

EVALUATION OF SEISMIC PERFORMANCE OF CONCRETE STRUCTURES USING LINEAR AND NONLINEAR ELASTOMERIC SEISMIC ISOLATORS

PROCENA SEIZMIČKIH PERFORMANSI BETONSKIH KONSTRUKCIJA UPOTREBOM LINEARNIH I NELINEARNIH ELASTOMERNIH SEIZMIČKIH IZOLATORA

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Keywords

- seismic isolation system
- linear isolator (LDRB)
- nonlinear isolator (LRB)
- time history analysis
- concrete building
- seismic isolator

Abstract

The isolation of buildings from the powerful movement of the earth is a new method that has been highly regarded in recent decades and is one of the scientific and practical methods for reducing the earthquake-caused losses which is performed as a simultaneous reduction in the inter-story displacement and acceleration of stories. The mechanism of this method is such that with an increase in the period and damping of the structure in the seismic isolation system, the effect of acceleration and destructive energy of earthquake are reduced. Thus, it is known as an earthquake-resistant design method substituting the reinforcement of the structure's load-bearing capacity. The use of a seismic isolator means that before the earthquake force reaches the structure, it is damped and, thereby, the energy is prevented from entering the structure. The present study is aimed to investigate the difference in the response of the 3, 6, and 9-story clamped building with nonlinear (LRB) and linear (LDRB) elastomeric isolators with superstructure height variations. Each isolator is modelled with periods of 2 and 3 seconds, the results of which clearly indicate the effect of proper use of seismic isolators on the reduction of seismic response. Based on the obtained results, it is recommended to use an isolator with a constant period for concrete buildings with height changes.

INTRODUCTION

The earthquake is one of the most destructive natural phenomena which occurs with vibration and movement of the earth in a short time due to the release of the energy, resulting from rapid rupture of the fault in the crust. The earthquake occurring in big and close-to-fault cities are an undeniable event. The occurrence of earthquakes is a natural phenomenon that has caused irreparable damages and casualties over the past years. This has prompted earthquake engineers to compile research regulations to prevent damages to structures and secure the lives of people. One of the approaches currently used to optimise buildings against seismic loads is the use of seismic isolators. The first journal of the FEMA

Ključne reči

- seizmički sistem izolacije
- linearni izolator (LDRB)
- nelinearni izolator (LRB)
- analiza vremenske istorije
- betonska zgrada
- seizmički izolator

Izvod

Izolacija zgrada od moćnih pomeranja zemljišta je nova metoda, visoko ocenjena tokom proteklih decada i čini jednu od naučnih i praktičnih metoda za smanjenje štete prouzrokovane zemljotresima, a izvodi se simultanim smanjivanjem međuspratnih pomeranja i ubrzanja spratova. Mehanizam metode je takav da sa povećanjem perioda i prigušenja konstrukcije u seizmičkom izolacionom sistemu, uticaji ubrzanja i destruktivne energije zemljotresa se smanjuju. Odnosno, poznat je kao metoda projektovanja protiv zemljotresa, izmenom ojačanja kapaciteta nosivosti konstrukcije. Upotreba seizmičkog izolatora znači da se prigušuje sila zemljotresa pre delovanja na konstrukciju, a time se dejstvo energije. Cilj ovog rada je istraživanje razlika u odzivima 3, 6 i 9-spratno ukleštenih zgrada sa nelinearnim (LRB) i linearnim (LDRB) elastomernim izolatorima sa superstrukturnim varijacijama visine. Svaki izolator se modelira sa periodima od 2 i 3 sekunde, gde dobijeni rezultati jasno pokazuju efekat ispravne primene seizmičkih izolatora za smanjenje seizmičkog odziva. Na bazi dobijenih rezultata, preporučuje se primena izolatora sa konstantnim periodom za betonske zgrade sa promenljivom visinom.

institute /1/ (Federal Emergency Management Agency), entitled FEMA 273, was released in September 1996 under the name of Seismic Rehabilitation Guidelines. Subsequently, this institute published FEMA 274, 356, and 357. These four journals became the basis for most of the plans for optimisation and reinforcement of deformations and displacements against earthquakes.

Typically, the seismic design of structures is based upon the concept of increasing the structures' capacity against earthquakes using shear walls, braced frames, and robust flexural frames. Traditional methods often increase the acceleration of stories in buildings with high stiffness and big relative inter-story displacements in flexible buildings, which is one

of the causes of damages to the nonstructural components of buildings. Therefore, in order to reduce the acceleration of stories, the concept of base isolation is highly regarded by researchers. The seismic isolation system has none of the problems related to the conventional clamped systems because the upper structure is displaced almost as a rigid object on the isolator. In fact, a major part of seismic movements of the ground is absorbed at the isolator level and, consequently, the seismic movement transmitted to the upper structure is reduced and, as a result, the fracture of structural and non-structural components is prevented, /2/.

When an earthquake occurs, the inertia forces are created in structures. The behaviour of asymmetric structures and inertia forces created in these structures in the case of exposure to an earthquake will be different from those in symmetric structures. When an asymmetric building is exposed to earthquake stimulations, it will undergo not only peripheral movements but also twisting movements, as a result of which the forces and deformations created in the resistant elements will be different in such buildings. Such a difference depends on the degree of deviation from the centre and other characteristic parameters of asymmetric buildings /3-4/.

Research on structures with seismic isolators is evolving rapidly throughout the world. In regular structures, in which the structure is modelled as a clamped one, the structure is totally rigid, and the effects of the structure's flexibility are not taken into account. However, in the case of using a seismic isolator, the effects of flexibility can be taken into account, which occurs as peripheral flexibility. In fact, the use of such a system will cause the fundamental period of the structure to increase and go far from the time period of the powerful movement of the earth, which decreases with the loss of energy due to peripheral displacement of forces transmitted to the superstructure, /5-11/.

The elastomeric damping system is a system consisting of rubber sheets and thin steel plates that are placed on each other alternately. Such a system is called seismic isolation system. The seismic performance of the isolated structures is commonly evaluated as base displacement, base acceleration, acceleration of stories, and inter-story drift. In terms of dynamic behaviour, the seismic isolation systems are divided into linear and nonlinear groups. A seismic isolation system equipped with LDRB (low-damper rubber bearing) that, in combination with viscous dampers, is called a linear isolation system. The rubber isolator with steel plates (LDRB) has a low damping so that by adding lead, the damping reaches from a critical value of 3 to 10 %, known as LRB (lead rubber bearing), /1/. Another type of isolator is the high-damping rubber isolator, modelled as a nonlinear system due to its nonlinear behaviour. However, in the case of applying the same stiffness and damping characteristics, this isolator can be also modelled as a nonlinear system, /12-13/.

A common approach in the studies on seismic isolated structures is to ignore the effect of superstructure's flexibility on the total or partial seismic response. Since the flexibility of the seismic isolated structure is concentrated mainly at the isolation system level and the superstructure exhibits the behaviour of a rigid object under the effect of earthquake,

the studies in which the flexibility of the superstructure is not taken into account the structure is assumed rigid /14-23/.

The total structure mass, M , includes mass of the superstructure (m_s), the base mass (m_b), and the share of the isolation surface. The mechanism is similar to the single degree-of-freedom system, shown in Fig. 1a. The natural period of the superstructure is assumed equal to zero. Also, $T_s = 0$ and the relative displacement of the superstructure relative to the base is zero. Thus, there is only a single degree of freedom. In addition, U_b indicates the displacement of the base and the superstructure. In the studies on the distribution of two types of mass, namely the base mass and the total mass of the superstructure, the flexibility of the superstructure is considered partial, /24-30/.

The 2D modelling, as shown in Fig. 1b, is assumed as a two degree-of-freedom system. In this case, U_b and U_s are the base displacement and superstructure displacement, respectively. Also, in this case, the period of the superstructure is not zero, and the stiffness value of the columns is adjusted proportionate to the period of the superstructure. Nonetheless, the distribution of stiffness in the height of the story has not been taken into account. The relative inter-story displacement cannot be explicitly expressed using this model.

