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Improving the Seismic Behavior of Symmetrical Steel Structures Under Near-Field Earthquake Using a Base Isolation Method Lead Rubber Bearing Isolator

Musa Mazji Till Abadi[1] & Behnam Adhami[2]

[1] M.S Student of Structural Engineering, Department of Civil Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran

[2] Faculy member, Department of Civil Engineering , Central Tehran Branch, Islamic Azad University, Tehran, Iran.

Correspondence: Musa Mazji Till Abadi, M.S Student of Structural Engineering, Department of Civil Engineering, Central Tehran Branch, Islamic Azad University, Tehran, Iran. E-mail: musamazji.till@chmail.ir

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Abstract

In this study, the function and application of seismic isolation system through lead rubber bearing isolator (LRB) in near-fault earthquakes are compared with fixed-base structures. As a result of their high frequency content, near-fault earthquakes impose huge energy on structures and cause severe damages. One of the appropriate solutions for this issue is the use of LRB which decreases the amount of imposed energy on structures. To improve the function of isolated structures under the near-fault earthquakes, isolators are designed in a way to tolerate the vertical component of earthquakes. To this purpose, we limit the displacements due to the horizontal movements of isolator through Gap spring which acts as a retaining wall and prevent shocks to other buildings. Moreover, this approach decreases the vertical movements of isolators and indirectly improves their behavior. In the current study, three buildings with four, eight, and 12 floors (with and without gap spring) were included. Isolators were manually designed in accordance with AASHTO-LRB regulations and the behaviors of both isolators and buildings are considered non-linear. Then we analyzed and compared the amount of energy, displacement, and acceleration of structure at the center of roof. The results indicated a significant decrease in the results of base shear, the acceleration of roof center, floors drift and energy imposed on the structure in the isolated system in comparison with the fixed-base structure.

Keywords: Lead rubber bearing isolator, near-fault earthquake, earthquake vertical component, gap spring, retaining wall, analysis of the non-linear time history

1. Introduction

The seismic isolation method includes isolation of the whole structure or a part of it from ground or other parts of the structure to reduce its seismic response during an earthquake. Common approaches for seismic design of structures are based on enhancing the structure's capacity. Based on this approach, the design of a structure with a defined stiffness, high resistance and plasticity, which tolerates interior forces of earthquakes is considered. Results demonstrate an increase in the dimensions of structural members and fittings, extra bracings, shear wall or other stiffening members of the structure. Moreover, increase of structural stiffness leads to absorption of more energy from earthquake and requires enhancement of structure's resistance which in turn causes a reduction in economic value of the project. According to the traditional approaches of constructing more resistant structures against earthquake, designing a safe structure is equal to prediction of the non-linear structural behavior which has been designed based on plasticity regulations. Moreover, absorption of vibrational energy is for protecting the structure against destruction. The traditional design methods may allow destruction of these members as a result of imposing non-linear transformations on structural and non-structural members (Strategic Supervision Department, 2010). The main advantage of seismic isolation system is increasing the period of main frequency to transform it from frequency of a fixed-base structure and dominant frequency time of earthquake to higher one. Another advantage of seismic isolation is dissipation of imposed energy on the structure which leads to reduction of transformed acceleration to upper structure during an earthquake (Naeim and Kelly, 1999). This role is more evident in the near-fault earthquakes because of the specific characteristics of these records which have higher frequency content and energy (Matsagar & Jangid, 2004; Walls et al., 2015; Chimamphant & Kasai, 2016). Therefore, the current study aims to analyze effects of near-fault earthquakes on isolated structures. Near-fault earthquakes have important vertical components which have always been a challenging issue in isolated structures because they lift the structure and slam it on the isolator. As a result, isolators will destroy. So, while designing isolators, an attempt is made to prevent lift of columns. In this research, isolators are designed in a way that increasing their dimensions leads to their resistance against vertical component of earthquakes. To hinder displacements originated from horizontal movements and shocks to adjoining buildings, a retaining wall was used. For this purpose, buildings were designed with 4, 8 and 12 floors, a lateral load-bearing system of steel special moment frame according to ACIS360-05, the consideration of P-effects and the seimic regulations of 2800. The relative between-floors displacements was studied according to the regulation 2800 in which they had permission. The three models were analyzed once as a fixed-base and then as an isolated structure without a gap spring; and the results were compared at the end (Ministry of Roads and City Planning and National Building Regulations Office, 2013; The Research Center of Housing and Urban Development, 2008).

2. The selected near-fault earthquakes and their characteristics

Records of near-fault earthquakes have specific characteristics which distinguish them from other records as a result of near distance between construction and the location of wave propagation. In this kind of earthquake, because of a short distance between the sites of earthquake and construction, attenuation of upper frequencies is not possible. Therefore, historical records of their acceleration have high frequency contents (Hasani, 2011). Moreover, given the upper periods of acceleration compared with speed and movement of earth, their records are pulse-like, having high periods and are similar to acceleration pulses in the form of shocks. The existence of acceleration pulses and pulses of speed and movement in near-fault earthquakes records cause damages in solid structures and significant damages in plastic structures, respectively(Hasani, 2011). These earthquakes may have one or several displacement pulses with the maximum speed of .5 m/s and the vibration of 1to 3 seconds. This fact influences the isolated system according to its period and may cause a big displacement in the isolator. In the current study, 3 pairs of near-fault accelerograms are used and their characteristics are represented in table. 1. The properties of records according to Fema p, 695 have been extracted from Peer website (Federal Emergency Management Agency , 2009).

Table 1. Near-fault earthquakes characteristics

Earthquake	Station	Year	Magnitude (Mw)	Diatance (Km)	V530(m/s)	PGA (g)
Northridge	Sylmar-Oliver view Med	1994	6.7	1.74	440.54	0.843
Loma prieta	Saratoga-Aloha Ave	1989	6.9	7.58	380.89	0.514
Chi-Chi	Tcu 084	1999	7.6	0	665.2	1.009

3. A linear model and design of the structure

The process of modeling and designing buildings has been performed through the SAP2000 V.15 Software (Habibullah & Wilson, 2005) and the three-dimensional view of buildings is represented in figure 1.

