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A Proposed Approach to Mitigate the Torsional Amplifications of Asymmetric Base-isolated Buildings During Earthquakes

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Abstract

In this paper, the rotational behavior of asymmetric base-isolated buildings is compared with the similar asymmetric fixed-base buildings. A vast range of lead rubber bearings with different periods is considered to evaluate the effect of the isolation degree on seismic responses of the structures. The simulation results confirm that the base isolators are able to reduce rotation of stories. However, this reduction is negligible in large eccentricities. The numerical simulations show that increasing period of isolators results in large displacement at bearings located on the flexible edge of the isolation system. This paper proposes practical solutions to reduce torsional responses of the base-isolated structures. In order to investigate the effectiveness of the proposed solutions, four structural models are defined. Considering three earthquake excitations, the simulation results of these models indicate that increase in stiffness of flexible edge of isolation system can reduce torsional responses of asymmetric 3-story base isolated structure. Furthermore, the simultaneous increase in stiffness of flexible edge of isolation system and superstructure lead to a suitable reduction of torsional responses in asymmetric 8-story base-isolated structure.

Keywords: *asymmetric structures, torsional amplification, base isolation, lead rubber bearings, flexible edge*

1. Introduction

Seismic isolation is an effective method to reduce or eliminate the potential damages caused by environmental loads such as wind and earthquake loads. This method is the only practical way to reduce the drift and acceleration of stories, simultaneously. Seismic isolation is a useful method for buildings with sensitive and critical equipment or buildings of which service duties are needed immediately after earthquakes. During an earthquake, a large proportion of seismic motion is taken up by the isolators. Therefore, the transferred seismic motions to the superstructure are reduced. It also prevents the failure of structural and non-structural members, especially the internal equipment of structures (Naeim and Kelly, 1999; Etedali *et al.*, 2013). Today, in order to protect the existing and new structures and bridges against earthquake, this technology is executed widely in many countries such as United States of America, Japan, New Zealand and Italy. In common, seismic isolations are classified into rubber bearings and roller bearings. High Damping Natural Rubber (HDNR) bearing and Lead Rubber Bearings (LRB) are types of the rubber bearings. Also, Friction Pendulum System (FPS) is a type of the roller bearings (Naeim and Kelly, 1999).

Extensive studies have been carried out on the behavior of base-isolated structures. Most of the studies deal with 2-D idealization which are reliable for symmetric buildings or buildings with negligible eccentricity. Nevertheless, torsional coupling may provide many structural damages in asymmetric structure. Many studies investigated the effects of torsional coupling on asymmetric fixed- base structures (De Stefano and Pintucchi, 2008). Meanwhile, few analytical and experimental studies are carried out on base-isolated structures. Su *et al.* (1989) showed that irregularity in height of the isolated structures, caused by stiffness or mass irregularity, does not have significant effect on the structural responses. In other words, the behavior of irregular base-isolated structure in height is similar to that of symmetrical base-isolated structures in height. In this study, the superstructure was modeled as a non-uniform shear beam. Lee (1980) studied the effect of bilinear hysteretic isolation on reduction of the base shear and rotation of a one-story asymmetric shear structure under El Centro earthquake (1940) in two directions. The result of the study showed that increasing the eccentricity of the isolation system enhanced the rotational responses. Also, it is found that eccentricity in the superstructure has low effect on displacement of isolators located on the flexible edge. Eisenberger (1986) studied the seismic response of asymmetric base-isolated structures under the records of El Centro (1940), Taft (1952) and Bathurst (1977) earthquakes and showed that random eccentricities of 5% to10% provided large rotation in stories of the structures.