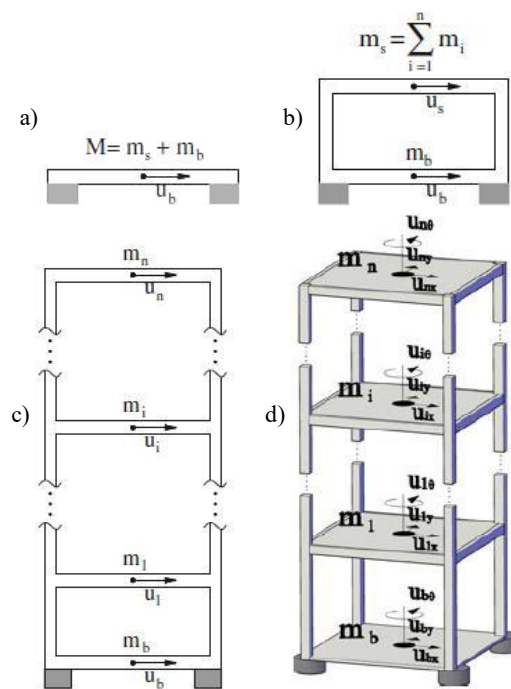


Figure 1. Model for seismic isolation: a) SDOF; b) 2DOF; c) 2D-MDOF; d) 3D-MDOF, /32/.

Although the abovementioned methods are very suitable for modelling and analysing the seismic isolated structures, none of them can demonstrate the effects of the higher modes of the superstructure. To obtain the higher modes, the superstructure must be in the form of a multiple degree-of-freedom (MDOF) system with separate masses for each story. A n -story building for 2D and 3D models is shown in Figs. 1c and 1d, respectively. For the 3D multiple degree-of-freedom model, there are two modelling methods, namely the shear model and the exact 3D model. The shear modelling is an idealised method in which beams have a high strength

against bending and axial forces. Also, the columns are buckling-restrained, and the roofs are assumed rigid and placed on these columns, /31/. This is a good assumption for obtaining the stiffness matrix and changing the mode of the story easily. Basically, the stiffness transmitted along the x and y directions is represented by K_{xxi} and K_{yyi} , respectively. Also, the twisting stiffness is equal to $K_{\theta\theta i}$. The stiffness of each story can be manually obtained by using the formula,

$$\begin{aligned} K_{xxi} &= \sum_{j=1}^{n_c} K_{xij} \cdot, & K_{yyi} &= \sum_{j=1}^{n_c} K_{yij} \cdot, \\ K_{\theta\theta i} &= \sum_{j=1}^{n_c} K_{xij} K_{yij}^2 + \sum_{j=1}^{n_c} K_{yij} K_{xij}^2 \cdot \end{aligned} \quad (1)$$

Using this formula, the stiffness matrix can be obtained. In this formula, n_c is the total number of columns, K_{xij} and K_{yij} are the transmitted stiffness of the j^{th} column in the i^{th} story along the x and y directions, respectively, and X_{ij} and Y_{ij} are coordinates of the j^{th} column in the i^{th} story regarding the place of the mass centre in the i^{th} story. In the idealisation of the shear building, the transmitted stiffness of each column equals $12E_c I_c / l_c^3$ so that E_c represents the elasticity modulus, I_c indicates the inertia moment, and l_c represents the column, /31/.

The research hypotheses are as follows:

1. three types of concrete structures, namely conventional 3, 6, and 9-story concrete structures, are modelled in 3D form;
2. the effects of interactions between soil and structure and also the vertical force of earthquake are ignored;
3. the superstructure remains in elastic state, and the peripheral displacement of the structure is done by the seismic isolator.

Considering the structures constructed over time as well as the architecture and various forms of these structures in terms of materials, etc., the main objective of the study is to present a simple, low-cost, and meanwhile, accurate solution for modelling and analysis of buildings with seismic isolators.

MATERIALS AND METHODS

Modelling

- Superstructure

The present study is conducted on conventional 3, 6, and 9-story concrete buildings, each of which were modelled, in accordance with ASCE7-16, /33/. Regulations, in the form of clamped structures with LDRB and LRB seismic isolators with two periods of 2 and 3 seconds for each isolator.

In terms of research approach, the present work is an applied one. Data are assumed based on conventional structures. Three types of structures, namely 3, 6, and 9-story structures, are modelled initially as clamped (fixed base) structures. Then, the structures are analysed with linear LDRB and nonlinear LRB isolator with periods of 2 and 3 seconds, respectively, in order to obtain results in relation to the use and performance of the isolator regarding the height changes in the building and optimisation of design. All structural models with 20×20 dimensions had 4 frames craters in each direction located at a regular distance of 5 m from each other (as shown in Fig. 2) and a height of 3 m at each story. The cross section of beams and columns is B40×40 cm and C60×60 cm, in respect, in the first three stories, B35×35 cm and C55×55 cm, respectively, in the second three stories, and B30×30 cm and C50×50 cm, respectively, in the third three

stories. Also, the length of rebars in beams and columns is 12T20 and 20T20, in respect. The elasticity modulus of concrete is assumed $25 \cdot 10^3$ MPa and the frames are connected by rigid junctions (Fig. 3).

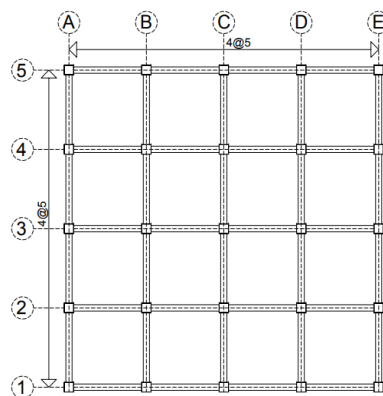


Figure 2. Plan of the structure.

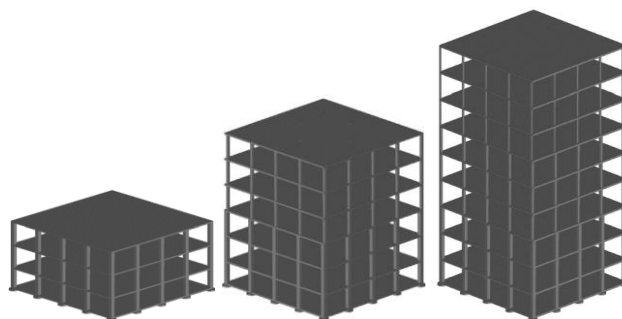


Figure 3. 3D view of the structure (3, 6, and 9-story) with reduced cross section in height.

- Seismic isolator

To reduce the seismic response, it is recommended to use seismic isolators, which are placed under the structure between the foundation and the main structure so that, with an increase in the period and a reduction in the input acceleration of the structure, they prevent destructive effects of earthquakes (Fig. 4).

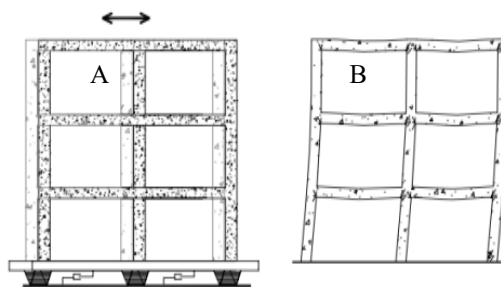


Figure 4. Function of the seismic isolation system. A: without seismic isolation system and using ductility; B: with seismic isolation system.

