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Determination of torsional irregularity in response spectrum analysis of building structures

Fatemeh Aliakbari[1a], Sadegh Garivani *[1] and Ali Shahmari[2]

[1]*Faculty of Engineering, University of Bojnord, Bojnord 94531-55111, Iran*
[2]*Faculty of Civil and Environmental Engineering, Tarbiat Modares University, Tehran 14115-143, Iran*

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Abstract. Torsional irregularity is one of the most probable types of horizontal irregularity and existence of this irregularity in most of the structural loading codes is determined by calculating the ratio of the maximum to the average story drift. No specific method has been previously recommended by the codes to calculate the mentioned ratio in the response spectrum analyses. In the current investigation, nine steel building structures with different plan layouts and number of stories have been analyzed and designed in order to evaluate the efficiency of three methods for calculating the ratio of the maximum to the average story drift in the response spectrum analyses. It should be noted that one of these methods is the approach used by current version of ETABS software andother ones are proposed in this paper. The obtained results using the proposed methods are compared with the time history analysis results. The comparisons show that one of these methods underestimates the mentioned ratio in all studied models, however, the other two methods have shown similar results. It is also found that the plan layouts and irregularities can affect how these methods estimate the ratios compared to those obtained by the time history analysis. Generally, it can be concluded that all of these methods can properly predict the ratio with acceptable errors.

Keywords: response spectrum analysis; Irregular structures; Horizontal irregularity; Torsional irregularity; Extreme torsional irregularity

1. Introduction

Earthquakes are one of the inevitable natural phenomena and it is impossible to control all of its outcomes. However, structural design codes are used to predict and control the seismic behavior of structures. The existence of irregularities in structures increases the probability of seismic structural damages. Considering aesthetic matters in design of various ranges of buildings, from residential to theaters and museums, imposes irregularity and asymmetry to the architectural design of buildings. The seismic behavior of irregular structures differs from that of regular structures and is more complicated. Thus, seismic loading codes classify the buildings in two groups of regular and irregular buildings. The irregularity of structures is mainly due to the asymmetric distribution of mass, strength and stiffness. The performance examination of the structures during the past earthquakes has shown that this feature can be the main source of severe damages and the irregular structures can be prone to more damage compared to the normal regular buildings (Jeong and Elnashai 2006). In the Mexico City earthquake in 1985, for example, it was observed that the buildings with horizontal irregularity were damaged more than the regular ones (Rosenbleuth and Meli 1986). Similar patterns of damage and collapse of buildings were also reported in other earthquakes that were due to their irregularity and asymmetry (Elnashai *et al*. 2010, Wyllie *et al*. 1986). The behavior examination of buildings with reentrant corner irregularity has shown the unsuitable performance of these structures against severe earthquakes (Penelis *et al*. 1988, Penelis and Kappos 1997). Vertical irregularities result in story failures because of non-uniform distribution of damage states along the height. However, plan irregularities result in non-uniform damage states among the columns of a floor (Jeong and Elnashai 2006). Seismic code provisions are constantly being updated to improve the seismic behavior of the designed structures. The updates are based on the gained experience from real earthquakes and the results of extensive researches carried out to control and to develop the rules of the standards (e.g. recent research works done in the fields of calculating the fundamental period of structures (Asteris *et al*. 2015, Asteris *et al*. 2017, Asteris and Nikoo 2019, Harris and Michel 2019), response modification factor (Aliakbari and Shariatmadar 2019, Avanaki 2019, Mohsenian *et al*. 2019), etc.).

Numerous studies have also been dedicated to the effects of the torsional irregularities on seismic behavior of the structures in recent years. Some researchers have focused on the nonlinear behavior of irregular structures to improve the push-over analysis methods of these structures. Modal Push-over analysis method has been successfully adopted to estimate and simulate the seismic demand of asymmetrical buildings with proper accuracy (Chopra and Goel 2004). However, in irregular buildings, it has been shown that results of push-over analysis method differ from

*Corresponding author, Assistant Professor
E-mail: garivani@ub.ac.ir
[a] M.Sc. Lecturer
[b] Ph.D. Graduate

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those obtained by the nonlinear dynamic analysis method. But, the results of the modified push-over analysis method presented by Fajfar *et al*. (2005) are consistent with the responses of nonlinear dynamic analysis (D'Ambrisi *et al*. 2009). A new pushover method was offered to estimate the seismic responses of asymmetrical structures in the plan in which the load was distributed in the height based on the combination of modal torsional moment and shear force of the stories (Shakeri *et al*. 2014). A robust computer code was developed and implemented to perform the nonlinear static analysis of the asymmetric reinforced concrete structures (Mazza 2014). Several studies have also been conducted to establish and develop consistent analytical methods in order to capture the deformational behavior of irregular structures (Penelis and Kappos 2002, Dogangun and Livaoglu 2006, Jinjie *et al*. 2008, Mahdi and Gharaie 2011).

