Influence of incident angles of earthquakes on dynamic responses of base isolated building with mass asymmetries in the superstructure

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SUMMARY:
The influence of incident angles of earthquakes on dynamic responses of both asymmetric fixed base and base isolated structures under bi-directional seismic ground motions is presented in this paper. The models with the change of relative eccentricity which is related to mass eccentricity of 5%, 10%, 15%, 20% and 25% of greatest dimension of structure regarding one-way and two-way asymmetry are considered in order to assess the effect of the various mass eccentricities of the structure. The peak responses of the symmetric and asymmetric fixed base and base isolated structures are compared in terms of the torsional irregularity and amplification factors. The amplification of asymmetric structure with respect to counterpart symmetric structure is considered. Moreover, the parameters are also compared according to the incident angles of ground motions between two-way and one-way asymmetry for each type of the fixed base and the base isolated structures.

Keywords: Angles of incident earthquake, fixed base structure, base isolated structure, dynamic responses

1. INTRODUCTION

Base isolation is used to protect structures from the destructive effects of earthquakes. There is a few works available in the literature where the dynamic response of base isolated asymmetric structures has been studied.

Satish, et al. (1993) studied the multistory asymmetric base isolated structure subject to the bidirectional ground motions. The objective of their research was to identify the important system parameter and to investigate the influence of various system parameters on the lateral torsional response of the asymmetric base isolated structure with the elastomeric isolator system. Jangid and Datta (1994) investigated the nonlinear response of torsionally coupled base isolated systems under random ground motions. The conclusion of their study is that effectiveness of base isolation is reduced for higher eccentricity of the superstructure; however, the eccentricity of the superstructure does not have any significant influence on base displacement. Moreover, the angles of incidence of earthquake excitation moderately influence the effectiveness of base isolation when identical records are used for the two directions.

Tena and Gomez (2002) presented the torsional response of three-story rigid structure with bilinear isolators subject to the bidirectional lateral ground motions when the eccentricity existed in: (a) superstructure, (b) the isolation system and (c) in both the superstructure and the isolation system. Their study is concentrated on peak responses for design parameters of base isolator such as displacement ductility demand, peak displacement, amplification factor etc. After that, torsional amplifications due to static eccentricities related to the differences in the lateral stiffness of the resisting elements were compared directly with those due to the positions of the centers of mass, which are investigated by Tena and Escamilla (2007). Simultaneously, it is also concluded that torsional amplifications in the isolation system are higher as the T_I/T_s (T_s is the period of fixed base structure, T_I is the period of the base isolated structure) ratio diminishes, particularly for systems with stiffness eccentricities in the superstructure.

Carlos, et al. (2008) used the dynamic interaction between the base and superstructure to study the seismic behaviors of asymmetric buildings.

In the other research, Zheng, et al. (2004) showed out that the effects caused by irregularity of plan layout of seismic structures have been emphasized in several codes. However, there is difference in the criteria from one code to another. The difference between codes in USA, China and Euro are investigated. It is indicated by the analysis results that some provisions are not reasonable.

Adibramezani, et al. (2009) assessed the effect of a bilinear hysteric elastomeric base isolation system to decrease the torsional moments generated in a superstructure due to the bidirectional actions of selected ground motions. The mean peak responses are compared to the corresponding responses of the fixed base system to investigate the effectiveness of base isolation.

Recently, the multistory fixed and base isolated structure with unidirectional and bidirectional asymmetric for regular and irregular plan under unidirectional earthquake are studied by Khante and Lavkesh (2010). Simultaneously, they mentioned the effect of mass eccentricity in the symmetric and asymmetric structure also. Besides, Etedali and Sohrabi (2011) compared the torsional behavior of the asymmetric structures with the fixed and isolated base. The analysis results have shown the efficiency of seismic isolations is to reduce the rotation of the asymmetric structure stories. However, increasing the eccentricity reduces the effect of isolations on decreasing torsion which is negligible for large eccentricity. Therefore, practical solutions to reduce torsion of the base-isolated asymmetric structures have been proposed by increasing the flexible edge stiffness of isolation system.

