Journal of Structural Engineering and Geotechnics,

6 (1), 1- 8, Winter 2016

Evaluation of Torsional Single Story Structure During Earthquake According to Canadian provision

Seiyed Ali Haj Seiyed Taghia[*,a], Masoud Ebrahimi[b], Abdoulreza. Sarvghad Moghadam[c]

[a] *Assistant Prof, Department of Civil Eng Qazvin Branch, Islamic Azad University, Qazvin, Iran.*

[b] *Department of Mechanical Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran*

[c] *International Institute of Earthquake Engineering and Seismology (IIEES). Tehran. Iran.*

Received, 5 January 2016; Accepted, 20 March 2016

Abstract

In this article, we tried to emphasis in how the range of torsionally stiff and flexible single story buildings works. The designed base was according to provisions of the Canadian standard, 2005 NBCC. The behavior of nonlinear dynamic time history of eight building models subjected to seven horizontal bi-directional ground motions compatible with design spectra are investigated. These models cover a wide range of torsionally stiff to flexible buildings. Response parameters are element ductility demand and building story drift ratio. These criteria are appropriate indices for structural and nonstructural damages, respectively. This investigation shows that the linear static and dynamic analysis of building codes such as the 2005 NBCC and its framework are not generally adequate for structures with extremely low torsional stiffness. The provisions in mentioned codes and its framework are able to limit ductility demand, but they do not limit drift to the allowable level for extremely torsional structure.

Keywords: Ductility, Torsion; National Building Code of Canada (NBCC); Non-linear dynamic analysis; Story drift ratio; Performance level

1-Introduction

One of the main reason of structural vulnerability is because of irregularity due to asymmetric mass, stiffness and strength distribution. This was shown by the evaluation of structural performance during past earthquakes. Such plan-wise irregular structures are divided into two classes with low or high "torsional to translational modal frequencies ratio (Ω_R)" that are named torsionally flexible and stiff structures, respectively. The farthest and the nearest edge of building from the center of rigidity is named flexible and stiff edges, respectively. In tortionally flexible buildings (Ω_R <1), both edges generally experience more displacement compare to their symmetric building counterpart. In torsionally stiff structures ($\Omega_R \geq 1$), flexible and stiff edges, respectively experience more and less displacement compare to their symmetric building counterpart [1].
According to the recent research, the amplification factor, A_j which is used in many design codes is insufficient for the extremely torsional building with irregularity in plan [2]. They proposed a reduction in "R" factor for this kind of structures (i.e. force modification factor related to ductility).This article investigates, an overview of torsional provisions and their_frameworks in the NBCC [3] are presented first, then the capability of these torsional provisions and their frameworks to control the effect of torsion in torsionally flexible and stiff structures are evaluated.

2-Review

Humar et al. [1] investigated torsional provisions in the 2005 editions of the NBCC [3] using models similar to Fig. 1.
In his study, they used the following model; the building floor is assumed to be infinitely rigid in its own plane. The entire mass of the structure is distributed at the floor level. The origin of the coordinate system is assumed to be at the mass center, denoted by *CM*. Lateral resisting elements are shown as hatched lines. In the Elastic range, the center of stiffness which is the center of resisting forces, *CR* too and it is eccentric with respect to *CM* and lies at a distance from *CM*.

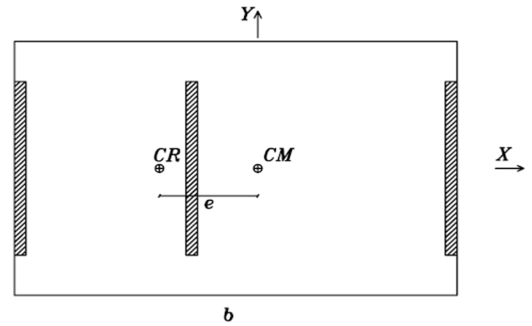


Fig. 1. General configuration of the models.

∗ Corresponding Author Email :Ali.taghia@qiau.ac.ir

The frameworks of the NBCC [3] are based on equaling displacements in static analysis with dynamic analysis for flexible and stiff edges in order to derive formulas to be used in static analysis.

The NBCC [3] restrict the use of the equivalent static load method of design to buildings that are relatively stiff in torsion. An alternative measure of torsional stiffness is being proposed. In the NBCC [3], a building with a rigid diaphragm will be considered torsionally sensitive if a ratio *B* exceeds 1.7.

Parameter *B* is estimated by calculating the ratio B_x for each level x, and independently for each orthogonal direction follows according to the eqn.(1)

$$B_x = \delta_{max} / \delta_{ave} \quad (1)$$

Where δ_{max} is the maximum story displacement at the extreme points of the structure at level x in the direction of the earthquake induced by the equivalent static forces acting at a distance $\pm 0.1b$ from the centers of mass at each floor; δ_{ave} is the average of the displacements of the extreme points of the structure at level x produced by the above forces, and *b* is the dimension of floor x perpendicular to the direction of earthquakes.

