

## Evaluation of Seismic Analysis Procedures for Concrete Moment-Resistant Frames with Horizontal Re-entrant Corners Irregularity

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**Abstract**— Seismic design codes and standards such as the IBC 2012 and ASCE/SEI 7-10 allow using different seismic analysis procedures for buildings having horizontal re-entrant corner irregularity. However, such codes allow using Equivalent Lateral Force (ELF) procedure for buildings having re-entrant corner irregularity but not exceeding 50 m in height. This study aims to quantify the limits on building height and on the percentage of the re-entrant corner of the building, where ELF procedure may not produce reasonable results when compared to Response Spectrum (RS) and Response Time History (TH) procedures. Usually, these limits in seismic design standards are based on judgments and experience rather than quantification studies. Based on the results of this study, it is observed that using ELF method mostly overestimates maximum displacements and drift ratio. However, this method can be used safely up to 12-storey buildings, because the maximum underestimation of column shear forces for buildings with higher stories gives 30% less compared to other procedures. Moreover, it has been found that the maximum underestimation of column shear forces for buildings without re-entrant corner is 0% less than those with re-entrant corners. Furthermore, buildings analyzed by ELF method are also exposed to have a higher percentage value of underestimation of column shear forces as the case of 12-story buildings with 40% less when compared to TH Procedure. Also, the column at the re-entrant corner is not effectively affected until a re-entrant corner of 25% exists in buildings. Thus the ASCE/SEI 7-10's limit for using ELF procedure for buildings with re-entrant corner irregularity may be increased from 15% to 25% with less conservative results.

**Keywords**— seismic analysis; equivalent lateral force; response spectrum; time history; irregularity; re-entrant corner.

### I. INTRODUCTION

Many studies were found in the literature for seismic analysis of structures with vertical and horizontal irregularity [1], [7]. Also, the seismic analyses using static or dynamic procedures are a controversial topic, because many studies showed that Equivalent Lateral Force (ELF) procedure is practical and safe for a large variety of structures [1]. The limitations on the applicability of this method on many building codes, such as the Uniform Building Code (UBC 97), are unnecessarily conservative for irregular structures [2]. Furthermore, even rigid mass irregularity structures designed with static analysis do not result in substantial negative effects on their seismic performance, and using dynamic analyses does not improve the seismic performance significantly [3]. In this study, buildings having horizontal re-entrant corner irregularity have been examined to quantify the proper limits on building height and the percentage of the re-entrant corner of the building [8], [9]. Meanwhile, ELF procedure may not produce reasonable results, when it is compared to Response Spectrum (RS) and Response Time History (TH) procedures, with using El-Centro as artificially adjusted records by response matching technique.

ASCE/SEI 7-10 defines re-entrant corner irregularity to exist where both plan projections of the structure beyond a re-entrant corner are greater than 15%. Also, it allows using ELF for buildings having re-entrant corner irregularity and not exceeding 50 m in height. However, these limits are based on judgments rather than quantification studies. Up to our knowledge, this is the first study that examines the applicability of ELF procedure for buildings having different percentages of re-entrant corner irregularities.

### II. MATERIAL AND METHODS

The present study deals with the evaluation of the response of particular reinforced concrete moment-resisting frame (SMRF) using ETABS v.15 software program. The effect of the re-entrant corner as plan irregularity has been evaluated for buildings having (0%, 10%, 15%, 25% and 35%) of re-entrant corners and varying the number of stories from four stories up to thirty-two stories incrementally increased by four stories at each case of study. Moreover, the effects of the seismic design categories (SDCs) B, C, D and E along with different seismic analysis procedures have also been investigated. The plan views of the buildings with different percentage of the re-entrant corner are shown in Fig.

1. Besides, Fig. 2 shows the 3-D view as a sample illustration with detailed description and data of building models [10].