By changing the period the isolator reduces the application of input acceleration to the structure, as a result of which the structural system enters a safe area. Increasing the period is also associated with some problems. In this case, displacement is increased. There are some mechanisms provided in the system for energy damping, due to which the displacement is reduced as well. Such a damping in the isolate structure is provided from two sources: (1) viscous energy loss;

(2) hysteresis energy loss. Viscous energy loss is directly related to the speed, but hysteresis energy loss results from the distance between the loading branches and curved load-bearing under cyclic, /34/. Inside the curve, the bilinear behaviour of a seismic isolator, which shows the coverage of a complete cycle of displacement, is indicative of the hysteresis energy loss in that cycle. This damping is also associated with some limitations. It must be taken into consideration that increasing or decreasing the damping shouldn't increase the force applied to the structure. Therefore, it is necessary for a seismic isolation system to have the following capabilities, /35/,

- it must be capable to tolerate orthogonal forces resulting from the structure's weight and the earthquake response at the time of an earthquake;
- it should have enough flexibility along the horizontal direction;
- it should be capable to absorb energy.

In the present study, both linear and nonlinear systems are used. The linear isolation system includes damper natural rubber. T_i indicates the natural period of the linear isolation system, and ω_i is the rotatory frequency of the LDRB system which can be obtained using the following equation /31/:

$$T_i = 2\pi \sqrt{\frac{w}{K_i}}, \quad \omega_i = \frac{2\pi}{T_i}, \quad (2)$$

where: w is total weight of building; g is earth acceleration ($g = 9.81 \text{ m/s}^2$); and K_i is overall stiffness of the isolation system. Also, the viscous damping coefficient, C_i , is calculated using the following equation, /31/,

$$C_i = 2\xi_i \omega M, \quad (3)$$

where: $M = w/g$ is total mass of the isolation system. In this study, the damping ratio, $\xi_i = 10\%$. Also, the period of the seismic isolation system has been assumed as $T_i = 2 \text{ s}$ and $T_i = 3 \text{ s}$. The total stiffness of the isolation system and the viscous damping coefficient can be obtained according to the following Table 1.

In the nonlinear LRB isolation system, usually the damper rubber layers have hysteresis behaviour along with nonlinear behaviour. The relationship between force F and displacement D for the isolation system is shown in Fig. 5. Moreover, F_y is yield force, D_y is yield displacement, Q is characteristic force, K_1 is initial-, and K_2 is secondary stiffness of the nonlinear isolation system. The period of the nonlinear isolation system can be obtained as follows, /36/,

$$T_0 = 2\pi \sqrt{\frac{w}{K_2}}. \quad (4)$$

Since the periods of the system are equal to 2 and 3 s, the value of K_2 is obtained from the above formula. To obtain the value of K_1 , the stiffness ratio α , equal to $\alpha = K_2/K_1$, is used. The value of this ratio is $\alpha = 0.1$. In addition, the value of characteristic force Q is obtained from the following, /2/,

$$Q = (K_1 - K_2)D_y, \quad (5)$$

where: D_y is yield displacement. For $T = 2 \text{ s}$ and $T = 3 \text{ s}$, the value of $D_y = 5 \text{ mm}$ and 10 mm , respectively. All of the abovementioned data are given in the Tables 1 and 2.

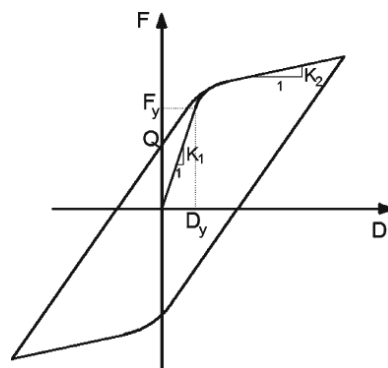


Figure 5. Behaviour of displacement force of the nonlinear isolation system, /2/.

Table 1. Specifications of the linear isolation system (LDRB).

Num. of stories	Linear isolation system				
	$T_i = 2 \text{ s}$			$T_i = 3 \text{ s}$	
	W (kN)	K_i (kN/m)	C_i (kNs/m)	K_i (kN/m)	C_i (kNs/m)
3	8634	8685	552	3860	368
6	16469	16568	1054	7363	703
9	23645	23787	1514	10573	1009

Table 2. Specifications of the nonlinear isolation system (LRB).

Num of stories	Nonlinear isolation system											
	$T_0 = 2 \text{ s}$						$T_0 = 3 \text{ s}$					
	W kN	K_1 kN/m	K_2 kN/m	D_y mm	F_y kN	Q kN	Q/W (%)	K_1 kN/m	K_2 kN/m	D_y mm	F_y kN	Q kN
3	8634	86859	8685	5	434	390	4.52	38604	3860	10	386	347
6	16469	165680	16568	5	828	745	4.52	73635	7363	10	736	662
9	23645	237872	23787	5	1189	107	4.52	105721	10572	10	1057	951

Nonlinear dynamic analysis

Different types of gravity and lateral loads are applied to a structure. The first step to properly understand the behaviour of the structure against loads, it is necessary to know how loads are distributed in the structure and what share of the load each member has. Structural analysis methods are divided into static and dynamic categories. The main difference in this method is the duration of load application in these analyses. In static methods and generally in statics, it is assumed that the applied load is constant over time without any change, while in dynamic, the applied load changes over time.

Linear analysis, as its name suggests, is an analysis that assumes there is a linear relationship between forces applied to the structure and the displacements of the structure due to those forces, in linear analysis, it is assumed that the stiffness matrix is constant during the application of load and there is no change in the stiffness of members.

Nonlinear analysis is an analysis in which there is a nonlinear relationship between the force acting on the structure and its displacements. The nonlinear behaviour is caused by 2 factors: geometric nonlinear behaviour (large shape changes in the structure) and nonlinear behaviour of materials that make up the structure. The stiffness matrix is not assumed to be constant during the load application period and is constantly changing.

The method of nonlinear analysis of time history is such that the effect of ground acceleration is entered as a function

of time at the base level of the structure, and the calculation of response of the mathematical model of the structure that includes its inelastic behaviour, will be done. The ground acceleration is recorded by acceleration zone maps system and the structure is analysed under these accelerations. This method has the highest calculation accuracy among other methods, that's why this method is very complicated.

In the present study, the structure underwent a nonlinear dynamic analysis (time history analysis). For this purpose, three heavy earthquakes occurring over time are used. Also, analysis of data is performed using SAP2000® software [37]. Using the time-based modal integration method, the eigenvalues and eigenvectors required for dynamic analysis of the buildings are obtained.

Earthquake records data

First, the earthquakes are downloaded from the website of the Pacific Earthquake Engineering Research Center (PEER) [38], Table 3. Then, the data are fitted in SEISMOSIGNAL software with a return period of 475 years. Thereby, the intended earthquake acceleration is obtained. The obtained acceleration is then applied with a modal damping of 10 %, time step of 0.005 s, and scale coefficient of 0.4.

Table 3. Earthquake data.

Earthquake	Date	Station	Component	PGA(g)
Imperial Valley	19/05/1940	El Centro	ELC180	0.280
Northridge	17/01/1994	Rinaldi	RSS228	0.874
Tabas	16/09/1978	9101 Tabas	TAB TR-1	0.862

Prelude

The present study investigates the effect of using low-damping rubber seismic isolator along with LDRB viscous damper that has been modelled linearly, and an LRB isolator with periods of 2 and 3 seconds in order to study the seismic response and performance of the seismic isolation system against dynamic loads in terms of reducing the damages to 3, 6, and 9-story concrete structures, which represent low-rise, medium-rise, and high-rise buildings. Figures 6-10, 11-15, and 16-20, respectively, show results obtained for 3, 6, and 9-story clamped buildings with seismic isolators.