Ratio *B* is then taken as the maximum of all values of B_x in both orthogonal directions.

Determination of δ_{max} and δ_{ave} requires an analysis of three-dimensional (3D) static of the structure to be carry out and also, NBCC [3] requires that a dynamic analysis to be carry out for determining the design forces whenever *B* exceeds 1.7.

If the equivalent static load method of design is permitted for buildings, the NBCC [3] specify the following values for the design eccentricities:

$$e_{d1} = e + 0.1b \quad (2)$$

$$e_{d2} = e - 0.1b \quad (3)$$

In this article from now on, the building models that cover a large variation of frequency ratios are introduced first, then the models subjected to seven recorded events and analyzed with pairs of appropriate components of horizontal ground-motion time history. The investigation shows that referred code provisions and their frameworks are not always satisfactory and the application of their static and dynamic analyses for torsionally flexible structures does not lead to structural safety.

3-Characteristics of Building models

In this research, to cover a wide range of torsional to lateral stiffness ratios, the architectural plan of models are considered. This is shown in Figure 2. Dimensions of plan are 42m x 10m and the story height is 3m. These models are able to represent stiff and flexible torsional behavior. The lateral stiffness of models is symmetric in the *y* direction. The structural system in two directions is concentric braced frame (*CBF*). Different configurations of braces in the x direction were applied and eight models that cover the required range for frequency ratio are produced. Each model has brace in A, B and C axes in the *y* direction. In the first four models, stiffness distributions are symmetric too in the x direction.

The schematic locations of braces are shown in Figure 3.

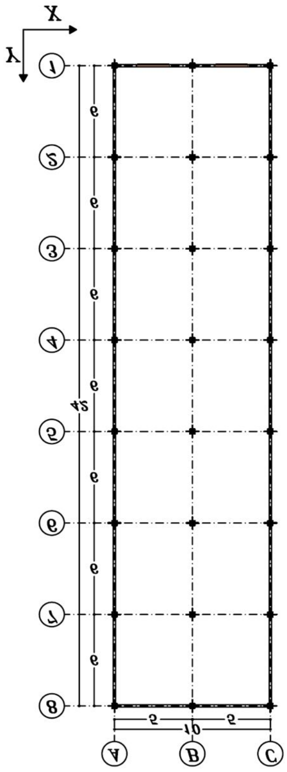


Fig. 2. The plan of the models

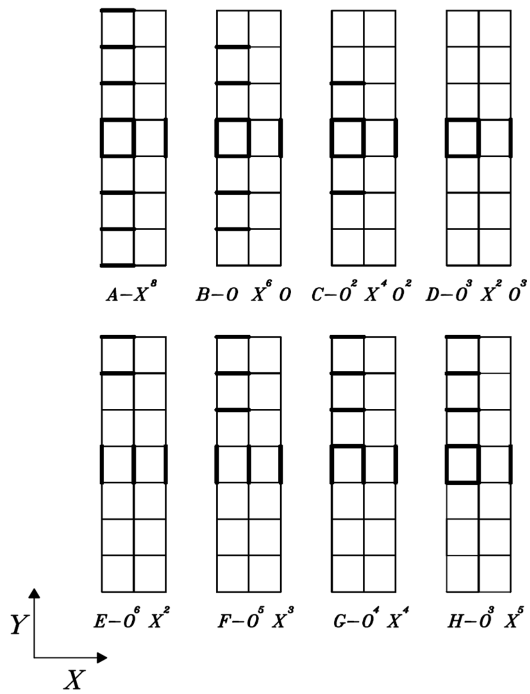


Fig. 3. Locations of braces in the eight selected models; models A to D with symmetric stiffness distribution in the *x* direction; models E to H with asymmetric stiffness distribution in the *x* direction; in all models the stiffness distribution in the y direction is symmetric.

Residential buildings with the rigid floors are considered as the selected models and located in high seismic zone.
The basis of applied loads on buildings are assumed according to Iranian national building code [4]. Accidental torsion is *0.05b*, where b is the dimension of the building model perpendicular to the direction of the earthquake. Using either linear static or dynamic analyses, the buildings are designed based on UBC97 [5] design provisions. Locations of braces in the x direction are used to identify each models such as $O^NX^NO^N$, where letters O and X refer to frames without and with braces, respectively. Letter N shows the number of O or X frames. For all models, configurations of braces in the y direction are the same.
The displacements of the flexible and stiff edges in the x and y directions are estimated with dynamic analysis. Based on this analysis, dynamic and static base shears are set equal according to the NBCC [3]. The effective eccentricity is also calculated in the static analysis by equaling displacements in the static analysis with those obtained in the dynamic analysis for flexible and stiff edges. Figure 4 shows the definition of positive and negative effective eccentricity in the two directions. It should be noted that eccentricity is defined with respect to mass center.