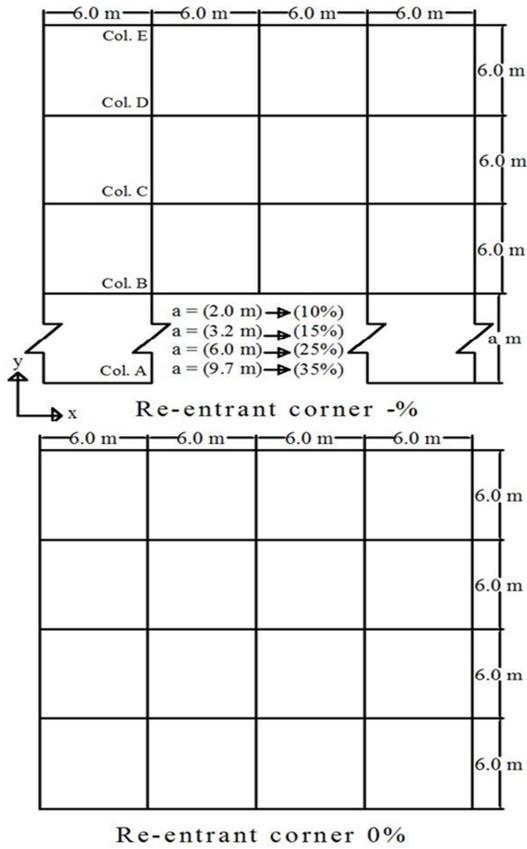


Fig. 1 Plan of selected building models

The ELF's base shear equations with different SDCs are shown in Fig. 3. Eq. 12.8.5 of ASCE/SEI 7-10 needs not to be considered in displacement calculations [11], but a similar proposal was not permitted for the case of using Eq. 12.8.6. of ASCE/SEI 7-10. Though, these equations are still required for base shear calculations.

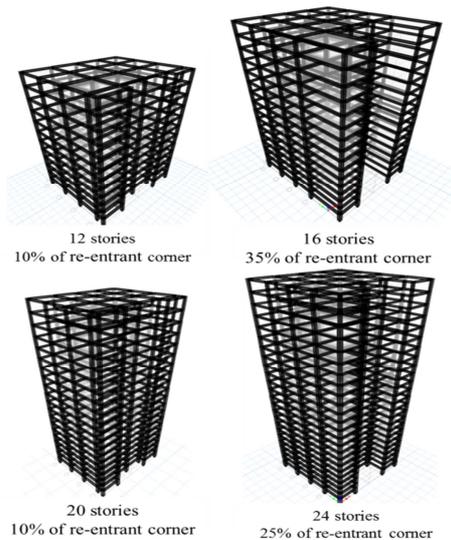


Fig. 2 Three dimensional building models

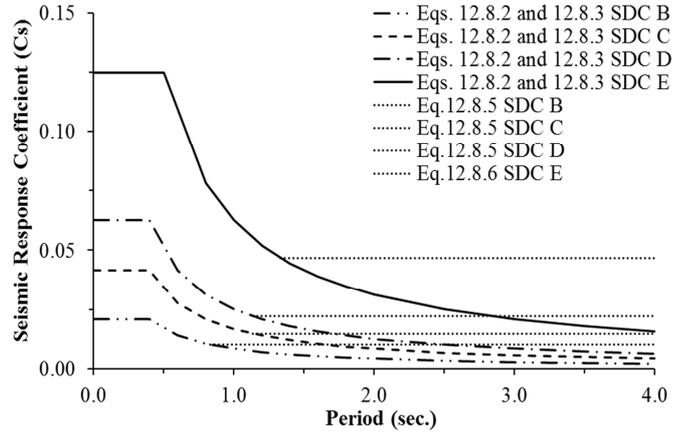


Fig. 3 ELF's base shear based on ASCE/SEI-10 equations

The value of transition period ( $T_s$ ) is the same in SDCs B, C, and D, while it differs in SDC E. The hazard levels between SDCs B, C and D can be roughly represented as follows ( $\text{SDC B} = 1/2 \text{ SDC C} = 1/3 \text{ SDC D}$ ). The N-S component of May 1940 El-Centro record was adjusted by using the spectral matching technique to allow comparing its results throughout different SDCs, which in turn is a non-uniform scaling of a ground earthquake motion to match its response spectrum with some target spectrum [12]. Fig. 4 shows the illustration of N-S component of May 1940 El-Centro record. Moreover, Fig. 5 shows response spectrums of matched earthquake records with their targeted response spectrums counterparts besides for different seismic design categories (SDCs).