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This issue should be considered in design of the base-isolated structures. Nagarajaiah *et al.* (1993) studied the behavior of asymmetric base-isolated structures subjected to El Centro and Taft earthquakes considering that the parameter L/B (ratio of length to width of the plan) equals to 4 and e/L (ratio of eccentricity to length of the plan) equals to 0 and 0.065. The obtained results showed that the main source of the rotational movement of the structure is the eccentricity of the isolation system. Considering the nonlinear responses of lead rubber isolations in asymmetric structures subjected to 20 world famous earthquake records, Jangid and Datta (1994a) found that the effect of seismic isolation on reduction of torsional couplings was reduced with increasing eccentricity. Furthermore, Jangid and Datta (1994b) indicated that near -fault earthquakes led to large displacements in the isolation level of the structures. Ryan and Chopra (2004) focused on torsional behavior of an ideal one-story structure with different eccentricities under two components of El Centro earthquake and showed that the displacement of isolators located on the flexible edges was reduced with increasing the eccentricity. Nevertheless, this issue was understated in the International Building Code (IBC). Tena-Colunga and Zambrana-Rojas (2006) assessed the effect of stories eccentricity of the superstructure and isolation system on torsional responses of structures. These studies focused on a three-dimensional, three-story structure with bracing system, which is isolated by nonlinear isolators. The results showed that the maximum structural responses depended on the eccentricity of the superstructure. Increase of the eccentricity reduces the effect of seismic isolations on reduction of the created rotation. Tena-Colunga and Escamilla-Cruz (2007) revealed that structural responses of the asymmetric base-isolated structure increased in comparison with the symmetric base-isolated structure by reducing the degree of isolation (I). By increasing I up to a specified amount, the structural responses are reduced, but further increase does not significant effect on reduction of the responses. For values of $I < 2$, inappropriate behaviors have been detected in torsional responses of the structure. Seguín *et al.* (2008) investigated the linear earthquake response of seismically isolated structures with lateral-torsional coupling. Also, two simplified models of the three-dimensional response of asymmetric buildings under a dynamic base-superstructure interaction formulation are proposed in the study. Considering Eurocode 8 and Uniform Building Code 97, it is found that CI = CM distribution is recommend for accommodating the torsional effects in the base isolation system. In this distribution, the eccentricity of the isolation system is required to be similar to the eccentricity of the superstructure. Considering the nonlinear behavior of the superstructure, Kilar and Koren (2009) found a significantly different conclusion, where CI = CM distribution might cause more damage in the flexible side frames. Khoshnoudian and Imani Azad (2011) evaluated the rotational response of base-isolated structure considering two horizontal components of earthquake compared with consideration of just one horizontal component and demonstrated that asymmetry in the superstructure or isolation system could have a significant effect on the rotational behavior of isolated structures. Also, it is showed that the use of rigid superstructures and calculation of dynamic rotation by multiplying eccentricity by the dynamic base shear are unacceptable assumptions. Kilar *et al.* (2011) studied the seismic response of asymmetric fixed-base and base-isolated high-rack steel structure and showed that asymmetry could increase the damage in the supporting structure on the flexible edge. Also, the central part of the rack structure remains in the elastic region only when the eccentricity is small. Furthermore, it is concluded that an eccentricity of 5%, which is prescribed in Eurocode 8, might not be sufficient in such structural types. Seguin *et al.* (2013) applied probabilistic techniques for a simplified asymmetric two-story base-isolated model subjected to a one-directional excitation. In this study, the lower story represents the isolated base and the upper story represents the superstructure. It is concluded that if the center of stiffness of the isolated system should lie in the vicinity of the (average) center of stiffness of the superstructure, the response of the superstructure may be increased. Khoshnudian and Motamedi (2014) investigated the seismic response of asymmetric steel isolated structures considering vertical component of earthquakes. The results of the study showed that the vertical component of earthquakes had significant effect on the responses of structures in terms of axial forces, local uplift of the columns, overturning moment of the structure and shear forces of beams. The effect of the vertical component of earthquake should be considered in designing of base-isolated structures. Considering the amplification factor for the displacement demand due to rotation of the structures, Wolff *et al.* (2014) presented a rational and simple improvement for predicting of amplification factors.

As can be seen from the literature review, there are few recommendations to control the torsional responses of asymmetric base-isolated structures. There are many existing buildings with high eccentricity which are very vulnerable to strong earthquakes. Seismic isolation is an effective method to retrofit and rehabilitate the structures against structural damages caused by environmental loads. Therefore, it required a suitable method to reduce torsional responses of the structures while taking advantage of isolation systems. In this paper, the rotational behavior of fixed and base-isolated asymmetric structures is compared. Furthermore, in order to reduce torsional responses of the structures, practical solutions are proposed. Four structural models are defined to investigate the effectiveness of the proposed solutions. These structural models are defined to assess the individual and simultaneous effects of increasing the flexible edge stiffness of the superstructure and isolation system on rotational amplifications of these structures. The proposed solutions will be useful to retrofit of existing asymmetric structures with isolation technology or design of asymmetric base-isolated structures.

The paper is organized as follows. The studied structures and the characters of isolation system are introduced in section 2. The rotational behavior of the asymmetric base-isolated structures is compared with the similar fixed-base structures in section 3. The proposed solutions to mitigate the torsional amplifications of the

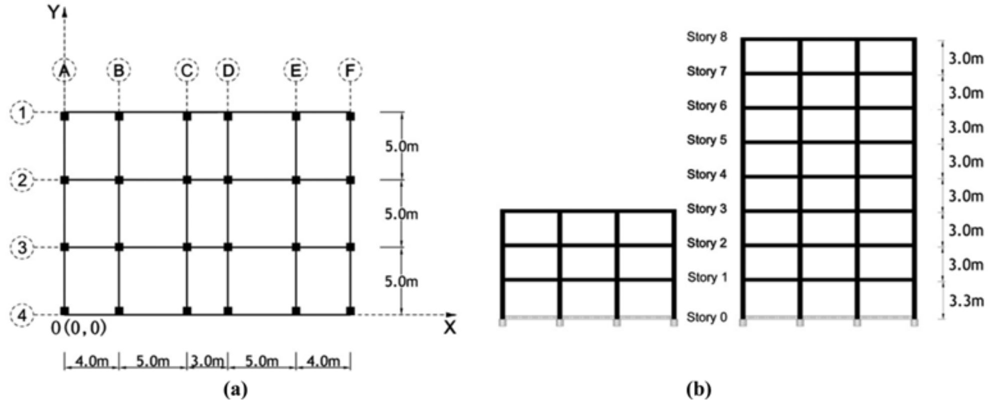

Fig. 1. (a) Plan, (b) Elevations of the Studies Structures

studied structures are evaluated in section 4. A summary of the simulation results is presented in section 5.

2. Studied Structures and the Characters of Isolation System

In this paper, the studied structures are three-dimensional, three- and eight-story steel structures with the moment resisting frame and the same plans as shown in Fig. 1(a). For All structures, height of the ground floor is 3.3 m and the height of other stories is 3 m as shown in Fig. 1(b).