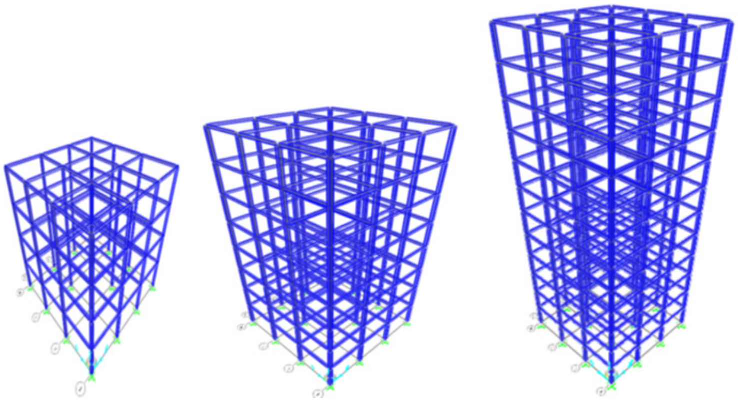


Figure 1. The three-dimensional view of the structure

The statistical seismic parameters are introduced in the software in the form of User Coefficient with a calculated C index. This index is multiplied with the seismic mass of building to determine the statistical seismic load. Seismic mass of structure is the sum of dead loads and 20% of live loads.

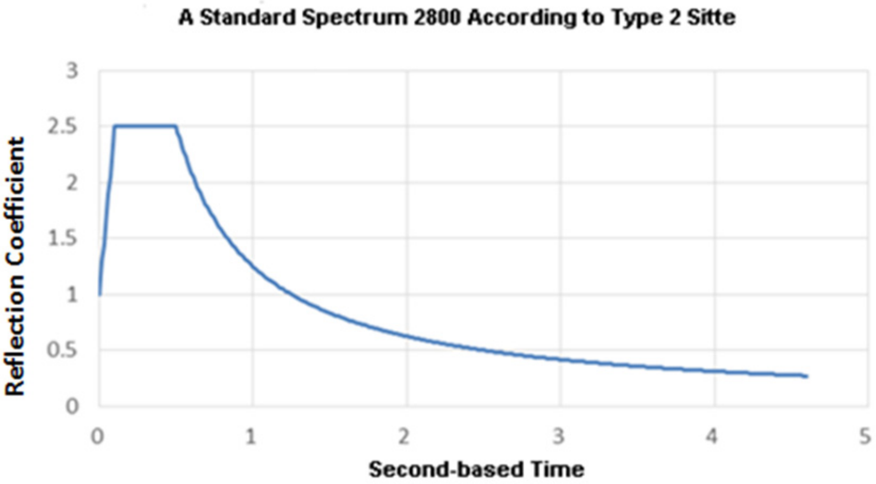


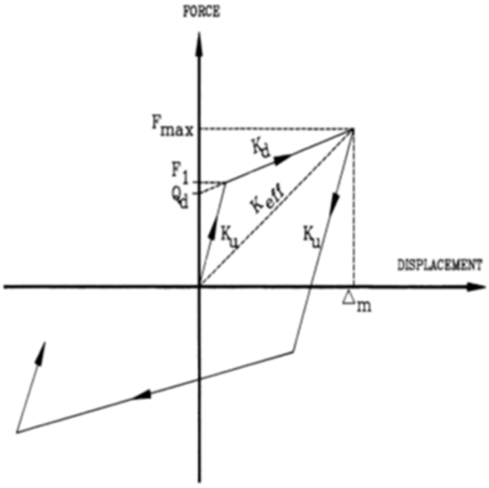
Figure 2. The response range introduced in software

Bars and columns act as rigid in connection area. We consider this feature by selecting the item End Length Offset in software and inserting the automatic amount with rigid zone factor equal to 5. Note that in dynamic analysis, sufficient modes should be considered for the study of structure; and the number of these modes should at least meet 90% of the structure's seismic mass. Figure 2 represents the response range introduced to the software for a linear design.

3.1 Design of Seismic Isolator

The common philosophy in seismic design of the structures is based on making rubber joints as to absorb energy of big earthquakes. Through this method, the capacity of structures in absorbing seismic energy is based on big transformations and structure's plasticity. This philosophy is neither acceptable in structures with low plasticity or in important structures such as hospitals.

Designing disabled controlling systems of structures is done according to another philosophy which is based on seismic isolation and energy absorption systems. The systems designed based on the mentioned philosophy do not require rubber junctures for energy absorption and resistance against seismic loads. However, energy absorption in these systems is concentrated in attenuators to minimize damages of the main structure. Details of LRB used in the current research are represented in figure 3. A lead cylinder is located inside these isolators to increase energy dissipation. Therefore, besides tolerating structure's weight, the LRB isolator system returns the vertical and horizontal plasticity to the initial status and creates essential hysteresis attenuation. Figure 4 represents the behavioral curve of LRB.



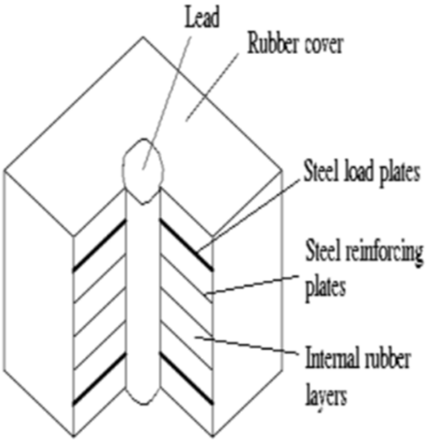


Figure3. Details of LRB Isolator Figure4. A two-Lined Hysteresis Diagram of Isolator’s Force-displacement

In this research, a retaining wall is used to control pounding- shock of structure to other adjoining buildings and to limit displacement of isolators. The wall is modeled by Gap element in the area of bearings and some places of the structure in the software. The stiffness of this element which is used for non-linear analysis is equal to stiffness of a wall which is 1 meter high. Given the hysteric circle, the required space for the function of gap elements is respectively considered 10, 20, and 35 cm for 4, 8, and 12-floor buildings. The isolator and retaining wall will be discussed in details later.

