



Influence of plan-irregularity in RC buildings on the spectral shape effect evaluating collapse safety

R.K. Badri,¹ M. Nekooei,² and A.S. Moghadam³

Abstract

The evaluation of spectral shape effect on the collapse safety has often been carried out over symmetric buildings and such an influence is almost unclear on the collapse safety of asymmetric-plan buildings. This study tries to show how much plan-irregularity can change the spectral shape effect on the collapse safety of a 5-story reinforced concrete special moment frame building. Irregularity is taken into account by several mass eccentricities at torsionally stiff and flexible cases. The results show that the influence of spectral shape on the collapse safety is dependent on the mass eccentricity and the frequency ratio. Accordingly, as the mass eccentricity increases, the collapse capacity can distinctly vary differently regarding to the expected spectral shape of the records of an area.

Introduction

As a main part of the collapse safety assessment procedure, nonlinear dynamic analysis is done by a large number of ground motion records. Therefore, the record selection strategy can influence assessment results. The spectral shape of records is considered as an effective factor used in an appropriate selection. It has always been of dominant importance in dynamic analysis methods of seismic design codes. However, It has been shown that a ground motion set which is selected consistent with the site-specific design spectrum or the uniform hazard spectrum (UHS) can lead to very conservative responses (Baker, 2005; Haselton and Deierlein, 2006).

Baker and Cornell (2006) introduced a vector-valued intensity measure that used a parameter named ε in addition to $S_a(T_1)$ in record selection. They concluded that the mean collapse capacity of a 7-story reinforced concrete (RC) non-ductile moment frame building underestimated by a factor of 1.7 when a set selected without regard to ε . Goulet *et al.* (2007) studied the collapse of a 4-story RC ductile frame with and without considering ε effect. They found that a set of ground motion selected to have a mean $\varepsilon = 1.4$ caused the mean collapse capacity to be 1.3-1.7 times larger than a set selected without regard to ε . Zareian (2006) used linear regression analysis to investigate ε effect in frame- and

¹ Department of Structural Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran.
E-mail address : ramini.badri@gmail.com.

² Department of Structural Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran.
E-mail address : msnekooei@gmail.com

³ Structural Engineering Research Center, International Institute of Earthquake Engineering and Seismology (IIEES), Tehran, Iran. E-mail address : moghadam.research@gmail.com

wall-buildings. He showed that the changes in ϵ from zero to 1.5 increased the mean collapse capacity by a factor of 1.5-1.6. All of these studies are on symmetric buildings.

Several studies have been conducted on asymmetric-plan buildings (De Stefano 2008). According to these studies, the importance of eccentricity and frequency ratio on the responses of a asymmetric-plan building should not be negligible.

The spectral shape effect on the collapse safety often has been studied on symmetric buildings. So, this study tries to show how plan-irregularity influences the spectral shape effects on collapse of a 5-story reinforced concrete special moment frame building when it behaves torsionally flexible and stiff.

Modeling Properties

The two-element models are simple models. But they are statically determinate and less efficient to simulate the response of most eccentric buildings (Annigeri *et al.*, 1996). Furthermore, Stathopoulos *et al.* (2004) showed that the simplified 1-story shear models were inadequate to model the behavior of realistic multi-story buildings in inelastic range. Therefore, 5-story buildings with four lateral load-resisting frames is used in this investigation, as shown in figure 1. The 3D building model is designed based on ACI 318-05 (American Concrete Institute, 2005) and Iranian seismic codes (Permanent Committee for Revising the Standard 2800, 2007). Table 1 shows the period and the base shear coefficient of design.

Table 1 . Design period and base shear coefficient

Num. of stories	Fundamental Period	Base shear coefficient ^a	bay width ^b (m)
5	0.6	0.078	5

^a based on code 2800

^b mean value based on most of observed designs

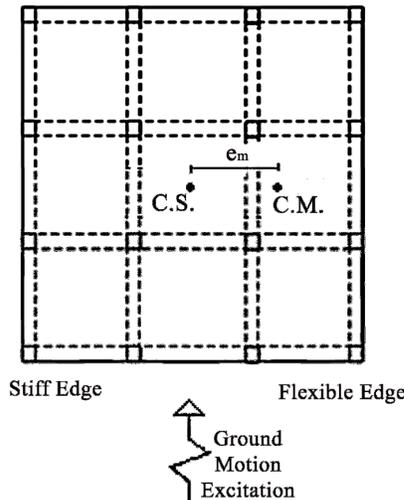


Fig. 1. The proposed asymmetric-plan 5-story building.