In addition, some researches have focused on the behavior of irregular structures and control/development of existing provisions for this type of structures. Given both the serviceability and the ultimate limit states, an optimized procedure have been developed for the design of torsionally unbalanced structures subjected to earthquake excitations by Duan and Chandler (1997). The effects of torsion on the moment and the shear values of vertical structural elements of irregular structures have been investigated in a parametric study. The typical studied buildings of this investigation were analyzed by both the methods of equivalent earthquake loading and dynamic analysis and the results were compared (Tezcan and Alhan 2001). Ozmen and Gulay (2002) performed a parametric study to observe the amplification of internal forces in torsionally irregular multi-story buildings and concluded that more rigorous measurement are required in the codes for this rather critical type of irregularity. An advanced analytical assessment methodology has been presented for irregular buildings (Jeong and Elnashai 2004). Bosco *et al*. (2004) described the results of a study devoted to the definition of the limits of application of an approximated design method of non-regularly asymmetric systems. They have shown that some clear limits could be defined in seismic codes for the applicability of simplified approaches on irregular structures. The differences between the torsional irregularity provisions in codes of China, USA and Europe have been studied and it was indicated that torsion effects have no correlation with the criterion adopted by the considered codes and some regulations of these codes are not reasonable (Zheng *et al*. 2004). The behavior of some reinforced concrete structures with extreme torsional irregularity in the plan has been studied under 56 ground motion records using nonlinear time history analysis to evaluate the accuracy of elastic analysis in estimation of plastic rotations. It was concluded that the response spectrum analysis could accurately estimate the plastic rotations for the buildings with a short fundamental period (Kosmopoulos and Fardis 2007). Ozhendekci and Polat (2008) introduced a new parameter, Q, which is the ratio of horizontal to torsional effective modal masses to define the torsional irregularity of the buildings. Parametric analyses were used for comparing Q with the ratio proposed in codes (the ratio of the maximum displacement drift of a floor corner to the average displacement drift of the considered edge of the floor). These parametric analyses showed that the dispersion with regard to the ratio between the eccentricity, which is parallel to the excitation direction and the radius of gyration is reduced if the modified Q ratio is used instead of the code proposed parameter. Demir *et al*. (2010) investigated the effective torsional irregularity factors in six types of multi storey structures with shear wall-frame system and various story numbers, plan views and shear wall locations. Gokdemir *et al*. (2013) studied the torsional irregularity effects on the behavior of structures during earthquakes. They compared the base shear forces and torsion values in various irregular structures and also evaluated some provisions of seismic codes about the structures with torsional irregularities. The results showed that splitting the large parts of a building into separate blocks or increasing the lateral stiffness of the weaker side of the structures could decrease the undesirable torsional effects. A parametric study was performed on six groups of typical structures with varying shear wall positions, number of stories and axis numbers to investigate the effect of torsional irregularities on the deformational behavior of multi-story buildings under the earthquake excitations (Ozmen and Gulay 2014). The validity of code provisions was discussed and a new provisional definition for torsional irregularity coefficient based on floor rotations was proposed. The accuracy of the empirical formulas of the fundamental period proposed in seismic codes was examined in tall steel concentrically braced frames (Young and Adeli 2016). Three types of irregularities including vertical irregularity, horizontal irregularity and a combination of vertical and horizontal irregularity were considered in the study. The results showed that regular structures have larger periods compared to irregular ones and this difference was less in the structures with horizontal irregularities. As a result, a new formula was proposed to calculate the fundamental period of irregular eccentrically braced tall steel frame structures (Young and Adeli 2016). The effect of the vertical geometric irregularities on the fundamental periods of masonry infilled RC structures has been investigated and the results showed that the fundamental period of the irregular building frames was smaller than the period of the regular building frames with the same parameters (Asteris *et al*. 2017). The effect of the ratio Ω which is structure uncoupled torsional frequency, ω_θ, to uncoupled transition frequency, ω_x or ω_y) on the torsional behaviour of the structure has been studied and the results showed that structures with $\Omega<1.0$ are more sensitive to the value of eccentricity between center of mass and center of rigidity (Mehana *et al*. 2019). Mohsenian *et al*. (2019) have evaluated the seismic behavior of tunnel-form buildings with the horizontal irregularity and developed appropriate design methodologies. Fragility curves were also derived for various levels of intensity and simple equations were introduced to estimate the uncoupled frequency ratios. The results demonstrated that the torsional behavior of this type of structures was flexible and their seismic capacity was adequate. Other studies have also been conducted to investigate the response of irregular structures

(Lee *et al*. 2011, Bigdeli *et al*. 2014, Landi *et al*. 2014).

In order to reduce the seismic hazards of irregular structures compared to regular structures, the seismic design codes have attempted to classify the structures into regular and irregular and then, impose more stringent provisions for irregular structures. For example, the ASCE7-16 (ASCE 2016) has classified irregularity of the buildings into two classes of horizontal and vertical irregularities and presents special provisions for both of them. Horizontal irregularity includes torsional and extreme torsional irregularities, reentrant corner, diaphragm discontinuity, nonparallel system, out-of-plane offset irregularity. Vertical irregularity, however, includes stiffness–soft story, stiffness–extreme soft story, weight (mass), vertical geometric, in-plane discontinuity in vertical lateral force-resisting element, discontinuity in lateral strength–weak story and discontinuity in lateral strength–extreme weak story irregularity. The main behavioral difference between irregular and regular structures in the plan is the significance of effects of torsional mode in the dynamic behavior of the irregular structures. Importance of the torsional modes depends on the amount of eccentricity of the mass and stiffness in the structure. One of the most possible irregularities in the structures is torsional or extreme torsional irregularities. According to the ASCE7-16 (ASCE 2016), if the maximum relative displacement at one end of the building is larger than 20% of the average relative displacement at both ends of the building in a structure, the structure has torsional irregularity andif the difference is more than 40%, the building has extreme torsional irregularity. In recent years, many studies have been conducted in order to predict the behavior and also to analyze and to design the irregular structures more accurately.

As discussed, the type of torsional irregularity is derived from the ratio of the maximum to the average amount of each story drift, based on the provisions of the seismic loading codes. So far, no method is presented to determine this ratio in response spectrum analysis in the codes. This paper examines the accuracy of some proposed methods for calculating the ratio of maximum to average story drift in response spectrum analysis. To compare the results of these methods with the results of time history analysis, some different structures in the plan and height have modeled and finally, the more suitable method is introduced.

2. Research significance

In equivalent static methods, the ratio of the maximum to the average amount of each story drift can be directly calculated using the static analyses results. But the use of these methods for the analysis of irregular structures has many limitations, which often leads to the necessity of using dynamic analysis methods, especially in the structure with torsional and extreme torsional irregularities. In the structural design process, it is essential to perform all design controls based on the results of the same method. While, as mentioned above, there is no robust and well-known method to calculate the ratio of the maximum to the average amount of each story drift in response spectrum analysis. In proposed method, the final value of any response is determined in different modes. Since displacements obtained from the modal analysis are the square root of the sum of squares (SRSS) combinations of the response of individual modes, the algebraic summation of them is not mathematically correct and it is not possible to calculate the ratio of the maximum to the average story drift directly from the combined displacements obtained from the modal analysis. On the other hand, since the ratio of the maximum to the average story drift is always greater than 1.0, the obtained SRSS value of this ratio results in an unrealistically large value which is inaccurate. For example, this value will always be larger than or equal to the square root of the number of combined modes in the SRSS combination method. Therefore, it seems that the discussed ratio should be calculated using a reliable method in the response spectrum analysis and this paper attempts to give an appropriate response to this need.

