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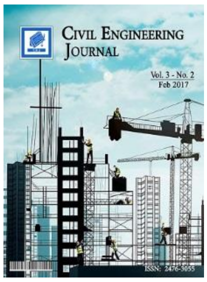

Comparing Seismic Performance of Steel Structures Equipped with Viscous Dampers and Lead Rubber Bearing Base Isolation under Near-Field Earthquake

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Abstract

In the present research, seismic behaviours of a steel frame equipped with either viscous damper or lead-core rubber bearings (LRB) isolator were evaluated and compared under the effect of near-fault earthquake records. For this purpose, three buildings of 5, 10, and 15 stories equipped with lateral bearing systems composed of steel moment-resisting frames were subjected to 7 near-fault earthquake accelerogram pairs at earthquake hazard levels 1 and 2, so as to evaluate their responses under three scenarios, namely without any energy dissipation system, with viscous damper, and with LRB isolator, using dynamic analysis of time history utilizing PERFORM 3D v5 software. The results were indicative of enhancement in seismic performance of the viscous damper-equipped structures at earthquake hazard level 1, as the corresponding performance level was enhanced from life safety to uninterrupted usability, while no significant seismic performance level enhancement was determined at seismic level 2. Seismic isolator-equipped structures were also associated with seismic performance level enhancement from life safety to uninterrupted usability at both earthquake hazard levels. Relative lateral displacement at floor levels in damper-equipped structures and seismic isolator-installed buildings were found to be about 29% and 68% improved over that of the structure with no energy dissipation system. Results of distribution of shear forces within structures equipped with viscous damper and seismic isolator, as compared against that of the structures with no energy dissipation system, indicted increased and decreased shear forces, respectively..

Keywords: Seismic Performance; Base Isolation; Time History Analysis; Near-Field Earthquake.

1. Introduction

Considering the importance of improvement and retrofit of buildings against earthquake and the attempts made to realize these goals, various methods have been invented and proposed by structural and seismology experts to reduce seismic response of structures. Among these methods, seismic isolators and viscous dampers represent two of the most efficient alternatives. Either of these devices comes with advantages and disadvantages compared to the other. Dampers serve as devices to dissipate the earthquake-derived energy developed within a structure. There are various types of dampers, among which viscous dampers are widely applied due to such advantages as easy installation and longer useful life. In seismic isolators, the structure is founded on supports which are of large lateral deformation capability. In case of an earthquake, resulted displacements are mainly bore by the support, with the structure acting as a solid object and vibrating with small displacements. Installation of an isolator results in lengthened period and damps the structure, so that seismic demand decreases instead of strengthening the structure's bearing capacity.

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2. Viscous Damper

In this type of dampers, movement of a viscous fluid within a cylinder results in the dissipation of energy. Due to some advantages as easy installation, adaptability and coordination with other structural members, and also variety of their dimensions and sizes are widely applied in the design and retrofit applications. Liquid dampers are developed based on the passage of a liquid through orifices. Viscous fluid dampers are developed with a crankshaft-piston mechanism for industrial and military application (Figure 1). In the chamber within the cylinder, incompressible silicone starts to flow as a force is applied to the piston. The piston has its head provided with several orifices with passive metallic thermo regulators to neutralize thermal changes, with some highly resistant caps used to keep the contents in place. Equation (1) defines the developed force in viscous damper as a function of orifice geometry, where α varies within 0.3 to 2. If α = 1, the damper exhibits linear behavior, while other values of α indicate nonlinear behavior of the damper. Smaller values of α render effective in reducing high-speed shocks. In contrary, α = 1 represents a suitable choice for structures to be protected against wind and earthquake [1]. Developed damping ratio in a structure using linear dampers can be calculated via Equation (2) [2]. Figure (2) demonstrates force-deformation loops and their dependence on vibration amplitude and frequency.

$$P_{(t)} = C_v |\dot{d}|^{\alpha} sgn(\dot{d}) \tag{1}$$

Where $P_{(t)}$ represents the developed force in the damper, C_v is frequency damping ration, $\dot{d}$ is the velocity at two ends of the damper, and α determines linearity/non-linearity of the damper behavior.

$$\xi_d = \frac{T\sum_j C_j \cos^2\theta_j \varphi_{rj}^2}{4\pi \sum_i m\,\varphi_i^2} \tag{2}$$

Where T is the corresponding period to principle mode of the structure, C_j is damping ratio of j th floor, φ_{rj} is relative horizontal displacement of damper ends, θj denotes the angle between damper and horizontal direction at j th floor, m is the seismic mass of the i th floor, and φ_i represents the displacement of the i th floor.

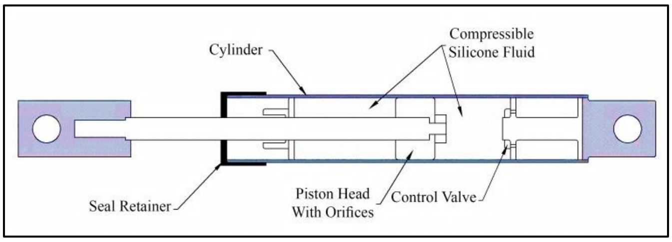

Figure 1. Details of viscous damper

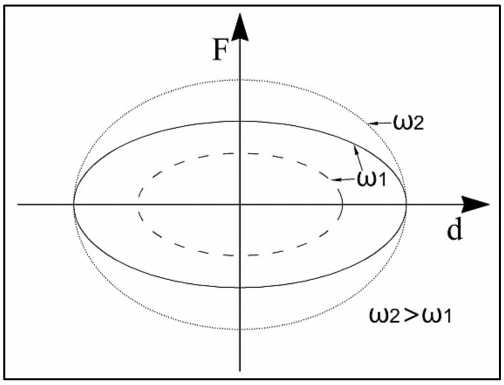

Figure 2. Force-displacement relationship of linear viscous damper [1]

3. Lead Rubber Bearing (LRB) seismic isolator

Seismic isolator reduce applied earthquake force to a structure by increasing the corresponding period to first mode (separated mode), decreasing spectral acceleration (pseudo acceleration) resulted from lengthened period, preventing from activation of higher modes by ground motion, increasing the damping effect of the isolator system, and their energy dissipation characteristics which is recognized as a secondary factor. Seismic isolators are in various types including elastomeric systems (natural rubber), low-damping natural and artificial rubber systems with steel sheets, LRB isolator systems, high-damping natural rubber bearing systems (HDNR), hybrid systems proposed by Earthquake Engineering Research Center (EERC), hybrid TAISEI Shake Suppression (TASS) systems, Resilient-Friction Base Isolator (R-FBI), Friction Pendulum System (FPS), and spring-based isolator systems [1]. Figure 3. demonstrates two LRB isolators with square-shaped and circular cross sections. Figure 4 presents nonlinear behavior curve of LRB isolators.