To examine the collapse performance of a frame-type building, it is necessary to simulate the elastic and inelastic behavior of its beam-column elements. A lumped-plasticity model which is developed by Ibarra *et al.* (2005) is used for this purpose, as shown in figure 2. This model is very suitable to simulate the strain-softening and cyclic deterioration of reinforced concrete beam-columns (Haselton and Deierlien, 2006). The parameters of model relates to the physical properties of beam-

columns using the empirical predictive equations developed by Panagiotakos and Fardis (2001) and Haselton (2006).

OpenSees software (Pacific Earthquake Engineering Research Center, 2009) is used for modeling and analysis. Floors are modeled as rigid slabs. Soil-Structure interaction effects are also considered to be insignificant. Zareian and Medina (2010) introduced a modeling method to avoid the unrealistic damping forces in inelastic responses. Structural damping (with 5% damping ratio) is modeled by using a Rayleigh-type damping and proportional to mass and initial-stiffness of structural elements based on their study. The specific provisions of special moment frame buildings is included in design to enforce the joints to remain elastic. Accordingly, the joints are not modeled in the collapse safety evaluation. The failure of non-structural components and local failures are assumed unlikely.

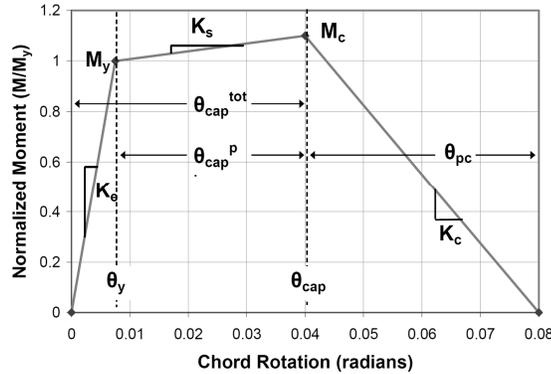


Fig. 2. Monotonic behavior of the lumped-plasticity model developed by Ibarra *et al.* (2005).

Irregularity in plan and frequency ratio

The irregularity of building are 5, 10 and 20% mass eccentricities in the one-way of plan. The mass eccentricity can strongly influence the responses of the buildings that usually experience translational and torsional motions simultaneously in earthquake excitations. According to the previous studies (Annigeri *et al.*, 1996; Tso and Zhu, 1992), the uncoupled frequency ratio has a significant effect on the behavior of building in elastic and inelastic range. As shown in equation 1, the ratio of the first torsional frequency to the first translational frequency is simply introduced as a measure of frequency ratio in this study and used to distinguish torsionally flexible building from torsionally stiff ones. Although this ratio is based on the coupled frequencies of the building, it still is simple and clear enough to understand how torsion is effective in response. The amount of mass moment of inertia in the building floors is assumed to be the same. The frequency ratio alters by changing the mass moment of inertia of floors in different mass eccentricities.

$$\Omega = \frac{\omega_0}{\omega_l} \quad (1)$$

Nonlinear Dynamic Analysis

The collapse assessment is performed by incremental dynamic analysis (IDA; Vamvatsikos ,2002) using a far-field ground motion set. Minimum limits on the magnitude, peak ground velocity and acceleration ensure that the records may cause collapse in modern buildings. The recent structural collapse assessments have used this record set (FEMA- P695, 2009; Goulet *et al.*, 2007; Haselton and Deierlein, 2006; Haselton *et al.*, 2009), as listed in table 2. Spectral acceleration at the first translational mode period in direction of excitation is considered as the ground motion intensity measure.