In this study, the influence of the mass eccentricity in one-way and one-way asymmetric structure is investigated with the fixed and isolated base. The effects of incident angles of ground motions are considered in order to demonstrate its important role in the design process. Moreover, the peak responses in term of the torsional irregularity and amplification factor are studied with the change in relative eccentricity.

2. STRUCTURAL MODEL

The fixed base structures are both two-way and one-way asymmetric single story building shown in Figure 1. The building consists of a rigid diaphragm where the entire story mass is lumped. CM, Ms and I_M denote the center of mass and the translational and rotational masses, respectively. At each column, the plastic hinges subjected to nonlinearities are located at the both ends of the column. The dimensions of square sections of columns are equal to 40 cm. The stiffness center (CS) and resistance center (CR) are coinciding with the center of geometry of the plan. In this study, the geometric dimensions b, a and h refer 10, 5 and 3m, respectively. The stiffness of the elements is equal to 5892 kN/m while the mass distribution is characterized by values of M and I_M, respectively, equal to 68.8 kN/(m/s^2) and 3000 kN(m/s^2).

Besides, base isolated structure which is idealized as a superstructure of fixed structure mounted on the base isolators. There are six base isolators which are arranged between base mass and foundation as shown in Figure 1. Each base isolator is placed under each column with the similarities. The base mass in this case is equal to 45.9 kN/(m/s^2). The distributed mass in the plan are varied in order to provide the eccentricity e between the CM and CR. The elastomeric bearing isolators which are designed for the base isolated structure. The elastomeric bearing isolators are designed following some recommendations of the ASCE/SEI 7-10 (2010). The effective stiffness of the isolation system at design displacement (k_{eff}) must be greater than one third of the effective stiffness at 20% of the maximum design displacement (k_{eff2}), this is, $k_{eff} > 1/3k_{eff2}$ as depicted in Figure 3.

Artificial earthquakes with peak ground acceleration (PGA) of 0.154g shown in Figure 4 are used according to the seismic design guideline of Korea (MOCT, 1997). Two same artificial ground motions are simultaneously applied in the main and secondary directions. The incident angles of the main and secondary ground motions are α and $\alpha+90$ to the x-axis respectively as shown in Figure 1. However, according to the real ground motions which are shown in Figure 5, the main and secondary ground motion are Usa00074 and Usa00073, respectively. The incident angle α of the bi-directional ground motion ranging from 0 to 360° with increments of 15° counter clockwise are considered.

Torsional irregularity (μ) are considered to exist when maximum story displacement at one end of the structure transverse to an axis (δ_2) is more than 1.2 times the average of the story displacement at two ends of the structure. The criterion is interpreted by following formula:

$$\mu = \delta_2 \Big/ \left(\frac{\delta_1 + \delta_2}{2} \right) > 1.2 \qquad (1)$$

Assuming that e_x and e_z are the eccentricities along x- and z-directions, some definite parameters are also shown as follow:

$$e_r = \sqrt{e_x^2 + e_z^2} / r \qquad (2)$$

$$r = \sqrt{(a^2 + b^2)/12} \qquad (3)$$

Where, e_r is the relative eccentricity for structures, r is the radius of torsion rotate of the floor; a, b are the length of structure along x- and z- directions.