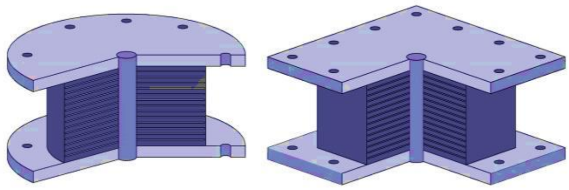

Figure 3. Lead rubber bearing base isolation

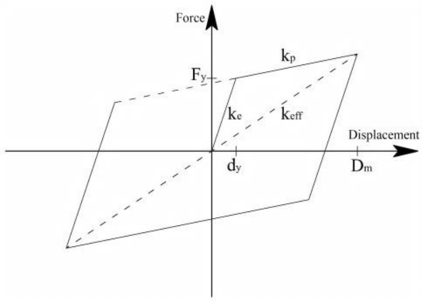

Figure 4. Force-displacement relationship of lead rubber bearing base isolation [3]

In Figure 4, force-displacement plot of LRB isolator is demonstrated. In this figure, k_e represents initial stiffness, k_p is secondary stiffness, k_{eff} is the effective stiffness, d_y is the displacement at yield of the lead core, and F_y refers to yield force of the lead core.

4. Near-Field Earthquake

Earthquake is indeed the phenomenon of wave generation and propagation due to the release of a large deal of energy as a result of turbulences and fractures through earth's crust or upper parts of mantle, which occurs within a short time. Within short distances to the earthquake epicenter, structures with short periods tend to be extensively affected by the earthquake waves, while in cases where the fault location is far from the setting, structures of relatively long periods tend to be considerably affected. Moreover, the response spectrum on soft soil in longer periods exceeds that on hard soils. Figure 5. shows a summary of the effect of offset on acceleration response spectrum [4].

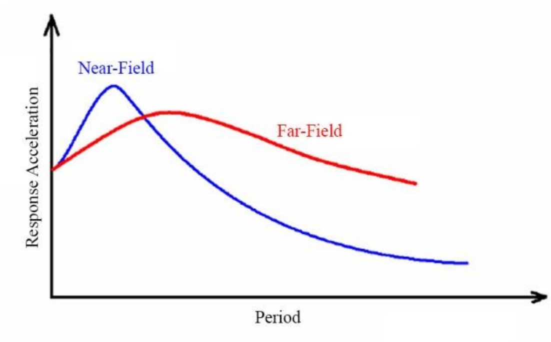

Figure 5. The effect of distance on response acceleration [4]

4.1. Records of Near-Field Earthquake

The earthquake record selection was based on Iranian standard 2800 and recommendations proposed in FEMA P-695 Code [5-6]. Details of the records selected to undertake dynamic analysis of time history are presented in Table 1.

Table 1. Selected records of near-field earthquake

No.	Magnitude	Years	Name	Vs30 (m/s)	R-rup (*km*)	PGA (*g*)
1	7.35	1978	Tabas	766.77	2.05	0.86176
2	6.93	1989	Loma Perieta	347.90	9.31	0.33123
3	7.01	1992	Cape Mendocino	422.17	8.18	0.66156
4	6.69	1994	Northridge	508.08	7.26	0.43282
5	6.52	2003	San Simeon	410.66	6.22	0.48245
6	6.63	2004	Niigata	375.00	8.93	0.59920
7	7.1	1979	Montenegro	462.23	6.98	0.37241

4.2. Scaling of the Accelerograms for the Design Basis Earthquake

Scaling was performed according to the instructions detailed in Iranian standard 2800 (4th edition). Figure 6. shows acceleration response spectra of earthquake accelerogram pairs once scaled to their maximum values (g) followed by summation via taking square root of the sum of squares, along with their average spectrum. Figure 7. demonstrates the obtained average acceleration response of spectrum of each accelerogram pair when multiplied by scale factor and matched to 1.3 times the proposed acceleration response spectrum in Iranian standard 2800 (4th edition). Scaling should be done in such a way that the acceleration spectrum for each period within the range of 0.2 T to 1.5 T would exceed 1.3 times the corresponding spectrum in the Iranian standard 2800 (4th edition) by no more than 10%.

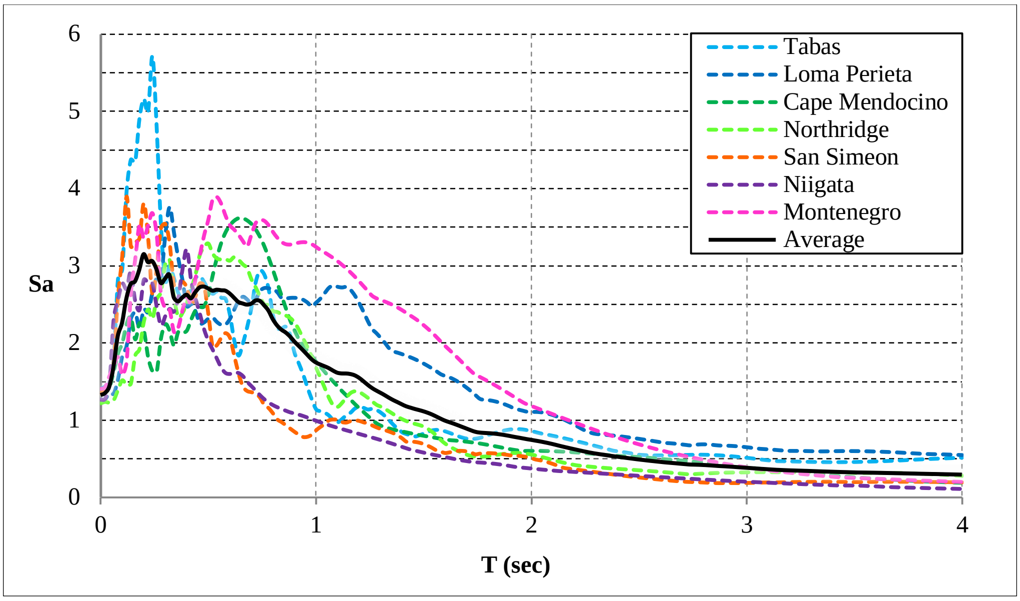

Figure 6. Acceleration spectrum of accelerogram pairs when combined via SRSS method, along with their average