Table 2. The ground motions data

EQ ID	Event	Year	Mag.	Fault Mechanism	Campbell Distance (km)	Vs_30 (m/s)	Lowest Useable Freq. (Hz)
12011	Northridge	1994	6.7	Blind Thrust	17.2	356	0.25
12012	Northridge	1994	6.7	Blind Thrust	12.4	309	0.13
12041	Duzce,Turkey	1999	7.1	Strike-slip	12.4	326	0.06
12052	Hector-Mine	1999	7.1	Strike-slip	12.0	685	0.04
12061	Imperial Valley	1979	6.5	Strike-slip	22.5	275	0.06
12062	Imperial Valley	1979	6.5	Strike-slip	13.5	196	0.25
12071	Kobe,Japan	1995	6.9	Strike-slip	25.2	609	0.13
12072	Kobe,Japan	1995	6.9	Strike-slip	28.5	256	0.13
12081	Kocaeli,Turkey	1999	7.5	Strike-slip	15.4	276	0.24
12082	Kocaeli,Turkey	1999	7.5	Strike-slip	13.5	523	0.09
12091	Landers	1992	7.3	Strike-slip	23.8	354	0.07
12092	Landers	1992	7.3	Strike-slip	20.0	271	0.13
12101	Loma Prieta	1989	6.9	Strike-slip	35.5	289	0.13
12102	Loma Prieta	1989	6.9	Strike-slip	12.8	350	0.13
12111	Manjil,Iran	1990	7.4	Strike-slip	13.0	724	0.13
12121	Superstation Hills	1987	6.5	Strike-slip	18.5	192	0.13
12122	Superstation Hills	1987	6.5	Strike-slip	11.7	208	0.25
12132	Cape Mendocino	1992	7.0	Thrust	14.3	312	0.07
12141	Chi Chi- Taiwan	1999	7.6	Thrust	15.5	259	0.05
12142	Chi Chi- Taiwan	1999	7.6	Thrust	26.8	705	0.05
12151	San Fernando	1971	6.6	Thrust	25.9	316	0.25
12171	Friuli,Italy	1976	6.5	Thrust	15.8	425	0.13

For more simplification, the buildings is considered to have one-way eccentricity. Although bi-directional excitation gives more realistic results, the aim of this study is to evaluate the spectral shape effects on collapse safety of 5-story asymmetric building in comparison with symmetric one. On the other hand, 3D models have the same structural properties in both direction of building. Therefore, the authors believe that uni-directional excitation can be used in the evaluations to reduce running time while the results accuracy are kept in an acceptable level. Each of two horizontal components of a ground motion record is used in nonlinear dynamic analysis. It is assumed that dynamic instability will occur when either of components make the building collapse. The structural responses are investigated based on the components that first cause collapse termed *controlling components*. The intensity measure increases in an IDA until the maximum inter-story drift ratio grows unlimitedly and the slope of its curve approaches zero. Figure 3 shows the results of IDA for all the components as well as the controlling components in the proposed building in symmetric case.

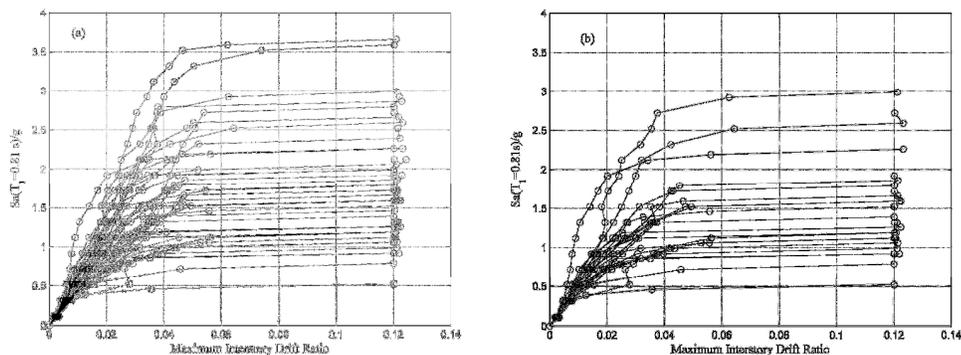


Fig. 3. Incremental dynamic analysis of the symmetric 5-story building using (a) all and (b) the controlling components.

Collapse capacity

The median collapse capacity of the 5-story building changes with increasing the mass eccentricity as shown in figure 4. According to the results, there is a descending tendency for torsionally stiff cases. However, torsionally flexible cases show an ascending trend. When a building is symmetric, it moves translationally and the lateral load resisting elements equally carry earthquake loads. In torsionally stiff cases, the translational mode is dominant. As the mass eccentricity increases, torsion makes the building experience more inter-story drift in its edges, especially in the flexible edge. The structural collapse occurs more rapidly when torsion-induced motions are in the same direction as the building translates. On the other hand in torsionally flexible cases, the dominant motions are torsional. As the mass eccentricity increases, the building experiences more torsional motions than translation. Therefore, the global dynamic instability happens in a higher level of intensity measure.

