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Effect of Brace Locations and Accidental Eccentricity on the Response of Asymmetric Structures

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ABSTRACT

The first objective of this paper is to consider asymmetric location of braces in steel structures. For this purpose, eccentricity effect of the center of stiffness toward the center of mass and the torsion caused by that is considered. For that, a building, which has been constructed in the past, is investigated by changing the arrangement of braces and the amount of steel consumption, as an important economic indicator, is considered in each items. Then the displacement parameter, which is the suitable criterion for detection of structural damages, was evaluated. Finally, changes of base shear toward eccentricity are examined. It is shown that with closing the center of mass and stiffness and reducing the eccentricity using the appropriate location of braces, how much base shear and structure weight (steel consumption) is reduced. Then, the sensitivity of the asymmetric structure under torsion to analysis type is investigated. For this purpose, two types of analysis included pseudo-static and dynamic spectral analysis are studied. As well, in the second objective, the effect of considering the accidental eccentricity is evaluated in designing phase of buildings. For this purpose, two asymmetric structures in plan are designed with and without considering the accidental eccentricity (e_a) equal to 5%. Whereas according to Iranian Seismic Code No. 2800, considering e_a is not necessary for the structures. These structures are analyzed by nonlinear time history and results indicate that e_a can reduce the response of structure considerably.

Keywords:
Asymmetric structures; Brace locations; Accidental eccentricity; Nonlinear dynamic analysis; Pseudo-static analysis; Dynamic spectral analysis

1. Introduction

One of the important issues in the analysis and evaluation of the structural behavior is the failure of buildings due to their irregularities during an earthquake. According to the statistics of different earthquakes devastation, the importance of this issue could not be ignored. For instance, the earthquake occurred in Mexico City in 1985, 42% of the buildings during the earthquake were destroyed or damaged significantly due to torsional effects of asymmetric structures, 15% of which were because of the asymmetry of the stiffness. Most irregularities were due to the architectural issues.

Investigation on the inelastic torsional response of structures has been attracting much attention over the past few decades. In the linear range, the torsional response of asymmetric-plan buildings is governed by only two parameters, the eccentricity between the center of mass and the center of stiffness in the exciting direction of the seismic action, and the ratio of the uncoupled lateral and torsional vibration period. During transition from the linear to the nonlinear range, the seismic behavior differs significantly as additional parameters contribute to effect of the inelastic response. Many studies have focused on evaluating the different influences of the mass, stiffness and strength distribution, respectively, and the influence of the ground motion features as well [1].

In areas of high seismicity, structures are generally designed for ductile response. However, the torsional design provisions, as the lateral design provisions, are mainly based on elastic analyses. Previous studies in torsional inelastic seismic response have focused on verifying the adequacy of current code provisions through numerical modeling. Chopra [2] investigated the effects of plan asymmetry on the earthquake response of code designed, one-story systems were identified with the objective of evaluating how well these effects were represented by torsional provisions in building codes. The results demonstrated that the design eccentricity in building codes should be modified to achieve the desirable goal of similar ductility demands on asymmetric-plan and symmetric-plan systems. Dusicka [3] obtained the maximum inelastic displacement and ductility demands for the lateral load resisting elements of torsionally susceptible single story structures. Irvine and Kountouris [4] studied the bilinear hysteretic response of a simple torsionally unbalanced building consisting of two identical frames supporting a diaphragm subjected to three different records and one artificially generated ground motions. Their results showed that the ductility demands are insensitive to the uncoupled torsional to lateral frequency ratio and ductility demands do not reach exceptionally high values when the uncoupled frequency ratio is unity [5]. Wolff et al. [6] have shown that the measured torsional amplification ratios correspond to accidental eccentricities of about half of the code-described value of 5-percent of largest plan dimension. Chandler and Duan [7] investigated the non-conservative of existing static torsional provisions and examined the aspect of element strength distribution and its influence on inelastic torsional effects. They improved the effectiveness of the code-type static force procedure for torsionally unbalanced multistory frame buildings. Poursha et al. [8] extended the consecutive modal pushover procedure for estimating the seismic demands of two-way asymmetric plan tall buildings subjected to bi-directional seismic ground motions taking the effects of higher modes and torsion into account. Tarbali and Shakeri [9] proposed a single-run pushover procedure to assess the seismic response of asymmetric-plan buildings, when subjected to unidirectional earthquake ground motions. Effects of the higher and torsional modes were incorporated into an invariant load pattern, which was calculated based on the height-wise distribution of the modal story shear and torsional moment.