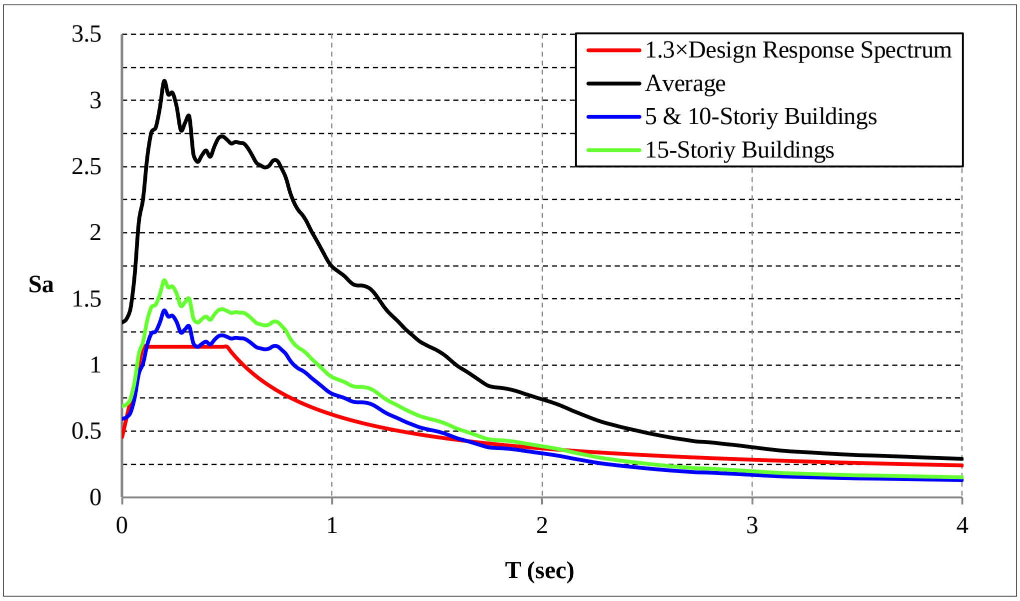

Figure 7. Scaling of average acceleration spectrum of accelerogram pairs and comparing them with 1.3 times the corresponding acceleration spectrum in Iranian standard 2800

5. Software Modeling

In order to extract sections of the structures under study, modeling with linear materials and dynamic analysis of linear response spectrum in ETABS 2016 v16.0.0 software were used, followed by utilizing PERFORM 3D v5 software to non-linearly analyze the structures. Design of structures for earthquake force was based on Iranian standard 2800 (4th edition). The structures under study were moment-resisting frames of medium steel with 5, 10 and 15 stories and 5 spans of 5 m spacing in both directions. In order to non-linearly model structural members via non-linear dynamic analysis method, the structure was modeled based upon force-component deformation relationship expressed in terms of some non-linear relationships. In this method, the structural response is calculated by considering nonlinear behavior of materials and nonlinear behavior of the structural geometry. In this approach, since stiffness matrix and damping ratio can changes over time, numerical methods are used to calculate the model response under earthquake acceleration different time steps. The relationships in Publication 360 can be used to model steel members. Figure 8 demonstrates these relationships in terms of force-general deformation for steel members [7].

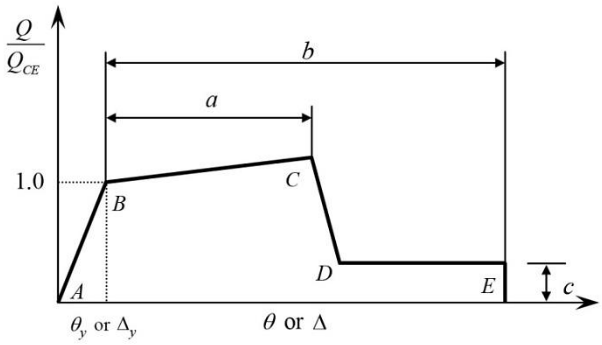

Figure 8. Generalized force-deformation Relation for steel elements or components [7]

The parameters Q and Q_{ce} in Figure (8) are generalized component load and generalized component expected strength, respectively. For beams and columns, θ is the total elastic and plastic rotation of the beam column, θ_y is the rotation at yield, Δ is total elastic and plastic displacement, Δ_y is yield displacement. The parameters a, b and c, as defined in Table 5-6 and 5-7 of FEMA 356 (2000), shall be used for components of steel moment frames [7].

5.1. Model Verification

In order to verify the software when it comes to modeling of viscous fluid dampers, the research by Lyan-Ywan Lu et al. (2013) was used, experimental evaluation of supplemental viscous damping for a sliding isolation system under pulse-like base excitations. In this research, a linear viscous damper with a damping ratio of 47.8 KN.s/m was subjected to harmonic loading at 0.7 Hz, with the experimental and numerical results compared against one another [8]. Figure 9. shows the hysteresis loop obtained from the analysis undertaken using PERFORM 3D software, and further compares experimental data to numerical results. As can be seen on Figure 9, numerical results were in good agreement with experimental data.

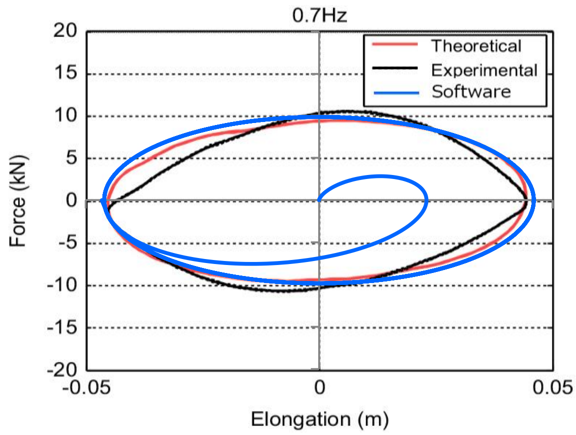

Figure 9. Comparing the hysteresis loop obtained from PERFORM 3D software to experimental data

In order to verify PERFORM 3D software in the analysis of LRB isolator, the paper by Rabinson (1982) was referred to. He investigated lead-rubber hysteretic bearings suitable for protecting structures during earthquakes, empirically analyzing isolators of different dimensions and geometries under different loading regimes, with the results evaluated. As a part of his evaluations, a LRB isolator of 650 mm in diameter, 197 mm in height, 170 mm in lead core diameter, 1.75 kN.mm-1 in secondary shear stiffness, and 600 kN.mm-1 in axial stiffness was subjected to an ultimate displacement of 91 mm under an axial load of 3150 kN and harmonic shear force of 0.9 Hz in frequency [9]. Figure 10. demonstrates a comparison between the hysteresis loop obtained from the analysis using PERFORM software and experimental data given in the paper by Rabinson (1982). As can be observed, the numerical results are well in agreement with experimental data.

