness of the prototype OPRCB isolating system for various vertical loads have been obtained from graphs like the one shown in Fig. 7. However, to have these values for different values of beds and rollers radii numerical calculations were necessary, as explained in the next section.

Numerical Studies of the OPRCB Isolators

For numerical studies of the OPRCB isolators a finite element analysis program was employed and by using very fine meshing it was tried to investigate the stress values created in the rollers and their beds at the contact surfaces. A sample of obtained results related to the prototype sample, depicting the values of von Mises stress in rollers and their beds, is shown in Fig. 8.

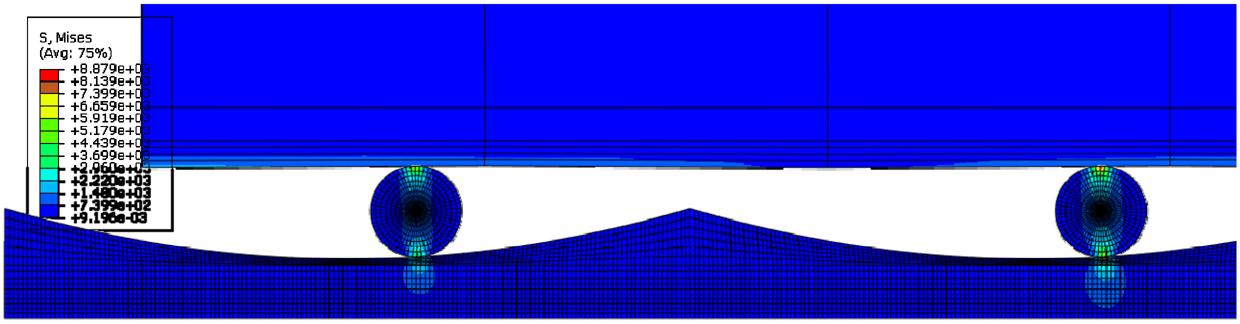


Figure 8. von Mises stresses for the prototype sample shown in Fig. 6 in case of 1.0cm lateral displacement under 600kN vertical load

The obtained stress values shows that yielding may not occur in rollers and their bed and the middle plate, provided that they are made of high strength steel, like MO40 alloy, whose yielding stress is around 900N/mm2 (see Table 1). By using the finite element analysis program in large displacement state and employing contact elements between rollers and adjacent surfaces the hysteretic behavior of the prototype sample, shown in Fig. 7, was obtained for various values of vertical loads (Soroor, 2009). A sample of these numerical results is shown in Fig. 9.

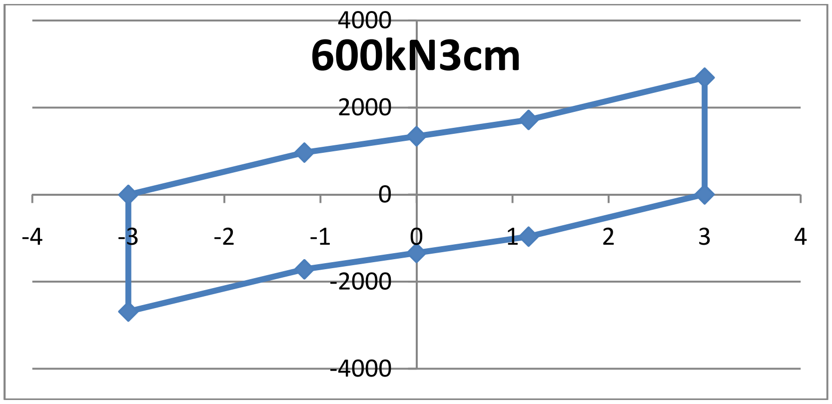


Figure 9. Von Misses stresses for the sample shown in Fig. 7 in case of 3.0cm lateral movement under 600kN vertical load

Comparison of Figs. 7 and 9 (and similar Figs. for other cases) shows that the experimental and numerical results are in good agreement, and therefore, it can be said that the values obtained by finite element analyses for rolling resistance and lateral stiffness of OPRCB isolators with different values of beds and rollers radii are reliable.