It is well-known that the drift of a frame, accordingly the total structural weight, can be drastically reduced by mounting braces, if the stiffness and strength of the beams, columns and braces are appropriately distributed. Takewaki et al. [10] optimized a frame with K-braces at the specified locations. Erduran and Ryan [11] evaluated the torsional response of buildings with peripheral steel-braced frame lateral systems. They created a three-dimensional model of a three story braced frame with various levels of eccentricity and assessed the effects of torsion on the seismic response for four hazard levels. In order to investigate effects of bracing pattern on the lateral load bearing capacity of Concentrically Braced Steel Frames (CBFs) and also on "Response Modification Factor" (R), Vetr et al. tested some 1/3 scale samples with various number and location of X bracing. However, the R values in codes, which is taking into account the possibility of plastic deformation of structures, does not depend on the number of braced spans and their relative location, the experimental and numerical results of the study illustrated that arrangement of braces plays an important role on the R values [12]. Kameshki and Saka [13] optimized frames with different kinds of braces, and compared the optimization results. Although the cross-sectional properties of beams, columns and braces were optimized for each optimization problem in their study, the types and locations of braces were not considered as design variables. Hence, the optimized braced frame would be overly stiffened, because of the limitation on the types and locations of braces. In order to increase the ductility of concentrically braced frames (CBF), Vetr used the alloy of LY steel and aluminum [14]. To improve seismic behavior of braced frames, a new system named new ductile CBF (DCBF) is characterized by Vetr using experimental studies [15]. To improve the performance of ordinary CBF (OCBF), an experimental study was carried out by Vetr et al. The results of which indicate that the appropriate arrangement of braces play a significant role in the response of the OCBF [15].

Irregularities in structures could be divided into two general forms of irregularities in height and plan. Due to earthquake regulations, asymmetric structures in plan are known as ones with the unbalanced distribution of hardness or ones with unbalanced distribution of mass versus hardness. First system is called the eccentricity of stiffness (SES) and the second system is named the eccentricity of mass (MES). Iran Standard No. 2800 [16] has also discussed the irregularity of buildings. It considers irregularities in plan due to some factors: first, plan asymmetric with respect to the principal axes; second, when the distance between the centers of mass and stiffness of a building becomes more than 20% of the building dimension; third, sudden changes in the stiffness of the diaphragm; and finally, discontinuity in the lateral resistant elements.

2. Torsional Relationships in the Regulations

To consider the effects of structural irregularities in plan, special rules are expressed in different building regulations. The most general form in codes is the application of lateral forces in order to calculate the torsional moment of each story. In other words, the torsion in each story is obtained from multiplying the story shear and the design eccentricity.

$$T = e_D . V \tag{1}$$

where V is story shear, and e_D is the design eccentricity in which the amount of the dynamic eccentricity is included.

Asymmetry along with eccentricity (e_s) is the distance between the center of mass (CM) and the resistance (CR). Hard side of a plan refers to the edge of a plan where resistance center is close to its edge and soft side refers to where its resistance is further [17].

Regulations for balancing the center of mass and the center of stiffness are expressed as the following equations:

$$e_{D1} = \alpha e_s + \beta b \tag{2}$$

$$e_{D2} = \delta e_s - \beta b \tag{3}$$

Design force of resistance elements is the most important achievement of the consideration of the equations above. The first relation refers to the eccentricity of the initial design and the second relation refers to the eccentricity of the second design. The first term shows that the eccentricity of the dynamic relationship is due to the unbalanced resistance distribution and the second term is due to the other factors such as accidental eccentricity of the torsional motion, errors of calculation and distribution of live load. Second term is the function of plan dimensions. In the above equation, e_s is the eccentricity of the mass and stiffness of the system and b is the plan dimension in the perpendicular direction to the earthquake. δ, β and α are Fixed parameters that have different values in different regulations. The values of these parameters presented in several regulations are tabulated in Table (1) [2].

3. The Aim of the Research

With regard to the size and geometry of the land in reality, we need to construct irregularities in plan. It is shown that for a building that was already constructed, repositioning of braces could result in the reduction of eccentricity and having closer values for the center of mass and the center of resistance. These relocations of braces would lead to lower weight of structure along with its base shear (steel consumption). The analysis for the sensitivity of irregularity in structures under torsion is also

Table 1. δ, β, and α of various regulations.

Area	Australia	Iran	New Zealand	Europe	Canada	Mexico	America
Code		IBC-99	NZC-84	EC8	NBC85	MFDC-77	UBC-88 ATC-3
α	A1	1	1	$1+ e_1 / e_s$	1.5	1.5	1
β	0.05	0.1	0.1	0.1	0.1	0.1	0.05
δ	0.5	1	1	1	0.5	1	1

investigated. In this regard, two types of quasi-static and dynamic spectral analysis is studied and economic parameters, as one of the important objectives of the present study, are investigated. In addition, displacement measurements and base shear changes are being checked. As well, the effect of considering the accidental eccentricity in designing phase of buildings is evaluated; for this purpose, two structures are designed with and without considering the accidental eccentricity (e_a) that is equal to 5%.

4. The First Sample

Economic parameters of the project are the main objective of the present study. However, displacement and base shear variation are reviewed. Three sample structures are chosen to determine the effects of asymmetric location of braces in steel structures. The structure is located on soil type 2, and the steel used in samples is St-37. The samples are six-story structures that are designed according to Iranian building and seismic code for a very high seismicity zone area. The height of first story is 5.5 m and the heights of others are 2.7 m.

The present study is trying to obtain the most economical state for a structure by closing the center of mass and stiffness. Different arrangements of braces are shown in Figure (1).

Model 2 is the one that was constructed in Bam city. Here, the locations of braces are changed in order to produce a model with less weight and a model with more weight in comparison with the one in reality. The characteristics of the materials used in modelling are tabulated in Table (2) and the characteristics of the soil are given in details.

The loads that are used for modelling are given in Table (3).