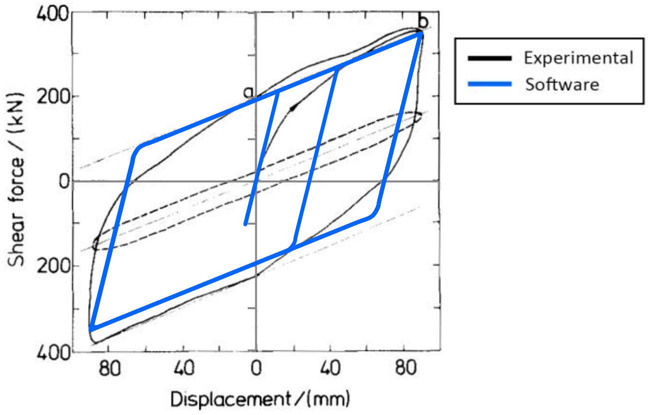

Figure 10. Comparing the hysteresis loop of LRB isolator as obtained from PERFORM 3D software against experimental data

6. Analytical Results

6.1. Building Performance Levels

A performance level indicates maximum expected damage to the structure, so that the performance level will change as soon as the corresponding damage level is exceeded. Performance levels of the entire building are defined based on performance levels of structural and nonstructural members as follows [7]:

- Operational Performance (OP)
- Immediate Occupancy Performance (IO)
- Life Safety Performance (LS)
- Collapse Prevention Performance (CP)

Respecting the fact that a performance level refers to the maximum possible damage to structural members by an earthquake, the earthquake hazard levels should be further investigated in this regard. Different earthquake hazard levels are defined in terms of average return period or probability of occurrence within useful length of the structure. Average return period refers to the average time (in years) between subsequent earthquakes of equal or greater than a given magnitude during a given time interval (commonly useful life of structure) [7].

Earthquake hazard level 1: An earthquake of 10% probability of occurrence within the 50-year useful life of building at a return period of 475 years – design basis earthquake (DBE).

Earthquake hazard level 2: An earthquake of 2% probability of occurrence within the 50-year useful life of building at a return period of 2475 years – maximum considered earthquake (MCE).

Considering the explanations given above, in order to determine seismic performance level of the tested buildings of 5, 10, and 15 stories, the structures (once without any energy dissipation system, once with viscous damper, and once with LRB isolation system) were subjected to analysis under DBE and MCE using 7 accelerogram pairs including those of Tabas, Loma Prieta, Cape Mendocino, Northridge, San Simeon, Niigata and Montenegro earthquakes, with the results presented in averages. Results of performance level across entire structure are summarized in Table 2.

Table 2. Performance Levels of all structures

Story	Without Energy Absorbers		With Viscous Dampers		With Base Isolation	
	DBE	MCE	DBE	MCE	DBE	MCE
5	L.S	L.S	I.O	L.S	I.O	I.O
10	L.S	L.S	I.O	L.S	I.O	I.O
15	L.S	L.S	I.O	L.S	I.O	I.O

Percentage of reduction in the ratio of rotation of the sections to elastic rotation of the buildings equipped with damper and isolator systems when compared to that of the building with no energy dissipation system is presented in Tables 3.

Table 3. Percentage of reduction in the ratio of rotation of the sections to elastic rotation of all retrofitted buildings

Story	With Viscous Dampers		With Base Isolation	
	DBE	MCE	DBE	MCE
5	41%	39%	75%	80%
10	40%	35%	69%	75%
15	18%	20%	77%	69%
Average	33%	31%	73%	74%

6.2. Lateral Displacement of Structure

Lateral displacement and lateral displacement of the structure's floors represent an important parameter when it comes to the determination of seismic behavior of structures. Relative lateral displacement of structure's floors indicates deformations in the main structural elements, e.g. girders, pillars, connections, and lateral bearing systems of the structure. Figures 11-13 represent lateral displacements in 5, 10, and 15-story buildings of no energy dissipation system, viscous damper system, and LRB isolator, respectively, at earthquake hazard levels 1 and 2.

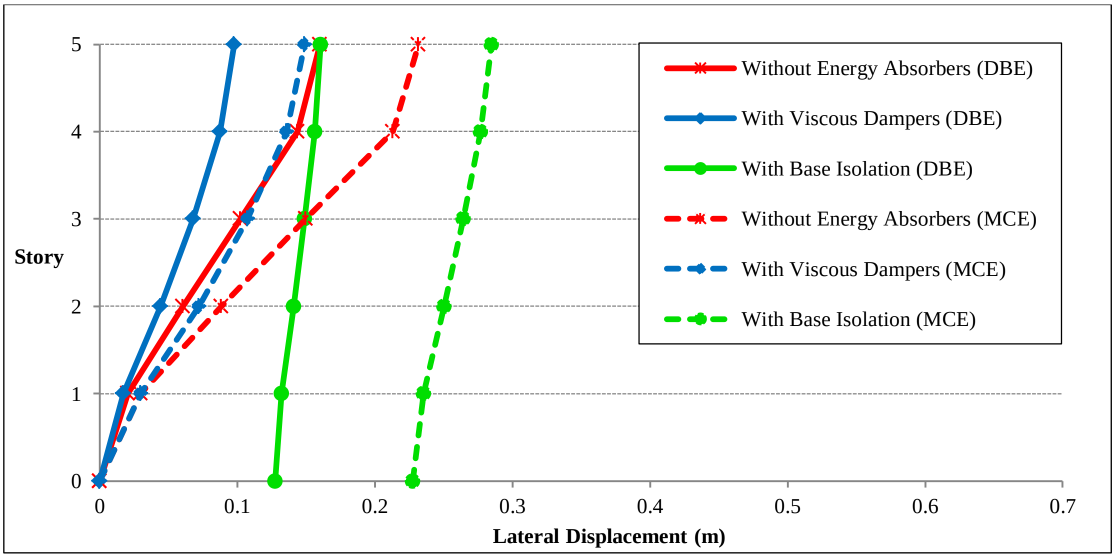

Figure 11. Lateral displacement of the floors of the 5-story building at earthquake hazard levels 1 and 2

