



A Numerical Evaluation of Anti-Vibration Mechanisms Applied to Frame Structures Under Earthquake

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ABSTRACT

Earthquakes are of great concerns to nuclear engineers. The consequences of earthquakes on nuclear reactors may even be the "shutdown" of nuclear power plant. Rather than increasing the structure's stiffness, one way to reduce the earthquake damages is the use of anti-vibration mechanisms. This paper deals with numerical evaluation of the efficiency of anti-vibration mechanisms applied to typical frame structures under earthquake. The most common vibration isolators and controllers are shortly described. To show the effectiveness of some anti-vibration mechanisms, an application example is presented. The building structure is modeled by finite elements, an anti-vibration mechanism is placed at the building base with special finite element, and an artificial earthquake equivalent to El Centro is generated and applied at the building base. The behavior of the frame, with and without anti-vibration mechanisms, is compared. The results in terms of floor absolute and relative displacements and shear forces at the base are reported.

KEY WORDS: Dynamics of Structures, Anti-vibration Mechanisms, Vibration Isolation, Vibration Control, Earthquake Isolation, Earthquake Control, Avoiding Earthquake Damages, Isolation and Controllers.

INTRODUCTION

In the design of a nuclear power plant, earthquake loads must be considered. The structural system may go under minor damages in the so called "upset" condition or may even go out of operation if major damages take place during an "emergency" condition. In any case, it is essential to prevent any leak of radioactive material to the environment. Earthquakes are dangerous and unexpected phenomena of nature. They represent the largest natural menace to life in this planet, being responsible for the destruction of countless cities and towns in almost all continents. The damages caused have so much of social as economical consequences. Earthquakes, as the one in Kobe, Japan, characterize this tragic show: 5500 people died, 42.500 were wounded, more than 100.000 buildings completely destroyed and more than 250.000 seriously damaged. The total economic damage was estimated in 100 billion dollars. Table-1 summarizes the most hazardous earthquakes in the last 30 years and some of the damages they produced [1].

Table-1: Recent earthquakes in the world

Date	Region of the World	Deaths	Magnitude	Comments
09/Feb/1971	San Fernando, California	65	6.5	Half billion dollars in damages
23/Dec/1972	Managua, Nicaragua	5000	6.2	Practically destroy the capital Managua
04/Feb/1975	Haicheng, China	1328	7.4	Was predicted
04/Feb/1976	Guatemala	22000	7.9	The flaw broke approximately 200km
27/Jul/1976	Tangshan, China	650000	7.6	More fatal victims in the last century
18/Sep/1985	Mexico	10000	8.1	US\$ 3.5 billions of losses
17/Oct/1989	Loma Prieta, California	57	7.1	US\$ 6 billions of losses
17/Jan/1994	Northridge, California	62	6.7	Losses around US\$ 15 billions
16/Jan/1995	Kobe, Japan	5500	6.8	Estimated US\$ 100 billions of losses
26/Jan/2001	Gujarat, India	100000	7.9	Losses around US\$ 10 billions

Some earth tremors are not only due to tectonic/volcano activities, but due to Induced Seismicity (IS). So, depending on the location site of your construction, this type of earthquake may become a serious threat. The formation of huge artificial lake from hydroelectric dams, can induce earthquakes. Although, scarce and infrequent - as there are only few reported cases of meaningful IS - enormous water reservoirs and hydroelectric dams can cause IS. Table-2 reports some important IS cases [1,2].

In General, structures should be designed to withstand the worst possible earthquake, so that human lives can be protected and damages in structures minimized. The design philosophy should accept the possibility of damages in

structural systems. It is cheaper to repair/substitute small parts of a structure deteriorated by an earthquake than to build robust structure assuming it to be "stiff enough" to avoid "any" damage. Clearly this concept constitutes a challenging problem to engineers of "how to conceive an economical project of a structure that can be susceptible to damages but that will not collapse when submitted to the largest possible earthquake."