3. Torsional irregularity and the importance of determining the ratio of maximum to average story drift

In ASCE7-16 (ASCE 2016), torsional irregularity is classified into two classes with the following definitions.

1a. Torsional Irregularity: Torsional irregularity is defined to exist where the maximum story drift, computed including accidental torsion with $A_x = 1.0$, at one end of the structure transverse to an axis is more than 1.2 times the average of the story drifts at the two ends of the structure. Torsional irregularity requirements in the reference sections apply only to structures in which the diaphragms are rigid or semi-rigid.

1b. Extreme Torsional Irregularity: Extreme torsional irregularity is defined to exist where the maximum story drift, computed including accidental torsion with $A_x = 1.0$, at one end of the structure transverse to an axis is more than 1.4 times the average of the story drifts at the two ends of the structure. Extreme torsional irregularity requirements in the reference sections apply only to structures in which the diaphragms are rigid or semi-rigid.

It should be mentioned that the extreme torsional irregularity was not defined in the older codes, but according to the importance of the issue, the subject is explained with more precision. As it is observed, the ratio of maximum to average story drift determines the type of the torsional irregularity in the structure. It is very important to determine the type of irregularity that depends on the value of this ratio because in some cases, the provisions of the structural loading change depending on the type of irregularity of the structure. For instance, the value of this ratio will be decisive to scale the design values of combined responses obtained by the response spectrum analysis and also to select the allowed analysis procedure. Another case that shows the importance of determining the correct value of this ratio is to calculate the torsional amplification factor, A_x. This factor can be calculated using Eq. (1) as follows.

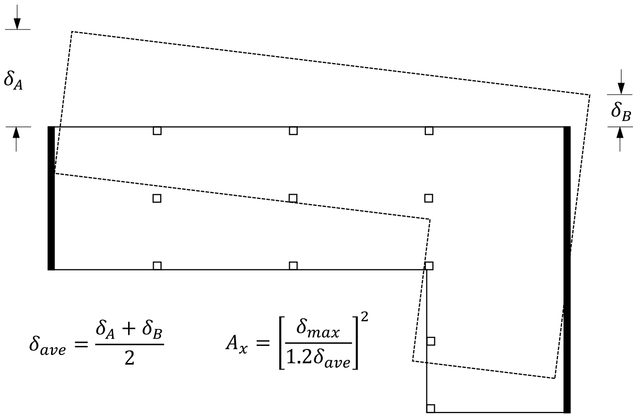


Fig. 1 Torsional Amplification Factor, A_x (ASCE 2016)

$$A_x = \left(\frac{\delta_{max}}{1.2\delta_{ave}}\right)^2 \tag{1}$$

where δ_{max} and δ_{ave} are the maximum and average of the displacement at level x computed assuming A_x=1.0, respectively (Fig. 1). It should be mentioned that since the average and maximum displacement values are both divided into the story height to obtain the amount of story drift, the maximum to average ratio is equal for both displacement and drift.

4. The proposed methods to evaluate/check the torsional irregularity

In this paper, three methods are examined to calculate the ratio of the maximum to the average story drift based on the displacement responses obtained by the response spectrum analysis as explained below. In all of these methods, the SRSS method is used to combine the responses of individual modes. It should be noted that it is not the only criterion of combination that can be adopted in modal analyses according to the literature and codes. For example, based on the ASCE 7-16, the value for each parameter of interest calculated for the various modes should be combined using the square root of the sum of the squares (SRSS) method, the complete quadratic combination (CQC) method, the complete quadratic combination method (CQC-4), or an approved equivalent approach. According to the specifications of this code, displacements/drifts are one of the responses that can be combined with the SRSS method. However, in this paper, considering the simplicity of the SRSS method compared to other ones, it is used to combine the displacement responses of individual modes.

Method 1: For each floor of the structure, the ratio of the maximum to the average story drift is obtained in each mode and then these values are combined using the SRSS method. Finally, the combined value is divided by the square root of the number of modes. In other words, the square root of the mean of squares of the maximum to average drift is computed in this method (Eq. (2)). It should be mentioned that the recent versions of ETABS (CSI 2016) software use this method to compute the ratio (CSI Knowledge Base 2013).

$$Ratio = \sqrt{\frac{\sum_i^n \left(\frac{D_{max}}{D_{ave}}\right)_i^2}{n}} \tag{2}$$

where i and n are the mode number and the total number of modes considered in the spectrum dynamic, respectively.

Method 2: For each floor of the structure, the combined drift values are obtained using the SRSS method at the end joints of the structure (the joints A and B in Fig. 1) and then, the maximum to average drift ratio is calculated (Eq. (3)).

$$Ratio = \frac{D_{max}}{D_{ave}} \tag{3}$$

where D_{max} and D_{ave} are the maximum and average drifts, respectively, which are calculated directly using the SRSS method. It should be noted that since in this method, the drift values are used to compute the average drift obtained from the combination of the modal responses, the method is not mathematically acceptable. However, as it is popular among the designers due to its simplicity, the results of the method are investigated in this paper.