The values of dead load (total weight of the roof and equivalent partitioning load) and live load for stories are 650 kg/m^2 and 200 kg/m^2, respectively. For the roof story, these values are considered as 550 kg/m^2 and 150 kg/m^2. A rigid diaphragm is assigned for each story level. Lateral force-resisting system consisting of an intermediate steel moment resistant frame is adopted for structural models. The following material properties are considered the same for all columns and beams: E=200000 MPa, F_y=240 MPa and F_u=360 MPa. The primary design of the structures has been carried out based on the Uniform Building Code (1997) using ETABS program (1999). For this purpose, it is assumed that the structures are located in region 4 of the seismic zone and the type of soil is S_D. The section properties of the structures are summarized in Table 1. L is the span length of beam. The fundamental periods of the fixed-base 3-story and 8-story structures are T_s = 0.48 s and 1.41 sec. Three ground accelerations with various frequency contents are selected to evaluate the proposed strategies. These selected earthquakes are Tabas earthquake 1978, Bam earthquake 2003 and El Centro earthquake 1940. The El-Centro earthquake is chosen as a near-field earthquake which has been used widely in the previous investigations. Also, Tabas and Bam earthquakes as near-field earthquakes have great value frequency contents in long period and they are suitable for studying isolated structures. The absolute Peak Ground Accelerations (PGA) of these earthquakes are 0.34 g, 0.93 g, and 0.79 g, respectively. All the earthquake records have been scaled to the maximum acceleration of 0.4 g. The nonlinear time history of the structures subjected to the bidirectional action of the earthquakes is analyzed using the computer program 3D-BASIS. The computer program was developed by Nagarajaiah *et al.* (1991) for nonlinear dynamic analysis of asymmetric plan multi story base-isolated structures. The superstructures and isolators are modeled using linear and nonlinear behaviors, respectively.

There are three main parameters for design of isolators, including the elastic stiffness (K_1), post-yielding stiffness (K_2) and characteristic strength (Q). Fig. 2 shows the hysteretic curve of the nonlinear behavior of LRB (Naeim and Kelly, 1999).

The characteristic strength is the collision point of the hysteresis loop and force axis. It is determined accurately based on the yielding stress of lead core. To isolate the studied structures, LRB has been used. The isolators are designed based on the Uniform Building Code 97 (1997). The design displacement of the isolation systems should be given according to the following equation:

$$D_D = \frac{g}{4\pi^2}\frac{C_{VD}T_{iso}}{\beta_D} \tag{1}$$

Table 1. Section Properties of the Structures

Structure	Story	Columns		Beams		
		Interior	Exterior	L= 5 m	L= 4 m	L= 3 m
3- story	1	BOX 26×26×10	BOX 25×25×10	IPE300	IPE300	IPE220
	2, 3	BOX 26×26×10	BOX 25×25×10	IPE300	IPE270	IPE200
8- story	1,2, 3	BOX 40×40×10	BOX 30×30×10	IPE450	IPE450	IPE270
	4, 5, 6	BOX 35×35×10	BOX 26×26×10	IPE360	IPE360	IPE240
	7, 8	BOX 26×26×10	BOX 22×22×10	IPE330	IPE330	IPE240

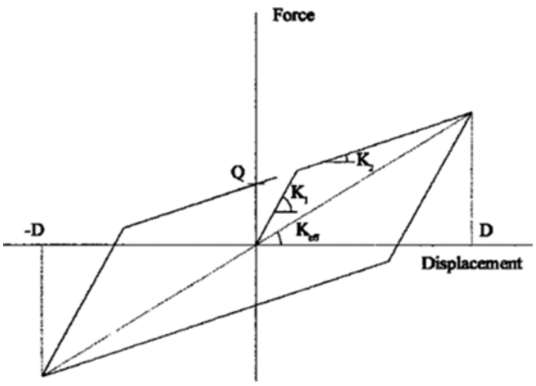

Fig. 2. Hysteretic Curve of the Nonlinear Behavior of LRB (Naeim and Kelly, 1999)

where C_{VD} is design 5-percent damped spectral acceleration at 1.0 second period. According to the seismic zone and the type of soil, this value is calculated. Also, β_D is the effective damping of the isolation system at the design displacement and g is the gravity acceleration. The minimum effective stiffness of the isolation system at the design displacement is given by:

$$k_{Dmin} = \left(\frac{2\pi}{T_{iso}}\right)^2 \cdot \frac{W}{g} \quad (2)$$

where, W is the total seismic dead load weight of the structure above the isolation interface. In this study, it is assumed that $k_{eff} = k_{Dmin}$. The values of the effective stiffness k_{eff} and effective damping β_{eff} at displacement greater than D_Y may be calculated by the following equations (Naeim and Kelly, 1999):

$$k_{eff} = k_2 + Q/D \quad (3)$$

$$\beta_{eff} = \frac{4Q(D - D_Y)}{2\pi(K_2 D + Q)D} \quad (4)$$

$$D_Y = \frac{Q}{K_1 - K_2} \quad (5)$$

The behavior of the bearings in the vertical direction is assumed to be elastic. The vertical stiffness of a rubber bearing is given by:

$$k_V = \frac{E_C A}{t_r} \quad (6)$$

where, E_c is the instantaneous compression modulus of the rubber-steel composite under the specified level of vertical load, A is the cross-sectional area of the bearings and t_r is the total thickness of rubbers in the bearing.