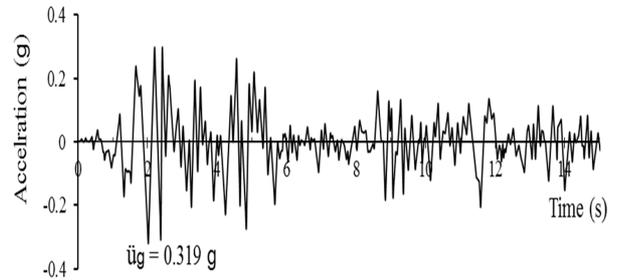


Fig. 4 The N-S component of the acceleration of May 1940 El Centro record

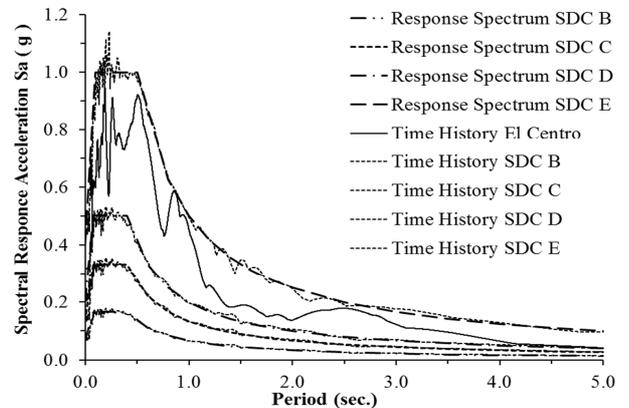


Fig. 5 Earthquake time history and their targeted response spectrums for different seismic design categories (SDCs)

### III. RESULTS AND DISCUSSION

The applicability of ELF as restricted by ASCE/SEI 7-10 has been examined for RC SMRF buildings with the different percent of re-entrant corners. ASCE/SEI 7-10 permits the use of all procedures of seismic design for structures not exceeding 50 m in height and having a horizontal irregularity of re-entrant corner. For buildings higher than 50 m, according to ASCE/SEI 7-10, ELF is not allowed to be used in SDCs D and E. The horizontal displacement, drift ratio, and column shear force responses using ELF, RS, and TH methods are introduced as summary results, while the detailed data and results [10].

#### A. Fundamental Period

The natural vibrational periods for buildings with or without re-entered corners are increased as the height of the building is increased. However, natural vibrational periods of buildings with re-entrant corners increased from 10% to 35% vary in a range of 4.64% less to 7.94% higher relative to those with 0% re-entrant corner. In most cases, natural vibrational periods increased as the percentage of the re-entrant corner increased. Generally speaking, building tends to be more flexible as its height, and re-entrant corner percent is increased. A similar result [13]. Besides, ASCE/SEI 7-10's approximate formula for period calculations gives the same periods for buildings with the different percent of the re-entrant corner and having the same height. This is because this formula depends only on the height of the structure and does not take into account the effect of the re-entrant corners.

#### B. Displacement and drift ratio

Throughout comparisons on lateral displacements and drift ratios, which are shown in Fig. 6 and Fig. 7, the following observations were noticed. The maximum lateral displacement using ELF is higher by a range of 8.7% to 55.3% compared to that obtained by using RS method. Also, it is higher by a range of 20.3% to 71.6% compared to that obtained by using TH method. Also, the maximum drift ratio using ELF is higher than that obtained by using RS method by a range of 6.9% to 46.4%. However, the range of maximum drift ratio obtained by ELF is varied by 1.4% less to 54% higher when compared to those obtained by TH method. Based on these results, it can be noted that ELF method always overestimates maximum lateral displacements for all of the model buildings under investigation whereas the drift ratio was overestimated for most cases of model buildings under investigation with one exceptional case with negligible 1.4% decrease. Therefore, and generally speaking, it can be concluded that as the height and re-entrant corner percentages of the buildings increase, their maximum lateral displacements and drift ratios are increased.