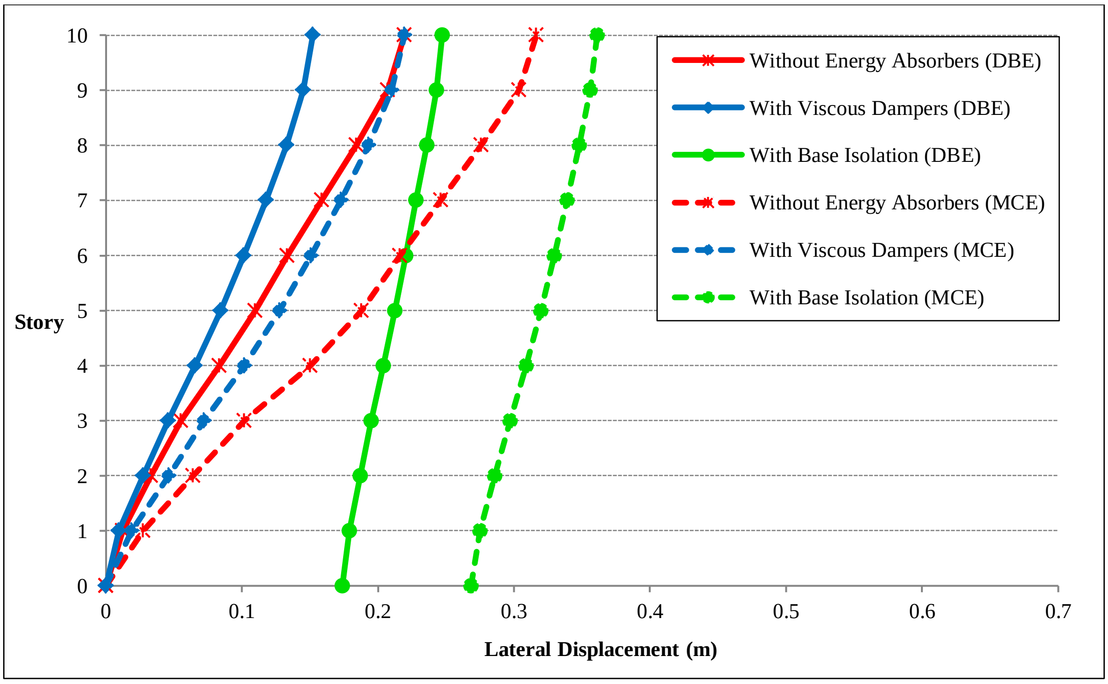

Figure 12. Lateral displacement of the floors of the 10-story building at earthquake hazard levels 1 and 2

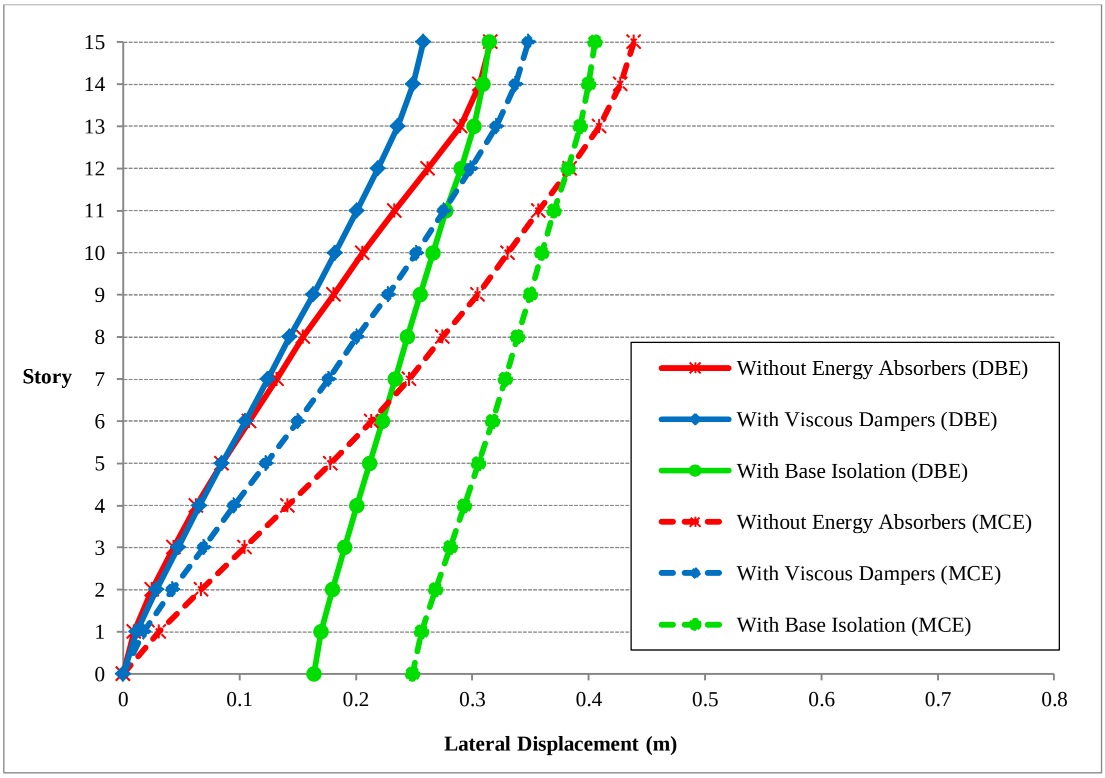

Figure 13. Lateral displacement of the floors of the 15-story building at earthquake hazard levels 1 and 2

Table 4. reports the reductions in relative lateral displacement at floors when the building is seismically retrofitted with either a damping or an isolator system. Table 4 indicates a reduction 2 – 3 folds in relative lateral displacement at floors of the building equipped with seismic isolator, as compared to that of structures equipped with viscous dampers.

Table 4. Percent reduction in relative lateral displacement at floors of the retrofitted buildings compared to the building with no energy dissipation system

Story	With Viscous Dampers			With Base Isolation		
	DBE	MCE	Average	DBE	MCE	Average
5	39%	36%	37%	79%	75%	77%
10	31%	31%	31%	67%	71%	69%
15	18%	21%	19%	52%	64%	58%
Average	29%	29%	29%	66%	70%	68%

6.3. Distribution of Shear Force

Figures 14-17. present plots of the distribution of shear force along the height of 5, 10, and 15-story structures without any energy dissipation system as well as when those are equipped with either a viscous damper or LRB isolator. As can be observed, the applied force to the buildings with their structures equipped with viscous damper or LRB isolator increase and decrease, respectively, compared to the building with no energy dissipation system.

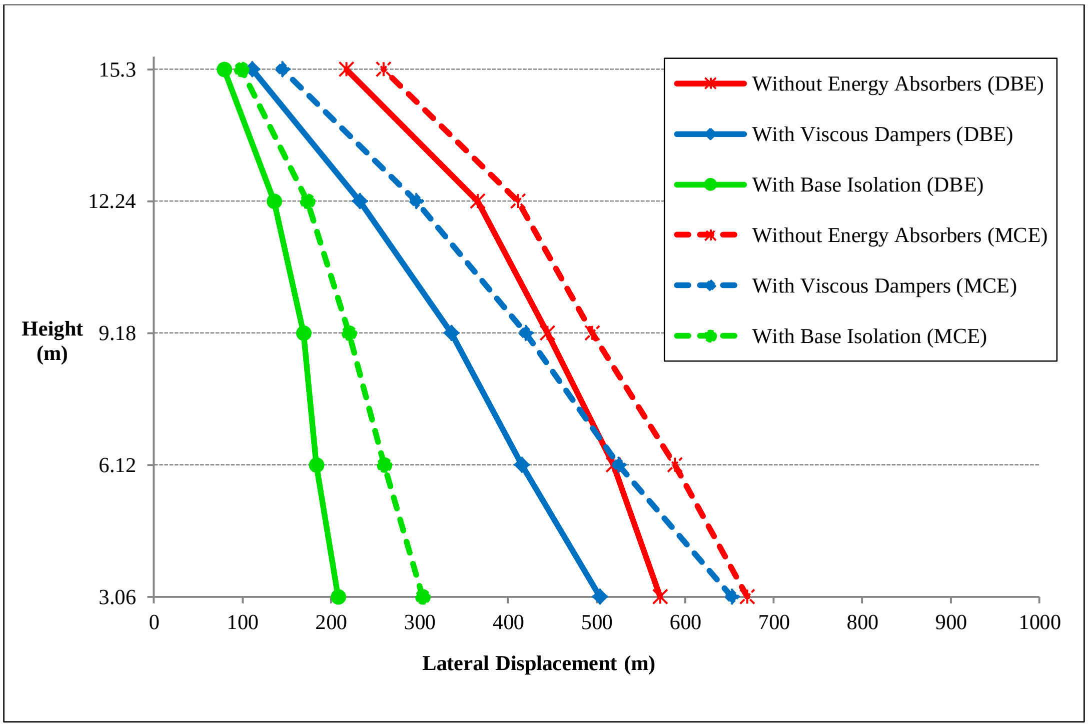

Figure 14. Distribution of shear force along the height of 5-story buildings at earthquake hazard levels 1 and 2