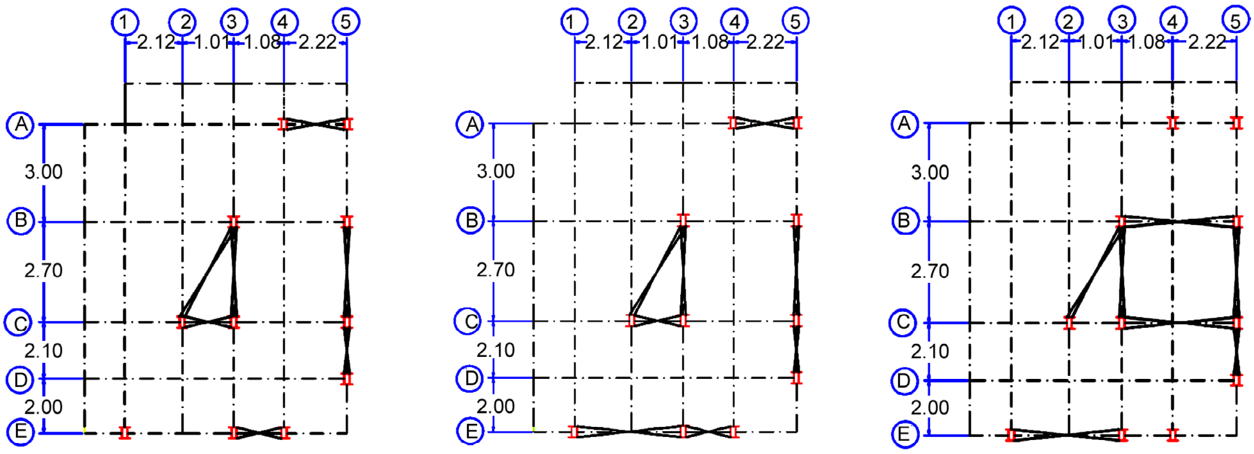
a: Parameters and Seismic Analysis Software: ETABS [18] is used to analyze and design of steel members in selected models. In addition, the earthquake forces are applied by two different

Table 2. The used materials and the soil specifications.

Steel Materials		
Unit Weight (*W*)	$77\ kN/m^3$	
Elasticity Modulus (E_s)	$2*10^5$ MPa	
Poisson's Ratio (u)	0.3	
Yield Stress (f_y)	235 MPa	
Breaking Stress (f_u)	363 MPa	
Concrete Materials		
Unit Weight (*W*)	$24.5\ kN/m^3$	
Elasticity Modulus (E_c)	$2.06*10^4$ MPa	
Poisson's Ratio (u)	0.2	
compressive Strength (f'_c)	21 MPa	
Yield Stress of Longitudinal Bar (f_y)	294 MPa	
Yield Stress of Stirrup (f_{ys})	226 MPa	
Specification of Soil		
Soil	k_s	q_a
Type 2	$1.8*10^4\ kN/m^3$	0.2 MPa

Table 3. Loads.

Dead Load	2 kPa
Live Load	1.5 kPa
Live Load	3.4 kPa
Snow Load	1.5 kPa



Model 1

Model 2 (The Constructed Model in the Past)

Model 3

Figure 1. Arrangement of bracess.

methods: dynamic spectral analysis method and 3D pseudo static analysis method.

b: Spectral Dynamic Analysis: In this method, structural dynamic analysis is performed with assuming linear behavior and using response spectrum analysis. This approach allows the multiple modes of response of a building to be taken into account. The response of a building can be defined as a combination of many special modes. Computer analysis can be used to determine these modes for a building. For each mode, a response can read from the design spectrum, based on the period of the first mode determined from modal analysis, and they are then combined to provide an estimation of the total response of the structure. In the magnitude of forces have to be calculated in all directions i.e. X, Y and Z and then see the effects on the building. Finally, after the analysis, base shears should be equivalent in both spectral dynamic analysis and pseudo static analysis. The adequacy of modes should also be checked.

It should be noted that the distribution of base shear in pseudo static analysis is equal to proportional of earthquake forces by the consideration of its distance from the base level, but in spectral dynamic analysis, earthquake forces of each floor are obtained from the combination of base shear modes.

c: Investigation of Economic Parameters: In design and construction of steel structures, one of the main economic indicators for assessing the acceptability of the project is the amount of consumed steel. Figure (2) shows the total amount of steel consumed in samples. According to these figures, the least amount of consumed steel is observed in model 1.

d: Evaluation of Displacement: One important criterion of structural response to lateral force is the parameters associated with displacement. One of these parameters is the maximum displacement in each floor that values for different models are presented in Figure (3).

e: Changes of Base Shear: Any change in the alignment of braces and therefore the values of eccentricity makes changes in the base shear values. As can be seen from the Table (4), the base shear in Model 1 is the lowest one.

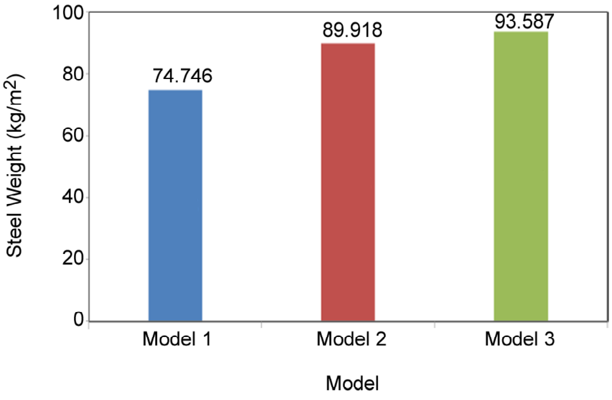


Figure 2. The amount of steel used in the models.