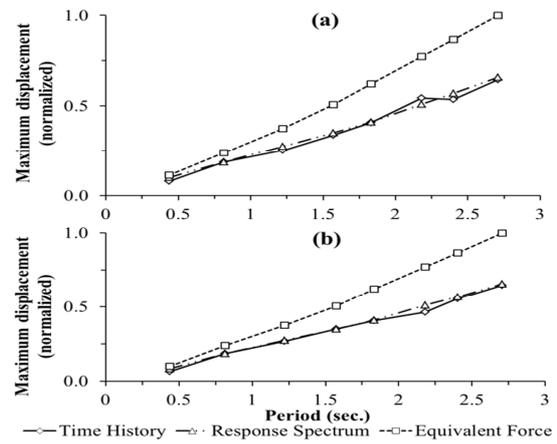


Fig. 6 Maximum displacements of buildings with 15% of the re-entrant corner: (a) SDCs B, C and D. (b) SCD E

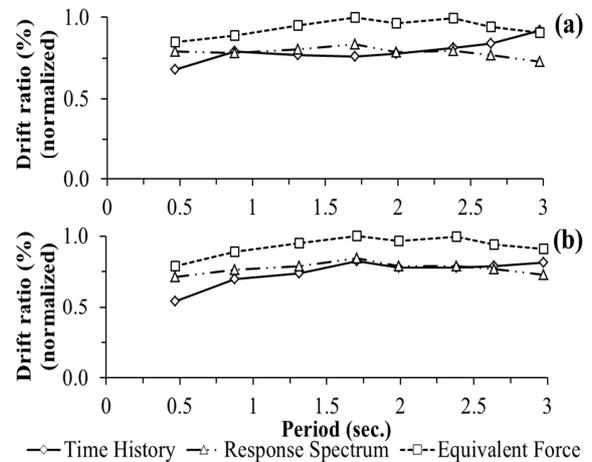


Fig. 7 Maximum drift ratio of buildings with 35% of the re-entrant corner: (a) SDCs B, C and D. (b) SCD E

#### C. Columns shear forces

1) *Comparison of results of columns shear forces:* The effect of the re-entrant corner and the distribution of columns shear forces along the height of structures were examined using ELF, RS and TH methods. It should be noted in Figure 1 that five columns were assigned as columns A to E, which are representing the exterior and interior columns including those found at the re-entrant corner locations. ASCE/SEI 7-10 requires scaling the base shear by a factor of 85% when the base shear obtained by using RS method is less than 85% of that obtained by using ELF method. Moreover, for TH method of using Eq. 12.8.5 or Eq. 12.8.6 of ASCE/SEI 7-10, a 100% scale factor is required. Both required scale factors were considered for RS and TH methods. The maximum underestimation and overestimation of column shear forces are varied along columns in the building with different height and percent of the re-entrant corner with a range of 99% less to 90% higher.

The decrease in shear forces happens near and at the top and lower stories of the buildings because higher modes effects tend to increase shear forces at these stories [14]. Moreover, the maximum underestimations of column shear forces are found to be very high for buildings with re-entrant corners especially at Column A. This is because ELF method often underestimates responses at the flexible side of buildings [15], [16]. However, this is valid only for regular asymmetric buildings where the stiffness of the building is concentrated at one side. Also, other studies show how ELF method underestimates shear forces at higher stories and the flexible side of buildings with geometric vertical irregularity [17]. In this study, the maximum underestimation of column shear forces using ELF method when compared to TH method almost reaches a minimum value of 40% less at the 12-story building in all examined percentages of re-entrant corners. It also reaches a minimum value of 33% less at the 12-story buildings when compared to RS method. However, RS method for models with 0% of re-entrant corner gives an underestimation of column shear forces reaches almost a value of 30% less at the 20-story building. Based on these results, it can be noted that ELF method can be used safely with proper conservative column shear forces for buildings up to 12-story in height. Table 1 and Table 2 show the ranges of percentages of change in columns' shear forces obtained by using ELF method relative to those obtained by using RS method with considering the 100% base shear scaling factor.