The Efficiency of OPRCB Devices in Seismic Isolation

To realize the efficiency of the OPRCB devices in seismic isolation of building systems, assuming that the stiffness of the isolated building is high enough to make it reasonable to consider the building as a rigid body with total mass of m_b, equation of motion for the isolated SDOF system can be used. Regarding that the value of rolling resistance force, F_r, is dependent on the value of rolling resistance coefficient, μ_r, and the values of normal forces between the rollers and their beds (N_1) and middle plate (N_2), and that the values of $\mu_{r(1,2)}$ themselves are dependent on the value of normal forces N_1 and/or N_2, whose values vary during each time step, it seems that the calculations get very complicated. However, since the time step in Runge-Kutta method is very short comparing to the time step of digitized accelerograms the variation of $N_{1,2}$ during these short time steps can be neglected and the calculated value of $N_{1,2}$ corresponding to the previous time step can be used for calculating the value of $\mu_{r(1,2)}$ in the next time step.

To show the efficiency of the OPRCB isolating system in decreasing the earthquake effect on the isolated systems the seismic responses of a SDOF system with a mass of 70ton (almost equivalent to the mass corresponding to the lowest-story columns of a 5-story building) and natural period of 0.5sec in fixed-base state, once with fixed base and once isolated have been calculated, to simultaneous effect of horizontal and vertical components of Tabas, Iran earthquake of 1978 with its PGA normalized to 0.5g. The time histories and spectra of Tabas earthquake and its various spectra are shown in Figs. 10 and 11 respectively, and the responses in Figs. 12 to 15.