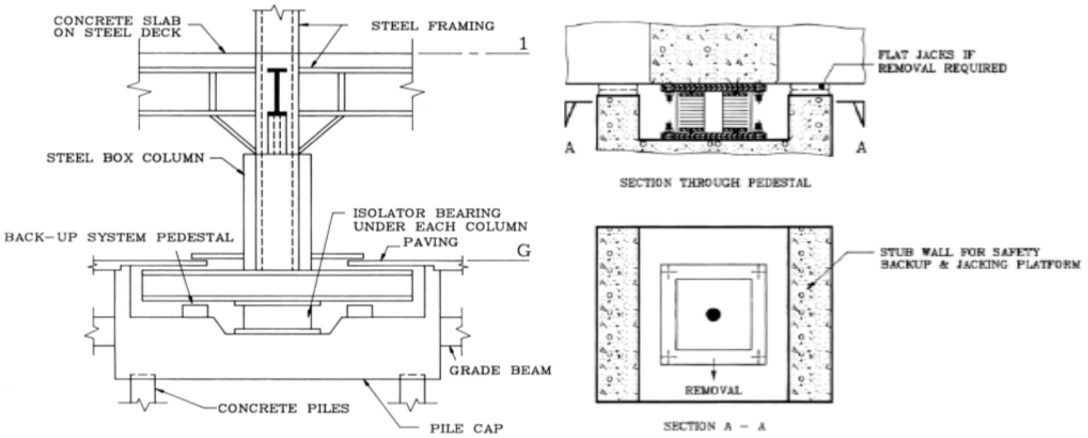


Figure5. Details of the Isolator and Location of the Retaining Wall

4. Discussion and Analysis of Results

Steel structures with mentioned characteristics and a seismic isolator without displacement limitation system were considered below the danger levels of DBE and MCE; then they were analyzed. To study behavior of these structures and also effects of controlling systems, in this part seismic behavior parameters are extracted for all the structures and results are interpreted.

4.1 Drift Parameter

Figures 6 to 8 show the drift parameter of structures with 4, 8, and 12 floors in fixed-base and isolated statuses with and without element gap and at DBE and MCE risk levels.

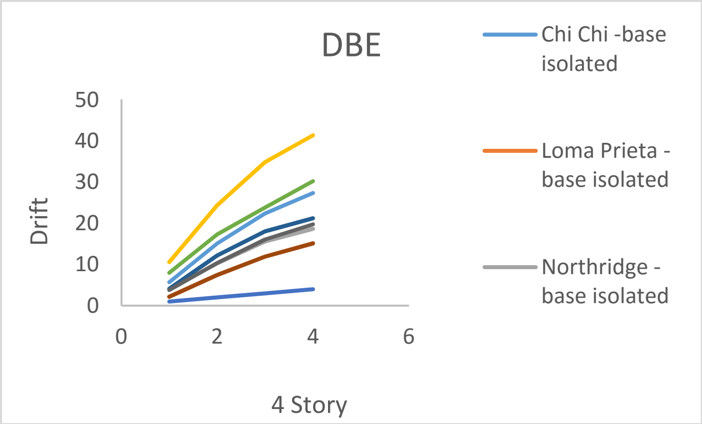


Figure6. Floor Drift of Structure in Fixed-base and Isolated Statuses with and without Gap Element at DBE Risk level

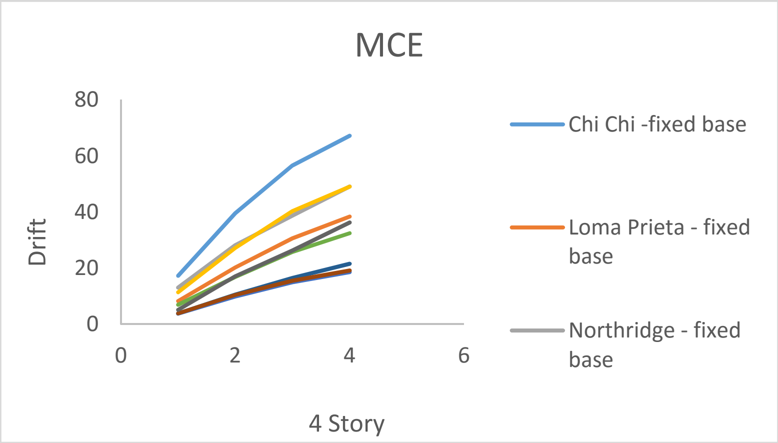


Figure7. Floor Drift of the Structure in Fixed-base and Isolated Statuses with and without Gap Element at MCE risk

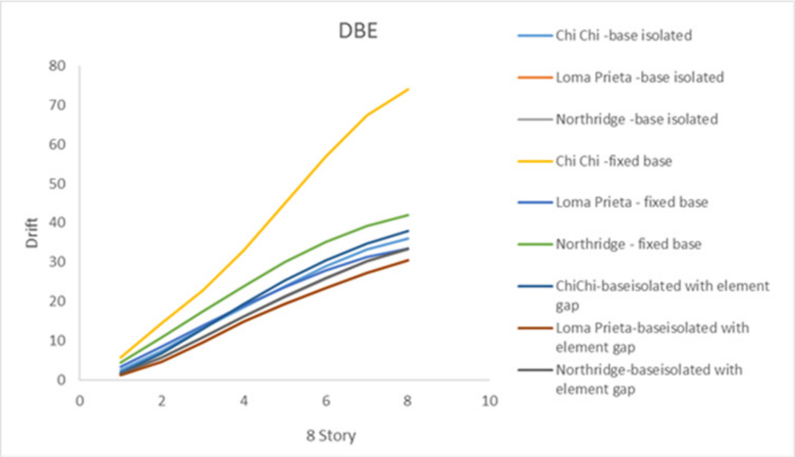


Figure8. The Drift of 8-Floor Structure in Fixed-base and Isolated Statuses with and without Gap Element at DBE Risk Level

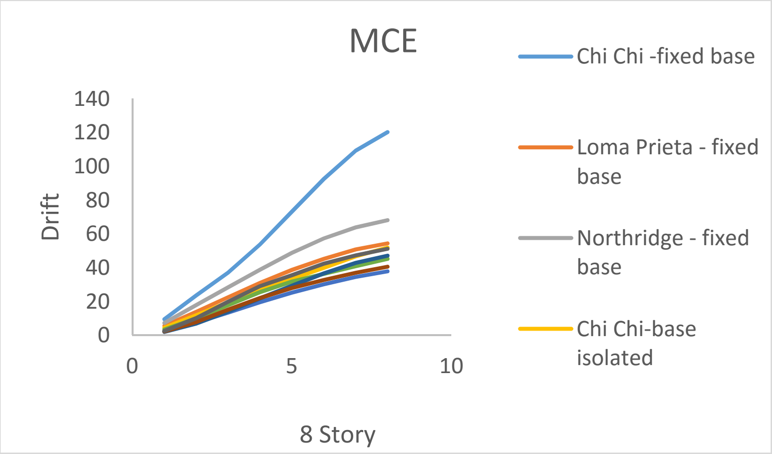


Figure9. Drift of the 8-floor Structure in Fixed-base and Isolated Statuses with and without Gap Element in MCE Risk Level