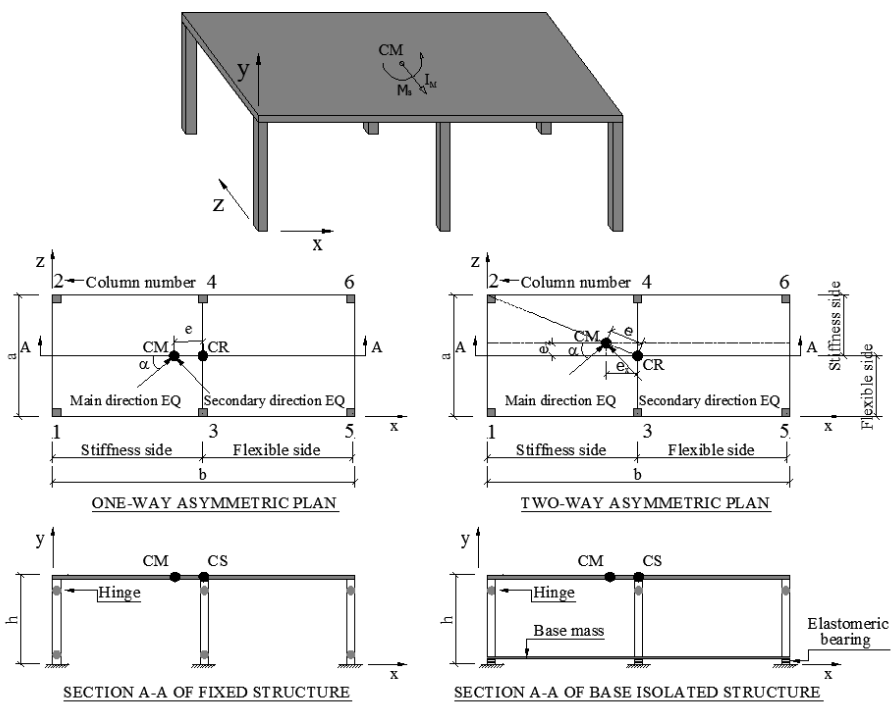


Figure 1. Structural models for investigation

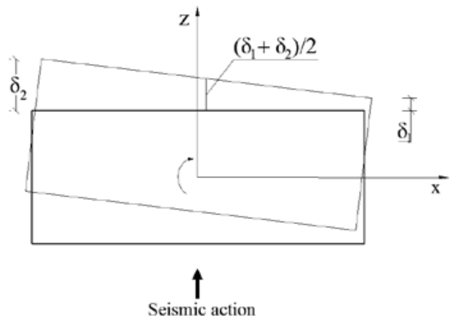


Figure 2 Graphic of torsional irregularity in GB50011-2001 Code

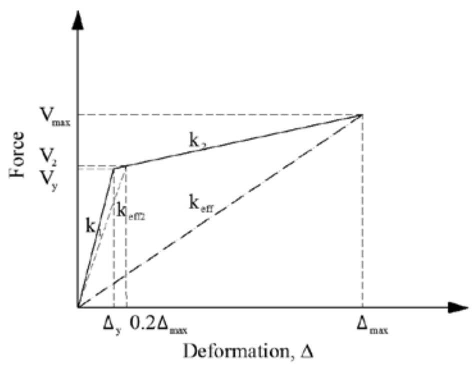


Figure 3. Design envelope curve for bilinear isolators

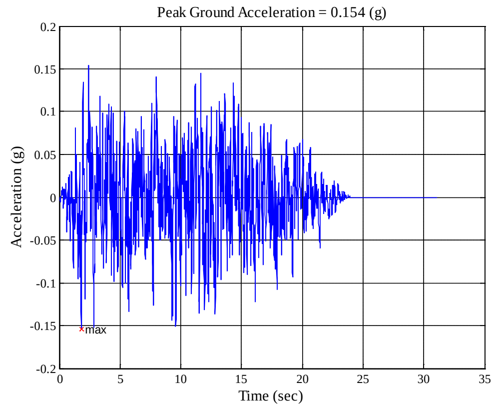
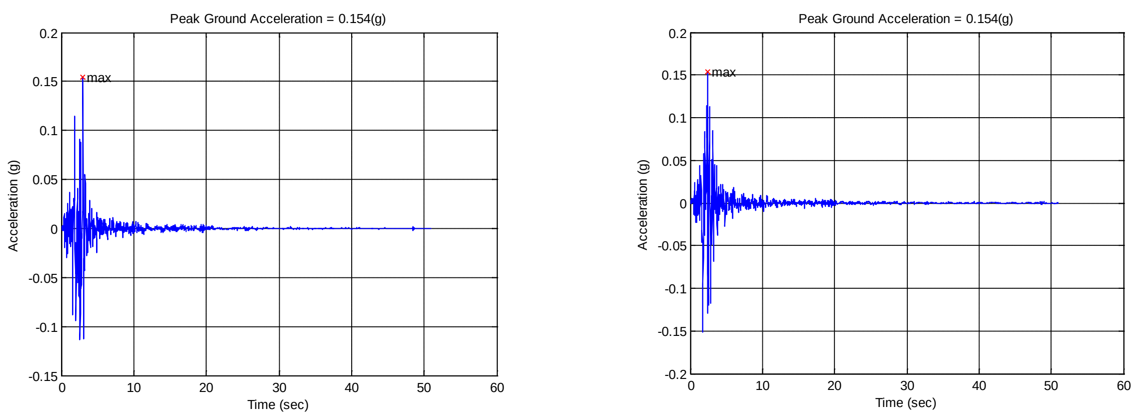