According to the analysis of the time history among the buildings considered in this analysis, which are middle-class buildings, and the results and graphs obtained by Sep software, it can be stated that:

- in Figs. 6-10, for a 3-story building, it can be seen that with the increase in the period of the structure, the acceleration of the base and the roof (top acceleration) decrease, and as a result of acceleration decrease, the forces entering the structure are greatly reduced;
- by comparing Figs. 11-15, it can be seen that there is a significant percentage of destruction in structures with the seismic isolation system and without it, and that the 6-story building is more active due to the reduction of acceleration of the entrance to the structure in the nonlinear system and the displacement of the roof has not increased compared to the rest of the displacements;
- according to the intensity and acceleration of the earthquake, the displacement of the roof (top displacement) changes and increases significantly. By increasing the height of the nonlinear separator system, the displacement of the

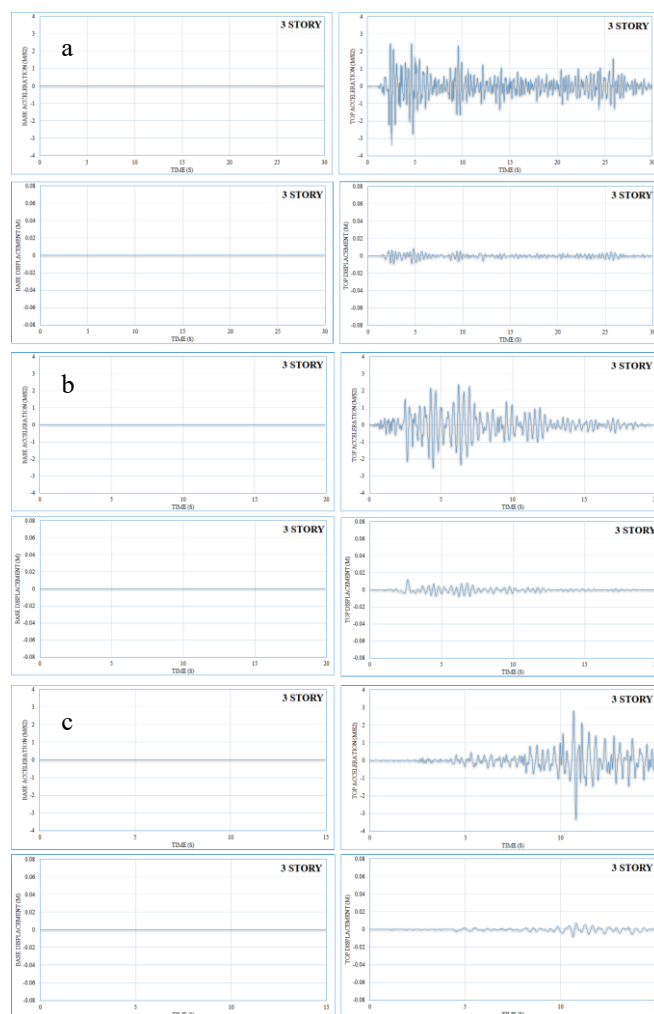
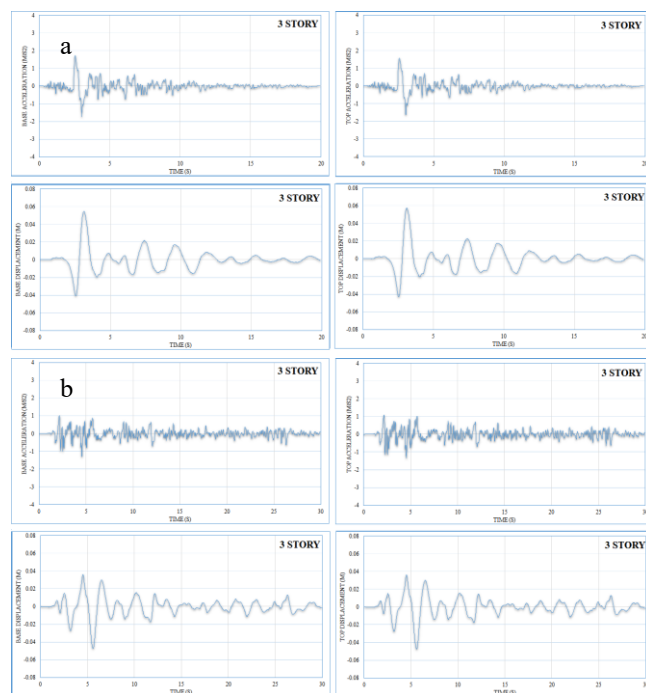


Figure 6. Diagram for base acceleration, top acceleration, base displacement, and top displacement of 3-story clamped building under stimulation: a) Imperial Valley earthquake; b) Northridge earthquake; c) Tabas earthquake.



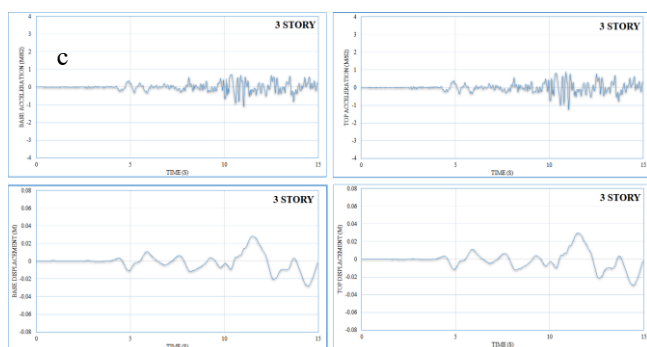


Figure 7. Diagram for base acceleration, top acceleration, base displacement, and top displacement of 3-story building with linear seismic isolator (LDRB) with a 2 s period under stimulation of earthquakes: a) Imperial Valley; b) Northridge; c) Tabas.

roof is reduced and a step can be taken towards the safety of the structure;

- the seismic isolator system is always suggested to improve the seismic response in order to increase the safety of the structure, and it is used by nonlinear analysis and the nonlinear isolator system in different intervals, considering the architecture and ideal engineering space in the design.

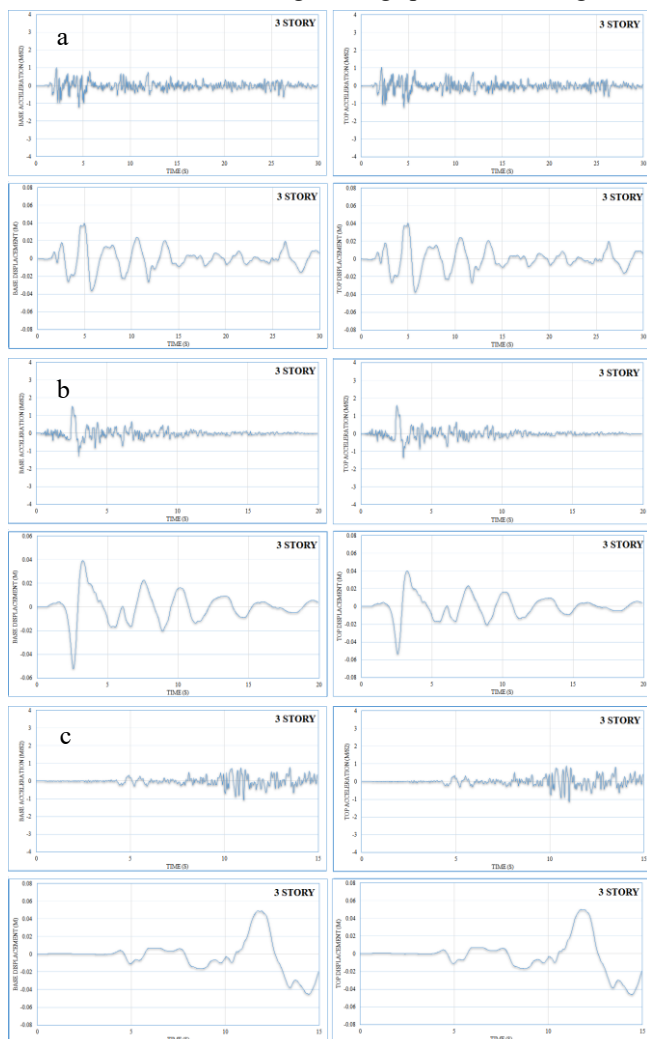


Figure 8. Diagram for base and top acceleration, base and top displacement of 3-story building with linear seismic isolator (HDRB) with 3 s period under stimulation of earthquakes: a) Imperial Valley; b) Northridge; c) Tabas.