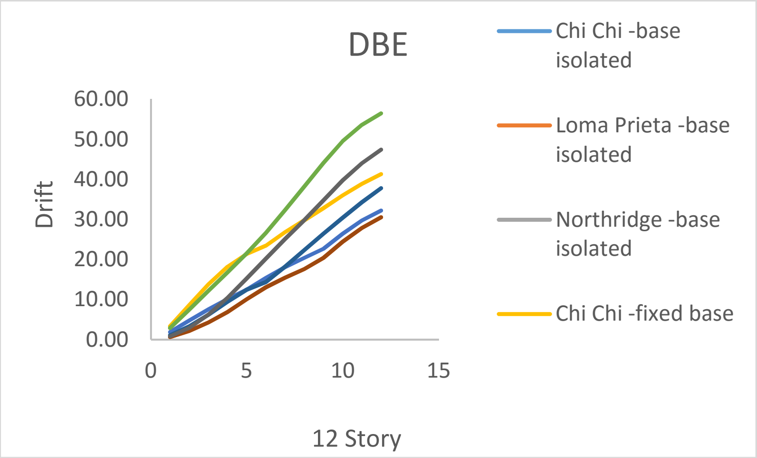


Figure10. Drift of the 12-floor Structure in the Fixed-base and Isolated Statuses with and without Gap Element at DBE Risk level

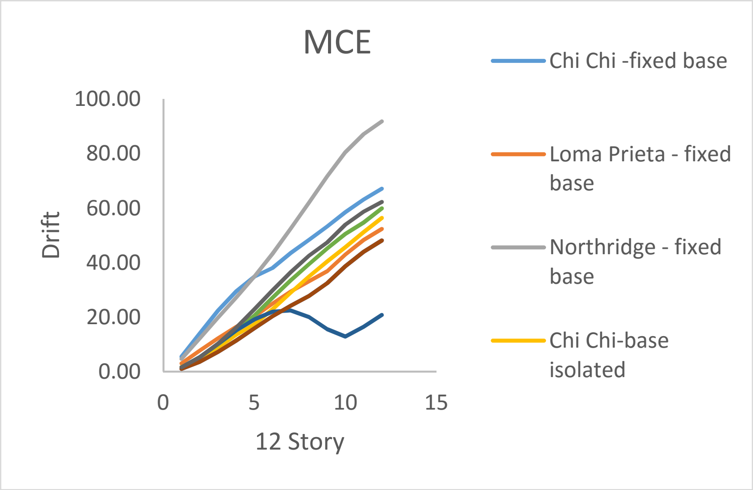


Figure11. Drift of the 12-floor Structure in the Fixed-base and Isolated Statuses with and without the Gap Element at MCE Risk Level

The diagrams of figure 6 to 11. demonstrate that the drift of floors in isolated structures at the risk level of MCE is equal to the fixed-base structures' at DBE risk level. As one of the criteria in a structure's failure is floors drift, using a seismic isolator may lead to stability of structures against major earthquakes (with long return period).

4.2 Acceleration Parameter

Figures 12 and 13 represent acceleration parameter on roof mass center of the structures with 4, 8, and 12 floors in fixed-base and isolated statuses with and without gap element at DBE and MCE risk levels.