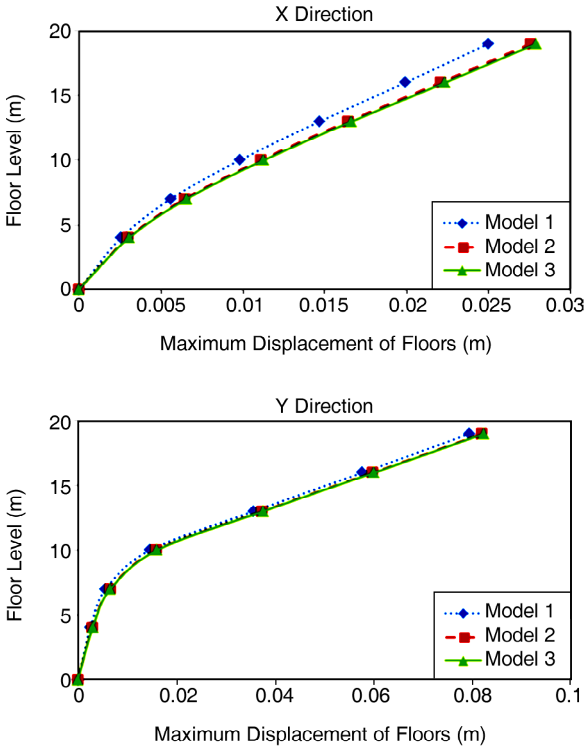


Figure 3. Maximum displacement of stories in each of the models for both X- and Y-direction.

Table 4. Base shear changes by applying the eccentricity of the models.

Model	XCOM	YCOM	XCR	YCR	e_{sx} (m)	e_{sy} (m)	e_s (m)	Earthquake Applied to X-Direction
								Vx (kgf)
1	4.93	3.61	6.06	2.91	1.14	0.70	1.33	100117
2	4.91	3.64	6.24	4.11	1.33	0.48	1.41	103841
3	4.89	3.59	6.25	1.03	1.36	2.56	2.90	104678

f: The Sensitivity of Base Shear on Analysis Type for Irregular Structures: In this study, spectral dynamic and pseudo static analysis have been performed and the sensitivity analysis of base shear is evaluated.

Base shear values for each of these analyses are shown in Table (5). According to this table, values of base shear for in pseudo static analysis, both directions are the same because of applying the same period value for both directions that is equal to $0.05H^{0.75}$.

g: Compare Natural Period of the First Three Modes in Different Models: For a better understanding of the models behavior, natural period of the first three modes are shown in Figure (4).

h: Economic Comparison of the Moment Resisting Frame with Braced Frame: Economic comparison of the moment resisting frame with braced frame is discussed in this section. This comparison is shown in Figure (5).

5. The Second Sample

For the second subject of this paper, to consider eccentricity effect in designing phase on response of asymmetric structures in plan, a 4-story building is designed by computer program ETABS13 [18], based on AISC 360-10 and seismic criteria of Iranian Standard No. 2800 [16]. This building is designed with and without 5% eccentricity for a very high seismic zone of Iran that is located on soil type 2. Plan of the building with dimension of bays and stiff and flexible sides are illustrated in Figure (6). The height of each story is 3.0 m. St-37 steel with yield stress of $F_y = 240$MPa is employed for structural elements. Loading information applied for the building is presented in Table (6).

Table 5. Base shear values for spectral dynamic and pseudo static analysis.

Model	Pseudo Static Analysis		Spectral Dynamic Analysis	
	Earthquake Applied to X-Direction	Earthquake Applied to Y-Direction	Earthquake Applied to X-Direction	Earthquake Applied to Y-Direction
	V	V	V	V
1	100117	100117	92701	89698
2	103841	103841	95042	91888
3	104678	104678	95567	92380

Table 6. The loading information employed for modelling.

Level	Distributed Dead Load (kPa)	Distributed Live Load (kPa)	Weight of the Perimeter Wall (kN/m)
Floor	5.88	3.43	8.83
Roof	6.86	1.47	2.94

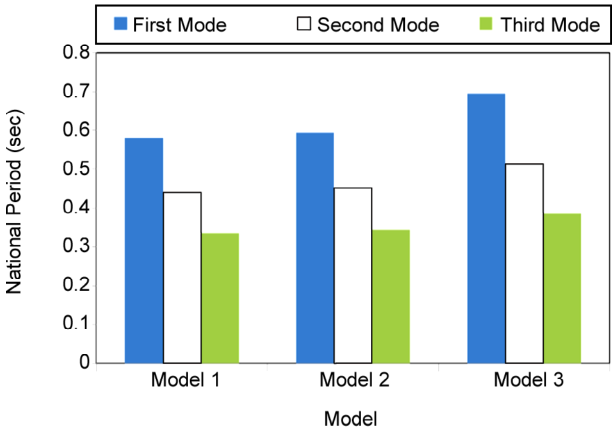


Figure 4. To compare natural period of the first three modes in different models.