Table-2: Meaningful Induced Seismicity around the world

Dam Name	Place	Dam Height (m)	Dam Volume (x10 ⁶ m ³)	Year of the Inundation	Year of the Greater IS	Magnitude
Koina	India	103	2708	1964	1967	6.5
Kremasta	Greece	165	4750	1965	1966	6.3
Xinfengkiang	China	105	10500	1959	1962	6.1
Oroville	US	236	4295	1968	1975	5.9
Kariba	Rhodesia	128	160368	1959	1963	5.8
Aswan	Egypt	111	164000	n.a.	1981	5.6
Volta Redonda	Brazil	56	2300	1974	1974	4.2

For a long time, men have been searching for structures to "resist" the effects of earthquakes. Great progresses in this area have been achieved only in the last three decades. Many researches and laboratories around the world are trying to create efficient anti-vibration mechanisms to isolate buildings and minimize damages caused by earthquakes. This kind of research is increasing considerably with the advance of technology. Experimental mechanics techniques are efficient in measuring the structure's response under an earthquake. Such measurements are, generally, sparse, expensive, very time consuming, and not sufficient to completely describe the complete fields of displacement, strain, and stress of a structure under vibration. On the other hand, numerical techniques such as the finite element method and, more recently, the boundary element method, among others, are precise tools ready to determine the displacement, strain, and stress fields in the whole structure for a reduced cost and short computational time. However, such numerical techniques require an accurate knowledge of the boundary conditions, i.e., the results are highly dependent on the boundary conditions. The ideal approach to study the behavior of a structural system seems to be the hybrid numerical-experimental technique [3]. Combining them, one can reduce the drawbacks of both techniques. Numerical evaluation of anti-vibration mechanisms can thus be helpful. Passive or active anti-vibration mechanisms are presently very well accepted. In this paper some anti-vibration mechanisms are presented. A typical frame structure with and without anti-vibration mechanism is submitted to a synthetic earthquake. The efficiency of such mechanisms are computed and compared. The response of the frame structure is determined by the finite element technique using standard software.

ANTI-VIBRATION MECHANISMS

Two main anti-vibration mechanisms are named isolators and controllers. Isolators cut off the ground motions arriving at the building bases, so that such motions are not completely transferred to the building structures. Controllers decrease the vibration amplitudes of the structure under earthquake, generally, with energy dissipators installed along the building parts.

Vibration controllers can be active or passive. Passive controllers need no information and no energy source to be put into action. Among the passive controllers, there are a) Tuned Mass Damper - TMD transfers the vibration energy from the structure to a mass tuned in one of the natural frequencies of the structure; b) Tuned Liquid Damper - TLD is similar to TMD, but, in this case, liquid replaces the tuned mass; and c) Viscoelastic Damper - VD converts part of the vibration energy into heat. Figure-1 shows passive controllers. Active controllers need some data from monitoring of the structure, so that their mechanisms can act. They are more efficient than passive systems but more expensive because an external energy source is needed to make them work. The Active Mass Damper and the Gyroscope are examples of active systems. Figure-2 illustrates some active controllers.

Isolators, as the name suggests, isolate the structure from the earthquake vibrations. They uncouple the structure from the ground motion, but still keep the equilibrium of the structure. Figure-3 shows the principle of an isolation system applied to a building frame. Among the principal isolators there are a) Rubber Bearing (RB); b) Lead Rubber Bearing (LRB); c) High Damping Laminated Rubber Bearing (HDLRB or HDRB); d) Frictional Pendulum System (FPS); and e) Resilient-Friction Base Isolator (RFBI). Figure-4 shows illustrations of isolation mechanisms.

Using numerical techniques, this paper evaluates the anti-seismic mechanism HDRB. Such isolator is applied at the base of a typical building frame. The behavior of the frame under a synthetic earthquake is observed considering the frame completely fixed at the ground, without the isolator, and with the HDRB isolator with different damping ratios applied to the frame bases. In the next section, the general Eq. and the corresponding rheological model governing HDRB are explained.

RHEOLOGICAL MODEL AND EQUATION FOR HRDB

The word "rheology" normally refers to the flow and deformation of "non-classical" materials such as rubber, molten plastics, etc.. In this sense, consider the rheological model of RB shown in Figure-5. Also consider that HDRB have a similar model. It is also assumed that the frame in Figure-3 remains in the elastic regime, and that all non-linearities are concentrated at the base in the isolator mechanism.