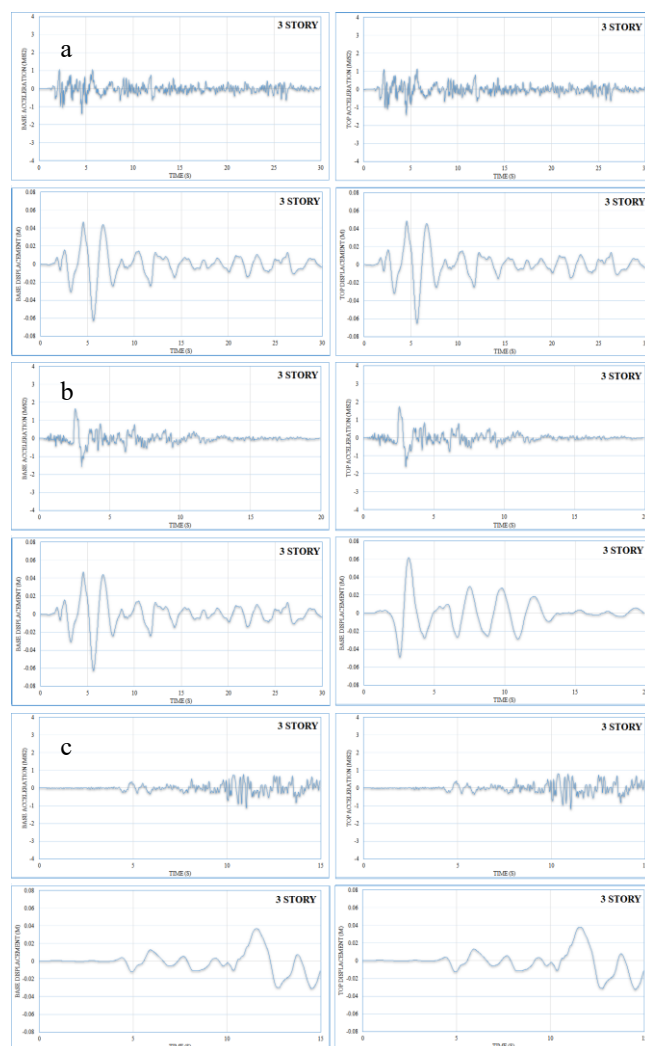
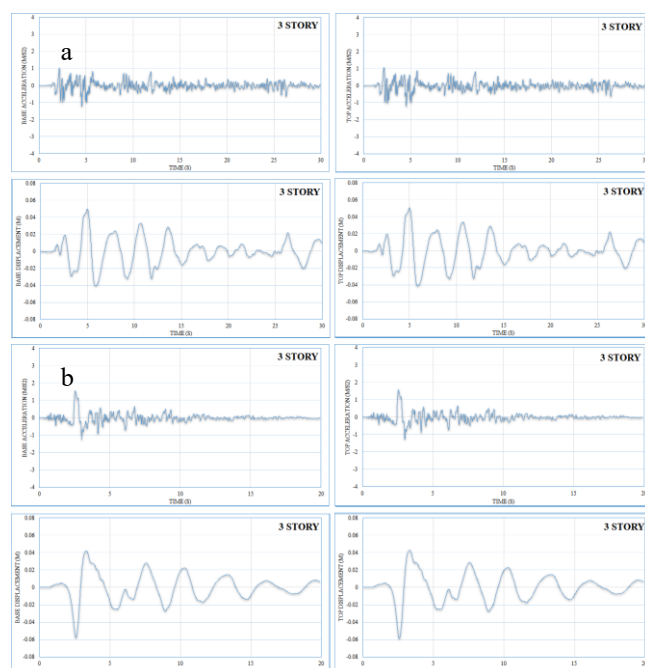


Figure 9. Diagram for base and top acceleration, base and top displacement of 3-story building with nonlinear seismic isolator (LRB) with 2 s period under stimulation of earthquakes: a) Imperial Valley; b) Northridge; c) Tabas.



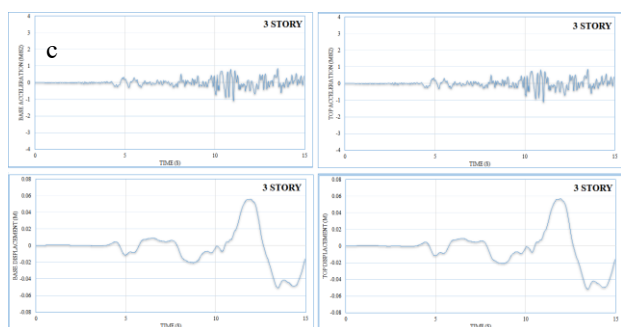


Figure 10. Diagram for base and top acceleration, base and top displacement of 3-story building with nonlinear seismic isolator (LRB) with 3 s period under stimulation of earthquakes: a) Imperial Valley; b) Northridge; c) Tabas.

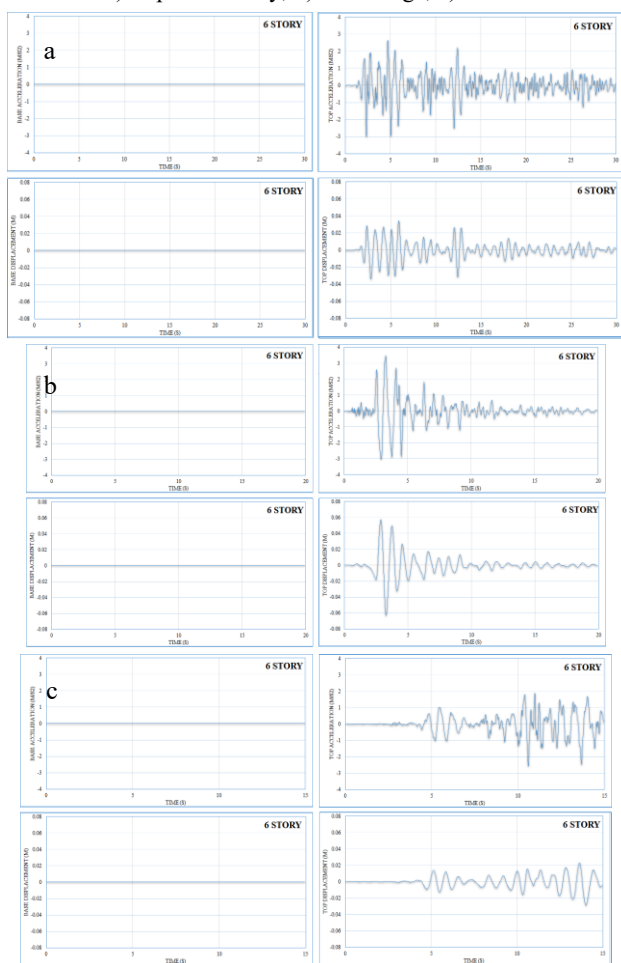


Figure 11. Diagram for base and top acceleration, base and top displacement of 6-story clamped building under stimulation of earthquakes: a) Imperial Valley; b) Northridge; c) Tabas.