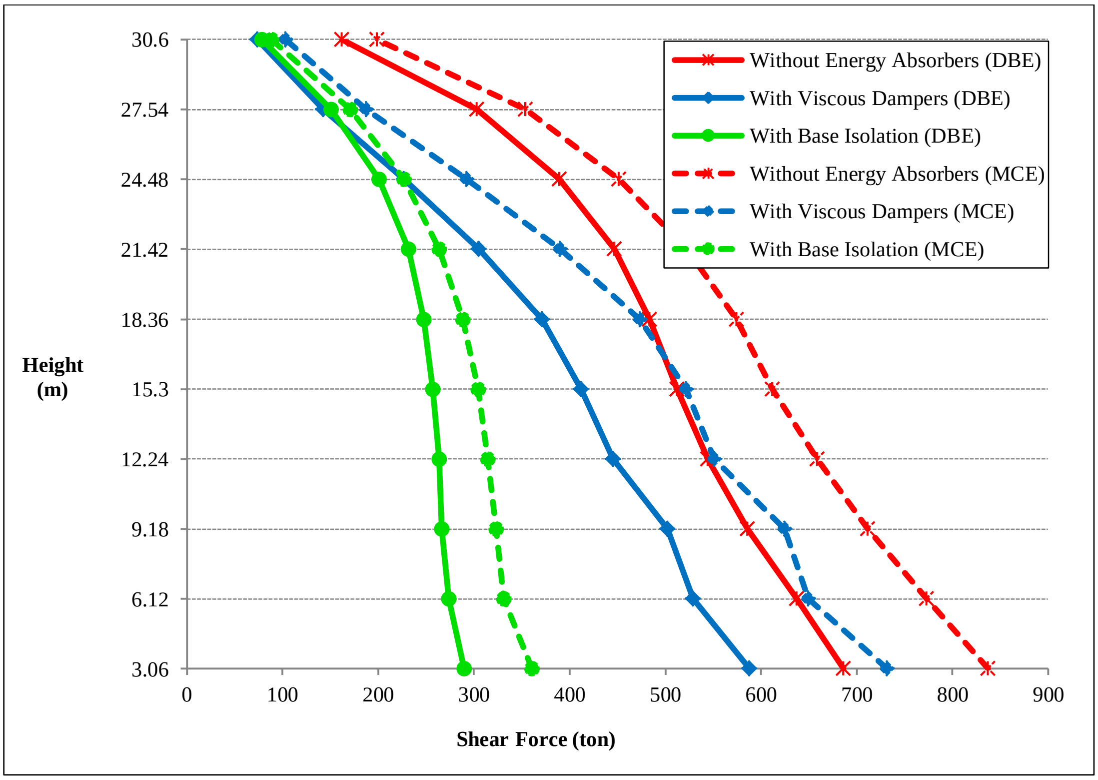

Figure 15. Distribution of shear force along the height of 10-story buildings at earthquake hazard levels 1 and 2

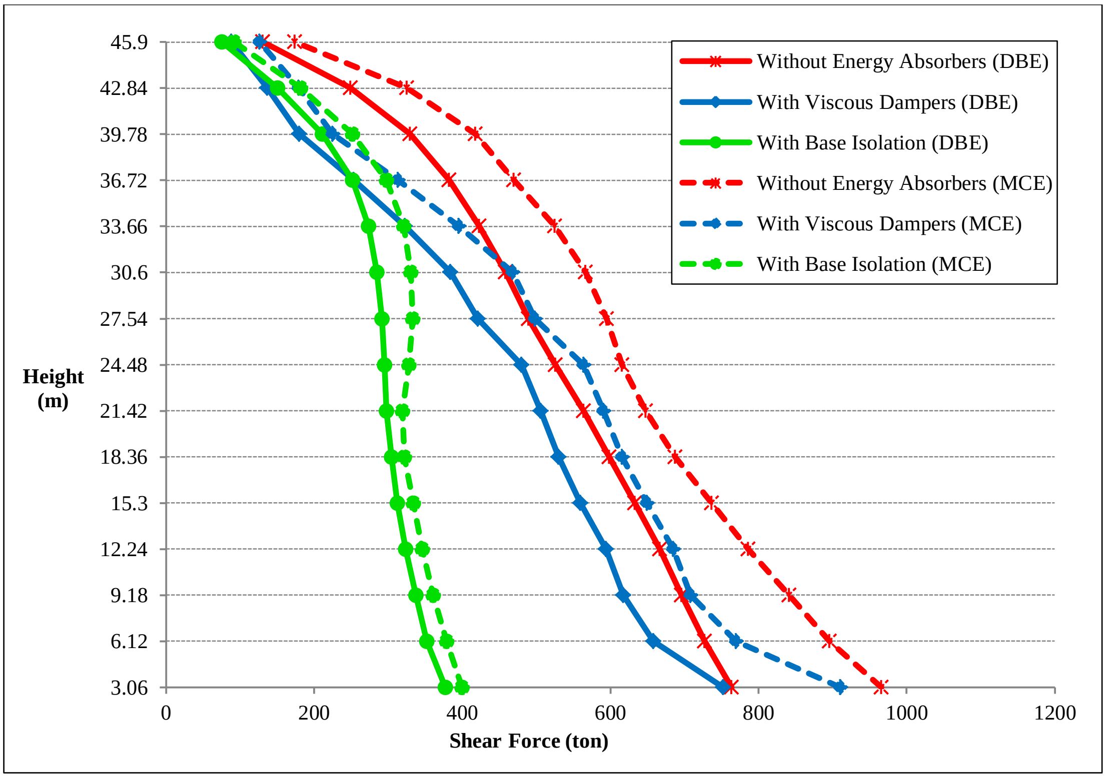

Figure 16. Distribution of shear force along the height of 15-story buildings at earthquake hazard levels 1 and 2

6.4. Energy Balance

Energy balance refers to the equality of the input energy into and absorbed energy from a structure. In Figures 17 and 18, energy balance curves are provided for the buildings without energy absorber, with viscous damper and with LRB isolator under earthquake hazard levels of 1 and 2, respectively. In Figures 17-19, plots of cumulative percentage of absorbed energy by structural members are provided along with such structural characteristics as kinetic energy absorbed, strain energy absorbed via strain deformations, absorbed energy via inherent damping properties of the system, absorbed energy via plastic deformations, and absorbed energy by energy dissipation devices in the 15-story building under near-field earthquake of Tabas under earthquake hazard level 2. In Figure 21, since none of structural elements (except for LRB isolator) has entered into its plastic (unrecoverable) deformation stage, the segment of plot marked in red (dissipated inelastic energy) represents the absorbed energy by seismic isolators.