Method 3: For each floor of the structure, the maximum and average drift values at the end joints of the structure are calculated for each mode and then the SRSS combination of the maximum and average drift is obtained separately (the joints A and B in Fig. 1). Then, these values are divided by each other as presented Eq. (4).

$$Ratio = \frac{\sqrt{\sum_i^n (D_{max})_i^2}}{\sqrt{\sum_i^n (D_{ave})_i^2}} \tag{4}$$

5. Description of the examined structures and the analysis method

To examine the accuracy of the proposed methods to compute the maximum to average story drift in response spectrum analysis, nine different three-dimensional steel structures are modeled, analyzed and designed using ETABS (CSI 2016) software. These models include 4, 8 and 12-story structures with three types of plans shown in Fig. 2. In this figure, CM shows the center of mass location in the plan. In Fig. 2(a), the dashed lines represent the X-braced bays in the plan. It should be noted that the studied structures do not have any vertical irregularities and all stories have an equal height of 3.2 m in all models. The imposed Dead and Live loads are summarized in Table 1. The floor diaphragms were assumed to be rigid and the structural steel materials were assumed to be ST37 with the yield stress and Young modulus equal to 240 MPa and 204 GPa, respectively. In addition, it should be noted that the analyses were performed in the Y-direction of Plan Types 1 and 2 and in the X-direction of Plan Type 3. However, in

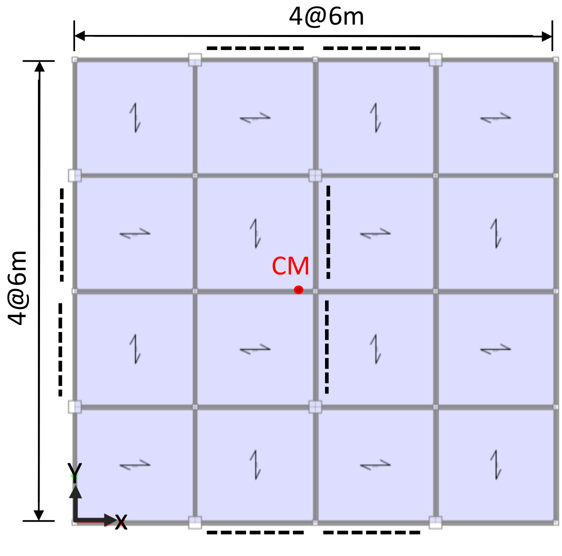
Plan Type 2, considering the plan configuration, there is no difference in the direction of analysis.

The gravity and seismic loads were determined and imposed in accordance with the ASCE 7-16 specifications and the structural members were designed according to the AISC360-10 provisions as well. It should be noted that the response spectrum analysis was adopted as per the ASCE7-16 to check the seismic performance of the structures. The models designation along with other properties are given in Table 2. As presented in this table, the lateral-force-resisting systems considered for Plan Type 1 and Plan Types 2 and 3 are ordinary concentrically braced frame and intermediate moment frame, respectively. It should be noted that the lateral-force-resisting systems and their component distributions in the plan, as well as the shape of plans, have been selected and arranged so that the resulting structures have the torsional and extreme torsional irregularities. For example, in Plan Type 1, with the aim of having a structure with extreme-torsional irregularity, the symmetrical distribution of the mass in the plan was considered with an asymmetric distribution of stiffness. Also, for the other plan types, the moment frame system is intended to have structures with torsional irregularity. In this table, T_1, C_s, R and M are the fundamental period, seismic response coefficient in the equivalent static method (used for scaling design values of combined responses), the seismic response modification factor (ASCE 2016) and the seismic mass of the structure, respectively. The adopted spectrum used for the seismic design of the frames is derived based on ASCE 7-16 (ASCE 2016). It is assumed that this building will be constructed in California for which $S_s = 1.0\,g$ and $S_1 = 0.6\,g$. S_s and S_1 are spectral response acceleration parameters at short periods and the period of 1 sec, respectively. For the soil condition, it is assumed that site class C is appropriate as shown in Fig. 8. The cross-sections of the beams, columns and braces are I-shaped, built-up Box and double-UNP sections, respectively. For example, the designed structural members of Model 8-2 are listed in Table 3.

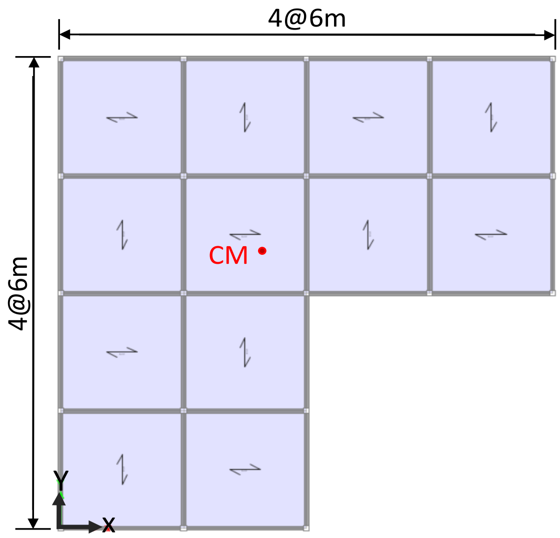
In order to examine the accuracy of the proposed methods to determine the ratio of the maximum to average story drift explained above, the response of the structures is obtained under seven artificial records. These records are generated by SeismoArtif software in a way that the average of their response spectrum is above the design spectrum in the range of 0.2T-1.5T for all studied structures, where T is the fundamental period of the structure. The main records features are given in Table 4 and the comparison of their response spectrums and design spectrum are given in Fig. 3.

Table 1 The assumed gravity loads in the structural models

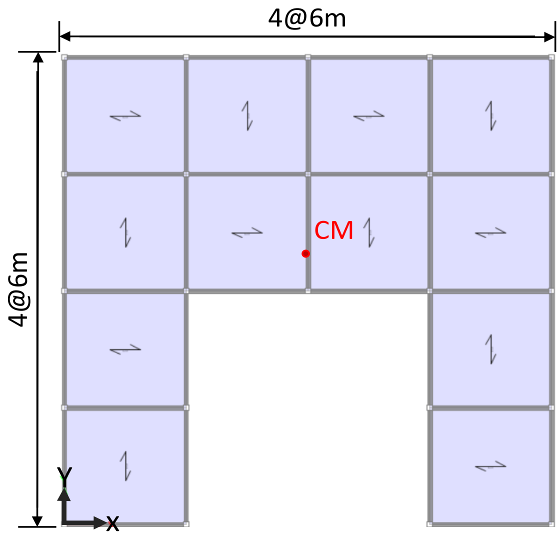
Dead load (kg/m^2)	Live load (kg/m^2)		Partitions load (kg/m^2)	Peripheral walls load (kg/m)	
	floors	roof		floors	roof
500	200	150	100	580	250