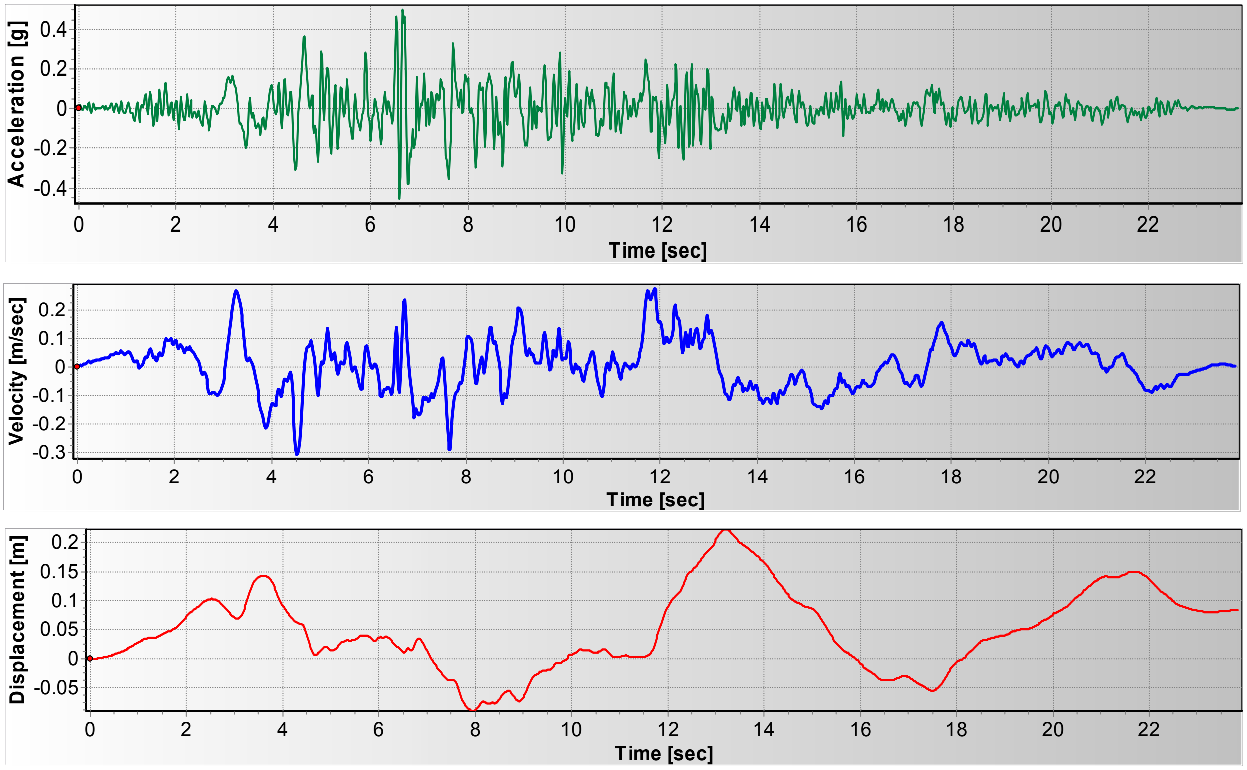


Figure 10. Acceleration, velocity, and displacement records of Tabas earthquake

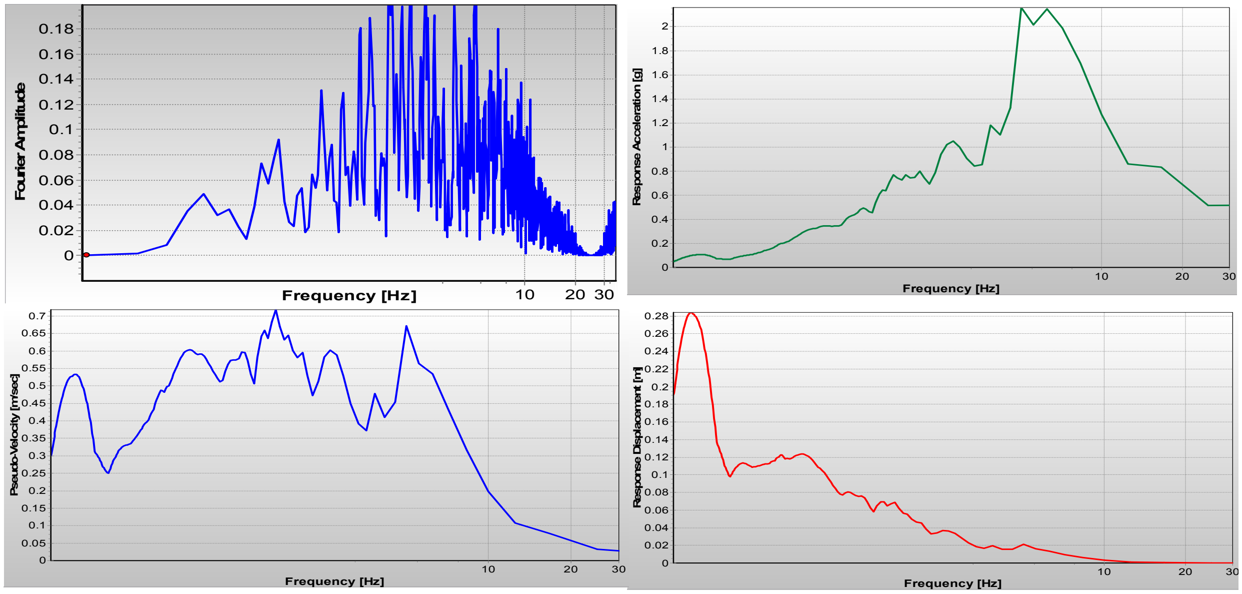


Figure 11. Tabas earthquake Fourier and response spectra

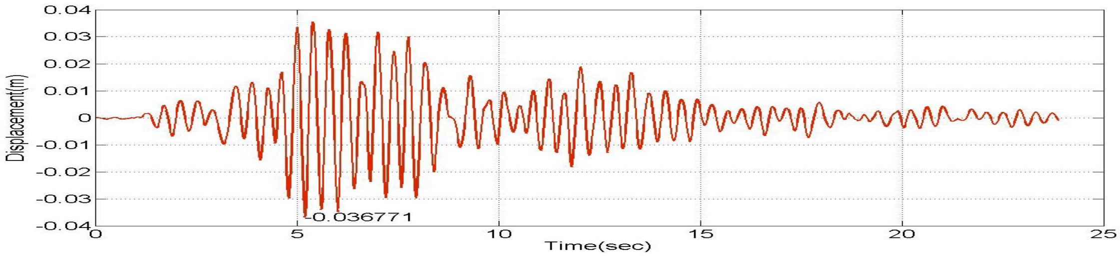


Figure 12. Displacement response history of the fixed-base equivalent 5-sotry building subjected to Tabas Earthquake

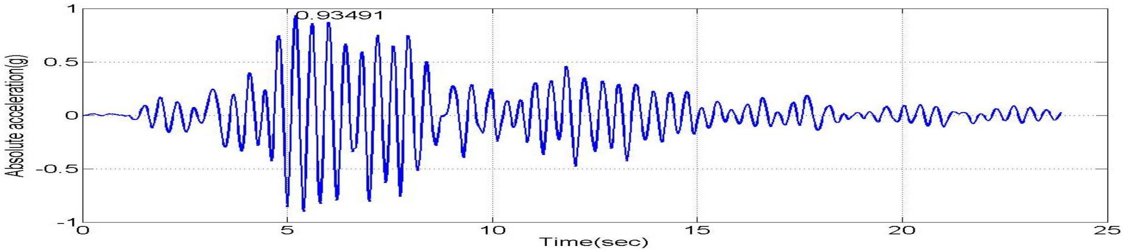


Figure 13. Acceleration response history of the fixed-base equivalent 5-story building subjected to Tabas Earthquake