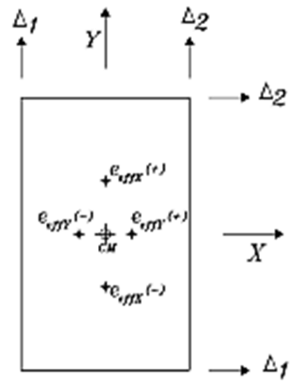


Fig. 4. The definition of positive and negative effective eccentricity in the two directions.

Using equations (2) and (3), analysis and design of models are carried out for 10% eccentricity and this was done according to the provisions of the NBCC [3]. A dynamic analysis is necessary for determining the design forces whenever *B* exceeds 1.7.
Table 1 shows fundamental period, rotational to translational frequencies ratio (Ω_R), parameter B, effective eccentricity (e_{eff}), whether static analysis is allowed or not for the eight selected models. This table indicates that, models A and B are almost torsionally stiff while the others are torsionally flexible structures.

Table 1. Fundamental period, rotational to translational frequencies ratio (Ω_R), parameter *B*, effective eccentricity (e_{eff}), whether static analysis is allowed or not for the eight selected models.

Model	*T* for direction		Ω_{RX}	Ω_{RY}	Ω_R [a]	*B*	(%)				static analysis
							X direction		Y direction		is allowed or not
	X	Y					e_{eff} [b]	e_{eff} [c]	e_{eff} [b]	e_{eff} [c]	
A-X^8	0.13	0.20	1.12	1.69	1.41	1.45	-5	5	-7	7	Yes
B-OX^6O	0.15	0.20	0.86	1.12	0.99	1.77	-5	5	-6	6	No
C-$O^2X^4O^2$	0.18	0.20	0.63	0.67	0.65	2.41	-5	5	-5	5	No
D-$O^3X^2O^3$	0.23	0.20	0.49	0.41	0.45	3.74	-5	5	-5	5	No
E-O^6X^2	0.56	0.14	0.52	0.44	0.48	2.12	-21	-27	-5	5	No
F-O^5X^3	0.53	0.18	0.57	0.54	0.56	2.29	-20	-26	-5	5	No
G-O^4X^4	0.39	0.20	0.63	0.73	0.68	2.42	-19	-28	-5	6	No
H-O^3X^5	0.13	0.20	0.75	0.91	0.83	2.37	-17	-32	-6	5	No

[a] Ω_R is average value for two directions
[b] It equalizes Δ_1 displacement in the static analysis with the dynamic analysis.
[c] It equalizes Δ_2 displacement in the static analysis with the dynamic analysis.

Table 1 shows that for models with symmetric mass and stiffness distribution (models A to D) 5% effective eccentricity is almost adequate in equivalent static analysis and this is according to the framework of the NBCC [3]. This conclusion is valid for models E to H that are symmetric with respect to mass and stiffness distribution in the y direction, but for models E to H in the x direction with asymmetric stiffness distribution, effective eccentricity is noticeable (maximum 32% in model H). Models are analyzed over based on the new effective eccentricities. The designed models are used in nonlinear bi-directional dynamic time history analyses subjected to seven pairs of horizontal ground motion components.
Table 1 shows that for torsionally stiff structures (models A and B) equivalent static analysis is allowed marginally (maximum of B is equal to 1.77) and this is according to the provisions of the NBCC [3] but for torsionally flexible structures, equivalent static analysis is not allowed (maximum of B is equal to 3.74 in model D).

Therefore, a linear dynamic analysis is necessary for these models. Spectral dynamic analysis is carried out whenever it requires. The design models are used in nonlinear bi-directional dynamic time history analyses subjected to seven pairs of horizontal ground motion components.
The letters "a" and "b" are used for identifying the frameworks and provisions of the NBCC [3] respectively.

4- Nonlinear dynamic time history analyses

Seven events recorded on soil profile type II based on Standard 2800 [6] to achieve better conclusion and probabilistic evaluation. High seismic zone are selected from Pacific Earthquake Engineering Research Center Database [7]. Table 2 shows the selected records and their characteristics.
The square root of the sum of the squares (*SRSS*) of the 5 percent-damped site-specific spectrum of the scaled horizontal components is constructed for each pair of horizontal ground motion components. The motions are scaled such that the average value of the *SRSS* spectra does not fall below 1.4 times the 5 percent-damped spectrum of the design-basis earthquake in the period range of 0.2T to 1.5T seconds. The both components of each pair of time histories simultaneously shall be applied to the models. See Figure 5, the *SRSS* spectra and its mean value.