A wide range of isolators with different periods, T_{iso}= 1.5, 2, 2.5 and 3 sec, have been designed to evaluate the effect of this parameter on the seismic response of the structures. In order to design the isolators, the ratio of k_2/k_1 is assumed 0.1 and the equivalent viscous damper is 10%. Isolators have a nonlinear behavior with two degrees of freedom related to shearing deformations and one degree of freedom related to the linear effective stiffness in vertical direction. Behavior of the isolators is modeled based on the bilinear performance suggested by Nagarajaiah *et al.* (1991). In order to provide a comparative study between the torsional behavior of fixed-base and base-isolated structures, nonlinear time history analyses of the structures are carried out subjected to the bidirectional action of Tabas, Bam and El Centro earthquakes. Different eccentricities, e=10, 20, 30%, for one direction are created in the structural models. These eccentricities are considered for all stories of structure. The eccentricities obtained by shifting the centers of mass of the superstructure from the geometric center of the plan. In order to shift the centers of stiffness of the superstructure, the stiffness properties of perimeter frames were modified until reaching the target positions, using an iterative procedure. Similarly, the centers of stiffness of the isolation system were modified until reaching the target positions.

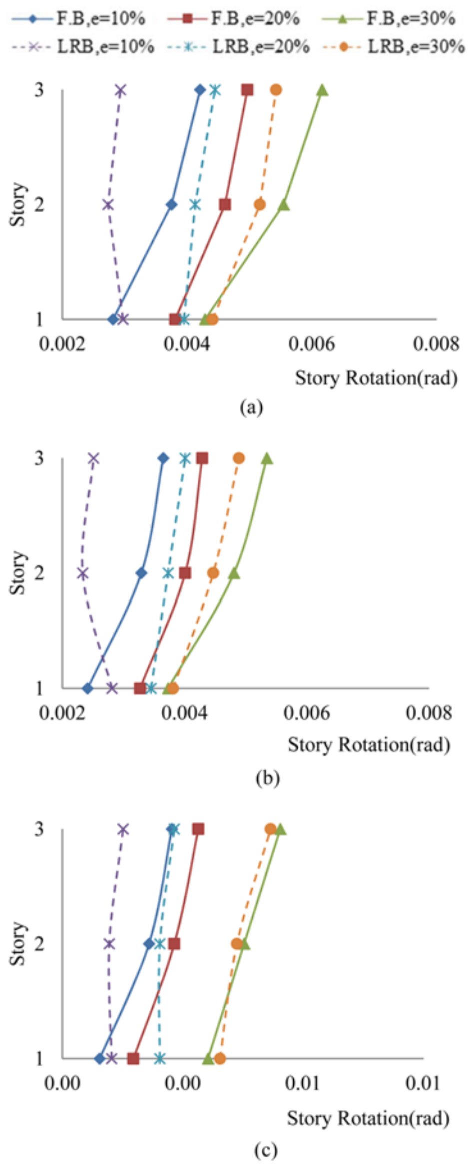

Fig. 3. Maximum Torsional Responses of the 3-Story Structure: (a) Tabas, (b) Bam, (c) El Centro

3. Comparison of Torsional Behavior of the Asymmetric Base-isolated Structures with the Similar Fixed-base Structures

The torsional behaviors of the asymmetric base-isolated structures with the similar fixed-base structures are studied. The simulation result of this study is shown in Figs. 3 and 4. It is assumed that the period of isolation system, T_{iso}, is equal to 2 sec. Fig. 3 shows the maximum torsional responses of the three -story structures for two Fixed-Base (F.B) and Base-isolated (LRB) cases with different eccentricities subjected to bidirectional action of Tabas, Bam and El Centro earthquakes. Similarly, Fig. 4 shows the maximum torsional responses of the eight-story structures. It can be seen that seismic isolators are able to reduce torsional responses of asymmetric structure. However, this reduction is negligible in base story and sometimes rotation of the story is more than their corresponding value in fixed-base structures. Increasing the eccentricities reduces the advantage of seismic isolation in reduction of rotational responses. So, with a large eccentricities (e = 30%), the effect of isolators in reduction rational responses is negligible. The maximum displacements of the isolators located on the flexible edge of the isolation system in X direction, subjected to Tabas, Bam and El Centro earthquakes are shown in Figs. 5 and 6.

Considering different periods of isolators (T_{iso} = 1.5, 2, 2.5 and 3 s) and two cases of symmetric structure (e = 0) and asymmetric structures with different eccentricities (e = 10, 20, 30%), the maximum displacements are shown in these figures. Fig. 5 shows the maximum displacements of the isolators for the three-story structure. Similarly, Fig. 6 shows the maximum displacements in the eight story structures. The results show that the displacements of isolators located on the flexible edge of the isolation system are increased by increasing the eccentricities of stories. So, eccentricity of 10% caused the minimum displacement and also the maximum displacement occurred in eccentricity of 30%. Moreover, the displacement of isolator is increased by increasing period of the isolation system. The risk of buckling and detachment of the rubbers of isolators may be increased with increasing the vertical displacements of the isolators located on the flexible