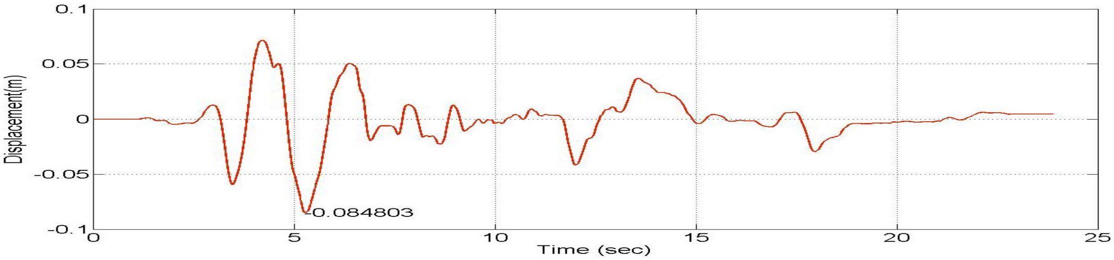


Figure 14. Displacement response history of the equivalent 5-story building isolated by the prototype OPRCB device subjected to Tabas Earthquake

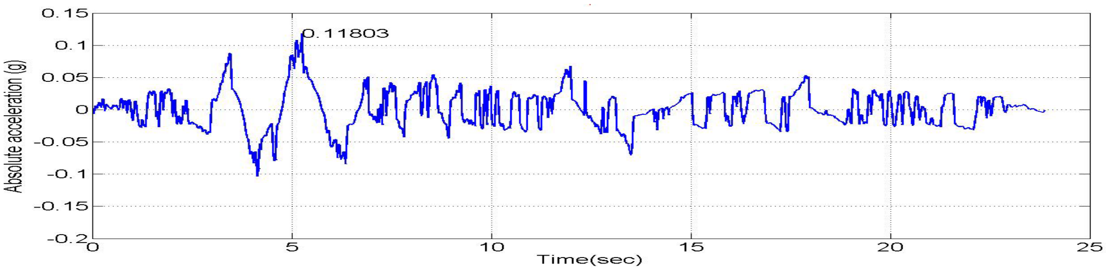


Figure 15. Acceleration response history of the equivalent 5-story building isolated by the prototype OPRCB device subjected to Tabas Earthquake

It can be seen in Figs. 12 to 15 that the peak displacement response of isolated system is almost twice as its fixed-base response, while its peak absolute acceleration response is just around 12% of its fixed-base response. It is also noticeable that the peak displacement response of the isolated system is almost 1/3rd of the maximum ground displacement and its peak acceleration response is almost 1/4th of the PGA value of the record. Response histories obtained for other values of bed's and rollers' radii show that the responses can be controlled easily for each earthquake and getting lower absolute acceleration responses is possible (Hosseini 2009; Soroor, 2009).

Conclusions

Based on the analytical formulations, the experimental and numerical results and also dynamic response calculations of SDOF systems isolated by OPRCB devices it is concluded that:

- The OPRCB seismic isolating system has a good performance for low- to mid-rise buildings, and can reduce the absolute acceleration of the isolated system up to ten times
- The effective natural period of the isolated system can be easily controlled by the ratio of rollers' radius to concave bed's radius (r/R), and achieving a period of 2.5 second or more is possible with no difficulty.
- In spite of the nonlinear force-displacement behavior of the OPRCB isolators the natural period of SDOF system isolated by this device is independent of the displacement amplitude and the rolling resistance, which gives a damping of the Coulomb type to the system.
- The advantages of OPRCB isolators, including simplicity of production and installation, low cost, and relatively small dimensions and low weight, are very encouraging for proposing its practical use in low- to mid-rise buildings.

Finally, it should be noted that keeping the dimensions of the OPRCB base isolators as low as possible is very important for practical advantages. However, in case of some near-field earthquakes, in which occurrence of large amplitude long period pulses is likely, the maximum displacement which the isolator should facilitate may be very large. To assure how large this displacement may need to be, more investigations are required.

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