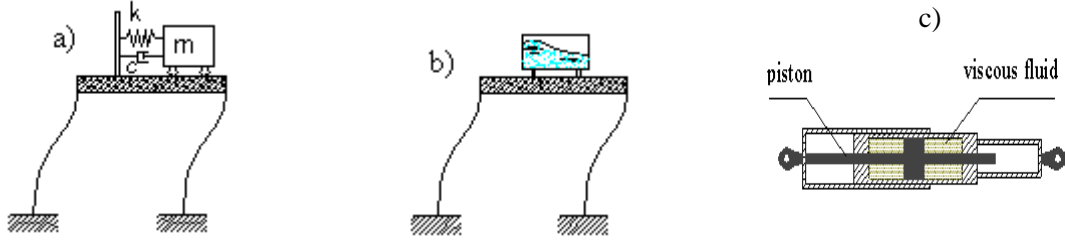


Figure-1: Passive controllers (a) Tuned Mass Dampers, (b) Tuned Liquid Dampers and (c) Viscous Damper

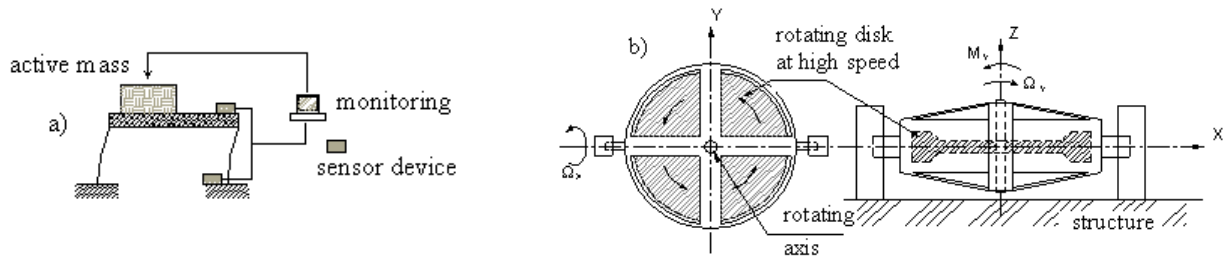


Figure-2: Active controllers (a) active mass and (b) gyroscope

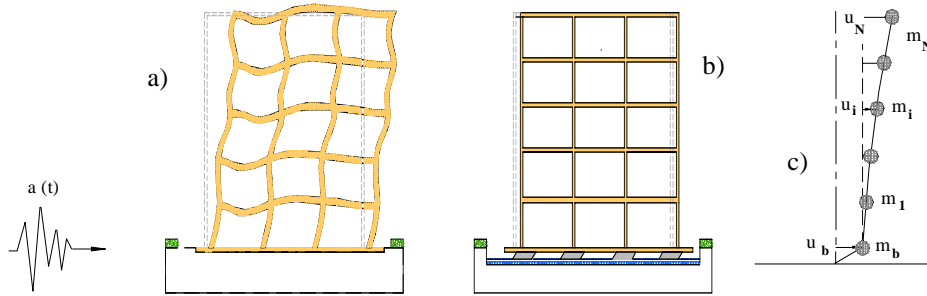


Figure-3: Structures under earthquake: (a) conventionally fixed and (b) "isolated" (c) dynamic model