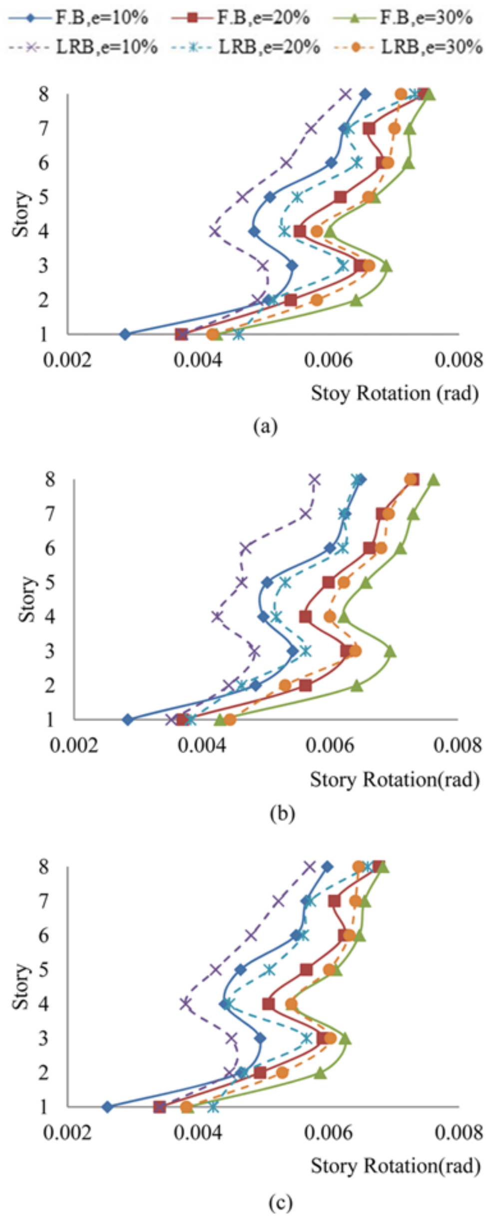

Fig. 4. Maximum Torsional Responses of the 8-Story Structure: (a) Tabas, (b) Bam, (c) El Centro

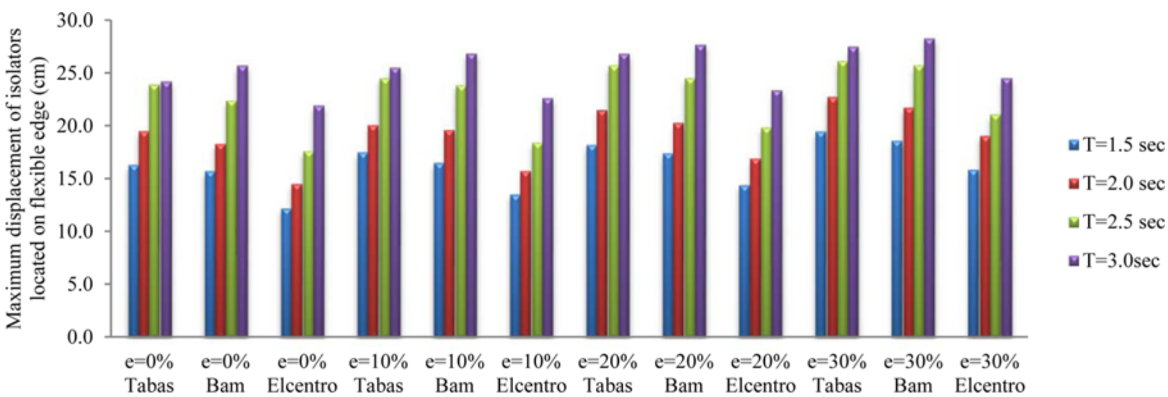

Fig. 5. Maximum Displacement of the Isolators Located on the Flexible Edge of the Isolation System with Different Eccentricities in Three-Story Structures

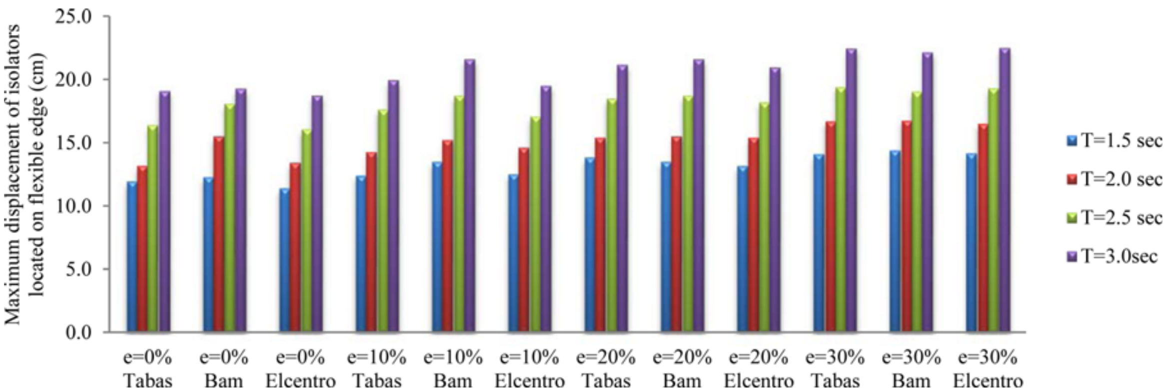

Fig. 6. Maximum Displacement of the Isolators Located on the Flexible Edge of the Isolation System with Different Eccentricities in Eight-story Structures

edge of the isolation system.