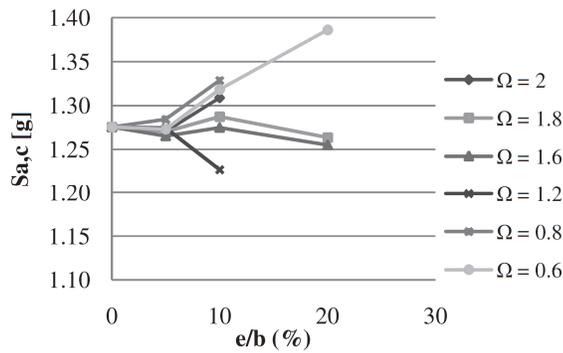


Fig. 4. Collapse capacity of the 5-story SMF building.

The collapse capacity generally increases as the frequency ratio grows, as shown in figure 4. In torsionally stiff buildings, the influence of torsional mode on the lateral drifts of the building becomes insignificant as the frequency ratio increases. Therefore, the global instability is unlikely in lower levels of ground motion intensity. However, in torsionally flexible cases, the torsional deformation is so dominant that inter-story drifts grow unlimitedly only at a higher intensity level. The effective modal mass of the first dominant translational and torsional modes is shown in figure 5 to verify conclusions. Moreover, the influence of frequency ratio are amplified by increasing the mass asymmetry, as shown in figure 6. This figure includes just 5 and 10% mass eccentric cases because there are enough results to show the effect of frequency ratio.

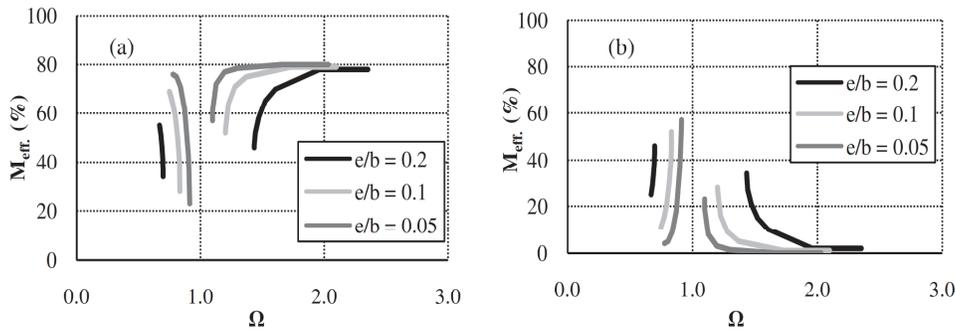


Fig. 5. Effective modal mass of the first (a) translational and (b) torsional dominant modes in excitation direction.

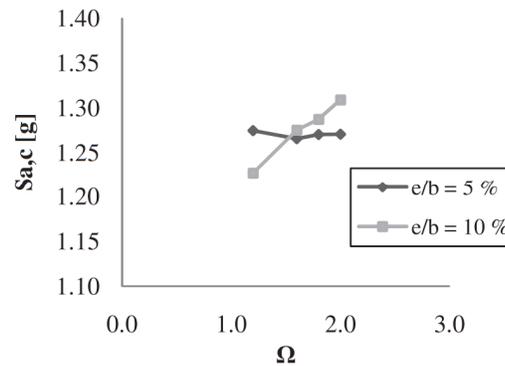


Fig. 6. The influence of frequency ratio on the collapse capacity of the 5-story SMF Building.

Uncertainty in the collapse capacity

Uncertainty in the collapse capacity generally comes from modeling and design uncertainty in addition to record-to-record variability. The estimation of uncertainty is out of the scope of this paper. Instead, a constant amount of 0.5 is selected as the uncertainty in modeling and design based on previous researches (Goulet *et al.*, 2007; Haselton and Deierlein, 2006; Haselton *et al.*, 2009). The record-to-record variability is included in the prediction of total uncertainty by the *mean estimate* approach. This method uses the square-root-of-the-sum-of-squares to account for all sources of uncertainty (Haselton and Deierlein, 2006). According to the results, collapse probability of the building with 20% mass eccentricity is about 30 percent for the maximum considered earthquake (MCE). This is unfavorably high for a special moment frame building. As shown later, the collapse probability will reduce considerably if the spectral shape effect is taken into account.

Collapse margin ratio

Collapse margin ratio is a simple indicator to express the collapse safety of a building in strong ground motions. It is defined as the ratio of the median collapse capacity to the ground motion intensity of interest (Haselton and Deierlein, 2006). This study investigates the margin against the maximum considered earthquake. The MCE spectral acceleration is approximated by 150% of the design spectral acceleration (FEMA-P695, 2009). Figure 7 shows the margin against collapse of the 5-story building. It varies very similarly with the mass eccentricity at different frequency ratios.