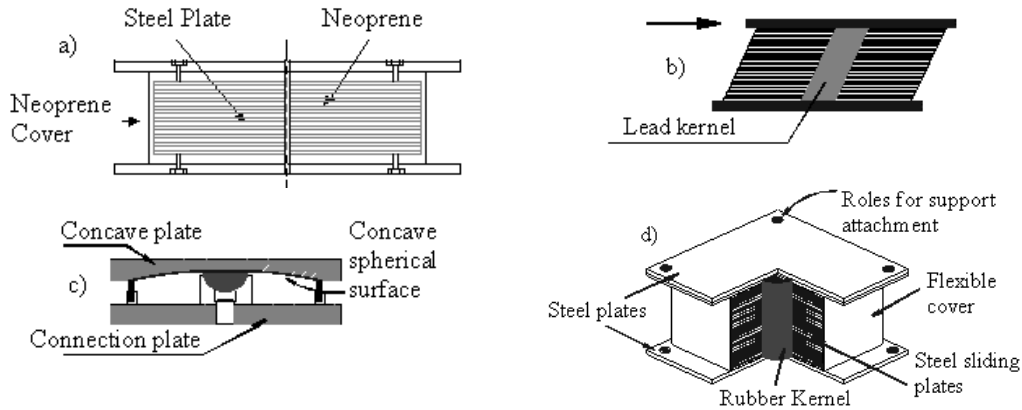


Figure-4: Types of isolation mechanism: (a) RB and HDLRB, (b) LRB, (c) FPS (d) RFBI

Considering the dynamic model shown in Figure-3c, the dynamic equation of the structure under a seismic acceleration $a=a(t)$ arriving on its base can be written as

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = -[M]\{J\}[\ddot{u}_b + a(t)] \quad (1)$$

where $\{u\} = \{u\}(t) = \{u_1, u_2, \dots, u_{N-1}, u_N\}$ is the vector representing the displacements of the floors with respect to the base, $\{\ddot{u}_b\}$ is the base acceleration with respect to the ground, $[M]$ is the mass matrix, $[C]$ is the damping matrix, $[K]$ is the stiffness matrix, $\{J\}$ is a vector relating the rigid body motion of the base with the degrees of freedom of the dynamic model (for example, in Figure-3, $\{J\}$ can be "1" for the horizontal displacement and zero for the vertical displacement). The term $\ddot{u}_b + a(t)$ is the absolute acceleration of the base. The initial conditions for solving this p.d.e. is: $t = 0 \mapsto \{u\} = 0, \{\dot{u}\} = 0$. Eq. (1) can also be rewritten as

$$\{J\}^T [C] \{\dot{u}\} + \{J\}^T [K] \{u\} = -\{J\}^T [M] \{\ddot{u}\} - \{J\}^T [M] \{J\} [\ddot{u}_b + a(t)] \quad (2)$$

The general solution for Eq. (1) can be obtained after uncoupling the system of equations and using the q first modes, the displacement can be expressed as

$$\{u\}(t) = \sum_{i=1}^q \varphi_i y_i(t) \quad (3)$$

where φ_i are mode shapes and $y_i(t)$ modal amplitudes that can be obtained by solving the uncoupled equation

$$\ddot{y}_i(t) + 2\zeta_i \dot{y}_i(t) + \omega_i^2 y_i(t) = -\frac{\varphi_i^T [M] \{J\}}{\varphi_i^T [M] \varphi_i} [\ddot{u}_b + a(t)] = Q_i [\ddot{u}_b + a(t)] \quad (4)$$

where ω_i and $\zeta_i (=c_i/2\omega_i)$ are, respectively, the natural frequency, and the corresponding critical damping ratio of the structure. Q_i is the modal participation factor. The displacement u_b of the base mass m_b can be found by solving

$$m_b (\ddot{u}_b + a(t)) + c_b \dot{u}_b + k_b u_b + \{J\}^T [M] \left\{ \sum_{i=1}^q \varphi_i \ddot{y}_i(t) + \{J\} (\ddot{u}_b + a(t)) \right\} = 0 \quad (5)$$

where m_b , c_b , and k_b are, respectively, mass, equivalent damping, and stiffness of the isolator. The modal amplitudes $y_i(t)$ and base displacements u_b are obtained by solving Eqs.(4) & (5). For RB, practical design value for the period of this type of isolator is $T_b=2s$, where $T_b=2\pi(m_b/k_b)^{1/2}$. The critical damping ratio may vary between $\zeta_b = 0.3$ and 0.05 , respectively, for small and large displacements. A recommend [6,7] mean value for ζ_b is 0.1 . Eq. (5) also governs the HDRB mechanism that we have used in the example of application.

Figure-5 shows a Rubber Bearing (RB) made of neoprene layers in-between metallic board plates. The neoprene is agglutinated to metallic boards forming a sandwich. The connection is horizontally flexible but vertically rigid. A structure supported by these elements has a fundamental period bigger than the structure itself when supported by fix base, thus dynamic amplifications [4,5] can be avoided. These types of supports are similar to those employed in bridges. The experience with neoprene on bridges has allowed the assurance on the durability of such dynamic isolators.