4. Proposed Approach to Mitigate the Torsional Amplifications of Asymmetric Base-isolated Buildings

The main source of the torsional motions of base-isolated structures is torsional motions of isolation systems. Therefore, control of torsional response of base story of the structures can reduce torsion in stories of the superstructure. In high-rise structures, flexibility of the superstructure can effect on its torsional motion. Therefore, simultaneous control of torsion in base story and superstructure stories can reduce the torsional response of the structure. In order to achieve an effective approach to mitigate the torsional amplifications of asymmetric base-isolated buildings, these strategies can be evaluated by assuming four structural models as shown in Fig. 7. Model A is defined as the base model. Torsional behavior of other models is compared with this model. In the model, the eccentricity is created in a pattern which the stiffness center of each story is located on the geometric center of the story and the mass center of each story is located on a supposed axis with 30% eccentricities in plan as shown in Fig. 8. In this Figure, C.M is the center of mass of the story, C.R.I is the center of rigidity of base story or isolation system and C.R.S is the center of rigidity of the superstructure stories. In Fig. 8, the terminal edge which is far from the center of mass is defined as rigid edge. Also, terminal edge which is closer to the center of mass is called flexible edge. The coordinates of C.M, C.R.I and C.R.S of the structural models are inserted in Table 2. In addition, the purpose of the study of each model as a proposed solution for torsional amplifications of base-isolated asymmetric structure is presented in the Table.

The maximum torsional responses of the three-story structural models subjected to Tabas, Bam and El Centro earthquakes are demonstrated in Fig. 9. Similarly, the results obtained for the eight-story structure are presented in Fig. 10. Relative rotation of the rigid diaphragms of the model is used to characterize the torsional behavior of the model. Fig. 9 shows that increase of flexible edge stiffness of superstructure has no significant effect on reduction of the torsional responses of the three-story structure. However, by increasing the flexible edge stiffness of isolation system, a significant decrease is seen in rotation of stories. As a result, model C is a suitable solution to mitigate the torsional

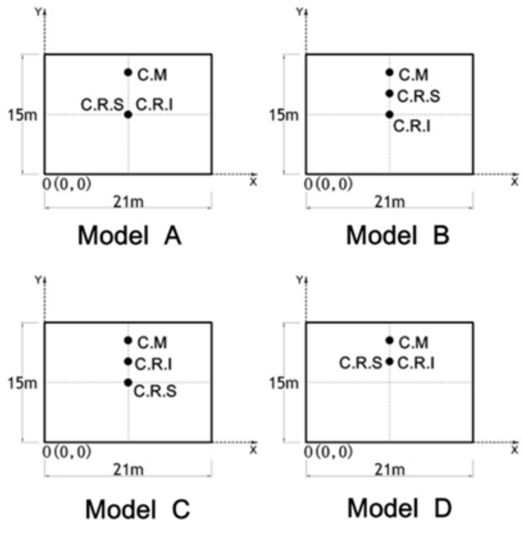

Fig. 7. Structural Models to investigate the Effectiveness of the Proposed Solutions

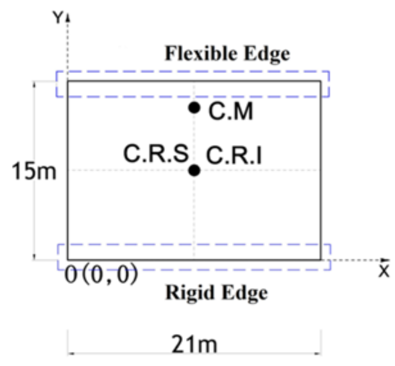

Fig. 8. C.M., C.R.I., C.R.S., Flexible Edge and Rigid Edge on the Plan of Structural Models

Table 2. Coordinates of C.M, C.R.I and C.R.S and the Purpose of the Study of each Model

Model	Model	C.M	C.R.I	C.R.S
A	A	X=10.5 m Y=12.0 m	X=10.5 m Y=7.5 m	X=10.5 m Y=7.5 m
Purpose: Base model				
B	B	X=10.5 m Y=12.0 m	X=10.5 m Y=7.5 m	X=10.5 m Y=10.0 m
Purpose: evaluation of the effect of increasing flexible edge stiffness of superstructure on torsional amplifications				
C	C	X=10.5 m Y=12.0 m	X=10.5 m Y=10.0 m	X=10.5 Y=7.5
Purpose: evaluation of the effect of increasing flexible edge stiffness of isolation system on torsional amplifications				
D	D	X=10.5 m Y=12.0 m	X=10.5 m Y=10.0 m	X=10.5 m Y=10.0 m
Purpose: evaluation of the effect of simultaneous increasing of flexible edge stiffness of superstructure and isolation system on torsional amplifications (combination of models B and C)				