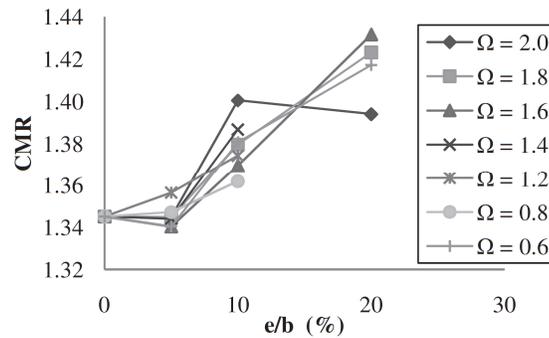


Fig. 7. The margin against collapse for the 5-story building using the controlling components.

The tendency of collapse margin ratio is ascending in both torsionally stiff and flexible cases. This is inconsistent with the trend of collapse capacity in the torsionally stiff cases. The difference between the collapse capacity of the 5-story building in symmetric case and asymmetric cases ($\Delta Sa,c$) is presented in table 3. Similarly, the difference between the MCE spectral acceleration in symmetric case and asymmetric cases (ΔS_{MCE}) is also presented in this table. More or less, both of the parameters vary in the same way at each frequency ratio. However, the amount of changes are not equal. For torsionally stiff cases, the decrease of the MCE spectral acceleration is higher than the reduction of collapse capacity. So, the collapse margin ratio increases. According to the recent studies (Baker, 2005; Haselton and Deierlein, 2006; Zareian, 2006), spectral shape is an effective factor on the structural responses. Therefore, the results should be revised to include its influences.

Table 3. The difference of the MCE intensity level and collapse capacity of asymmetric cases from symmetric case

Ω	e_m/b (%)			e_m/b (%)		
	5	10	20	5	10	20
	ΔS_{MCE} [g] (%)			$\Delta Sa,c$ [g] (%)		
2.0	-0.37	-1.47	-5.67	-0.40	2.59	-2.24
1.8	-0.40	-1.61	-6.36	-0.42	0.91	-0.93
1.6	-0.45	-1.85	-7.56	-0.81	-0.05	-1.62
1.2	-0.92	-5.84	-	-0.08	-3.77	-
0.8	0.54	2.87	-	0.69	4.15	-
0.6	0.17	0.68	3.14	-0.19	3.35	8.68

The influence of spectral shape

The spectral shape of ground motions is one of the effective parameters on the collapse safety of modern buildings. Recent studies (Baker, 2005; Goulet *et al.*, 2007; Haselton and Deierlein, 2006) show that the structural responses can strongly change when records are selected based on spectral shape. Baker and Cornell (2006) suggested ϵ to identify the spectral shape property of a record in the fundamental period of a building. This parameter indicates the number of standard deviations by which an observed logarithmic spectral acceleration differs from the mean logarithmic spectral acceleration of a ground motion prediction (attenuation) equation (Baker and Cornell, 2006). Baker (2005) showed that the intensity measure used in a time-history analysis should be consistent with the intensity measure of the ground motion prediction equation. Structural engineers generally use the spectral acceleration of an arbitrary component of the ground motion in the assessment of structural responses. This study uses an

attenuation equation introduced by Boore *et al.* (1997) to consistently account for the effect of ε based on the intensity measure which structural engineers are more familiar with.

The first translational mode period of the 5-story building is about 0.8 second in different mass eccentricities and frequency ratios. The mean ε of the selected records for this range of the structural period is about 0.23. This study uses a linear regression method to investigate the effect of spectral shape on the collapse safety. Zareian (2006) introduced this method to consider the effect of ε on the collapse capacity of wall- and frame-type buildings. Haselton (2006) also used this method to assess the collapse safety of 65 reinforced concrete frame buildings.

The expected mean ε for a seismic region can be termed *target ε* . To examine the influence of ε on the collapse assessment results, the target ε is considered to be +2 and the variation of results is studied in different asymmetric cases. According to table 4, the mean collapse capacity of asymmetric-plan, 5-story buildings in all frequency ratios is approximately underestimated by a factor of 1.2 when the influence of ε is not taken into account. The variability in the collapse capacity that was computed directly from the records ($\sigma_{Ln Sa,c RTR}$) decreases by a factor of 0.73 considering the spectral shape effect and the collapse probability reduces by 35%. These results show that ε is very effective parameter on the prediction of collapse safety.