Figure 4. The artificial earthquake in seismic design guidelines II, Seoul, Korea (MOCT, 1997)



(a) The real earthquake Usa00073

(b) The real earthquake Usa00074

Figure 5. Selected real ground motions

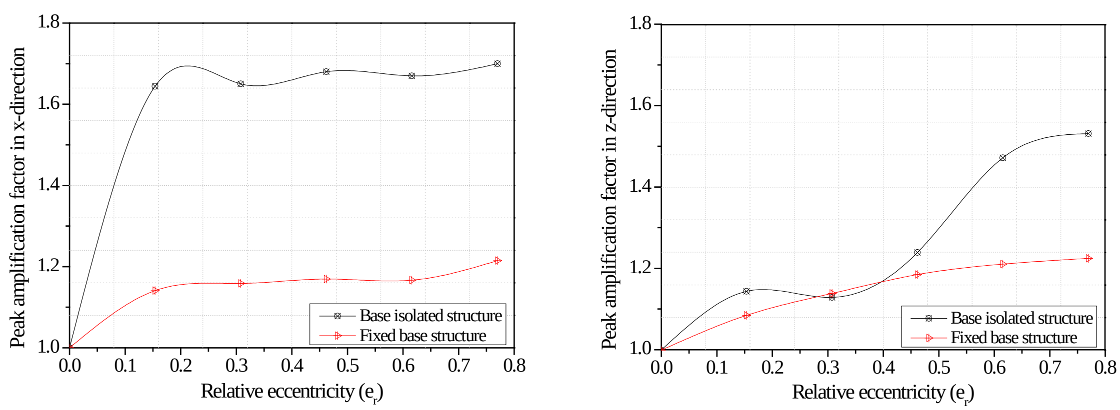
3. RESULTS AND DISCUSSION

3.1 Comparison of peak displacements of asymmetric structures with respect to symmetric structures

In order to compare the peak displacements of the symmetric structures i.e. e=0% (mass eccentricity, e is the percentage of greatest dimension of structure) with the asymmetric structures i.e. e≠0%, the peak displacements of the symmetric systems [$\Delta_{max\ disp}$ (e=0%)] are divided by those of the asymmetric system [$\Delta_{max\ disp}$ (e≠0%)], which is called the amplification factor.