Table 2. The selected records and their characteristics

No.	Earthquake	Station	Date	Magnitude	Distance from source(km)	*PGA* (g)
1	Northridge	24087 Arleta Nordhoff Fire Sta	1994/01/17	6.7	9.2	0.344
2	Northridge	24400 LA – Obregon park	1994/01/17	6.7	37.9	0.355
3	Northridge	Beverly Hills -12520 Mulhol	1994/01/17	6.7	20.8	0.314
4	Victoria Mexico	6604 Cerro Prieto	1980/6/9	-	-	0.304
5	N.Palm Springs	12149 Desert Hot Springs	1986/7/8	6	8	0.331
6	N.Palm Springs	5071 Morongo Valley	1986/7/8	6	10.1	0.395
7	Whittier Narrows	24400 LA – Obregon park	1987/10/4	5.3	-	0.374

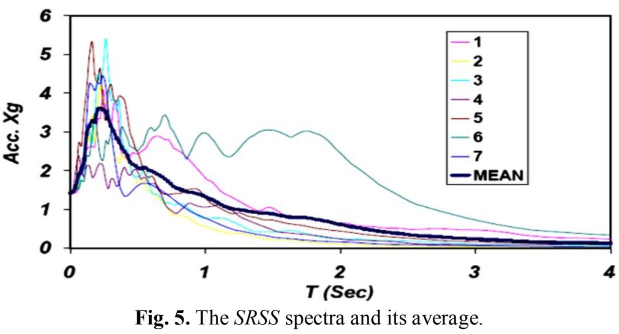


Fig. 5. The *SRSS* spectra and its average.

SAP2000 is used for conducting nonlinear dynamic time history analyses [8]. Figure 6 indicates satisfactory compatibility of frequency content between the scaled average values of the SRSS spectra and 1.4 times the design spectra of Standard 2800 [6] in the period range of interest.

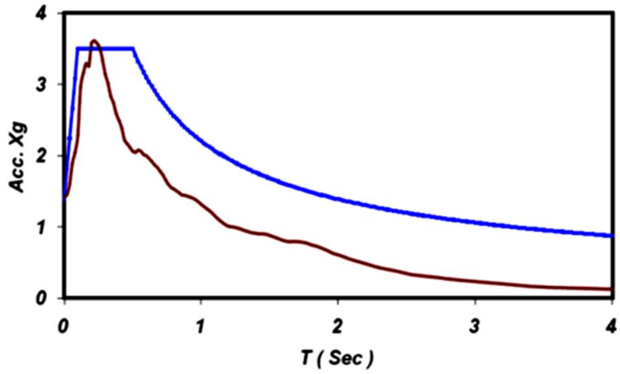


Fig. 6. Comparison of the scaled average value of the *SRSS* spectra with 1.4 times the design spectra of Standard 2800 [4].

4.1. Nonlinear dynamic modeling assumptions

Some of the main modelling and analyses assumptions are:
1- The effect of accidental eccentricity is considered by change in mass distribution in such a way that the center of mass displaces by *0.05b*, where *b* is the dimension of the building model in the direction of the structural eccentricity.
2- The walls are assumed isolated from the frames, thus infill effects have been neglected.
3- The proportional damping is assumed with damping ratio equal to 5 percent at two periods of 0.1 and 1 second.
4- Plastic hinge model considering axial load-moment interaction (*PMM*) is assigned to the middle and two edge columns and axial plastic hinge model (*P*) is assigned to braces based on FEMA356 [9]. Fig. 7 shows force-displacement relation for brace, schematically.

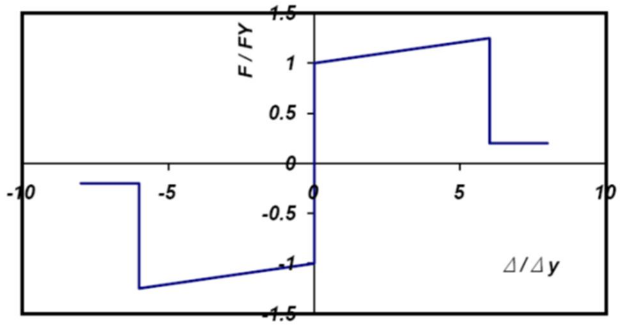


Fig. 7. Force-displacement relation for brace, schematically.

5-Analysis type is nonlinear direct integration time history.
6- In our analysis, the time step is considered as 0.0025 second for convergence matters.
7-Geometric nonlinear effect (P-Δ) is considered.
8-Each analysis is performed initially for gravity load, then seismic analysis is started from the state at the end of previous analysis. The parameters of interest shall be

calculated for each time history analysis. Because seven time-history analyses are performed, the average values of the response parameter of interest should be used. Response parameters considered here are ductility demand in plastic hinge and story drift ratio. The story drift ratio is calculated in both flexible and stiff edges of each orthogonal direction.

5- Nonlinear analyses results

For torsionally flexible or stiff "symmetric" models (A to D) in the x direction, in accordance with Fig. 8, the frameworks and provisions of the NBCC [3] have adequate efficiency in limiting story drift ratio for critical edges (to a value less than 0.70% for the approaches "a" and "b").