Table 4. Comparison of collapse risks with and without accounting for $\varepsilon = 2$ in torsionally stiff and flexible cases

Torsionally cases	Method	Median Sa_{col} [g]	$\sigma_{LnSa,c RTR}$	P[ClSa _{MCE}]
Stiff	with ε adj.	1.49	0.33	0.21
	with no ε adj.	1.27	0.43	0.31
Ratio :		1.17	0.75	0.69
Flexible	with ε adj.	1.60	0.31	0.20
	with no ε adj.	1.32	0.44	0.32
Ratio :		1.21	0.71	0.62

The spectral shape effect vs. plan-irregularity

This study tries to explain how the irregularity of the building in plan changes the spectral shape effect on the collapse results. The ratio of the adjusted to the unadjusted mean collapse capacity ($adj.Sa_{col}/unadj.Sa_{col}$) takes the effect of ε into account. This ratio varies with the mass eccentricity as shown in figure 8. The ratio is higher in the mass eccentricities lower than 10% in the torsionally stiff buildings. Whereas, the higher ratio occurs in the mass eccentricities higher than 10% in the torsionally flexible buildings. These unequal variations can significantly change the trend of collapse assessment results. In the torsionally stiff cases, the collapse capacity that is adjusted to a negative target ε , reduces more in the mass eccentricities lower than 10%. Therefore, the adjusted collapse capacity rises while the mass eccentricity increases. When ε has positive values, the results increases more in the mass eccentricities lower than 10%. So, the trend of results is descending. The tendencies reverse when the building has torsionally flexible behavior.

Furthermore, taking into account the spectral shape effect make the median collapse capacity and the collapse margin ratio vary similarly with the mass eccentricity in all frequency ratios, as shown in figure 9 for $\varepsilon = 2$.

The influence of frequency ratio is investigated by torsionally stiff cases, as shown in figure 10. The effect of ε does not differ so much as the frequency ratio increases. There is only

a noticeable variation in the mass eccentricities higher than 10% when the frequency ratio is 2. Therefore, the frequency ratio does not change the influence of spectral shape on the collapse assessment results.

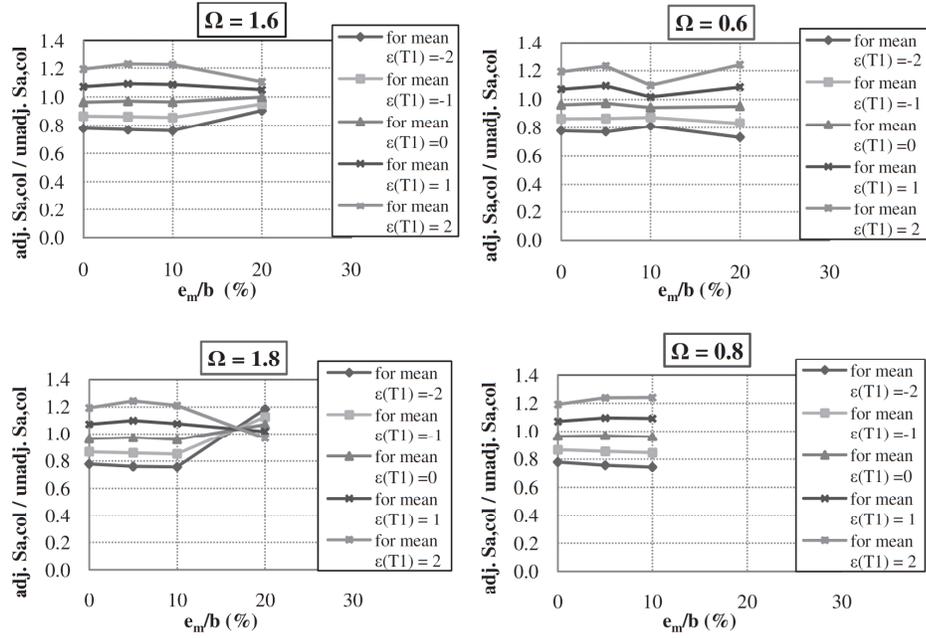


Fig. 8. The changes of spectral shape effects on collapse capacity of 5-story building due to mass eccentricity.