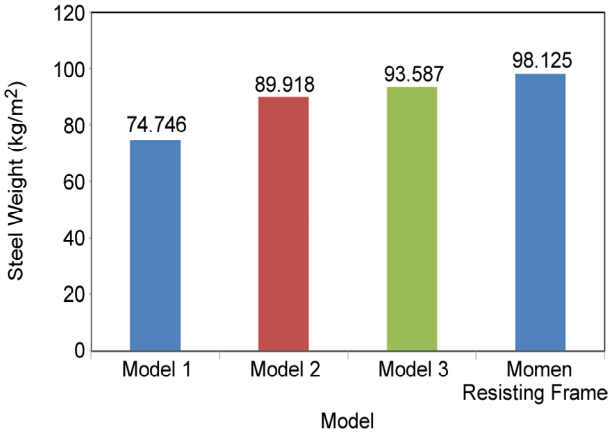


Figure 5. Economic comparison of the moment resisting frame with braced frame.

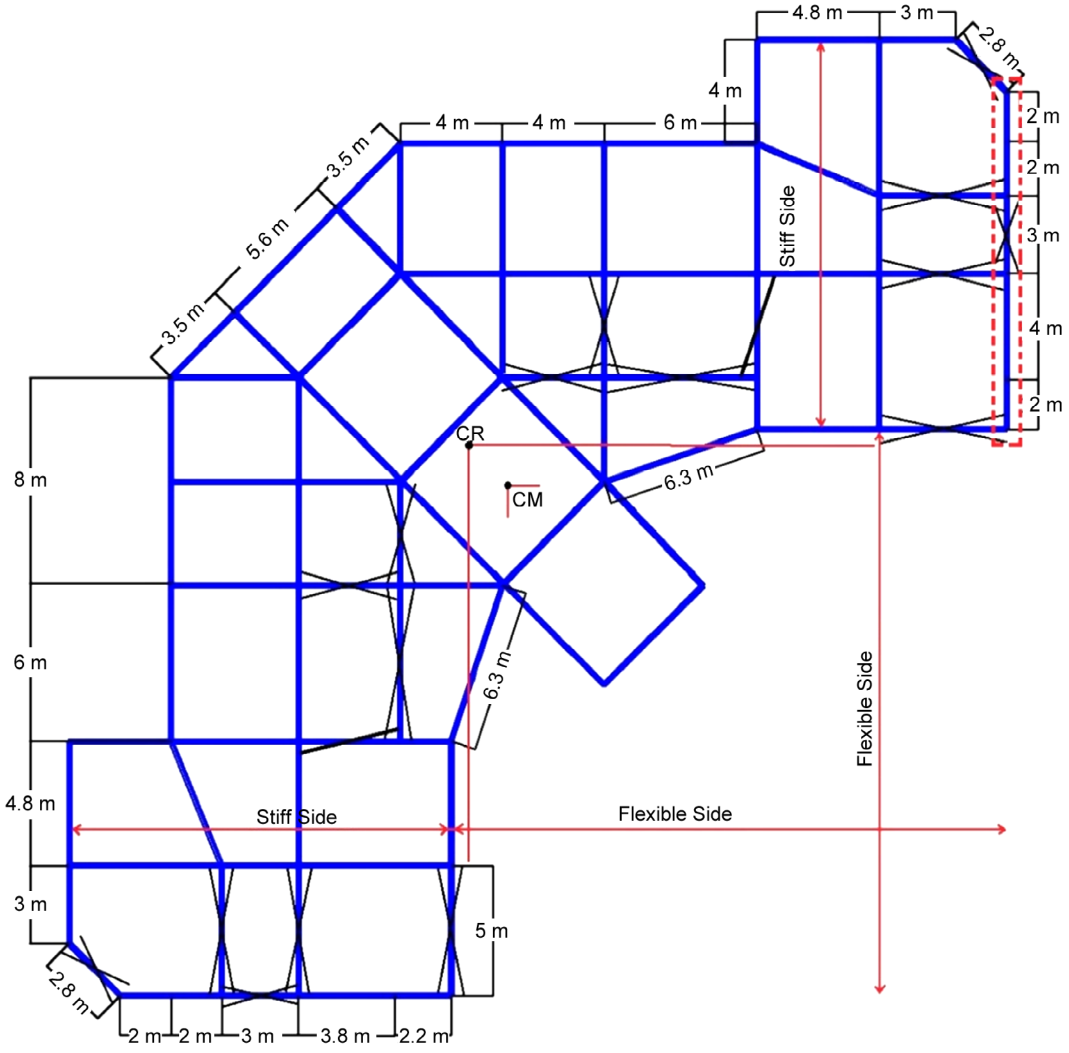


Figure 6. Asymmetric plan of the model building in the second sample.

It should be noted that in designing phase, drift criteria are considered and element sizes have been selected to satisfy these criteria. Designed sections of the considered frames are shown in Table (7).

As previously mentioned, the eccentricity consists of two terms: the first term caused by the distance between the center of mass and center of stiffness (e_s), whereas the second term is considered in order to account the risk of accidental changes in the distribution of mass and stiffness as well as the torsional component of an earthquake (e_a). According to section 3-3-7-4 of Iranian Seismic Code No. 2800 [16], in buildings up to 5-story or shorter than 18 m, as the distance between the center of mass and stiffness is less than 5% of building dimension perpendicular to the direction of ground motion (b), considering accidental eccentricity (i.e., the second term of eccentricity) is not necessary. In this study, the effect of considering the accidental eccentricity in designing phase of the buildings is evaluated. For this purpose, two structures are designed with and without considering the accidental eccentricity (e_a) that is equal to 5%. The distances between the center of mass and stiffness (e_s) to building dimension perpendicular to the direction of ground motion (b) for the different stories are presented in Table (8).