Plan Type 1



Plan Type 2



Plan Type 3

Fig. 2 Three types of plan in studied structures

Table 2 The properties of studied structures

Model ID	Plan Type	No. of stories	Seismic Force-Resisting System	R	$T_1\ (s)$	$M\ (kg)$	C_s
Model 4-1	Type 1	4	OCBF*	3.25	0.66	1810694	0.25
Model 4-2	Type 2	4	IMF**	4.50	0.79	1420857	0.18
Model 4-3	Type 3	4	IMF	4.50	0.93	1465539	0.18
Model 8-1	Type 1	8	OCBF	3.25	0.71	3722970	0.25
Model 8-2	Type 2	8	IMF	4.50	1.27	2883500	0.13
Model 8-3	Type 3	8	IMF	4.50	1.24	3014341	0.13
Model 12-1	Type 1	12	OCBF	3.25	1.13	5685558	0.23
Model 12-2	Type 2	12	IMF	4.50	1.70	4394245	0.09
Model 12-3	Type 3	12	IMF	4.50	1.73	4602335	0.09

* Ordinary concentrically braced frame
** Intermediate moment frame

Table 3 Sectional properties of Models 8-1, 8-2 and 8-3

Model	Story	Beam		Column		Brace
		Web plate	Flange plate	Adjacent to Brace	Not Adjacent to Brace	
8-1	1	PL320×6	PL220×10	BOX620x35	BOX280X15	2UPN320
	2	PL320×6	PL220×10	BOX620x35	BOX280X15	2UPN300
	3	PL320×6	PL220×10	BOX620x35	BOX280X15	2UPN300
	4	PL320×6	PL220×10	BOX560X30	BOX280X15	2UPN280
	5	PL320×6	PL220×10	BOX560X30	BOX270X10	2UPN260
	6	PL320×6	PL220×10	BOX450X25	BOX270X10	2UPN240
	7	PL320×6	PL220×10	BOX450X25	BOX270X10	2UPN200
	8	PL320×6	PL220×10	BOX450X25	BOX270X10	2UNP180
8-2	1	PL600×8	PL220×12	Box450×450×25		----
	2	PL600×8	PL220×12	Box450×450×25		----
	3	PL600×8	PL220×12	Box450×450×25		----
	4	PL600×8	PL220×12	Box340×340×20		----
	5	PL600×8	PL220×12	Box340×340×20		----
	6	PL600×8	PL220×12	Box340×340×20		----
	7	PL400×6	PL220×10	Box280×280×15		----
	8	PL320×6	PL220×10	Box280×280×15		----
8-3	1	PL600×8	PL220×12	Box450×450×25		----
	2	PL600×8	PL220×12	Box450×450×25		----
	3	PL600×8	PL220×12	Box450×450×25		----
	4	PL600×8	PL220×12	Box340×340×20		----
	5	PL600×8	PL220×12	Box340×340×20		----
	6	PL600×8	PL220×12	Box340×340×20		----
	7	PL400×6	PL220×10	Box280×280×15		----
	8	PL320×6	PL220×10	Box280×280×15		----

6. Precision control of the proposed methods

To evaluate the accuracy of the proposed methods, the ratios calculated using these methods are compared with those ones obtained by the linear time history dynamic analysis which conducted using the Hilber-Hughes-Taylor method to linear direct integration. The ratios of the maximum to average story drift for all the proposed methods and studied models are shown in Fig. 4.

Method 2 and 3 would give similar results, however, one cannot mathematically and dynamically interpret the former approach results despite its simplicity. Therefore, Method 2 can be used with reasonable accuracy for rough estimation purposes. In addition, the results show that

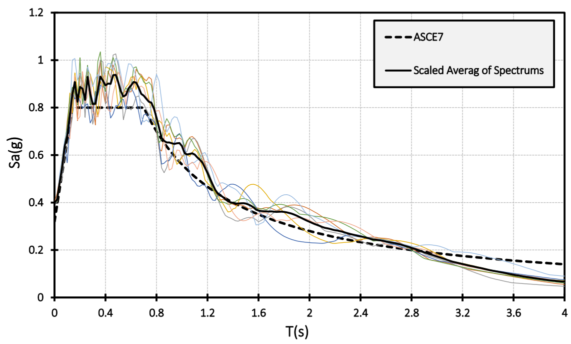
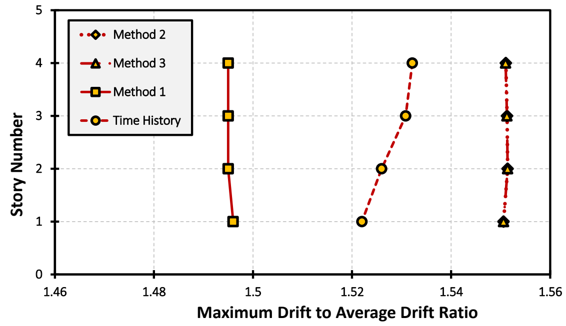


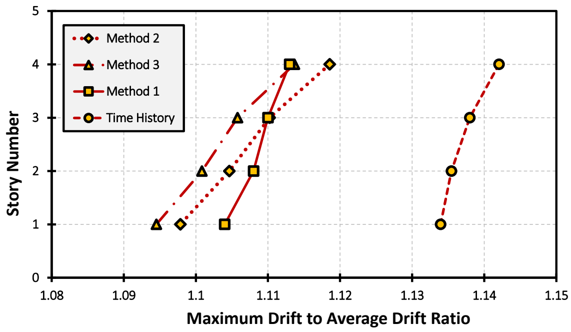
Fig. 3 Design spectrum and response spectra of the selected artificial records

Table 4 Artificial records data list

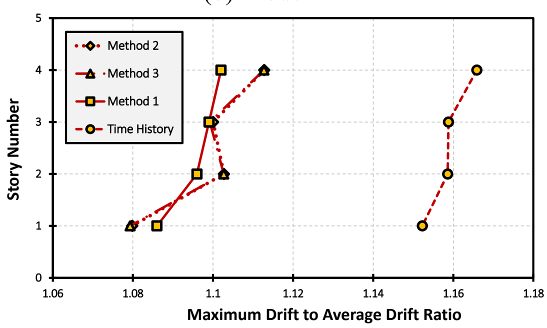
Record	PGA (g)	5-95% Duration (sec)
Artificial-01	0.61	6.79
Artificial-02	0.52	6.37
Artificial-03	0.48	7.79
Artificial-04	0.54	7.63
Artificial-05	0.59	6.66
Artificial-06	0.50	7.99
Artificial-07	0.52	7.59