In the approach "a" for model E in the x direction, story drift ratio (6.57%) is greater than drift limit, but in the approach "b" for models E and F in the x direction, story drift ratios (2.89% and 2.69%, respectively) are greater than drift limit. These models (E and F) are representative of extreme low torsional stiffness structures (Ω_{RX} are equal to 0.52 and 0.57, respectively) and distribution of their resisting elements are asymmetric in plan. Therefore, the efficiency of the frameworks and provisions of the NBCC [3] for drift limit in such models are questionable. It is concluded that drift has been increased with decreasing parameter Ω_{RX}.

In considering drift, the approach "a" is suitable for structures with asymmetric stiffness distribution and low torsional stiffness (models F, G and H with Ω_{RX} >0.57) (maximum drift of 1.99% in model F), but in the approach "b", these provisions are only adequate for models G and H with Ω_{RX} >0.63 maximum drift of 1.20% in model G).

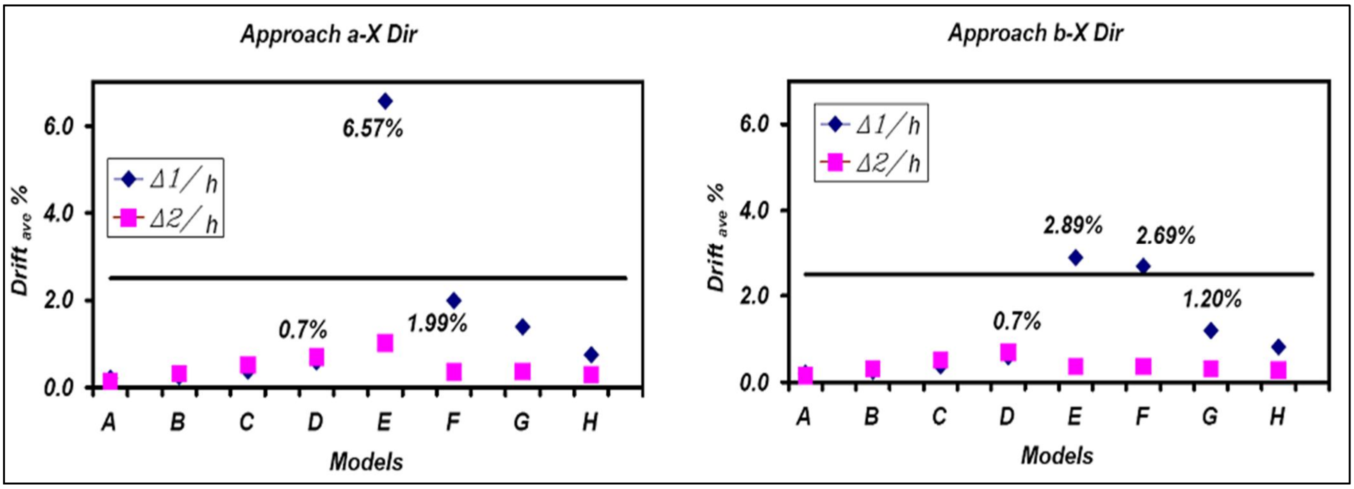


Fig. 8. Average maximum story drift ratios for the flexible and stiff edges in the x direction.

Average maximum story drift ratios for the flexible and stiff edges in the y direction are shown in Fig. 9. All the structures are symmetric in the y direction. Conclusion is similar to those obtained from Fig. 8 for symmetric cases. Therefore, the frameworks and provisions of the NBCC [3] have adequate efficiency in limiting drift for critical edges (drift values of 1.37% and 0.68% in the approaches "a" and "b", respectively).

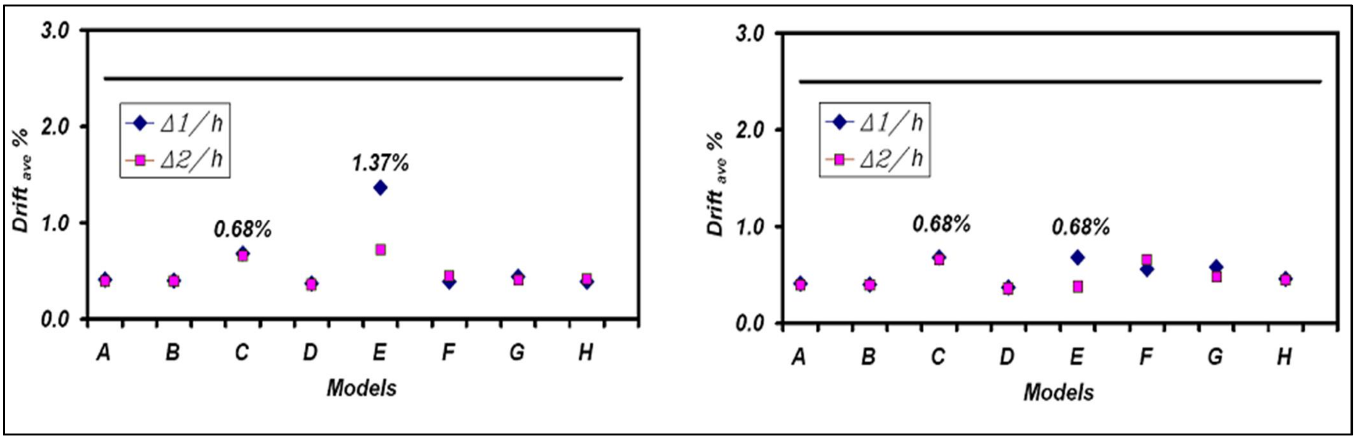


Fig. 9. Average maximum story drift ratios for the flexible and stiff edges in the y direction.