Table 7. Cross sections of all members.

Model	With Considering e_a		Without Considering e_a	
Story	Columns	Beams	Columns	Beams
1	260x260x8	IPE 270	250x250x7	IPE 270
2	260x260x8	IPE 270	250x250x7	IPE 270
3	220x220x8	IPE 240	220x220x7	IPE 220
4	220x220x8	IPE 240	220x220x7	IPE 220

Table 8. The proportion e_s to b for different stories.

Story		Story 1	Story 2	Story 3	Roof
e_s/b (%)	X-direction	3.9	3.9	4.1	3.7
	Y-direction	4.2	4.5	4.4	4

According to Table (8), the maximum value of e_s is less than 0.05b, thus the structures evaluated in this study, according to Iranian Seismic Code No. 2800 [16], do not need to consider accidental eccentricity equal to 5%.

5.1. Nonlinear Time History Analysis

To take into account the effect of considering e_a on structures response, two structures are designed with and without considering this factor in designing phase. For nonlinear time history analysis, two-dimensional frame indicated by the dotted rectangular box in Figure (6) is selected, and records of Bam (station of Bam), Manjil (station of Abbar) and Tabas (station of Tabas), according to Figure (7), are selected for the time history analysis. These analyses are performed using the program code OpenSees [19].

Spectral matching is one of the most common record selection method proposed by seismic codes. The selection of the earthquake records is performed regarding to compatibility between their response spectrum and the design spectrum of Soil Type 2 presented by Iranian Seismic Code, Standard No. 2800 [16]. The records were selected from the Pacific Earthquake Engineering Research Centre NGA-West2 database [20]. To minimize the difference between the design response spectrum

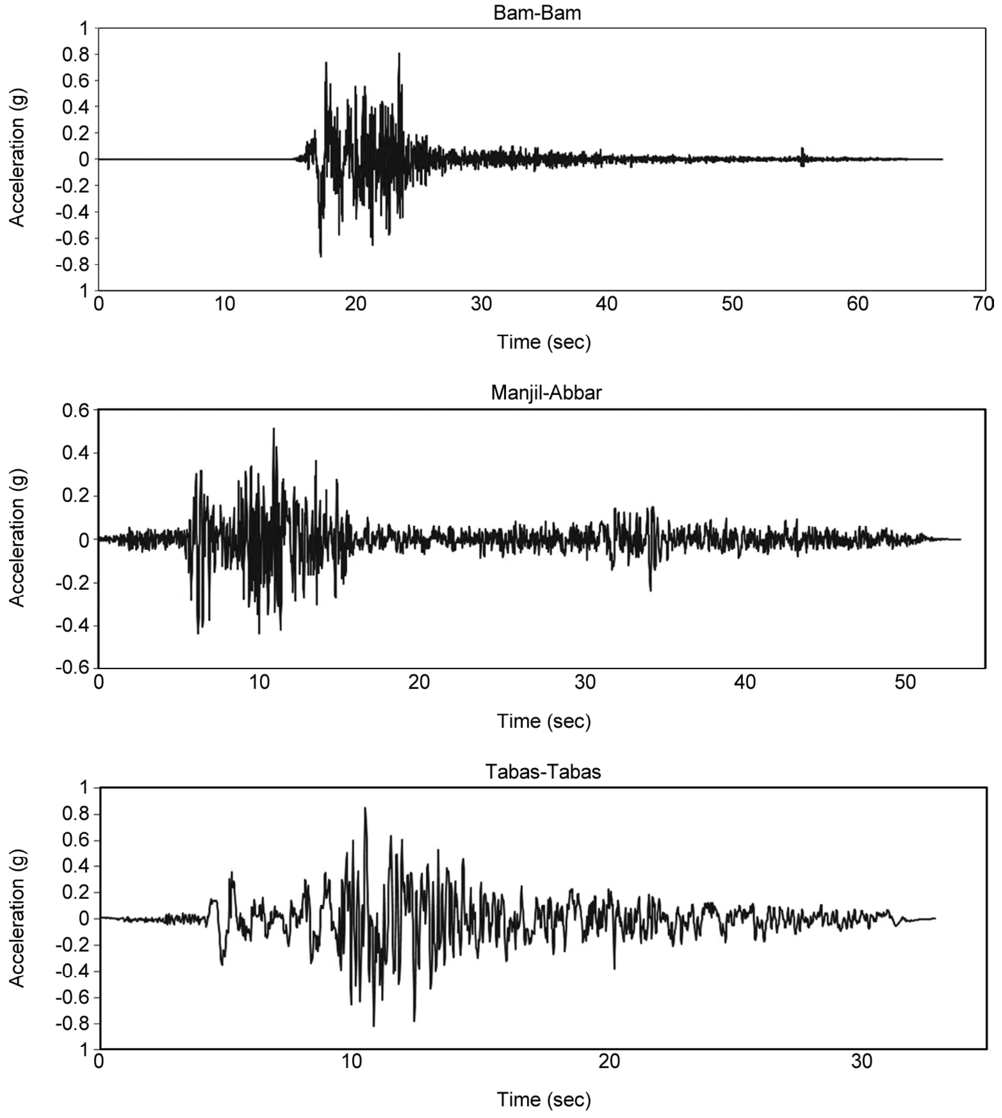
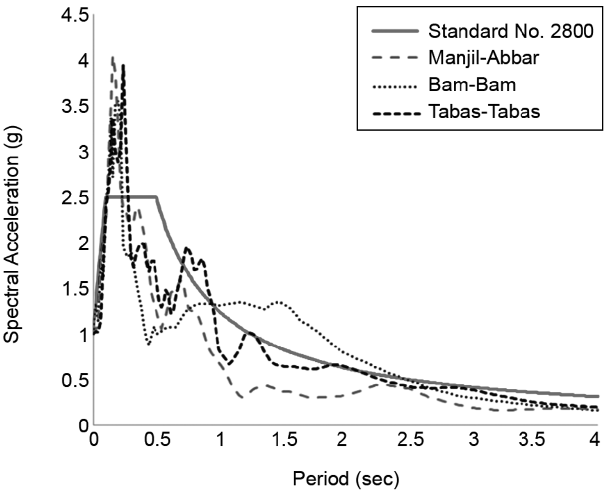