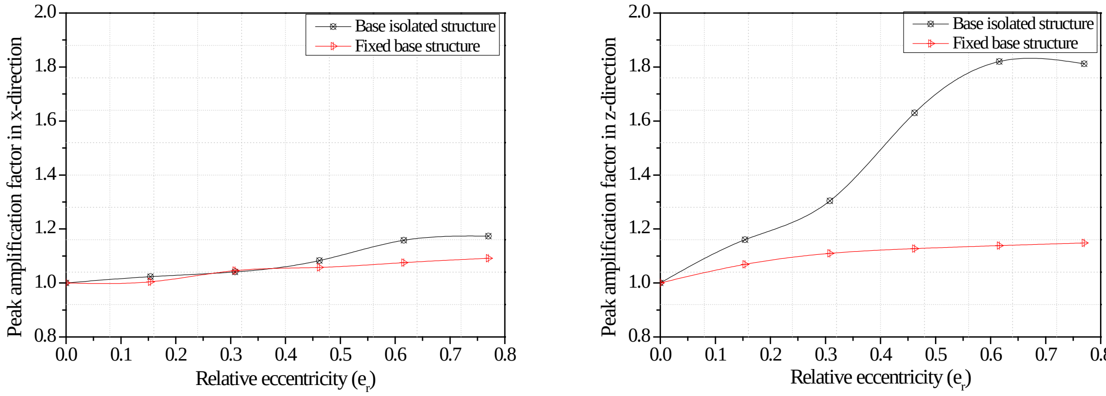
Considering the incident angles of ground motions, the relation between the relative eccentricity and peak amplification factors for the one-way asymmetric fixed base and base isolated structure are respectively shown in the Figures 6(a, b) for the artificial earthquakes and in the Figures 7(a, b) for the real earthquakes. It is being observed from the Figures 6(a, b) and 7(a, b) that the peak amplification factor in x-direction of the fixed base and base isolated structure does not seem to be much different when the relative eccentricity ranges from 0.154 (e=5%) to 0.77 (e=25%). Also, the peak amplification factors in z-direction of both of the structures are directly proportional to the relative eccentricity. Moreover, for the one-way asymmetric structure, the peak amplification factors of the base isolated structure are larger than those of the fixed base structure.

The Figures 8(a, b) depict the relation between the relative eccentricity and the peak amplification factor for the two-way asymmetric fixed base and base isolated structure, respectively, for the artificial earthquakes, while Figures 9(a, b) depict it for the real ground motions. It can be seen that the peak amplification factors in x-direction of the base isolated structure decrease and are larger than those in the fixed base structure when the relative eccentricity increases from 0.154 (e=5%) to 0.462 (e=15%). However, when the relative eccentricity exceeds 0.462, the peak amplification factors in x-direction of the base isolated structure start increasing and are smaller than those of the fixed base structure. The tendency of the amplification factors curve in x-direction is similar for both types of artificial and real ground motions. In z-direction, the peak amplification factors of the base isolated structure are always larger than those of the fixed base structure when the relative eccentricity increases. Besides, in case of the fixed base structure, the peak amplification factors in both x- and z-directions are directly proportional to the relative eccentricity. Simultaneously, the results for the two-way asymmetric structure, which show that the changing of the amplification factors of the two-way asymmetric structure are more complicated than those of the one-way asymmetric structure, such as for base isolated structure with two-way eccentricity, the maximum amplification factors suddenly increase or decrease when the relative eccentricity increases.