Fig. 10 presents overall evaluation of the frameworks and code provisions in limiting drift of all edges at each direction. It is realized that structural behavior in the x direction is generally dominant with respect to overall structural behavior. Therefore, the conclusions in Fig. 8 are also valid here.

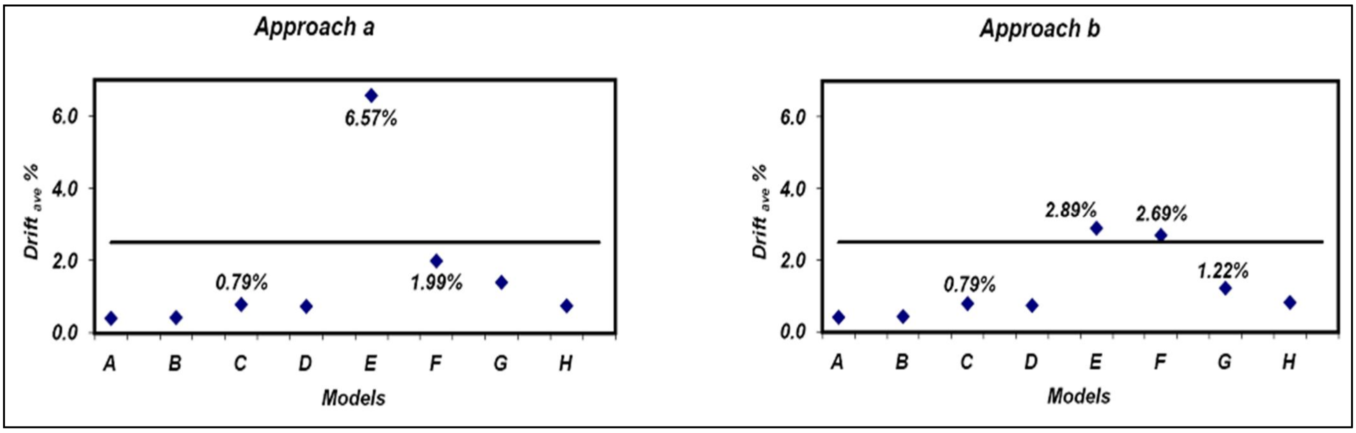


Fig. 10. Average maximum story drift ratios of all edges and each direction.

Fig. 11 shows the average maximum floor rotations for the eight models. In models with symmetric mass and stiffness distribution (A to D), floor rotation caused by accidental torsion is small for the two approaches "a" and "b" (less than 0.58x10E-3 radian for the approaches "a" and "b"), but for models with asymmetric stiffness distribution, floor rotation is larger and it is increasing, with decrease in parameter Ω_R. Model E, with respect to brace configurations, has minimum frequency ratio and its floor rotation is maximum (5.40x10E-3 radian for the approach "a" and 2.29x10-3 radian for the approach "b").

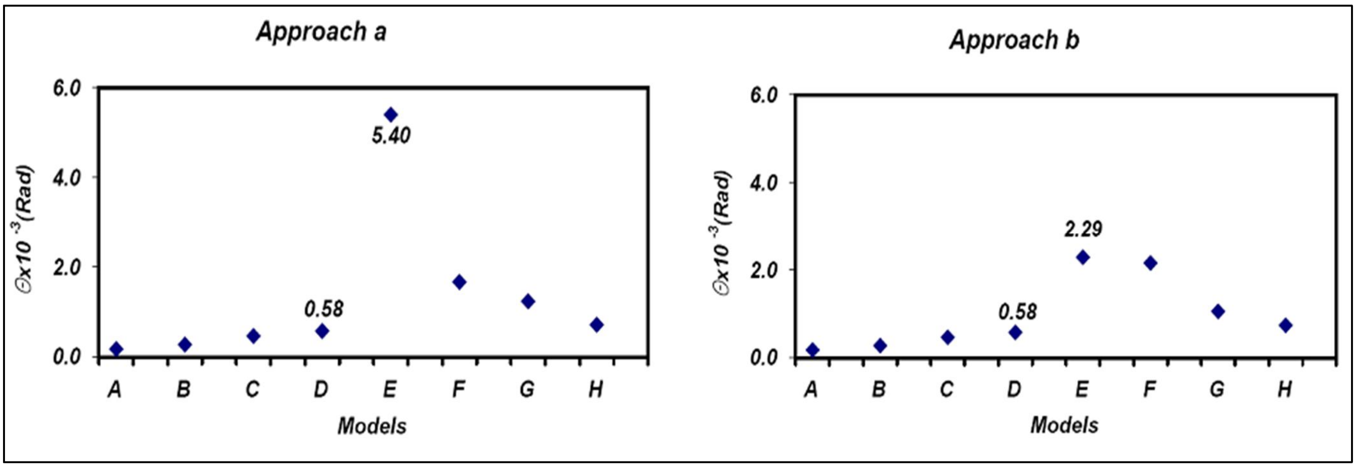
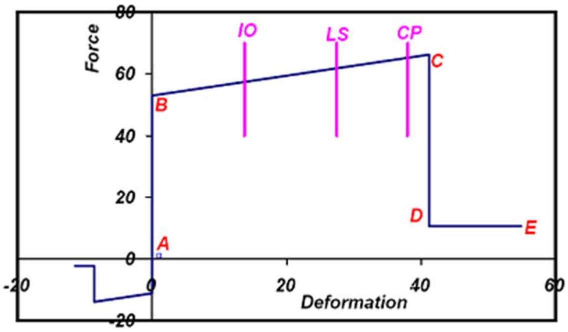