Figure 7. Records selected for nonlinear time history analysis.

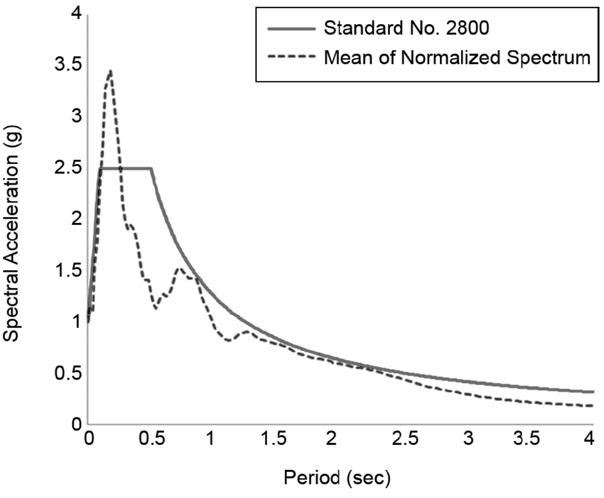
and average of the records, each record was normalized by its peak ground acceleration (PGA) and is compared with the target spectrum of soil type 2 of the Standard No. 2800 [16] in Figure (8a). Comparison between their average acceleration response spectra with 5% of damping was in accordance with the design spectrum of the Standard No. 2800 [16], as shown in Figure (8b).

One of the important factors to detect the structural damage is story drift, hence time history of roof drift of the structures designed with and without considering 5% accidental eccentricity for the three records mentioned above are illustrated in Figures (9) to (11). As well, maximum drift values of each stories for these records are presented in Table (9).

According to Table (9), considering accidental

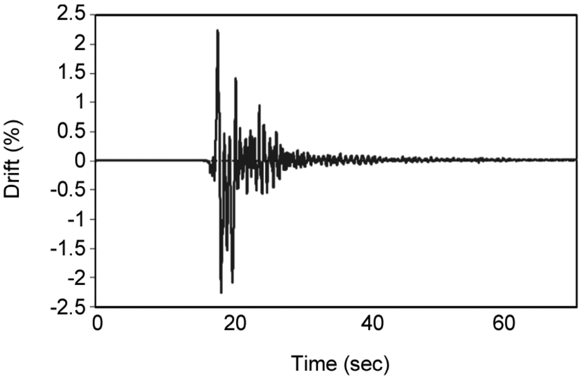


(a) Normalized Response Spectra of the Earthquake Records

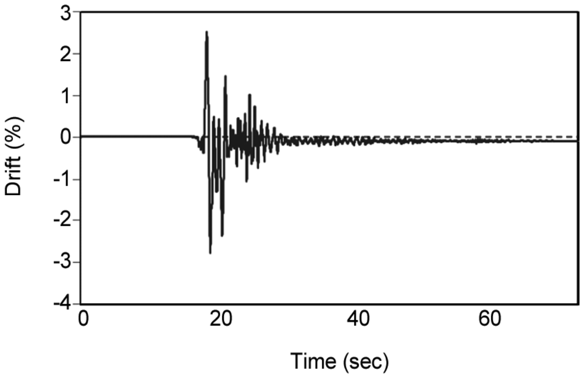


(b) Comparison of Target and Average of Normalized Spectra

Figure 8. Comparison between response spectra of the ground motions normalized by PGA and Standard No. 2800.