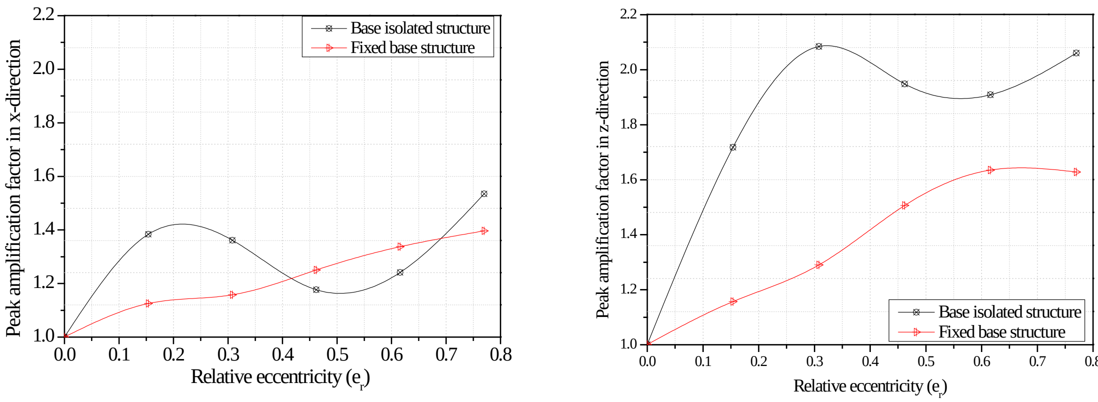
(a) x-direction (b) z-direction

Figure 6. Ratio between the peak displacement for one-way asymmetric structure [$\Delta_{max\ disp}$ (e≠0)] and symmetric structure [$\Delta_{max\ disp}$ (e=0)] under bi-directional input of artificial earthquakes



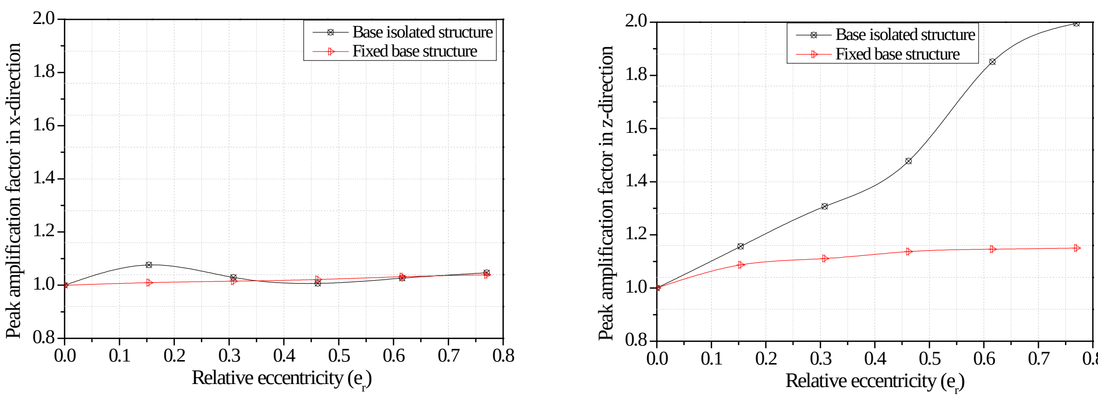
(a) x-direction (b) z-direction

Figure 7. Ratio beween the peak displacement for one-way asymmetric structure [$\Delta_{max\ disp}$ (e≠0)] and symmetric structure [$\Delta_{max\ disp}$ (e=0)] under bi-directional input of Usa00074 and Usa00073 ground motion records



(a) x-direction (b) z-direction

Figure 8. Ratio between the peak displacement for two-way asymmetric structure [$\Delta_{max\ disp}$ (e≠0)] and symmetric structure [$\Delta_{max\ disp}$ (e=0)] under bi-directional input of artificial earthquakes