Fig. 11. Average maximum floor rotations for the eight selected models.

Fig. 12 shows average maximum ductility demand (μ) in plastic hinges for the eight selected models. The ductility demand is defined here by subtracting elastic deformation from plastic deformation divided by yield deformation. Fig. 12 shows in the approach "a" for torsionally stiff models (A and B) and asymmetric models with $\Omega_R > 0.56$ (F to H), ductility demand is less than 2, but for torsionally flexible symmetric models (C and D) and asymmetric models with $\Omega_R < 0.56$ (E), ductility demand is less than 4 that corresponds to immediate occupancy performance level. In the approach "b" for torsionally stiff models (A and B), ductility demand is less than 2, but for torsionally flexible models (C to H), ductility demand is less than 4. Standard 2800 [6] considers life safety performance level (μ<6) for a residential building. For the two approaches "a" and "b", it is concluded that ductility demand in the selected models, especially torsionally stiff models is less than acceptable limit. Therefore, the frameworks and provisions of the NBCC [3] have appropriate efficiency in limiting ductility demand.



Performance level definition

symbol	Ductility demand	Performance level
■	< 2	B
●	2-4	IO
X	4-6	LS
◆	> 6	CP,C,D,E

Guideline for Figs. 12

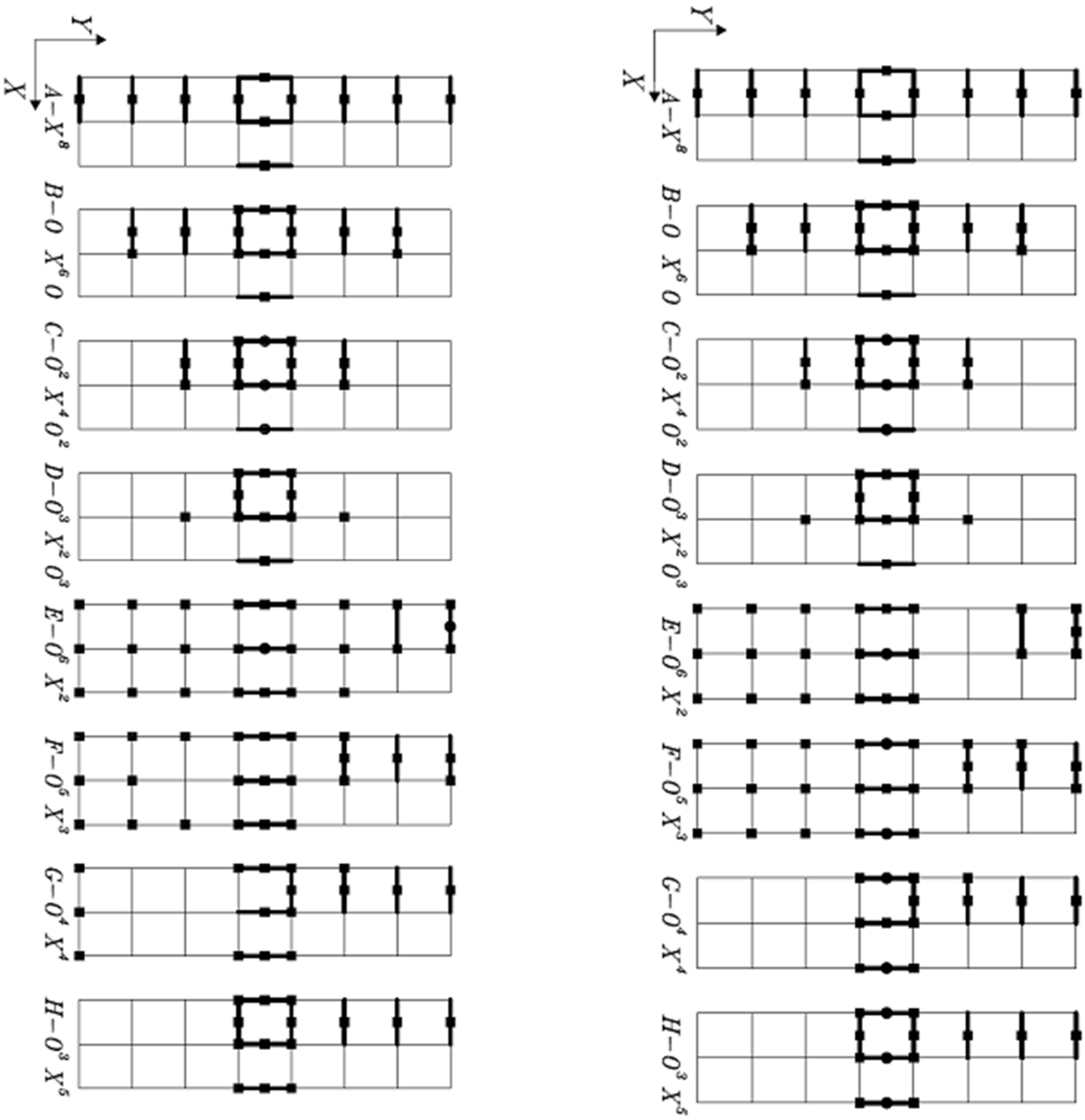


Fig. 12. Average maximum ductility demand for the eight selected models.
Left (Approach a) - Right (Approach b)

6- Conclusions

The conclusions of this research had several cores for the symmetric and asymmetric models.

1- For symmetric models, including both torsionally flexible and stiff structures, the frameworks and provisions of the NBCC [3] for static and dynamic analysis have adequate efficiency to limit story drift ratio for critical edges. Also for asymmetric cases with low torsional stiffness those provisions are suitable. But for asymmetric cases with extreme low torsional stiffness, the efficiency of the provisions is questionable. It is concluded that drift has increased with decrease in parameter Ω_R.

2- For symmetric models, floor rotation caused by accidental torsion is small for the two approaches “a” and “b”, but for asymmetric models, floor rotation is larger and it is increasing with decrease in parameter Ω_R.

3- For the two approaches “a” and “b”, it is concluded that ductility demand in the selected models, especially torsionally stiff models is less than its limitation. Therefore, the frameworks and provisions of the 2005 NBCC [3] have appropriate efficiency to limit ductility demand.