2) *Effect of the re-entrant corner on shear forces:* The lateral and vertical distribution of columns shear forces were examined to specify at which percent of the re-entrant corner, column B found at the re-entrant corner location will have higher shear forces than the other columns. Herein, it should be noted that the columns B, C, and D will always have larger shear forces than the exterior columns A and E because they frequently have larger cross-sections. The range of percent of shear force on column B relative to column C obtained by using ELF, RS and TH methods is found to be 0% for buildings with 0% of re-entrant corner, while as it generally increases as the number of stories is increased for the cases with re-entrant corner ranges from 10% to 35%. It can be noted that the columns' shear forces obtained by ELF method

TABLE I  
THE RANGE OF PERCENT OF COLUMNS SHEAR FORCES USING ELF RELATIVE TO RS FOR BUILDINGS WITH 10% AND 15% OF RE-ENTRANT CORNER

Number of stories	The range of percent of change in columns shear forces		
	SDC	Percent of the re-entered corner	
		10%	15%
4	B,C,D	-16.26 to 9.22	-15.39 to 8.70
	E	-15.93 to 9.57	-15.02 to 9.09
8	B,C,D	-23.77 to 12.99	-22.41 to 11.86
	E	-18.56 to 10.20	-16.88 to 9.14
12	B,C,D	-32.55 to 22.36	-37.29 to 20.24
	E	-24.41 to 19.08	-29.57 to 17.10
16	B,C,D	-46.67 to 24.49	-56.79 to 21.82

20	E	-41.08 to 25.20	-51.99 to 22.30
	B,C,D	-63.88 to 25.66	-77.47 to 23.72
	E	-59.03 to 25.84	-74.21 to 23.86
24	B,C,D	-79.27 to 27.27	-97.53 to 26.52
	E	-76.52 to 26.55	-97.20 to 26.16
28	B,C,D	-74.94 to 30.25	-93.95 to 28.92
	E	-72.18 to 29.47	-93.25 to 28.27
32	B,C,D	-90.42 to 30.45	-88.99 to 32.92
	E	-89.28 to 29.48	-87.65 to 32.05

TABLE II  
THE RANGE OF PERCENT OF COLUMNS SHEAR FORCES USING ELF RELATIVE TO RS FOR BUILDINGS WITH 25% AND 35% OF RE-ENTRANT CORNER

Number of stories	The range of percent of columns shears forces		
	SDC	Percent of the re-entered corner	
		25%	35%
4	B,C,D	-11.43 to 3.63	-22.07 to 6.06
	E	-10.90 to 3.86	-21.57 to 7.50
8	B,C,D	-26.17 to 6.74	-38.35 to 13.52
	E	-18.76 to 4.05	-32.09 to 10.32
12	B,C,D	-44.88 to 19.01	-54.02 to 23.30
	E	-38.34 to 16.03	-49.27 to 20.60
16	B,C,D	-70.62 to 24.82	-76.98 to 28.44
	E	-67.15 to 25.74	-74.16 to 29.32
20	B,C,D	-95.20 to 30.74	-99.15 to 34.25
	E	-94.22 to 35.77	-99.02 to 34.17
24	B,C,D	-71.68 to 35.39	-70.30 to 37.80
	E	-70.18 to 34.80	-67.26 to 37.11
28	B,C,D	-76.81 to 38.99	-70.20 to 40.01
	E	-74.15 to 38.69	-67.00 to 39.12
32	B,C,D	-60.67 to 41.05	-64.55 to 66.62
	E	-56.35 to 40.12	-68.20 to 40.98

Are the same for all SDCs due to its static nature. However, the columns' shear forces obtained by using RS method in SDCs B, C, and D are different from those obtained for SDC E due to the difference in  $T_s$  as discussed earlier. On the other hand, the columns' shear forces obtained by TH method are changed in high scattering manner compared to those obtained by ELF and RS methods. This is because the columns' shear forces obtained by TH are depending strongly on the characteristics of the individual earthquake records used for analysis [18].