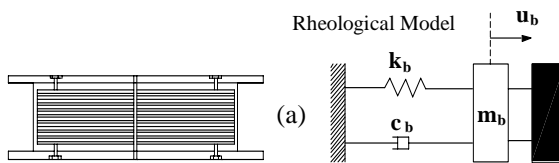


Figure-5: RB Rheological model for RB and HDRB

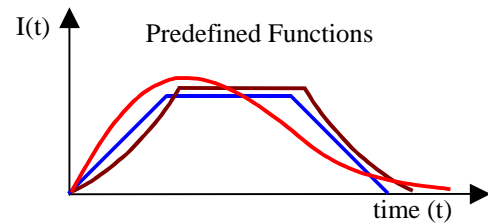


Figure-6 Commonly predefined intensity function

SEISMIC ANALYSES

For the analysis of structural system under earthquake, we are primarily interested in natural frequencies, mode shapes, displacements, stresses and strains. It is very important to use a reasonable mathematical model to represent the behavior of the structural system and a representative input for the expected seismic dynamic load. For structures under non-linear regimes a good practice is to perform a step-by-step transient analysis in time domain using finite element technique. For the input of the seismic dynamic load, one can employ registered earthquake histories of the site or apply artificially generated time histories. There are some advantages in using artificially generated earthquakes: a) generate short duration time histories equivalent to real tremors and, accordingly, less computing time step will be needed in the

numerical solutions; b) synthetic signals are generated from recommended design response spectrum which can take into account soil characteristics of the site. The artificial time histories may be constructed according to certain norms, codes, standards, or recommendations, e.g. the Unified Building Code [9], the Eurocode-8 [10], or even local recommendations [11, 12], among others.

ARTIFICIAL TIME HISTORY

Artificial time histories require artificial seismic movements to be compatible to real earthquake data. Therefore, artificial time history have to: a) provide correct description of frequencies' content of real seismic movements, and b) develop along time, growing quickly until reaching a certain level, then keeping that level for a moment, and at last decreasing smoothly, until zero which corresponds to the end of the earthquake. Most of the methods [14] to generate time histories compatible to recommended response spectrum expand the seismic acceleration signal in sine series, like

$$\ddot{x}(t) = I(t) \sum_{i=1}^n A_i \sin(\omega_i t + \phi_i) \quad (10)$$

where ϕ_i , ω_i and A_i are, respectively, phase angles, frequencies, and amplitudes. $I(t)$ is a predefined function to simulate the intensity of the transient acceleration $\ddot{x}(t)$. Common shapes for $I(t)$ are represented in Figure-6. In reference [13], the algorithm that uses Eq. (10) begins by fixing a number n of frequencies ω_i regularly spaced in a strip of frequency, so that the acceleration contains every desired level of frequencies in that strip. Afterwards, n phase angles ϕ_i are randomly generated in the range $[0; 2\pi]$, giving the stochastic character for the tremor. For different ϕ_i and a specified response spectrum in velocity, $S_v(\omega_i)$, prescribed (e.g. [11,12]) different artificial acceleration signals, with same frequency content, can be obtained by Eq. (10). For such operation, n amplitudes A_i are calculated such that the equivalent response spectrum in velocity, obtained from the artificial $\ddot{x}(t)$, is similar to the given response spectrum in velocity, $S_v(\omega_i)$. The amplitudes A_i can be expressed as a function of the Power Spectral Density $S_{\ddot{x}}(\omega)$ that can be approximately obtained from the predefined $S_v(\omega_i)$.