In order to model elastic damping characteristics of systems, Rayleigh damping model was used assuming a damping of 5%. In this model, the damping matrix [C] can be calculated via Equation (3).

$$[C] = \alpha[M] + \beta[K] \tag{3}$$

Where [C] is the damping matrix, α[M] is the damping resulted by the structure mass, and β[K] refers to the damping effect due to the structure's stiffness.

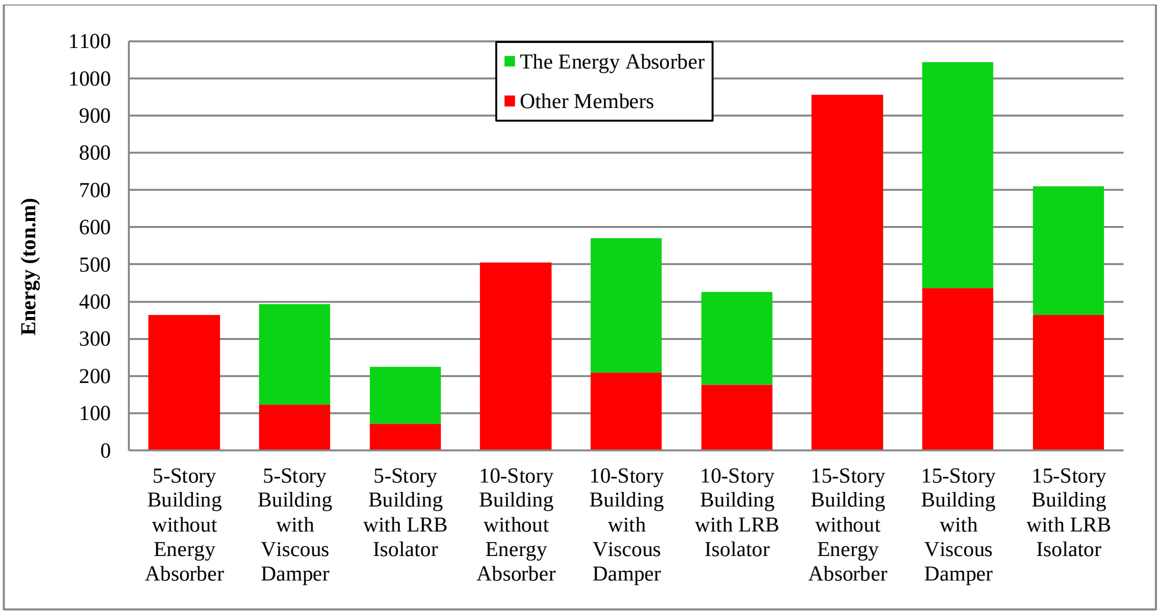

Figure 17. Absorbed energy by structural elements and energy dissipation devices at earthquake hazard level 1

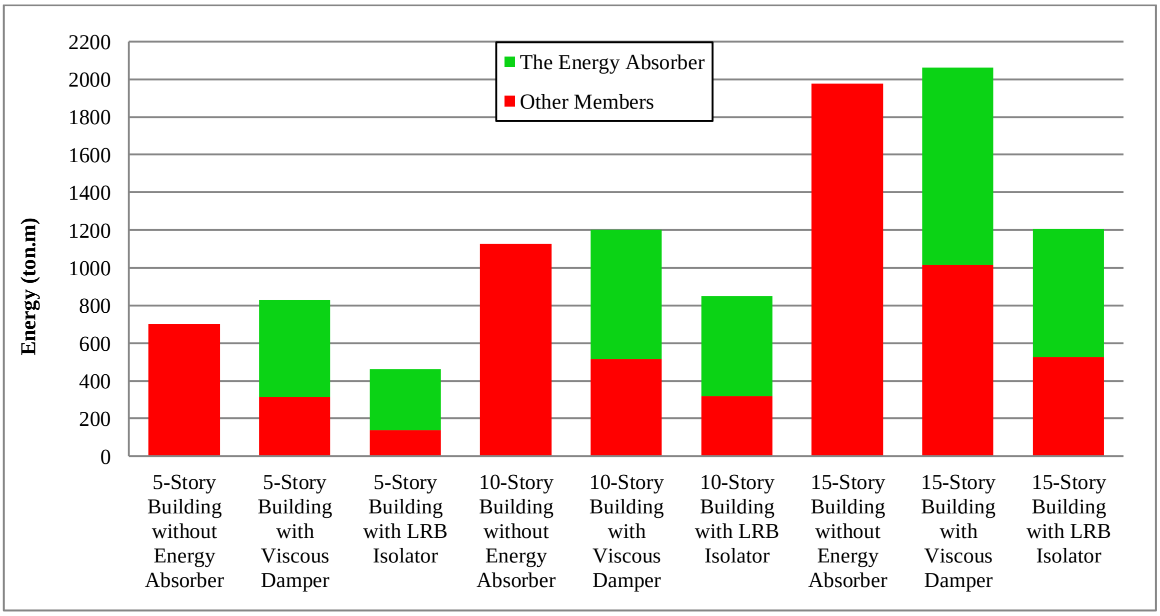

Figure 18. Absorbed energy by structural elements and energy dissipation devices at earthquake hazard level 2

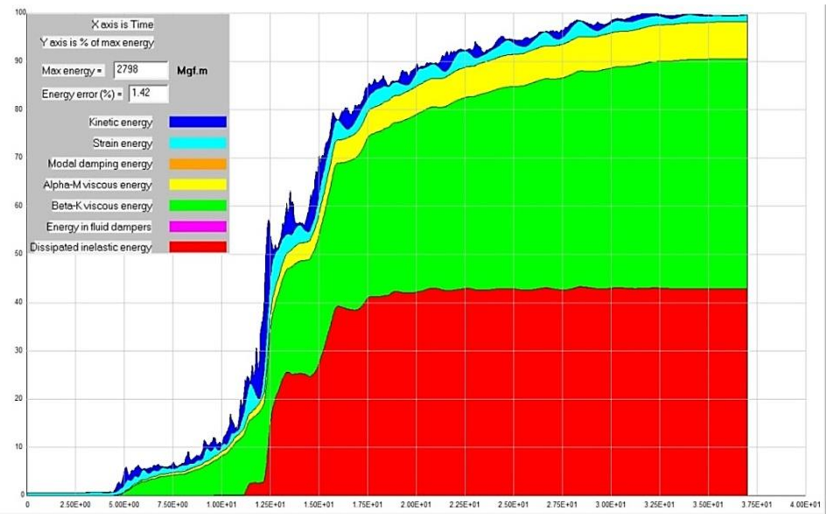

Figure 19. Cumulative percentage of dissipated energy in the 15-story building with no energy dissipation system under Tabas earthquake at earthquake hazard level 2