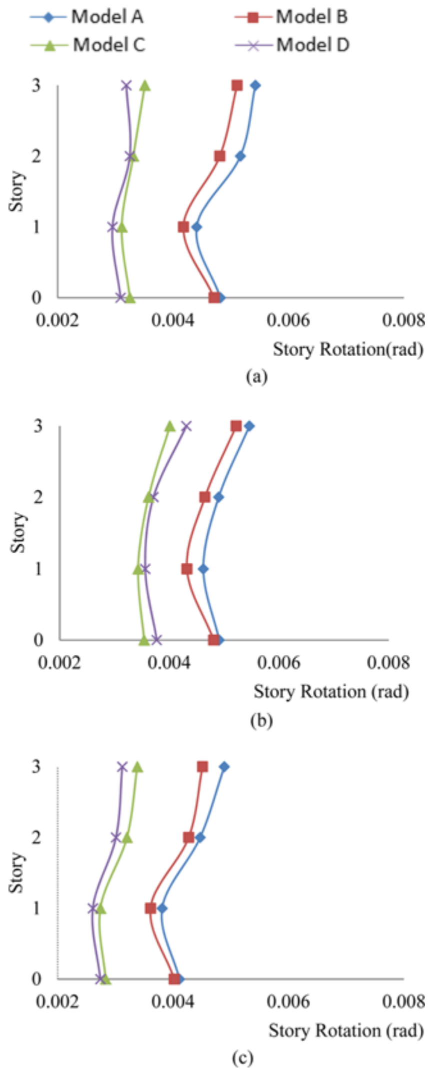

Fig. 9. Maximum Torsional Responses of the 3-Story Structural Models: (a) Tabas, (b) Bam, (c) El Centro

amplifications of low-rise base-isolated structures. Considering the result obtained from model D, it can be concluded that increase of flexible edge stiffness of the superstructure stories reduces the rotation of stories. This result is given in the case of the C.R.I is close to C.M. In comparison with the result obtained from the analysis of the three- story structural models, Fig. 10 illustrates that increase of flexible edge stiffness of superstructure has higher effect on decrease of the torsional responses of the eight-story structure. Evaluation of the obtained results from models C and D for this structure confirms that increase of flexible edge stiffness of isolation system has a significant effect on decrease of rotational responses. Nevertheless, in comparison with the model C, model D is more appropriate for rotational amplification of the stories. In other words, simultaneous increasing of flexible edge stiffness of superstructure and isolation

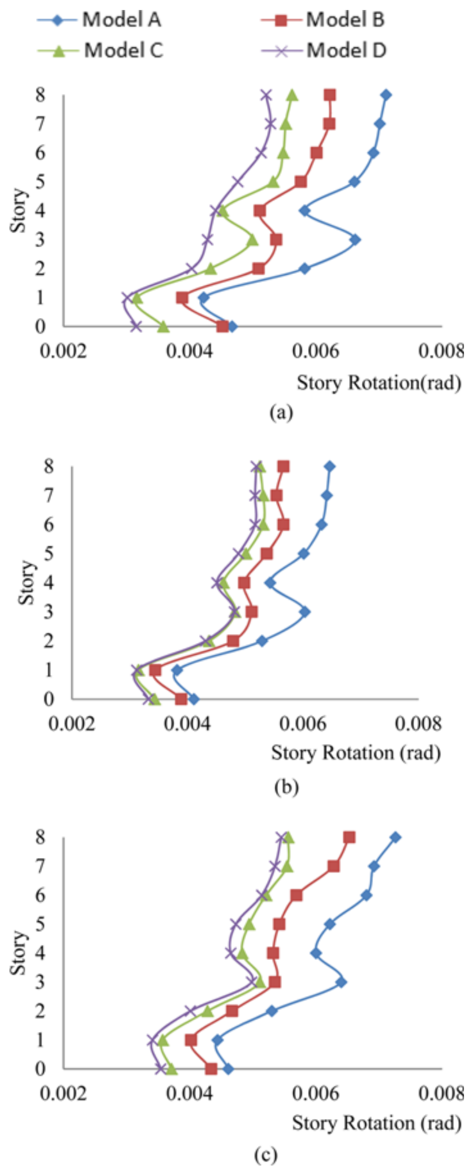

Fig. 10. Maximum Torsional Responses of the 8-Story Structural Models: (a) Tabas, (b) Bam, (c) El Centro

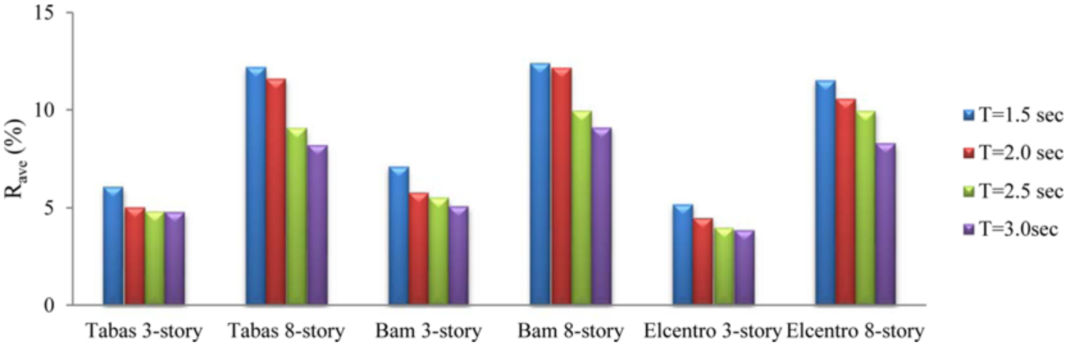

Fig. 11. Average Reduction of Torsional Responses of Model B in Comparison with Model A