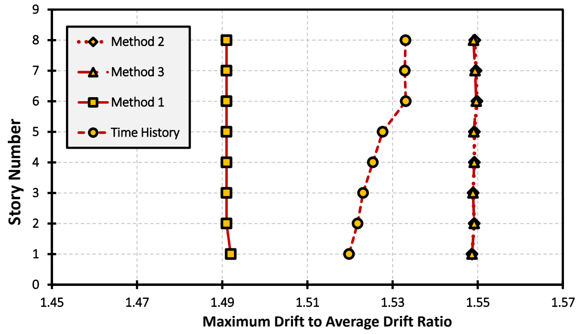
(a) Model 4-1



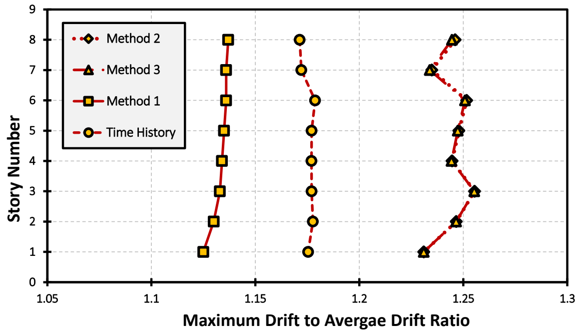
(b) Model 4-2



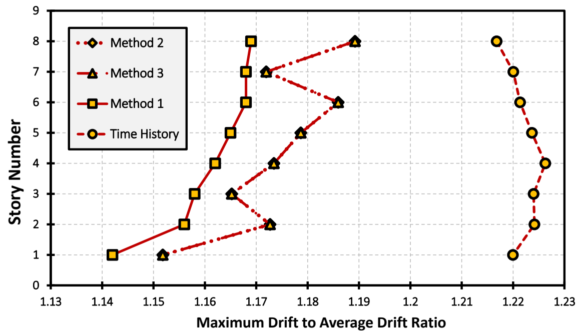
(c) Model 4-3



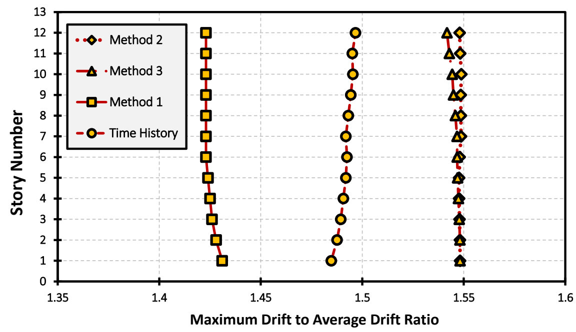
(d) Model 8-1



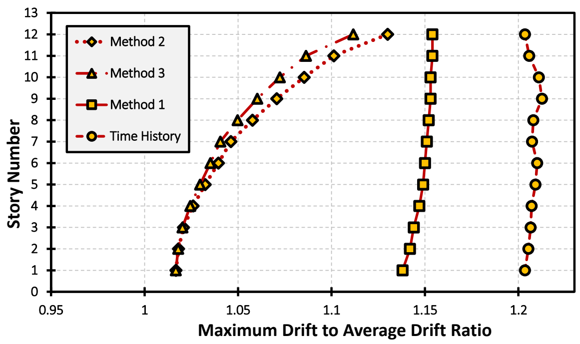
(e) Model 8-2



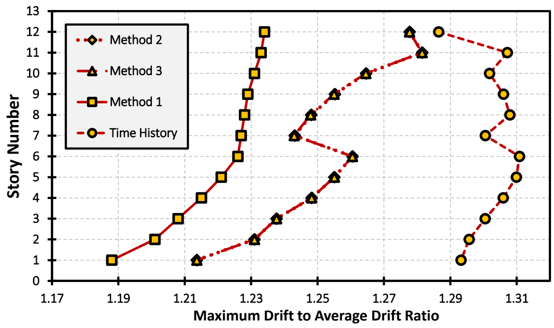
(f) Model 8-3



(g) Model 12-1



(h) Model 12-2



(i) Model 12-3

Fig. 4 Ratios of maximum to average story drift in studied models

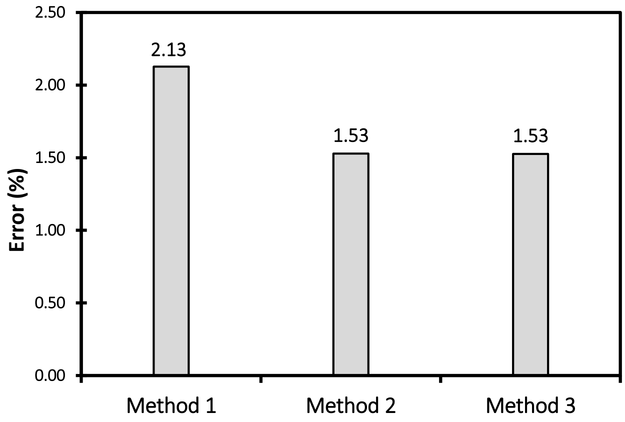
Method 1 predicts smaller values for the ratio of the maximum drift to the average drift ratios compared to Method 2 and 3 except for Model 12-2 as well as some lower stories in model 4-2 and model 4-3. Therefore, it seems that if the methods 2 or 3 are used, the values of the mentioned ratio are computed more conservatively and these methods offer stricter results.

On the other hand, the comparison of the ratios obtained from proposed methods with the time history analysis results shows that Method 1 underestimates the ratios in all studied models. Therefore, it can be concluded that this method is non-conservative for determining the ratio of maximum to average story drift. In methods 2 and 3, however, the results of the models with Plan Type 1 show that the ratios are greater than those determined from time history analysis. However, in all models with plan types 2 and 3, an opposite pattern is observed except Model 8-2. Thus, it seems that the source of torsional irregularity affects the results of the methods 2 and 3 and making a definitive judgment about conservancy of these methods needs more analysis.