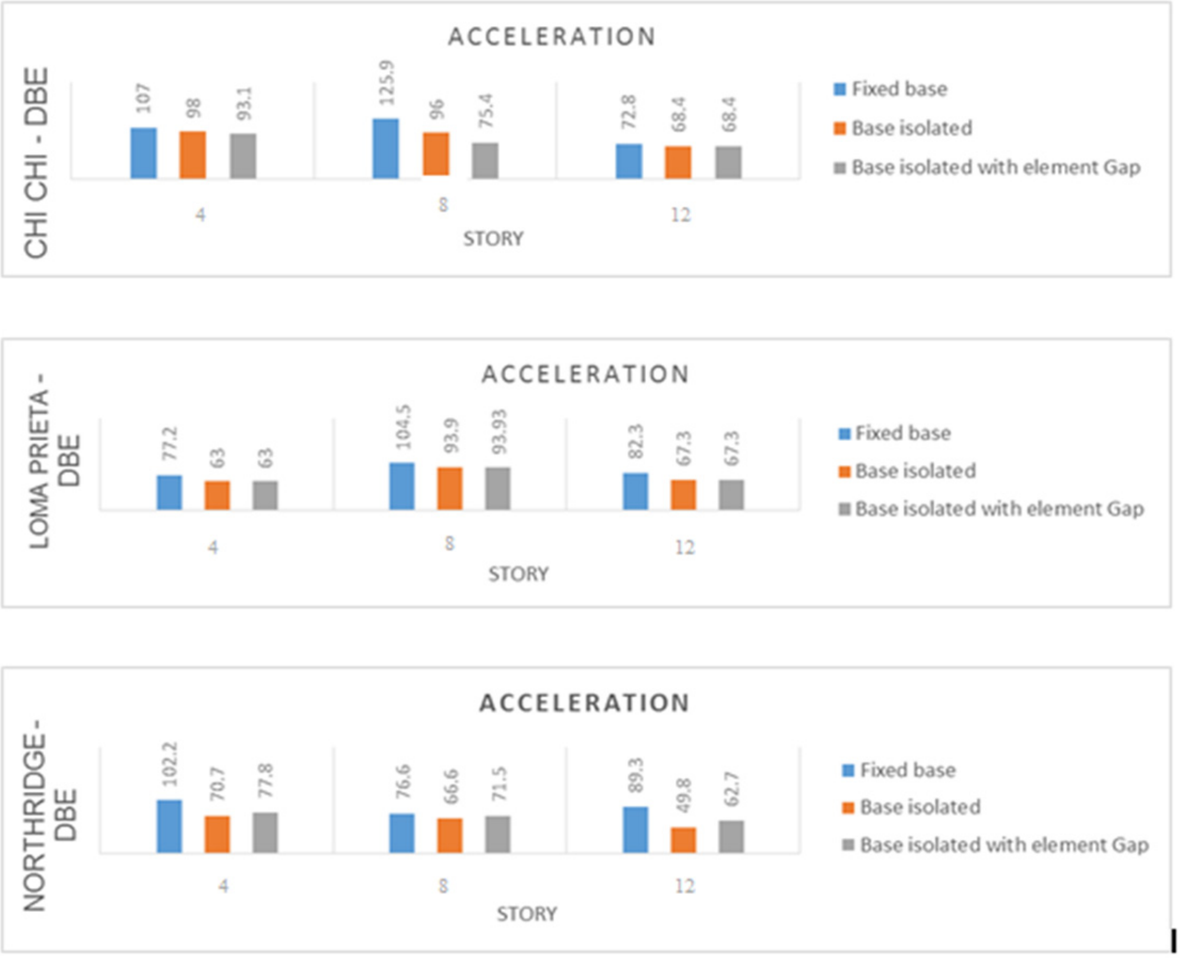
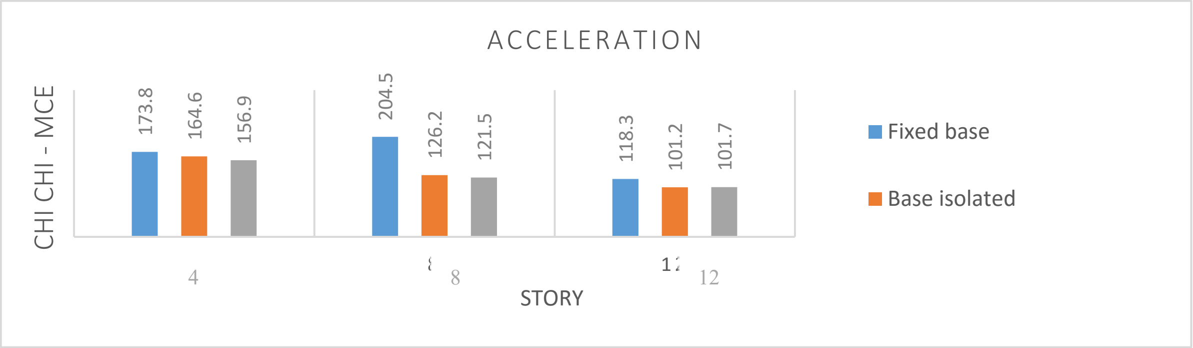


Figure 12. Acceleration on the Roof Center in Fixed-base and Isolated Statuses with and without Gap Element at DBE Risk Level



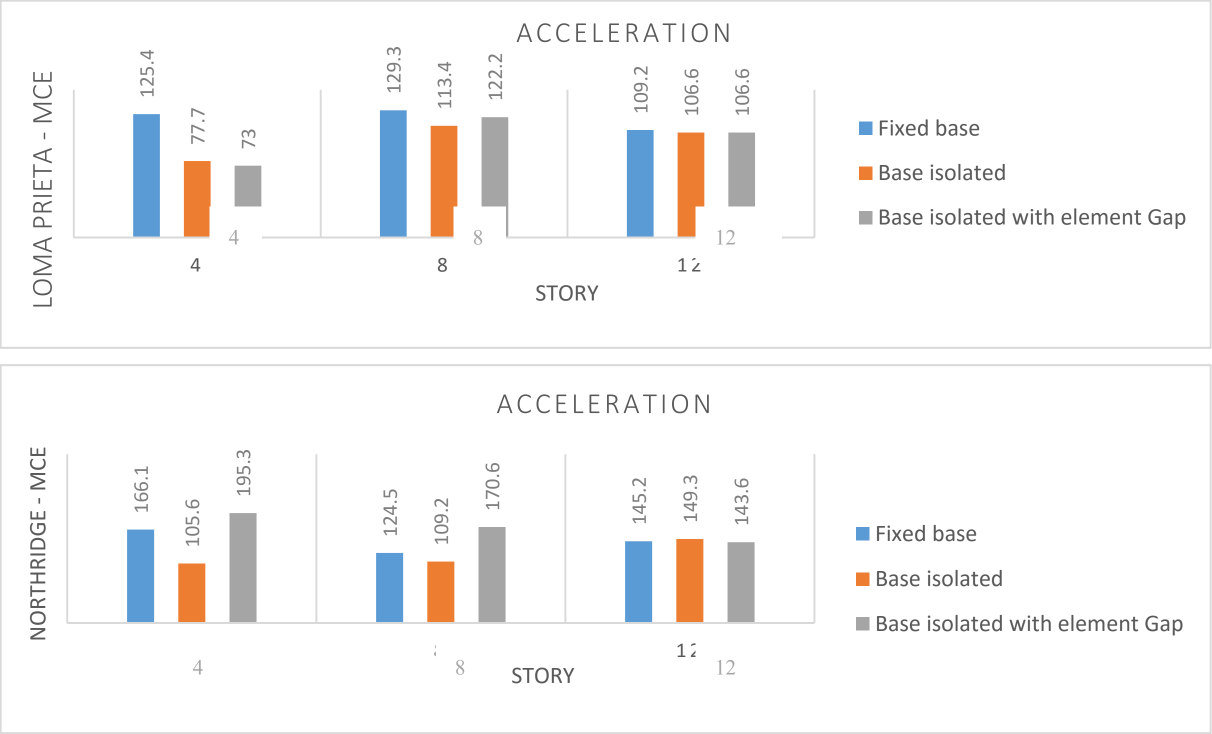


Figure 13. The Acceleration on the Roof Center in Fixed-base and isolated Statuses with and without Gap Element at MCE Risk Level

According to figures 12 and 13, the seismic isolator has a significant role in reducing a structure's acceleration response. However, the amount of reduction in shorter structures is more than higher ones. Although the roof acceleration of an isolated structure increases in the presence of a gap element, acceleration may be controlled through the change of gap elements' parameters. Moverer, the advantages of a gap element in reducing displacement of a basic level may be benefited and a more safe structure may be constructed through a little increase in acceleration.