NUMERICAL EXAMPLE

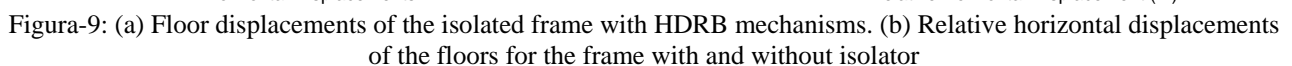
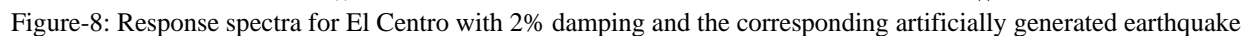
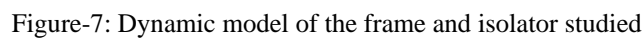
In this illustrative example a typical building structure frame made of reinforced concrete is analyzed with and without the use of isolator system, see Figure-5 and [19, 20]. The building has 4 floors and is composed by columns 3m height, cross-section 0.3mx0.5m, inertia $I=3.1 \times 10^{-3} \text{m}^4$, and beams with span of 4.5m, cross-section 0.24mx0.55m, and inertia $I=3.5 \times 10^{-3} \text{m}^4$. The first natural frequency of the building is 2.3Hz. The isolation system applied at the base of each column was the HDBR (High Damping Rubber Bearing), which is very much used in Japan and USA [17,18]. The finite element method was used for the dynamic analysis of the structure with and without anti-seismic devices. A simplified model representing a typical building structure was generated using the finite element method program Ansys [16]. The dynamic response of the structure was obtained by solving the following Eq.

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F(t)\} \quad (11)$$

where $[M]$, $[C]$, and $[K]$ are, respectively, the structure mass, damping, and stiffness matrices. $\{F(t)\}$ is the load vector and $\{\ddot{u}\}$, $\{\dot{u}\}$, and $\{u\}$, are, respectively, the nodal acceleration, velocity and displacement vectors. The procedure employed by Ansys to solve Eq. (11) along time is the Newmark time integration method [15]. Special elements from Ansys, COMBIN40. Also element MASS21, were employed for the isolation system to simulate the seismic isolation effect. Figure-7 shows the HRDB applied to the frame, which parameters are: stiffness - k_b , damping - c_b and mass - m_b . Based in parametric values used by the majority of the isolator producers we have adopted the following values: $k_b=4.00 \times 10^3 \text{kgf/m}$, $c_b=1.131 \times 10^3 \text{kgf.s/rad.m}$ ($\xi_b = 60\%$) and $m_b=5 \times 10^4 \text{kgf}$. The frame structure was excited by a ground acceleration represented in Figure-8. The time history was artificially generated using the program described before. The artificial earthquake was generated from the El Centro response spectrum in velocity $S_v(\omega)$ with 2% damping. El Centro took place in Mexico in 1940 and reached a magnitude of 6.9 in the Richter scale. This earthquake is a well-known earthquake with frequencies in the range 0.5Hz to 3.5Hz and maximum ground acceleration arriving approximately to $2.5\text{-}3\text{m/s}^2$ - common range of frequency required by some standards [11,12]. The isolation system used corresponds to HDRB applied at each column base with varying critical damping parameter ξ_b set to 0%, 2%, 20%, and 60% so that the effect of higher damping could be observed.

Instead of plotting the horizontal displacement time history of the frame nodes it is better to observe the maximum absolute and relative displacements of the floors of the building. Therefore, to measure the efficiency of the isolation system and observe the uncoupling degree of the building from the ground, Figure-9 (a) and (b) show, respectively, the maximum absolute and relative horizontal displacements of the floors taking into account the variation of the damping

Another way to assess the isolation of the structure is the amount of shear force acting at the base. The smaller the shear force, the more isolated the structure is. The plot shown in Figure-9 represents the amount of shear force at the base. Note that the absolute displacements include the base displacements due to the earth tremor. Observe in Figure-8 that the floors of the frame with rigid connection displaced, in absolute values, less than the floors from the other frames with HDRB base isolation. Also from Figure-8 one can observe that the rigid connected frame presents greater relative horizontal displacements and also a higher value of the shear as can be observed in Figure-10. Comparing all the curves with isolation, notice that the frame with small relative displacement was the one with HDRB with $\xi_b=20\%$.