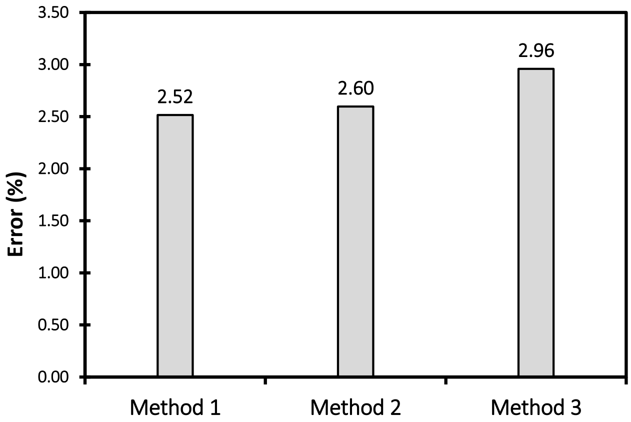
For a better and more consistent comparison, the average of absolute values of errors in each method are compared to the time history responses and are shown in Fig. 5 for all studied models. In addition, the values of errors are computed separately in terms of the type of plan and number of stories in Figs. 6-7, respectively. As seen in these figures, methods 2 and 3 have lower errors compared to method 1 in the models with the plans types 1 and 3. However, method 1 has a lower error in the models with plan 2. This shows that the type of plan can directly affect the error of the studied methods. In addition, it can be seen that increasing the height of the structure increases the error of the proposed methods. If the average of all frames is set to the benchmark presented in Figs. 6-7, it can be concluded that the absolute values of errors do not differ significantly in the three proposed methods and hence it seems that designers can simply use each of these methods although the method 2 seems to be simpler and more straightforward than other ones.

7. Conclusions

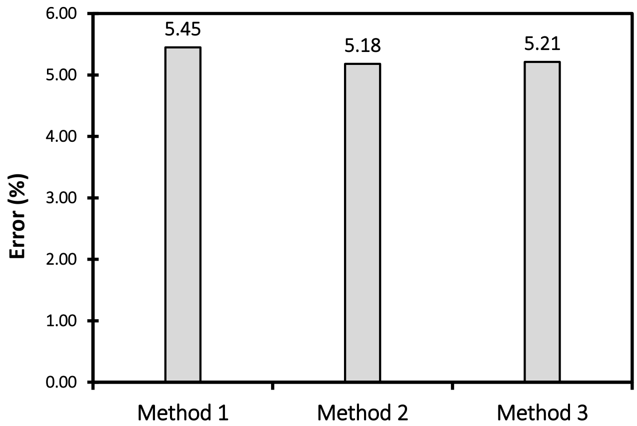
In this paper, three different methods are introduced and examined to determine the ratio of the maximum to average