At the end, parameters e_{eff} in the frameworks of the NBCC [3], generally increase the stiffness of structure and therefore, seismic forces due to the shape of design spectra in Standard 2800 [6] for torsionally flexible structures. In this study static and dynamic analysis approaches of the frameworks and provisions of the NBCC [3] were able to restrict ductility demand, but they did not limit drift to the allowable level for extreme low torsional structure with $\Omega_R<0.56$ for the approach “a” also $\Omega R<0.68$ for the approach “b”. Based on these research four methods can be considered in future one:

Limit the use of linear analysis for structures with at least a minimum frequency ratios (Ω_R) that are equal to 0.56 for the approach “a” and 0.68 for the approach “b” in linear analysis.

With suitable design, limit frequency ratio (Ω_R) of the building to mentioned domain.

Generate modified formulas for increasing the structural stiffness in order to reduce drift in the two approaches.

Evaluate new modification factor.

7-Acknowledgments

The authors gratefully acknowledge the contribution of the members of the International Institute of Earthquake Engineering and Seismology, IIEES through critical comments and suggestions.

8-References

[1] Humar, J., Yavari, S., and Saatcioglu, M. 2003. Design for forces induced by seismic torsion. Can. J. Civ. Eng. 30

[2] Haj Seiyed Taghia, S. A. Moghadam,A.S., and Ghafory Ashtiany,M. Seismic performance of torsionally stiff and flexible multi-story concentrically steel braced buildings. THE STRUCTURAL DESIGN OF TALL AND SPECIAL BUILDINGS. 2012.

[3] National Building Code of Canada (NBCC) 2005. Associate Committee on the National Building Code. National Research Council of Canada, Quebec

[4] Standard No. 519, Part 6. 2004. Iranian National Building Code for Structural Loadings, Ministry of Housing and Urban Development, Tehran, Iran

[5] Uniform Building Code (UBC). 1997.

[6] Standard No. 2800. 2005. Iranian Code of Practice for Seismic Resistant Design of Buildings, Third Revision, Building and Housing Research Center, Iran

[7] PEER Strong Motion Database, peer.berkeley.edu website

[8] SAP2000, Structural Analysis Program 2008. Computers and Structures Inc. Berkeley, California, U.S.A.

[9] FEMA 356. 2000. Prestandard and Commentary for the Seismic Rehabilitation of Buildings, Federal Emergency Management Agency