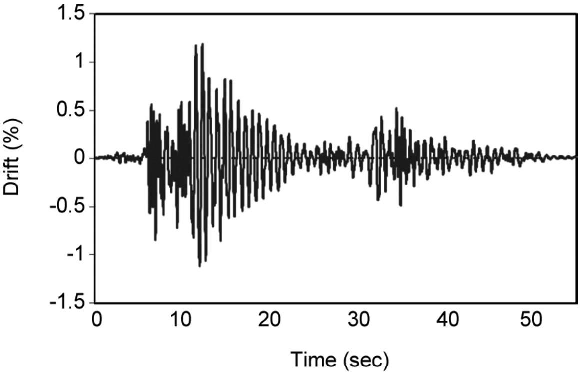


(a) With 5% Accidental Eccentricity

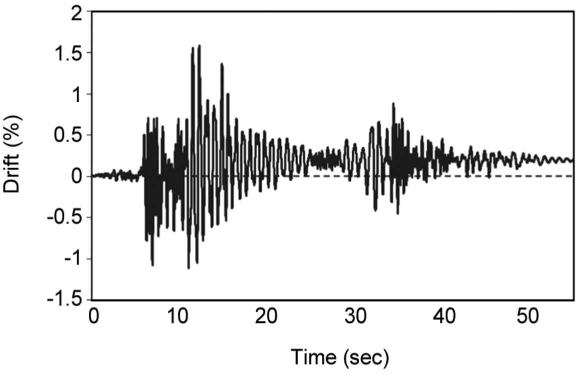


(b) Without 5% Accidental Eccentricity

Figure 9. Time history of roof drift for Bam record.



(a) With 5% Accidental Eccentricity

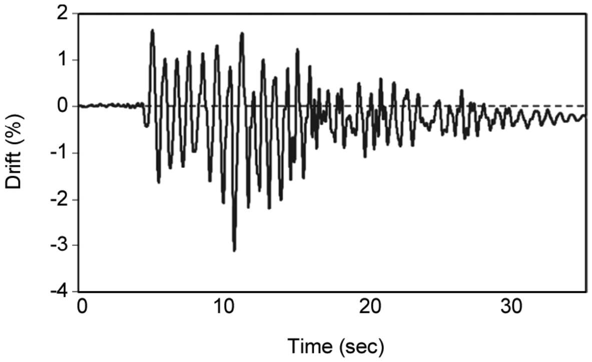


(b) Without 5% Accidental Eccentricity

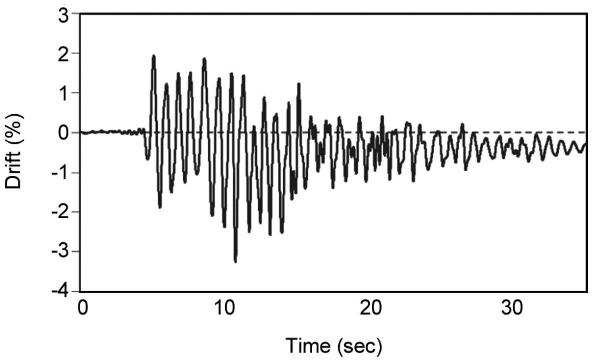
Figure 10. Time history of roof drift for Manjil record.

Table 9. Maximum drift values of each stories for these records.

	Records	Story	Story 1	Story 2	Story 3	Roof
Maximum Drift (%)	Bam Record	With Considering e_a	0.8	1.3	1.5	2.3
		Without Considering e_a	0.8	1.4	1.6	2.8
	Manjil Record	With Considering e_a	0.5	0.9	0.9	1.2
		Without Considering e_a	0.6	1	0.9	1.6
	Tabas Record	With Considering e_a	0.9	1.5	1.8	3.1
		Without Considering e_a	1.1	1.7	1.6	3.3



(a) With 5% Accidental Eccentricity



(b) Without 5% Accidental Eccentricity

Figure 11. Time history of roof drift for Tabas record.

eccentricity in designing phase can reduce maximum drift story up to 25%. As can be seen, in case of Bam record, considering e_a causes that maximum drifts reaches down to its allowable value.

6. Conclusions

In the first objective of this paper, in order to consider the effect of asymmetric location of braces on seismic behavior of structure and economic parameters, a building, which has been constructed in the past, is investigated with different arrangements of braces. Then, the amount of steel consumed in the building is considered as an important economic indicator. In order to investigate seismic behavior of the building, two analytical methods, pseudo-static and dynamic spectral analysEs, are employed and some important seismic parameters such as displacement of stories and trend of base shear changes towards eccentricity are investigated.

In the second objective of the study, the necessity of considering the accidental eccentricity (e_a), equal to 5%, is investigated in an asymmetric building. For this purpose, two asymmetric structures are designed with and without considering e_a in the designing phase. The structures are analyzed with nonlinear time history method during three ground motion records. Lateral drifts due to seismic forces caused by the records are investigated and compared with drift criteria of the Standard No. 2800. According to Iranian Seismic Code No. 2800, considering e_a is not necessary in the designing phase for the building, although ignoring e_a leads to lack of rehabilitation of the building for Life Safety Performance Level. Some important conclusions associated with the study can be enumerated as:

Proper bracing arrangement to minimize eccentricity can reduces the total steel used up to 20%. This reduction in the large structures is very significant.

With increasing eccentricity, displacement of each story, which is a criterion for approximating the structural damage, is increased up to 10%.

With increasing eccentricity, base shear is increased by 5% approximately. It should be noted that the torsion in a direction that reduces the base shear should be denied and critical state (i.e., the maximum base shear) must be considered.

In irregular structures, spectral dynamic analysis results less base shear than pseudo static analysis and base shear values of spectral dynamic are about 90% of pseudo static analysis. Therefore, base shear of spectral dynamic analysis should be modified by normalizing toward the base shear of pseudo static analysis.

Moment resisting frame in irregular structures is far more economical than braced frame with a suitable arrangement of braces.

Considering the accidental eccentricity (e_a) equal to 5% can reduce the maximum story drift up to 25%.

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