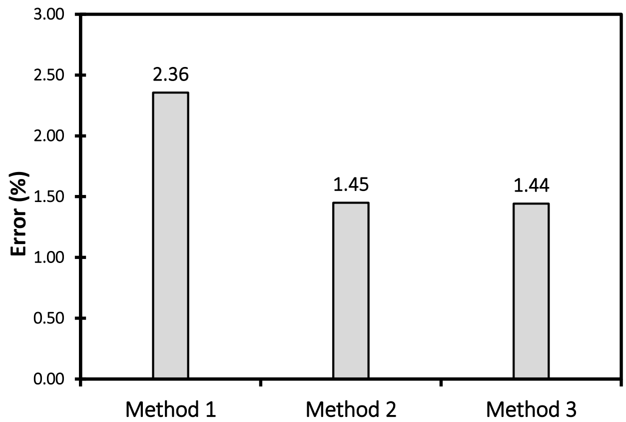
(a) Model 4-1



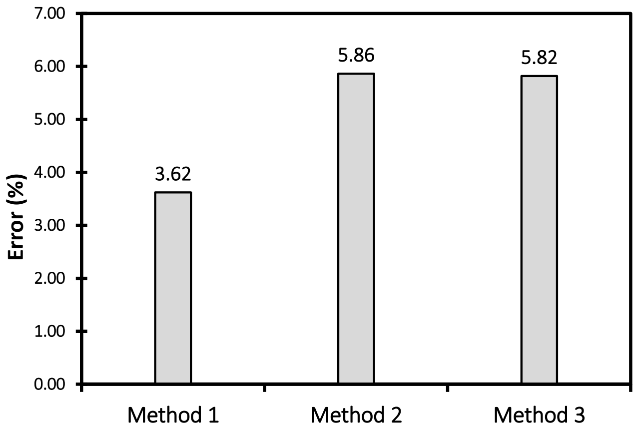
(b) Model 4-2



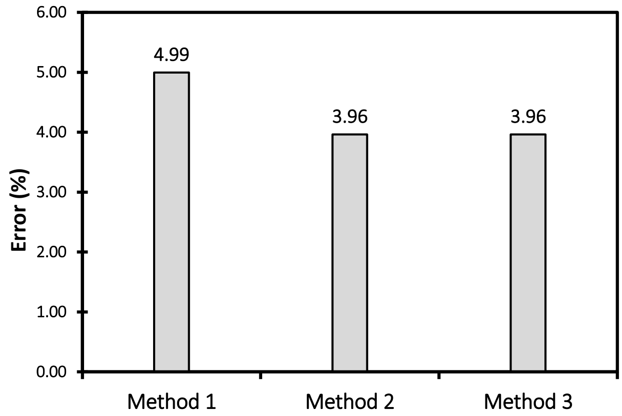
(c) Model 4-3



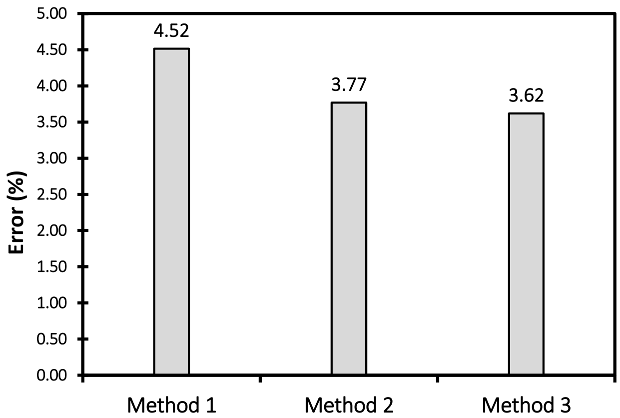
(d) Model 8-1



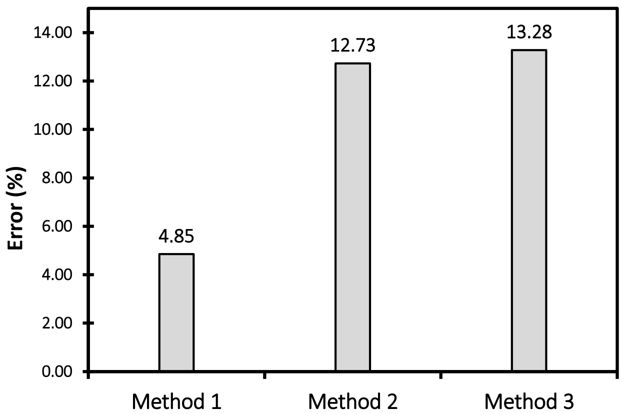
(e) Model 8-2



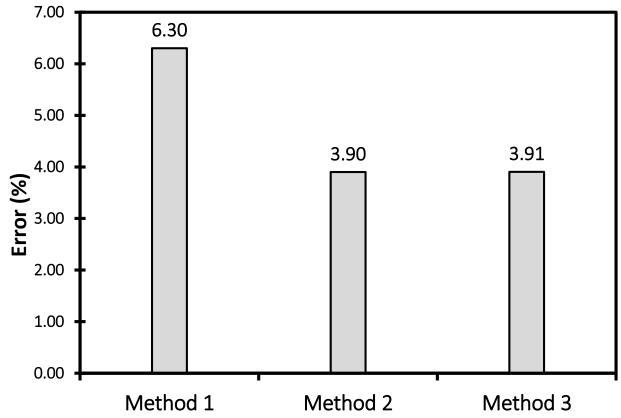
(f) Model 8-3



(g) Model 12-1



(h) Model 12-2



(i) Model 12-3

Fig. 5 Average of absolute values of the errors of proposed method in all studied models

story drift in order to identify the torsional irregularity of the structures in the response spectrum analyses and their precision was examined. In this regard, numerical simulations are performed and the response of the studied structures was determined based on the time history and response spectrum analyses. The results were obtained using the proposed methods and compared with the responses of the time history analyses. To sum up, the following results were obtained:

- Although Method 2 is not theoretically correct but is the simplest approach and it can give similar and relatively conservative results compared to Method 3.
- Compared to Method 1, the other methods can estimate the ratio of the maximum to average story drift larger and present stricter results.
- Method 1 underestimates the ratio of maximum to average story drift and gives less conservative results.
- If the total average of absolute errors in all studied models is considered as the acceptable criterion for design purposes, the error of all proposed methods are close, so designers can choose one of these methods depending on their preferences.
- As a general suggestion, with consideration of all aspects, Method 3 is suggested for calculating the ratio of maximum to average story drift.

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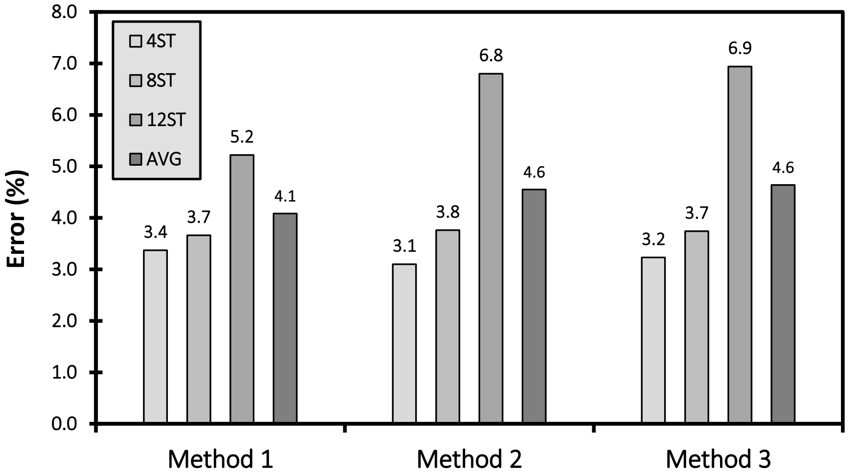

Fig. 6. Average errors of proposed method in term of the number of stories

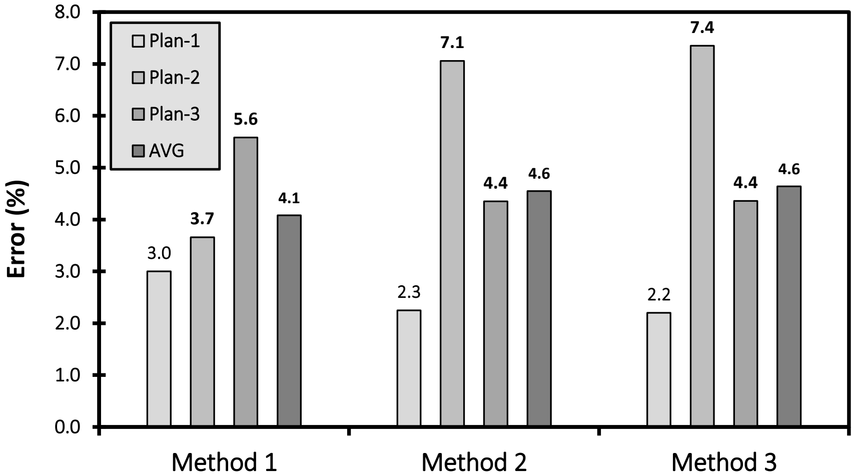

Fig. 7. Average errors of proposed method in terms of the type of the plan

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