4.3 Base Shear Parameter

Figures 14 and 15 represent a base shear parameter on 4, 8, and 12-floor strucures in fixed-base and isolated statuses with and without a gap element at the risk levels of DBE and MCE.

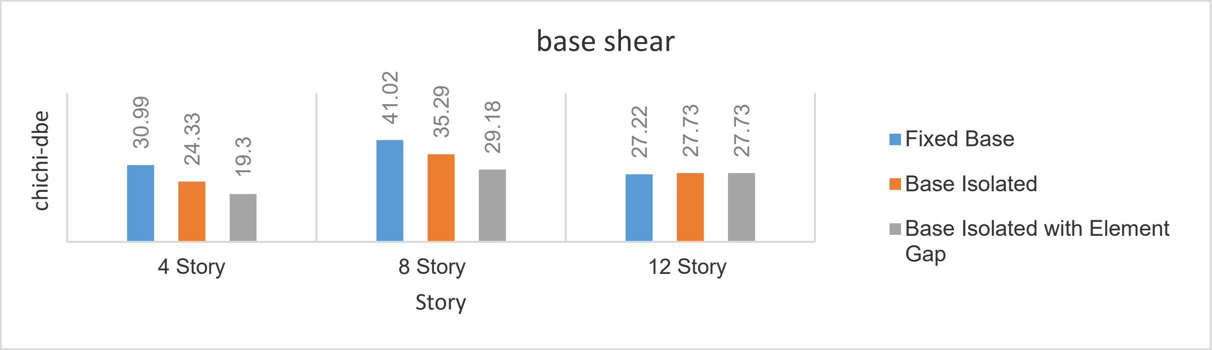


Figure 14. Base Shear in Fixed-base and Isolated Statuses with and without Gap Element at DBE Risk Level

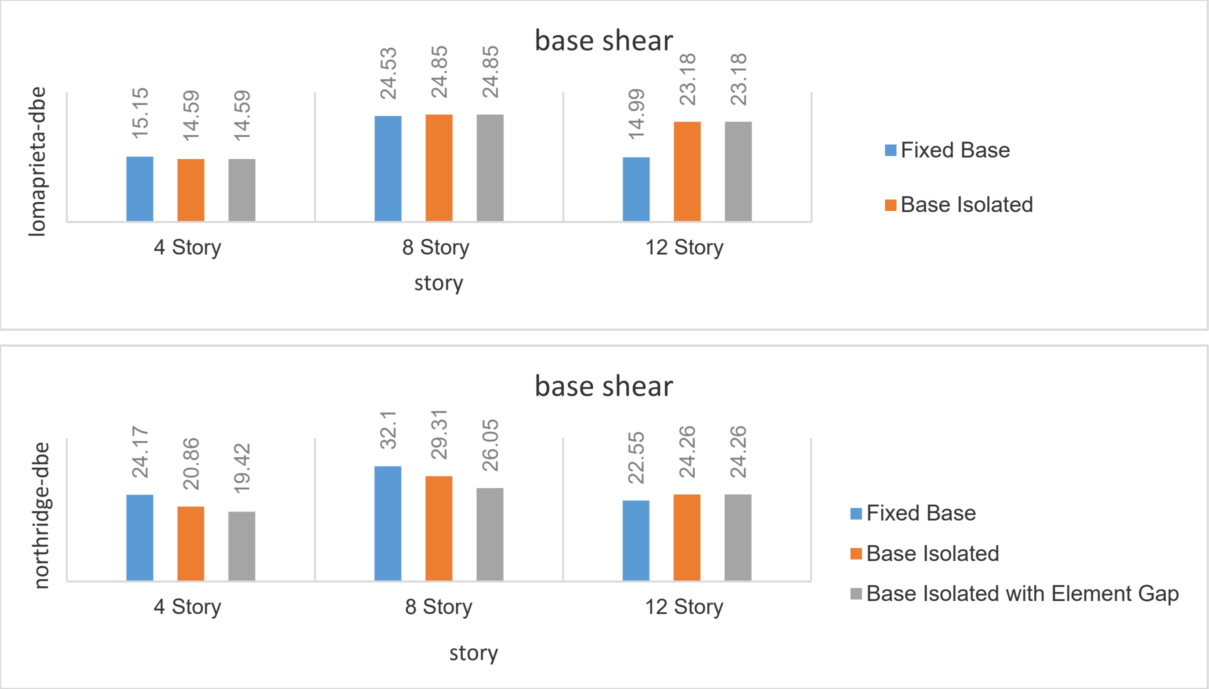
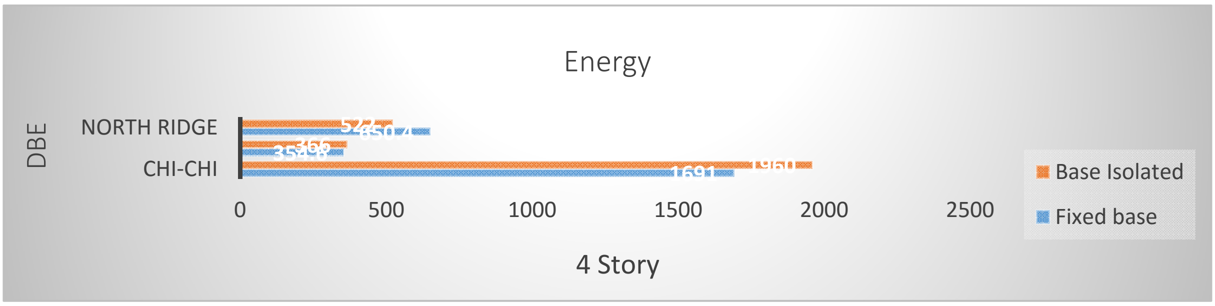