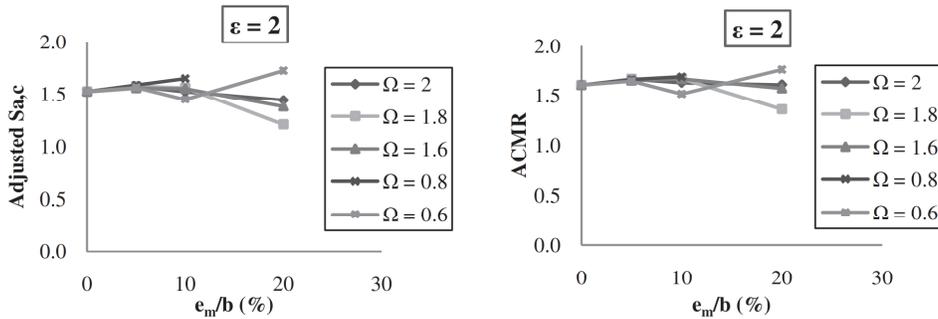


Fig. 9. Adjusted median collapse capacity and collapse margin of the 5-story building for target $\epsilon = +2$.

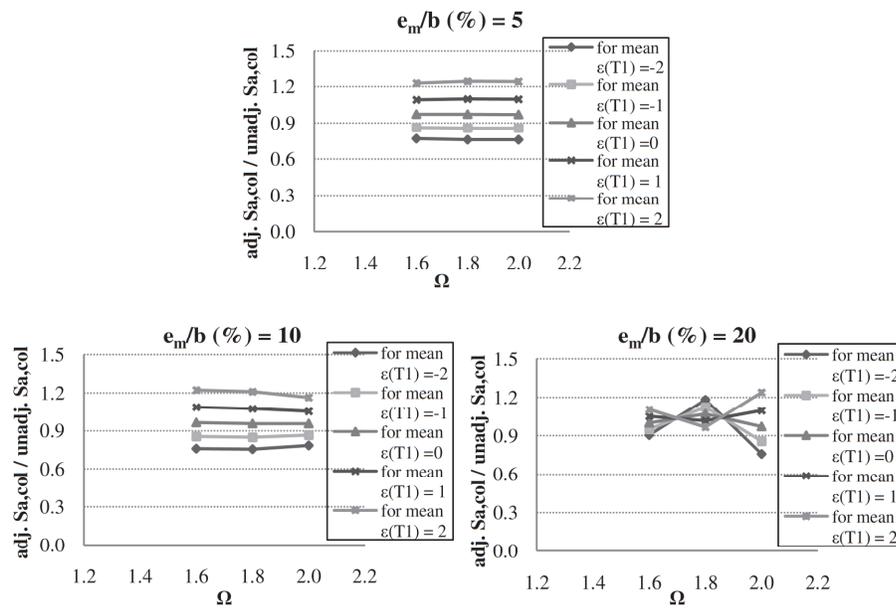


Fig. 10. The changes of spectral shape effects on collapse capacity of 5-story building due to frequency ratio.

Justifying the effect of plan-irregularity

Strong ground motions often lead to the collapse of modern buildings. The return period of such intense earthquakes are generally much longer than the return period of typical events. According to the USGS maps, in the U.S. such earthquakes often have a positive ε value (Haselton and Deierlein, 2006). To illustrate the influence of spectral shape, three sets of records are taken into account. The first set is termed “Basic far-field set” which is selected without regarding ε . The second and third sets are selected to have $\varepsilon(1\text{sec}) = +2$ and $\varepsilon(2\text{sec}) = +2$, respectively. These sets are scaled so that the mean acceleration response spectrum of them would be the same as the mean spectral value of the first set at the period of 1sec and 2sec, correspondingly. As figure 11 shows, the spectral shapes of record sets are distinctly different and this demonstrates how the results of evaluation can remarkably vary due to the selected set.

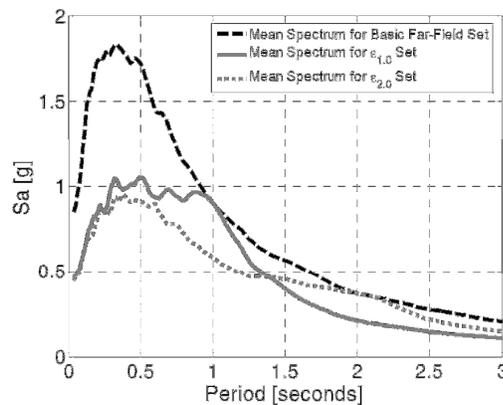


Fig. 11. Mean spectrum of the record sets including : basic far-field set selected without regarding to ε and the other sets regarding to $\varepsilon = 1$ and 2, (Haselton and Deierlein, 2006).