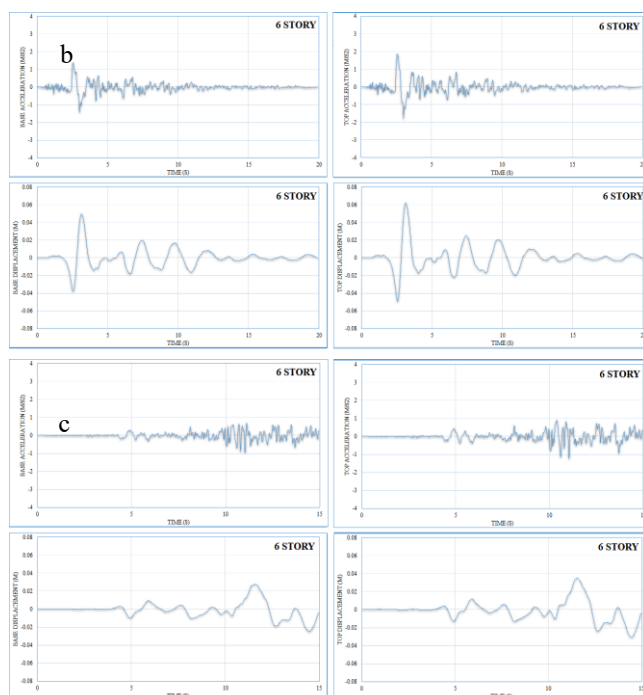
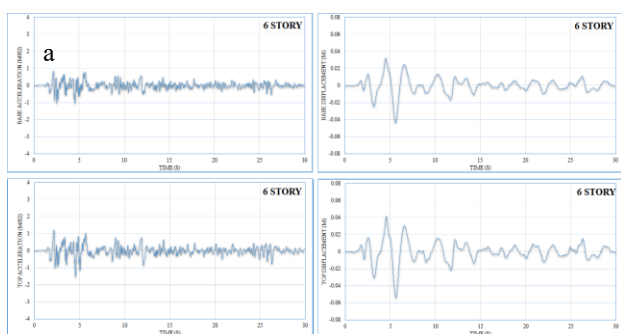


Figure 12. Diagram for base and top acceleration, base and top displacement of 6-story building with linear seismic isolator (LDRB) with a 2 s period under stimulation of earthquake: a) Imperial Valley; b) Northridge; c) Tabas.

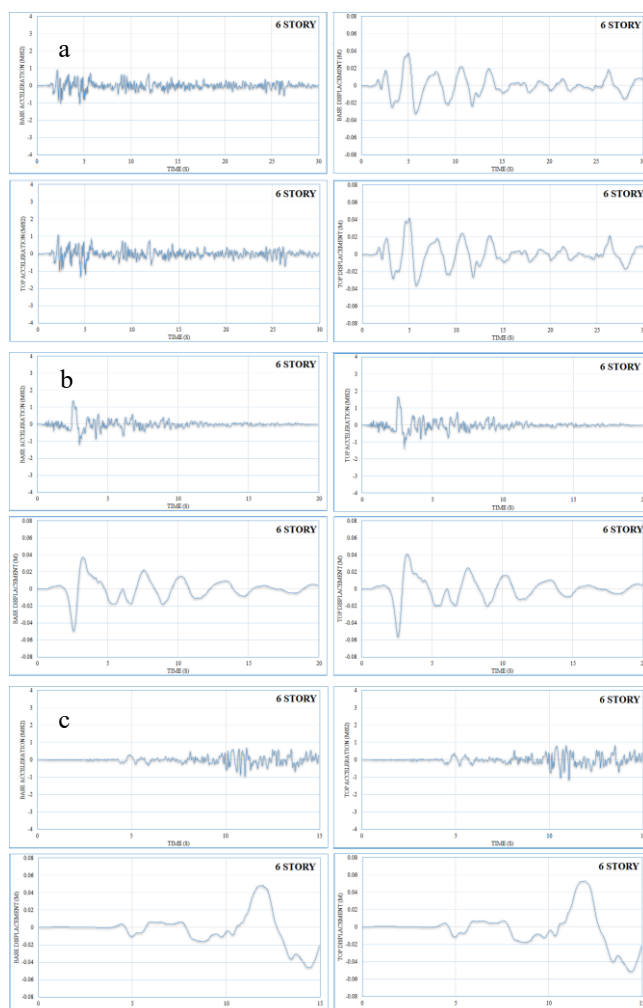


Figure 13. Diagram for base and top acceleration, base and top displacement of 6-story building with linear seismic isolator (LDRB) with a 3 s period under stimulation of earthquake: a) Imperial Valley; b) Northridge; c) Tabas.

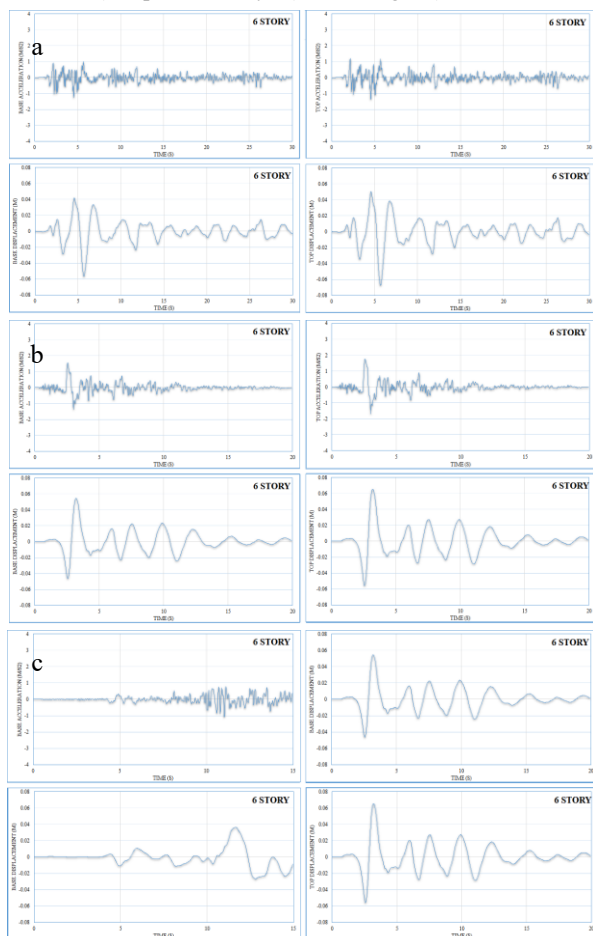


Figure 14. Diagram for base and top acceleration, base and top displacement of 6-story building with nonlinear seismic isolator (LRB) with a 2 s period under stimulation of earthquake: a) Imperial Valley; b) Northridge; c) Tabas.

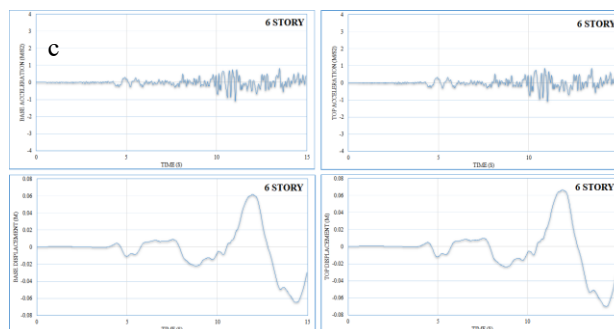
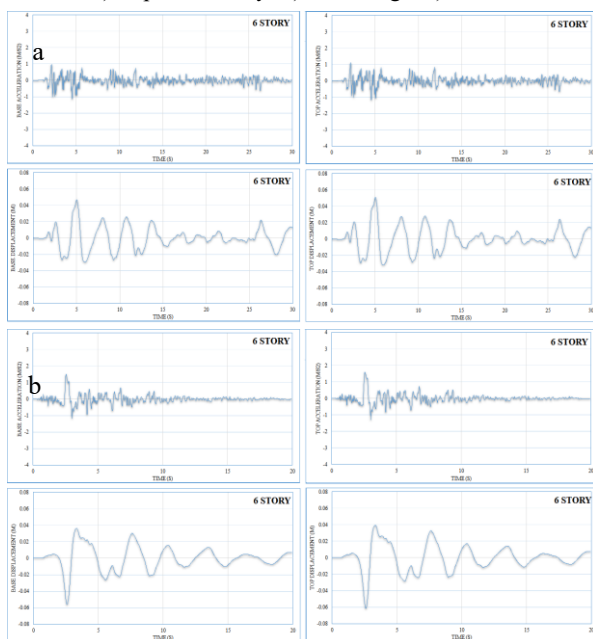


Figure 15. Diagram for base and top acceleration, base and top displacement of 6-story building with nonlinear seismic isolator (LRB) with a 3 s period under stimulation of earthquake: a) Imperial Valley; b) Northridge; c) Tabas.