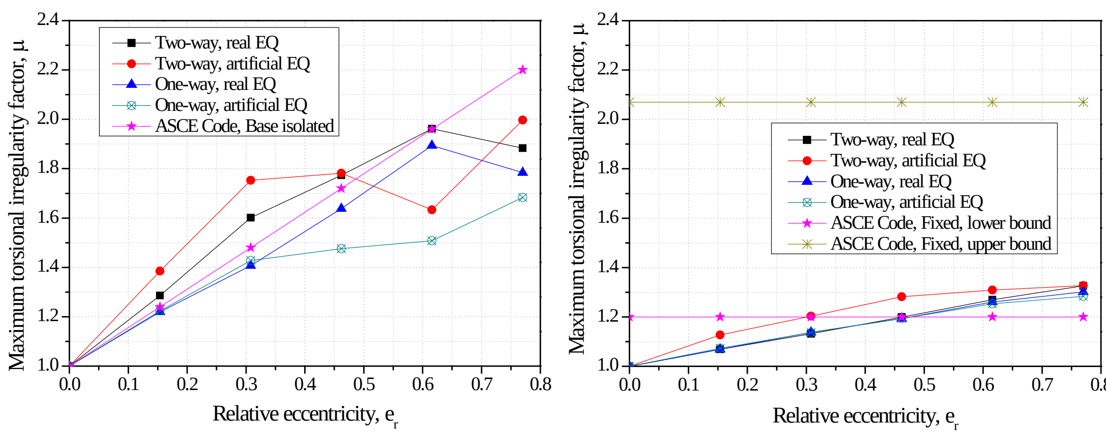


(a) x-direction (b) z-direction

Figure 9. Ratio beween the peak displacement for two-way asymmetric structure [$\Delta_{max\ disp}$ (e≠0)] and symmetric structure [$\Delta_{max\ disp}$ (e=0)] under bi-directional input of Usa00074 and Usa00073 ground motion records

3.2 Torisonal irregularity

Based on the previous research of the same authors (2012), the results pointed out that in case of the base isolated structure, the displacement at the isolated base is most important to assess and calculate the torsional irregularity of the base isolated structure. The torsional irregularity factor of the base isolated and fixed base structures with different incident angles of the artificial ground motions as well as the real ground motions are considered for both two types of asymmetries which are one-way and two-way eccentricities. The obtained results have shown that the torsional irregularity factor always obtain the maximum value at non-orthogonal incident angles of ground motions, which signifies it as an important factor to be considered. The maximum torsional irregularity factor related to the changing of the relative eccentricity is respectively shown in Figures 10(a, b) for the base isolated and fixed base structure. From Figures 10(a, b), it is observed that the tendency of maximum torsional irregularity factor curves of the fixed base and base isolated structure is similar; however, the maximum torsional irregularity factors of the base isolated structure are larger than those of the fixed base structure. Besides, for the base isolated structure with two-way eccentricity, when relative eccentricity is equal or more than 0.154 (e=5%), the torsional irregularity factor value exceeds limited value which is calculated using the total design displacement value obtained from the design process in ASCE/SEI 7 (2010) and FEMA (2006). Therefore, the relative eccentricity of the base isolated structure with two-way eccentricity is not required to exceed 0.154 (e=5%). However, the relative eccentricity of the base isolated structure with one-way is satisfied with the requirement of design progress in this case. Moreover, it can be seen from Figure 10(a) that the deviation of the torsional irregularity between two-way and one-way eccentricity of the base isolated as well as the fixed base structure is largest when relative eccentricity is equal to 0.308 (e=10%). The maximum torsional irregularity factors of the fixed base structure are directly proportional to the relative eccentricity; however, for the base isolated structure, the curve of the maximum torsional irregularity factors relative to changing the relative eccentricity is more complicated; for instance, the maximum value of torsional irregularity factor obtained at e=20% is smaller than those obtained at e=15% and e=10% by using the real earthquakes (Figure 10(a)). In case of the fixed base structure, when e_r =0.77 (e=25%), the difference of maximum torsional irregularity between two-way and one-way asymmetry is negligible; however, it can't be negligible in case of the base isolated structure.



(a) Base isolated structure (b) Fixed base structure

Figure 10. Maximum torsional irregularity factor

CONSLUSION

The peak amplification factors of the base isolated structure are larger than those of the fixed base structure, which means the influences of the asymmetry for the base isolated structure, are larger than those for the fixed base structure. The amplification factor as well as the torsional irregularity factor is not constant according to the different incident angles of ground motions for both the fixed base and base isolated structures. Such factors often get the maximum value at non-orthogonal incident angles of ground motions. Therefore, the incident angles of ground motions play an important role in considering design parameters.

In case of the structures with the one-way eccentricity, the peak amplification factor in x-direction of the fixed base and base isolated structure is not much different when the relative eccentricity ranges from 0.154 (e=5%) to 0.77 (e=25%); however, the peak amplification factor in z-direction is augmented by increase in the relative eccentricity. Besides, for the two-way asymmetric fixed base structure, the maximum amplification on the response of asymmetric systems with respect to symmetric systems is directly proportional to the relative eccentricity for both x- and z-directions. However, regarding the two-way asymmetric base isolated structure, the maximum amplification factor in x-direction is noticeable when relative eccentricity is equal to 0.154 (e=5%).