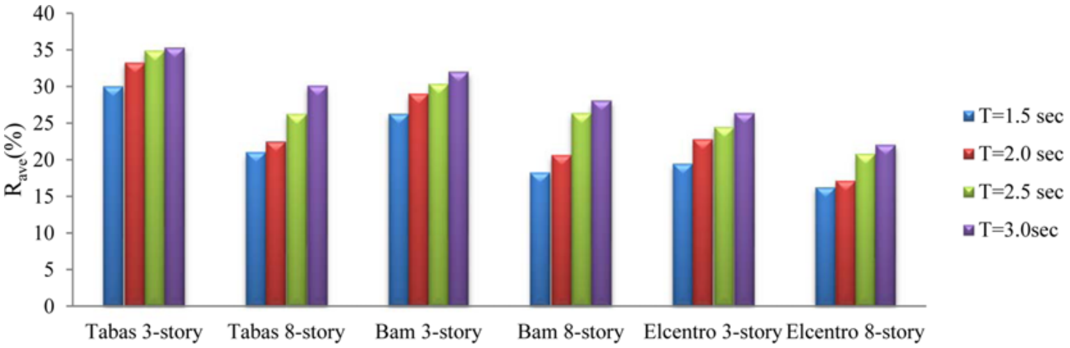

Fig. 12. Average Reduction of Torsional Responses of Model C in Comparison with Model A

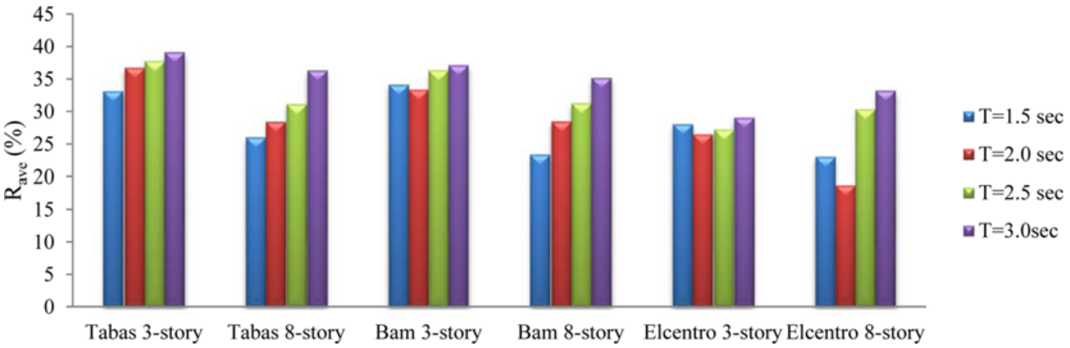

Fig. 13. Average Reduction of Torsional Responses of Model D in Comparison with Model A

system can significantly reduce torsional responses of 8-story base-isolated structure.

In order to evaluate the proposed approaches, the average reduction (R_{ave}) of torsional responses in structural model B, C and D compared with model A are shown in Figs. 11, 12 and 13, respectively. Considering a vast range of periods of isolators, the obtained results for the three and eight story structural models subjected to Tabas, Bam and El Centro earthquakes are illustrated in these figures. Considering the three- story structural models, Fig. 11 illustrates that increasing the flexible edge stiffness of superstructure has slight effect on reduction of rotational responses. Also, by increasing the period of isolation system, rotational responses are slightly increased. As can be seen, similar results are given for the eight- story structure. As a result, since torsional motion of the superstructure is mostly affected by isolators' movement, reduction of the eccentricities in stories of the superstructure has minor effect on reduction of the rotation of stories. The average reduction of torsional responses of the model C in comparison with model A for different periods of isolation system is shown in Fig. 12. As can be observed from figure, increase of the flexible edge stiffness of base story had a significant effect on reduction of rotational responses. In this case, in comparison with the three-story structural models, increasing the period of the isolators is more effective in reduction of torsional responses of the eight-story structural models. The simulation results of model D, shown in Fig. 13, confirm that this strategy can be useful to reduce torsional responses of asymmetric 8-story base-isolated building. In comparison with 3-story structures, the torsional motions of superstructure of 8-story structure are less affected by the torsional motions of isolation systems. In this case, the simultaneous increase in stiffness of flexible edge of isolation and superstructure system causes a suitable reduction in torsional responses of the base-isolated structures. Furthermore, it is observed that the average reduction of story rotations in the case of models C and D increases while the period of isolation system increases.

5. Conclusions

In this paper, the torsional behavior of asymmetric base-isolated buildings and similar asymmetric fixed- base buildings was compared. The results approved that seismic isolation could significantly reduce the rotation of stories. However, this effect is negligible in the case of large eccentricities. A wide range of lead rubber bearings with different periods is considered to assess the effect of the isolation degree on seismic responses of the structures. Numerical simulations indicate that displacement of isolators located on the flexible edge increases with increasing period of the isolation system. In this case, the risk of buckling and detachment of the rubbers of isolators may be increased. In order to reduce rotation of the base-isolated structures, practical solutions were proposed. The effectiveness of the proposed practical solutions is evaluated by studying the torsional behavior of four structural models subjected to Tabas, Bam and El Centro earthquake excitations. Considering these excitations, the simulation results showed that increase in stiffness of flexible edge of isolation system can reduce torsional responses of asymmetric 3-story base-isolated structure. Additionally, the simultaneous increase of flexible edge stiffness of isolation and superstructure system causes a suitable reduction in torsional responses of 8-story base-isolated structure.

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