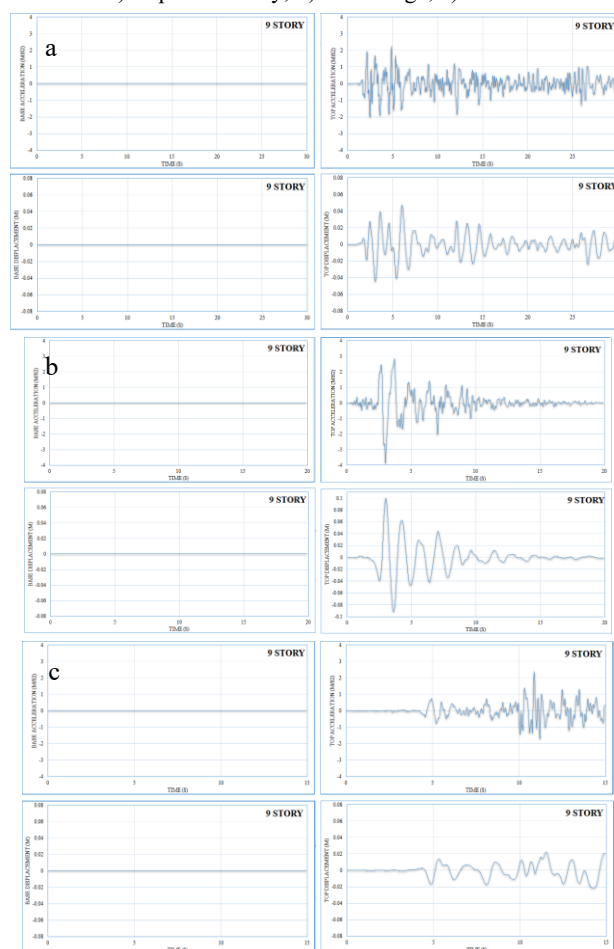
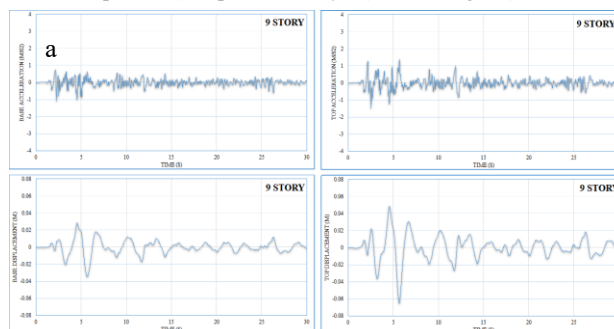


Figure 16. Diagram for base and top acceleration, base and top displacement of 9-story clamped building under stimulation of earthquake: a) Imperial Valley; b) Northridge; c) Tabas.



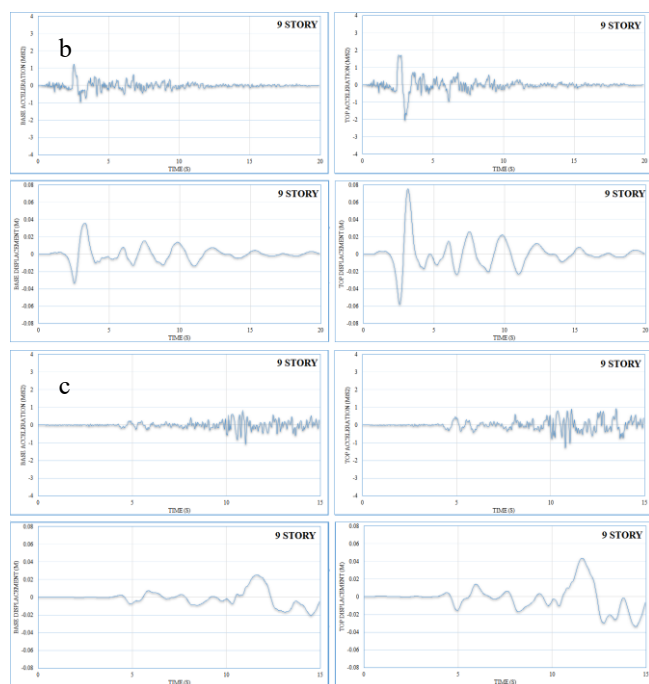


Figure 17. Diagram for base and top acceleration, base and top displacement of 9-story building with linear seismic isolator (LDRB) with a 2 s period under stimulation of earthquake: a) Imperial Valley; b) Northridge; c) Tabas.

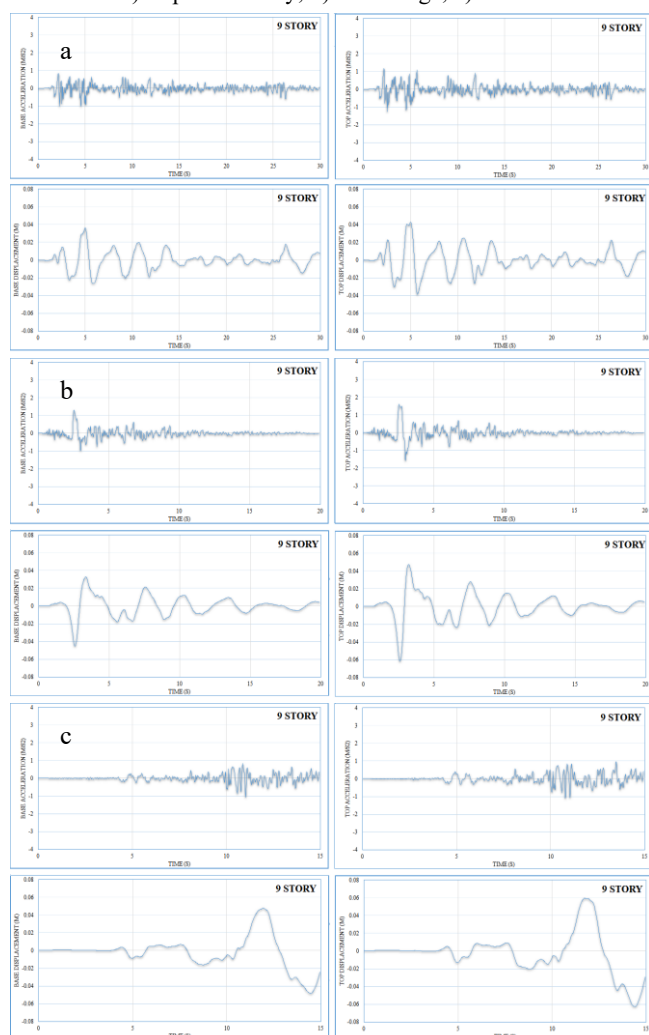


Figure 18. Diagram for base and top acceleration, base and top displacement of 9-story building with linear seismic isolator (LDRB) with a 3 s period under stimulation of earthquake: a) Imperial Valley; b) Northridge; c) Tabas.