A building experiences period elongation when its lateral stiffness degrades and inelastic behavior spreads among the structural elements. So, when the building collapses it has a longer period than its fundamental period. The acceleration response spectrum of the second ground motion set is lower than the first one for periods longer than 1 second. Therefore, the second set needs a larger scale factor to cause structural instability than the first one. As a result, the structural collapse capacity is higher if the records are selected regarding $\varepsilon(1\text{sec}) = +2$. On the other hand, the influence of spectral shape reduces when the fundamental period is longer. Because as shown in figure 11, the longer the period, the closer the response spectrum will be to the acceleration response spectrum of the first set. This is in agreement with Baker's study.

Regarding the aforementioned issues, the influences of irregularity on the variations of spectral shape effect are discussed below. When the building is torsionally stiff, the higher mass eccentricity is accompanied with rising the mass moment of inertia that causes the period of structure to increase as shown in figure 12. Thus, it is concluded that a higher variation is obtained in the lower mass eccentricity by adjusting the collapse capacity to the effect of ε . This phenomenon is reversed in torsionally flexible cases because the increase of asymmetry reduces the period of structure.

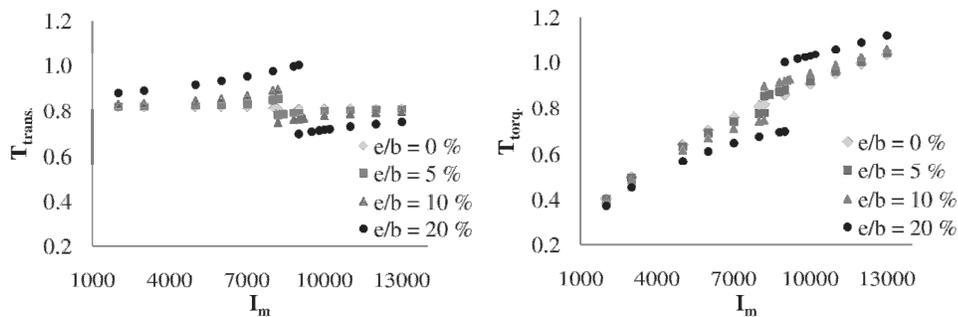


Fig. 12. The variation of the first translational and torsional mode periods with the mass moment of inertia of floors.

As the frequency ratio gets higher values in torsionally stiff cases, the increase of mass eccentricity does not change the mass moment of inertia so much and the period of eccentric cases are nearly the same. Consequently, approximately an equal amount of variation in the collapse capacity of eccentric buildings happens when the spectral shape effect is taken into account, as shown in figure 11. In contrast, the periods get closer together in the lower frequency ratios of torsionally flexible buildings. Hence, in the lower frequency ratios, the spectral shape effect produces almost an equal amount of variation in the collapse capacity of eccentric cases.

Summary and conclusion

This study assesses the collapse safety of a 5-story reinforced concrete special moment frame building designed to meet the seismic code provisions. The 5, 10 and 20% mass eccentricities are used to introduce the one-way asymmetric-plan cases in this study. The influence of *coupled* frequency ratio is also examined on the collapse safety of asymmetric buildings. The assessment results are adjusted to take the effect of ε into consideration by linear regression method introduced by Haselton (2006). The epsilon is defined by a ground motion prediction equation introduced by Boore *et al.* (1997) based on the arbitrary component of records. The ratio of results adjusted to ε effects to unadjusted results are investigated to show how much asymmetry in plan may influence the spectral shape effects. It is concluded that :

- The increase of mass eccentricity generally reduces the collapse capacity of torsionally stiff cases without regarding to the effect of ε . However, in torsionally flexible cases the collapse capacity rises when asymmetry increases.
- Torsionally stiff cases with a lower mass eccentricity experience higher changes in the collapse capacity when the effect of ε is taken into account. In torsionally flexible cases, this happens in higher eccentricities.
- The variation of frequency ratio does not change the effect of ε on the results of the proposed mass eccentric cases so much. There is only a higher change in the effect of ε when the building is more eccentric. There is not a clear observation in torsionally flexible cases because of the limits of frequency ratio. However, the same observation is expectable in torsionally flexible cases based on the reasons given about the influence of plan-irregularity on the spectral shape effect.
- The variation of collapse assessment results are dependent upon the target ε values in addition to two latter above-mentioned results.
- It is worthy to mention that the results' validity in this study is limited to its assumptions. However, the authors are still carrying out further studies and researches in the field.

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