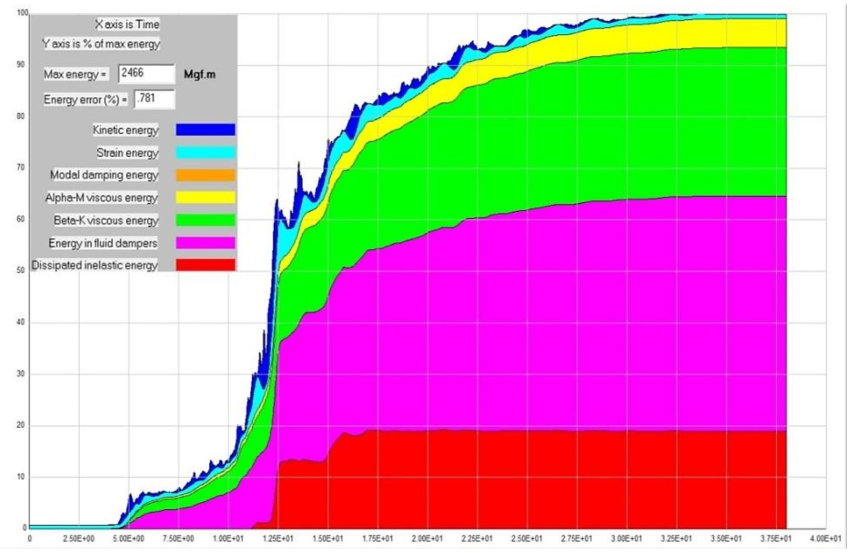

Figure 20. Cumulative percentage of dissipated energy in the 15-story building equipped with viscous damping system under Tabas earthquake at earthquake hazard level 2

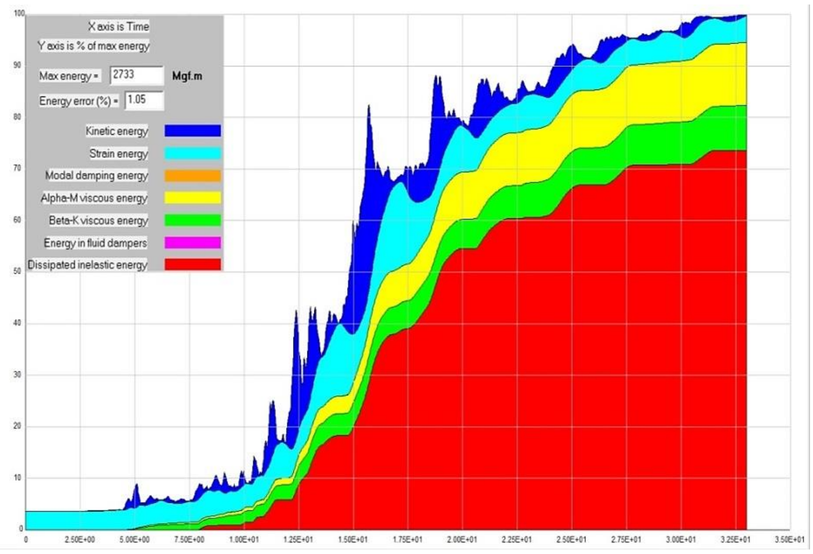

Figure 21. Cumulative percentage of dissipated energy in the 15-story building with LBR isolator system under Tabas earthquake at earthquake hazard level 2

In Figures 19-21, besides kinetic energy and strain energy which have clear definitions, "Alpha-M viscous energy" refers to the viscous damping energy generated by the mass of the structure as calculated in the damping equation by Rayleigh, "Beta-K viscous energy" refers to the viscous damping energy generated by the structural stiffness as calculated in the damping equation by Rayleigh, "Energy in fluid Dampers" defines viscous dampers' energy, and "dissipated inelastic energy" is the energy absorbed via inelastic deformations.

7. Conclusion

In the present research, seismic behavior of structures without energy dissipation systems was evaluated and compared against those structures equipped with either viscous damping systems or seismic isolators, under the effect of near-field earthquake records. Accordingly, the following conclusions were drawn:

- When subjected to earthquake hazard level 1, viscous dampers in 5, 10, and 15-story buildings succeeded to reduce the ratio of rotation-to-maximum elastic rotation of section with respect to the building with no energy dissipation systems by 41, 40, and 18%, respectively; the corresponding figures to earthquake hazard level 2 were found to be 39, 35, and 20%, respectively. Such a reduction at earthquake hazard level 1 resulted in the enhancement of seismic performance of the structures from life safety to uninterrupted usability; however, the reduction under earthquake hazard level 2 was not significant enough to bring about enhancement in seismic performance level. The corresponding figures to the structures equipped with seismic isolators were 75, 69, and 77%, respectively, at earthquake hazard level 1, and 80, 75, and 69%, respectively, under at earthquake hazard level 2. Such a reduction at earthquake hazard resulted in the enhancement of seismic performance of the structures from life safety to uninterrupted usability at both earthquake hazard levels.

- On average and at both earthquake hazard levels, viscous damper-equipped structures were associated with about 29% enhancement in relative lateral displacement at floors, when compared to the structures with no energy dissipation system. The corresponding figure to the structures equipped with LBR absorber was found to be about 68%.
- At all floors and on average over all structures under both earthquake hazard levels, shear force exhibited 19% and 52% reductions in the structures equipped with viscous damper and LRB isolators, respectively.

Input energy to 5, 10, ad 15-story buildings with viscous dampers under earthquake hazard levels 1 and 2 was, on average, increased by about 10% compared to the structures with no energy dissipation system. At earthquake hazard level 1, 68, 63, and 58%, and at earthquake hazard level 1, 62, 57, and 50% of input energy was absorbed by the dampers installed into 5, 10, and 15-story structures, respectively. Input energy to 5, 10, ad 15-story buildings with LRB isolators under earthquake hazard levels 1 and 2 was, on average, reduced by about 30% compared to the structures with no energy dissipation system. At earthquake hazard level 1, 68, 58, and 48%, and at earthquake hazard level 1, 70, 62, and 56% of input energy was absorbed by the isolators installed into 5, 10, and 15-story structures, respectively

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