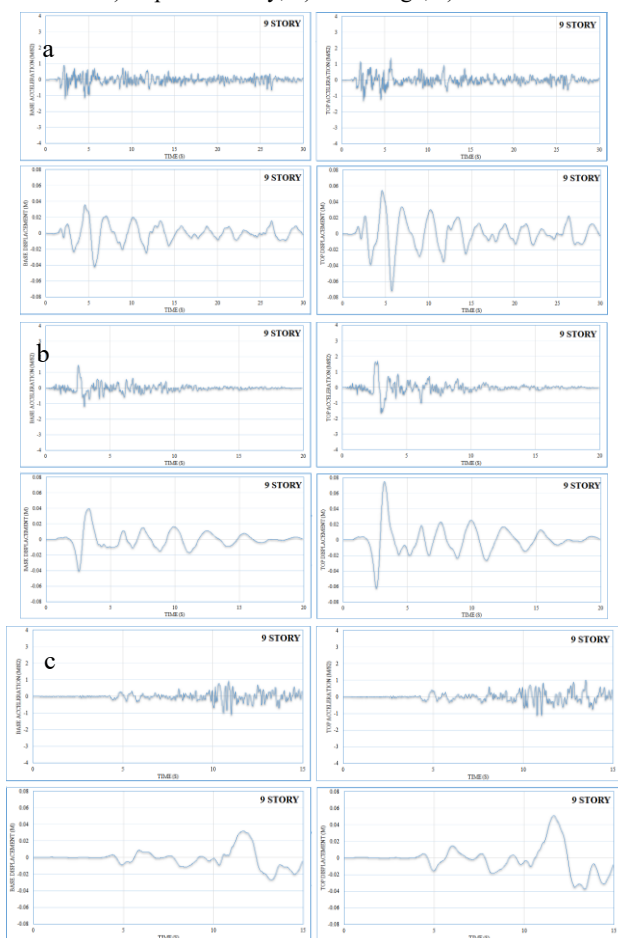
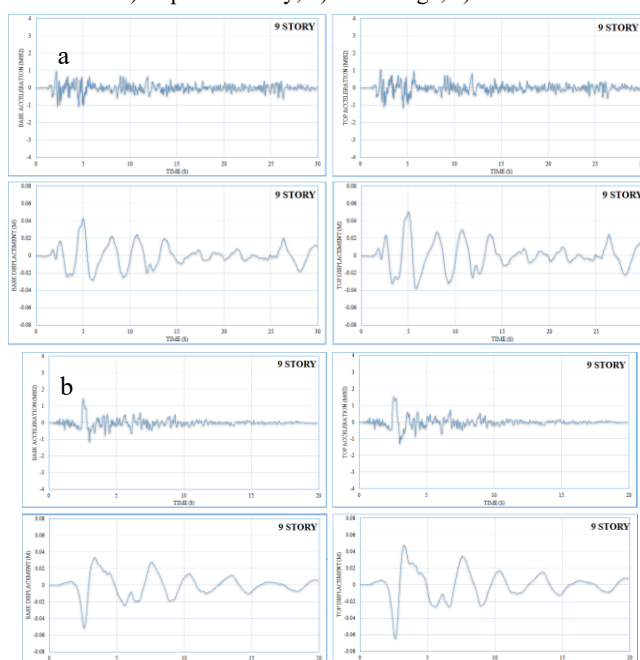


Figure 19. Diagram for base and top acceleration, base and top displacement of 9-story building with nonlinear seismic isolator (LRB) with a 2 s period under stimulation of earthquake: a) Imperial Valley; b) Northridge; c) Tabas.



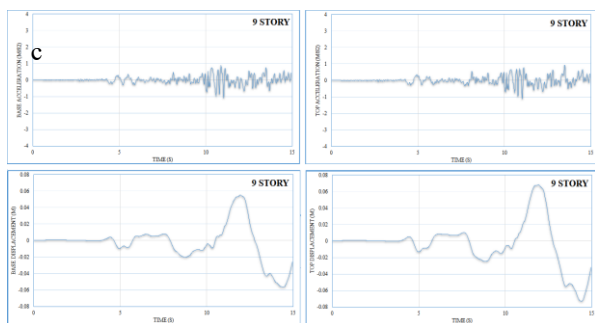


Figure 20. Diagram for base and top acceleration, base and top displacement of 9-story building with nonlinear seismic isolator (LRB) with a 3 s period under stimulation of earthquake: a) Imperial Valley; b) Northridge; c) Tabas.

- Effects of height variations on seismic response

The maximum seismic response (base and top acceleration, base and top displacement), the height variation range (H_{eff}) can be obtained using Eq.(6):

$$H_{(eff)} = \left| \frac{PR(3) - PR(6,9)}{PR(3)} \right| \times 100, \quad (6)$$

where: $PR(3)$ is seismic response of the 3-story building and $PR(6,9)$ is the maximum seismic response of 6 and 9-story buildings. Figure 21 shows the effect of the structure height on seismic response. As can be seen, an increase in height of structure leads to the decreased maximum acceleration and increased maximum displacement. In the seismic isolation system, the peripheral drift control exhibits a good response, suggesting the use of the seismic isolation system.

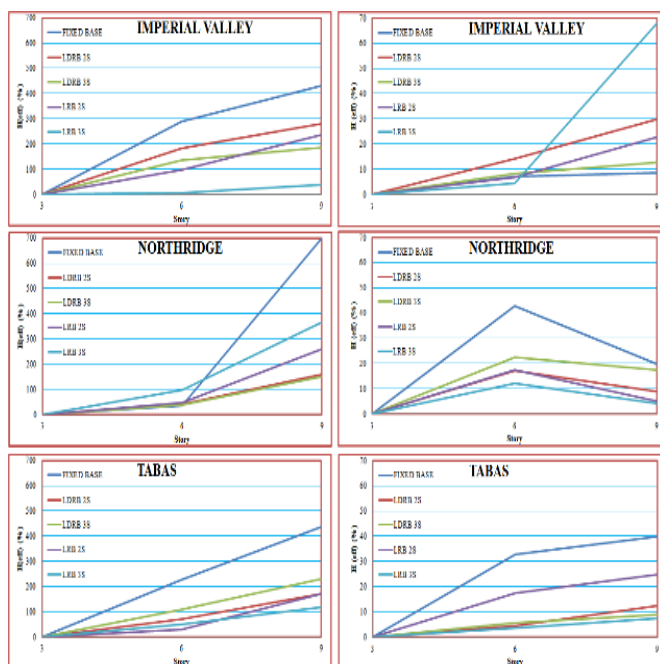


Figure 21. Diagram for response variations in clamped structure with linear isolation system (LDRB) and nonlinear isolation system (LRB) vs. increase in structure height under the stimulation of earthquakes Imperial Valley, Northridge, and Tabas: a) inter-story displacement; b) top acceleration.

CONCLUSION

The method utilised in the present work is a simple modelling method that represents a medium-rise regular building

from the group of regular-plan buildings. In this study, three types of regular-plan isolated buildings in the form of 3, 6, and 9-story structures are investigated. The buildings are assumed as clamped structures with linear (LDRB) and nonlinear (LRB) isolation systems with 2 and 3 s periods.

- The performance of the seismic isolator studied in this work is used to control the drift and input acceleration of the structure. Increasing structure height led to increased inter-story drift, the minimum value of which belonged to the clamped structure. As for the acceleration, the maximal acceleration response occurring with an increase in the height is related to the clamped structure. This result indicates failure of the optimal design of clamped structure against the performance of the seismic isolation system.
- In the elastic state, the maximum displacement of the LRB isolator is higher than that of the LDRB (10-20 %) but both isolators exhibit an excellent performance against inter-story drift. As for maximum acceleration, it is shown that in both isolators, the acceleration does not exhibit considerable variations, and the LRB isolator exhibits a 2-5 % more reduction in acceleration compared to the LDRB.
- The best performance in terms of reducing acceleration is observed in low-rise (3-story) buildings with LDRB isolator and a 3 s period. With increasing the height of the structure from 3 to 6 stories, the maximum acceleration decreases in the base but the maximum top acceleration increases both in the seismic isolation system and clamped structure. With increasing the height from 6 to 9 stories, the maximum acceleration exhibits a considerable reduction. It is recommended to use the LRB isolator with a period of 3 s in high-rise buildings (9-story).
- In high-rise buildings, since the basic period of the building is high, the application of the seismic isolation system (i.e., reducing the input acceleration of the building) is reduced due to increased displacement resulting from the increased period of the building. Thus, to prevent excessive displacement of the building at higher periods, it is recommended to utilise seismic damping systems that can reduce the input energy and, thereby, reduce system displacement.

An important point to be mentioned here is that the present study is exposed to limitations and assumptions presented in the 'Introduction'. Thus, it is recommended to use seismic isolators in irregular buildings. All analyses in this work are modelled as nonlinear time history analysis.

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