The frame with HDRB with $\xi_b=2\%$, 0% and 60% showed greater values for the relative floor displacement comparing to the floor displacement of the frame with HDRB with $\xi_b=20\%$. This means that the rise in the value of the damping parameter ξ_b of the HDRB isolators not always causes small relative displacements of the floors. On the other hand the use of isolators like the HDRB, generally, produces greater absolute displacements but smaller relative displacements when compared with the frame displacements without isolators. The floor absolute displacements of the frames with HRDB grow because part of the earthquake displacement is absorbed by the HRDB isolator system and transmitted to the frame out of phase with the ground motion. The frame isolated with HRDB with damping parameter $\xi_b=0\%$ shows the biggest absolute displacement, with $\xi_b=20\%$ (although the absolute displacement of the floors remains bigger than with $\xi_b=60\%$) the relative displacement top-base is the smallest of all – see Figure-8.

The frame with the biggest shear force at the base is the rigid frame and the one with the smallest value of the shear force is the frame with HRDB with $\xi_b = 20\%$. Note that all the frames with isolators presented a considerable reduction of the shear force when compared to the shear force achieved at the base of the rigid connected frame.

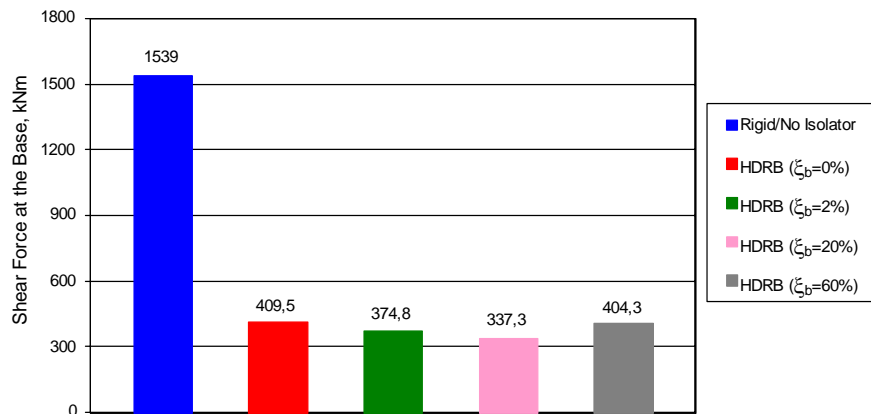


Figura-10: Shear force at the base of the building frame isolated with HDRB.

CONCLUSIONS

In this article, the principal earthquakes in the world and their respective damages were presented. The possibility of induced seismicity was discussed. The main types of anti-seismic mechanisms were described. Advantages and disadvantages, functional sketches and governing equations of the main anti-vibration devices were also presented. An example of a typical building frame under an artificially generated earthquake equivalent to El Centro was examined. The frame was examined when rigidly fixed at the base and also when some types of HRDB are employed at the base. The structural response of the frame in terms of displacements and shear forces at the base was discussed. The HRDB isolation system used was efficient to uncouple the structural floor displacements from the ground motion. The relative displacements for the isolated system decreased significantly either at lower or higher levels of the frame structure. The HRDB isolators have absorbed great part of the earthquake energy. In terms of shear forces at the base, the advantages of using HRDB makes the shear force decrease considerable when compared the amount of shear force in the case of the frame rigidly connected to the base. There are situations where the use of isolators is indifferent, for example, in structures with low natural frequencies, out of the range of the earthquake predominant frequencies. For such a case there is no advantage (or disadvantage) in using anti-seismic isolation mechanisms. Safety and comfort can be achieved when the difference of the floors' horizontal displacements, especially between top and base, are as small. Figures 9 and 10 show that the best results were obtained for HDRB with a damping parameter of $\xi_b=20\%$. We suggest that isolators could also be installed along the frame structure, not only at the base, for example, but also at each floor or at some selected floors. Energy dissipators could also be used in association with the isolation systems.

The use of anti-seismic mechanisms is an important engineering contribution to minimize structural damages caused by earthquakes. Many buildings are adopting such mechanisms nowadays. Other interesting study about vibration isolation and control may also be found at references [19, 20], among others. Finally, we notice the importance of numerical experimentation in the research of anti-vibration mechanisms. Such experimentation may give the researcher indications about the behavior and the effectiveness of the devices. Experimental tests are essential but before time and money are allocated for laboratory testes, numerical techniques must be used to point out more profitable direction in the anti-vibration mechanisms research.

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