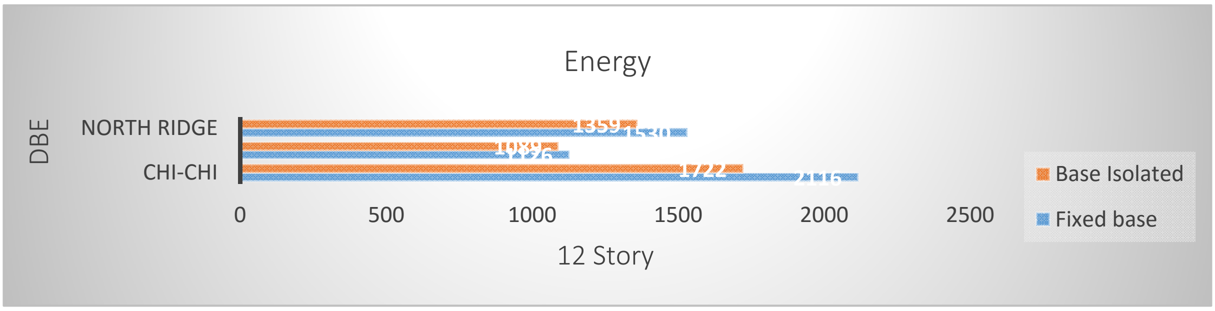
Figure 15. Base Shear in Fixed-base and Isolated Statuses with and without Gap Spring at MCE Risk Level

As figure 8 indicates, the amount of base shear decrease in isolated structures with a gap element is significant compared with fixed-base structures. As an example, at the risk level of DBE in the Chi Chi earthquake, the amount of base shear in fixed-base status was equal to 30.99 ton which reduced to 19.3 in the presence of a gap spring. This reduction was observed at the risk level of MCE, too.

4.4 Energy Parameter

Figures 16 and 17 represent the energy parameters on the 4, 8, and 12-floor structures at the fixed-base and isolated statuses at DBE and MCE risk levels.





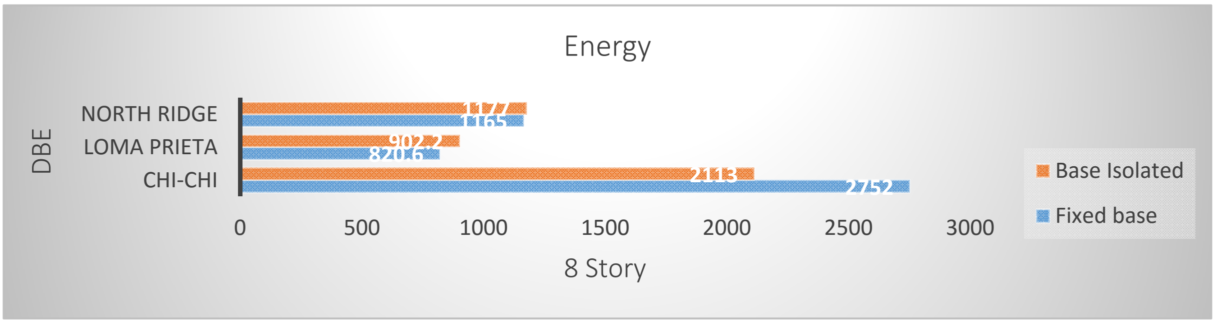
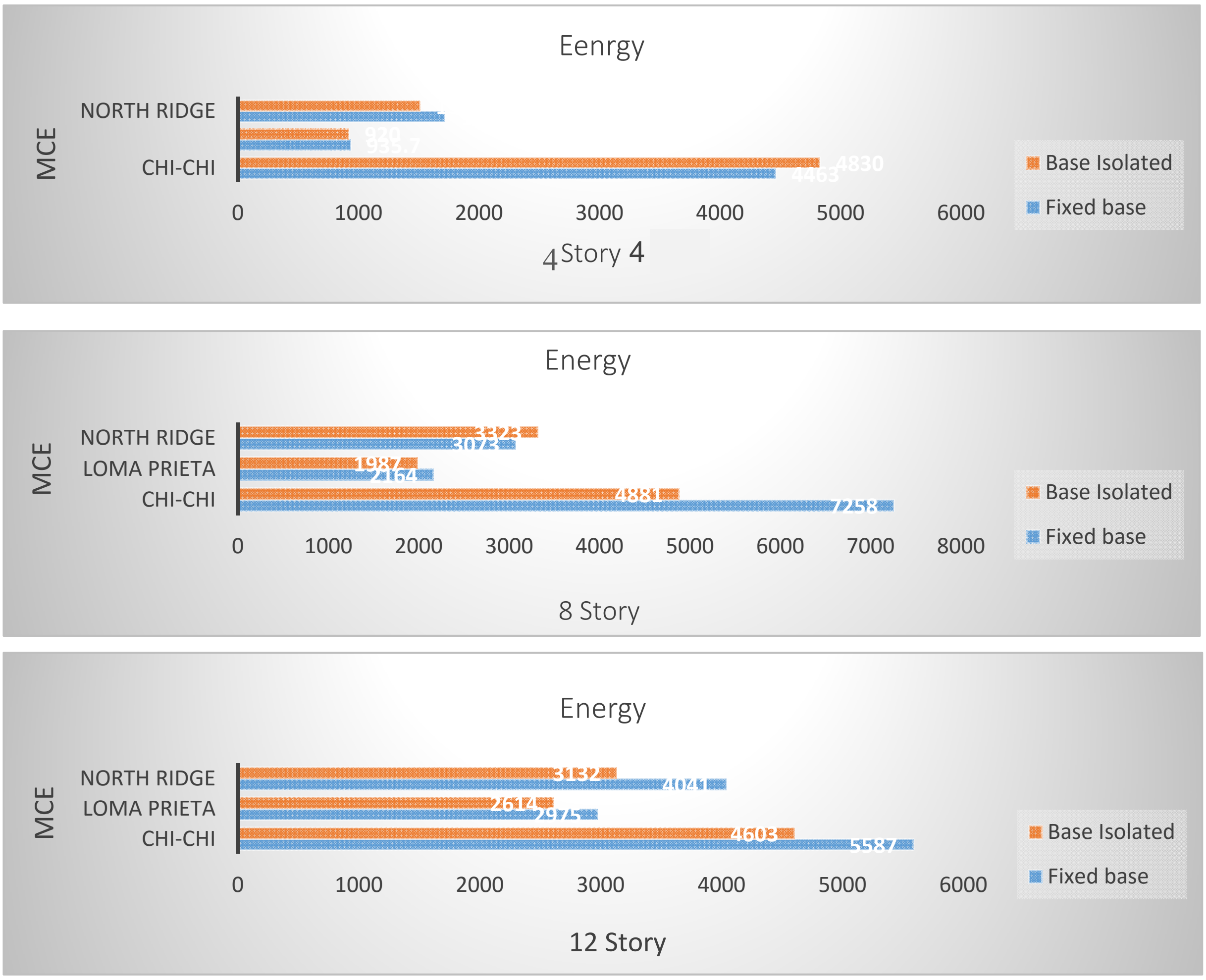


Figure16. Energy Imposed on System in fixed-base and Isolated Statuses at DBE Risk Level



17. Input Energy of System in Fixed-base and Isolated Statuses at MCE Risk Level

As figures 16 and 17 demonstrate dissipated energy in the isolated system of short structures is significantly more than high structures. This fact originates from the form of response range of a structure's acceleration modes. In higher structures (with higher period modes), and in mode acceleration range diagram, the drop rate of acceleration response has an inverse relationship with period increase.