Regarding the base isolated structure, the obtained results of the torsional irregularity factor point out that the relative eccentricity should not exceed 0.154 (e=5%) according to the two-way eccentricity. The deviation of the maximum torsional irregularity between two-way and one-way asymmetric base isolated as well as the fixed base structure is largest when relative eccentricity is equal to 0.308 (e=10%). The peak torsional irregularity factors of the fixed base structure are directly proportional to the relative eccentricity. However, for the base isolated structure, the curve of the maximum torsional irregularity factors relative to changing the relative eccentricity is more complicated. In case of the fixed base structure, when the relative eccentricity exceeds 0.616 (e=20%), the difference of maximum torsional irregularity between two-way and one-way asymmetry is negligible; however, it can’t be negligible in case of the base isolated structure.

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REFERENCES

Adibramezani M, Moghadam AS and Ziyaeifar M (2009), “Assessment of technique for the torsional response reduction of seismic isolated asymmetric structures,” *Journal of Applied Sciences,* 9 (15): 2653-2670, ISSN 1812-5654.

Carlos ES, Juan CL and Jose LA (2008), “Base–structure interaction of linearly isolated structures with lateral–torsional coupling,” *Engineering Structures*; **30:** 110–125.

Etedali S and Sohrabi MR (2011), “Torsional Strengthening of Base-Isolated Asymmetric Structure by increasing the Flexible edge stiffness of isolation system,” *International Journal* of *Civil & Environmental Engineering,* IJCEE-IJENS **Vol: 11** No: 02.

Jangid RS and Datta TK (1994), “Seismic response of torsionally coupled structure with elastoplastic base isolation,” *Engineering structure*; **16(4):**256-62.

Jangid RS and Datta TK (1994), “Nonliner response of torsionally coupled base isolated structure,” ASCE *Journal of structure engineering*; **120(1):**1-22.

Khante SN, Lavkesh RW (2010), “Study of seismic response of symmetric and asymmetric base isolated building with mass asymmetry in plan,” *International Journal of Civil and Structural Engineering*. **Volume X**, No X.

Saiful Islam ABM, Jameel M and Jummat MZM (2011), “Study on optimal isolation system and dynamic structural responses in multi-storey buildings ,” *International Journal of the Physical Sciences*, **Vol. 6(9**), pp. 2219-2228.

Satish N, Andrei MR and Michalakis CC (1993), “Torsion in Base-Isolated structures with elastomeric Isolation systems,” *Journal of Structural Engineering*, **Vol. 119**, No 10.

Tena A and Gomez L (2002), “Torsional response of base-isolated structures due to asymmetries in the the superstrucuture,” *Engineering Structures*; **24:** 1587-1599.

Tena A and Escamilla JL (2007), “Torsional amplifications in asymmetric base-isolated structures,” *Engineering Structure*; **29:** 237-247.

Zheng N, Yang Z, Shi C and Chang Z (2004), “Analysis of criteria for torsional irregularity of seismic structure,” *13th World Conference on Earthquake Engineering;* Vancouver, BC., Canada August 1-6, Paper no.1465.

GB50011-2001. “Code for seismic design of building.” (2001).

ASCE/SEI 7-10. “Minimum Design Loads for Buildings and Other Structures” (2010).

Tu N V, Dookie K, Sung G C and Yang H J (2012), “Dynamic responses of base isolated structure with mass asymmetric in plan under random seismic ground motions,” *9CUEE & 4ACEE*, Tokyo, Japan March 6-8, pages 1413-1418.

FEMA (2006), “NEHRP Recommended Provision: Design Examples (FEMA-451),” Federal Emergency Management Agency of the Department of Homeland Security, Washington D.C.