4.5 The Shock Parameter to the Adjoining Building

Figure 18 shows the shock parameter to adjoining building for the structures with 4, 8, and 12 floors in the isolated status with a gap element at the risk levels of DBE and MCE.

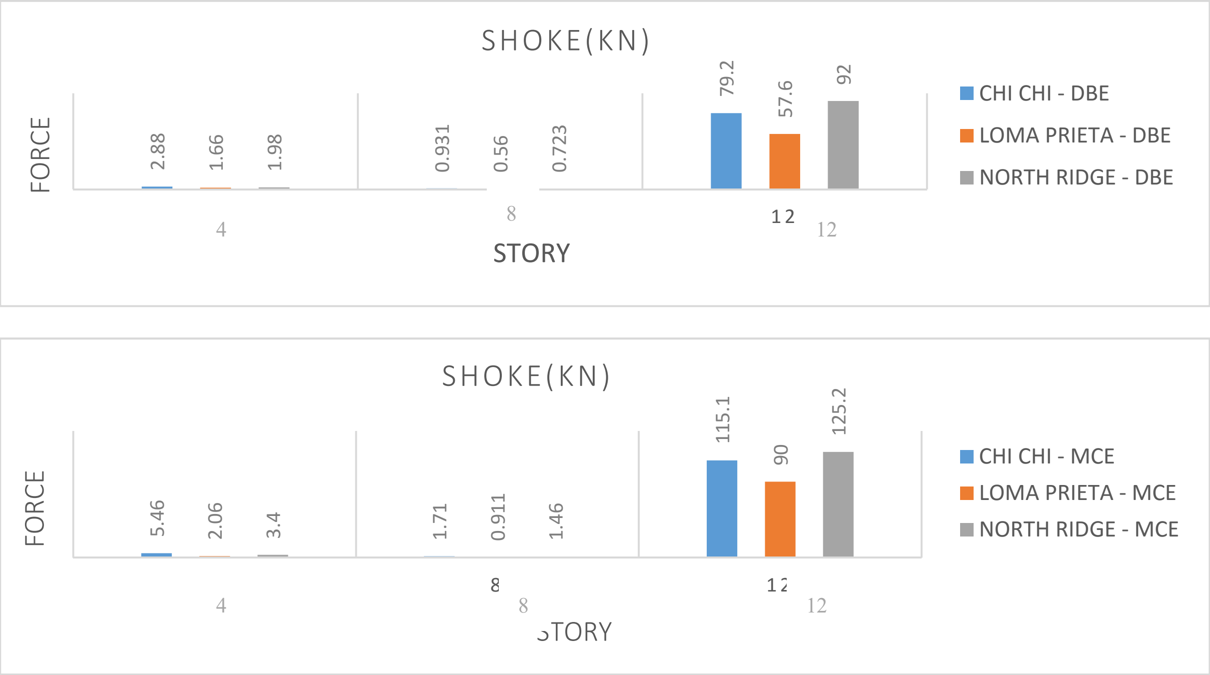


Figure18. Force Imposed as a Result of Shock to Adjoining Buildings at MCE and DBE Risk Levels

According to figure 18, isolated structures with more displacements in high isolated buildings impose more shocks on adjoining buildings under very big earthquakes.

5. Concluding Remarks

In the current paper, under the near-fault seismic stimulations, the following results were obtained through analyzing and comparing dynamic responses of three steel buildings with 4, 8, and 12 floors in three statuses of: 1) with fixed-base, 2) with seismic isolator having a displacement gap spring, and 3) with an seismic isolator without a displacement gap spring.

1. Compared with non-isolated buildings, in the structures isolated by plastic seismic isolator of lead core, the amount of dissipated energy in bigger earthquakes (at MCE risk level) is more than smaller earthquakes (at DBE risk level).
2. Transformation of structural members in isolated structures at the risk level of MCE is less than transformation of structural members in non-isolated structures at DBE risk level.
3. Dissipated energy in isolated system of short structures is significantly more than high buildings.
4. Seismic isolator decreases base shear of a building. In this regard, first the amount of reduction in earthquakes at the risk level of MCE is more than DBE, next the influence of isolator in reducing base shear of shorter buildings is more than higher buildings.
5. The seismic isolator has an important role in reducing drift of the structures' floors in such a way that the floor drift of isolated structures at the risk level of MCE is almost equal to the floors drift in fixed base structures at DBE risk level. As one of the failure criteria of structures is the floors drift, using a seismic isolator may ensure the stability of structures under big earthquakes (with long return periods).
6. Seismic isolator has a significant influence on reducing the acceleration response of structure's floors. This reduction is relatively more in shorter buildings compared with higher buildings.
7. The reduction amount of base shear in isolated structures with a gap spring element is significant compared with fixed-base structures.
8. Although the floor drift in isolated structures with a gap spring is more than isolated structures, yet this amount of increase is significantly less than drift of non-isolated buildings without isolator. Therefore, using a gap spring not only can control the building displacement in fixed balance but also it is very influential in increasing structural safety under big earthquakes as a result of floors drift reduction.

9. Using gap spring element has a very fundamental influence on controlling pounding of high-rise isolated structures. This fact is important because of heavy shocks that high-rise structures impose on adjoining buildings under big earthquakes.
10. Using a gap spring, not only improves behavior of an isolated structure through controlling its horizontal movements, but also it subtly improves the isolator's behavior through decreasing its vertical movements.

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