It has been seen that ELF method produces higher shear forces on column B found at the location of the re-entrant corner for all buildings with 25% of the re-entrant corner but with height up to 12-story compared to those obtained by using either RS or TH methods. Whereas, this is not the case when using TH method for buildings with 25% of re-entrant with height up to 20-story where column B has shear forces changes in range 7.4% less to 3% higher compared relatively to columns C and D. Similarly, RS method produces shear forces at column B which changes in range of 2.7% less to 2%

higher for buildings with 25% of re-entrant corner with height up to 24-story, where the same percentage of re-entered corner, the ELF method produces shear forces at same columns ranges from 2.8% less to 2.6% higher but up to 28-story in height. In all model cases with 35% of the re-entrant corner, the shear forces on column B obtained by using RS and TH methods were found higher than other columns. However, the ELF method produces higher shear forces on column B in building with more than 20-storey in height. The results are summarized in Table 3 which shows the cases for different methods of analysis where the shear forces in column B found at the re-entrant corner location is the higher than these exerted in other columns for a different number of stories and different percentage of the re-entered corner. Results in Table 3 consider the 100% scaling factor required by ASCE/SEI 7-10.

TABLE III  
CASES WHERE THE SHEAR FORCES IN COLUMN B ARE HIGHER THESE OF OTHER COLUMNS

Cases where shear force at column B is the highest				
Re-entrant corner %	Number of stories			
	4	8	12	16
0%	-	-	-	-
10%	-	-	-	-
15%	-	-	-	-
25%	-	-	-	-
35%	RS, TH	RS, TH	RS, TH	RS, TH
Cases where shear force at column B is the highest				
Re-entrant corner %	Number of stories			
	20	24	28	32
0%	-	-	-	-
10%	-	-	-	-
15%	-	-	-	-
25%	TH	RS, TH	All	All
35%	All	All	All	All

The ranges of a percent of increase of shear force in column B located at the re-entrant corner are generally higher using RS and TH methods than using ELF method especially for buildings with 35% of the re-entrant corner. Moreover, the maximum increase in shear forces in column B occurred for the 32-story building in SDCs B, C, and D with 35% of the re-entrant corner with an increase of 6.5%, 16% and 24% when ELF, RS and TH, respectively. However, using TH method for SDC E, the maximum increase in shear forces at column B occurred for the 28-story building with an increase of 19.7%. Based on the above results, it can be noted that the column at the re-entrant corner is not effectively affected until a building have 25% of the re-entrant corner. Thus, the limit for re-entrant corner irregularity given by ASCE/SEI 7-10 may be increased from 15% to 25% with acceptable conservatively level of analysis. One may keep in mind the slight increase of shear forces at the column B which is observed at the 32-story building with 15% of re-entrant corner, which found to

be less than 1.5% and may be considered minor with proper design.

#### IV. CONCLUSIONS

The following conclusions were made based on the results of the study: Keeping in mind that ASCE/SEI 7-10's formula gives the same periods values for buildings with different percent of re-entrant corner since it depends only on the height of structure and does not take into account the effect of the re-entrant corners, it is found that the percent of natural periods of buildings with re-entrant corner relative to these with 0% of re-entrant corner increase as the height of the building is increased but increase in most cases when re-entrant corner is increased.

ELF method overestimates maximum lateral displacement and drifts ratio for buildings in most cases. Moreover, and generally speaking, as the height and re-entrant corner percent of the buildings are increased, their maximum lateral displacements and drift ratio are also increased.

The applicability of ELF as restricted by ASCE/SEI 7-10 has been examined for RC SMRF buildings with the different percent of re-entrant corners. From the results of this study, it can be concluded that ELF method can be used safely for buildings up to the 12-story in height with any percent of re-entered corner horizontal irregularity because the maximum underestimation of column shear forces for buildings with more than 12-story in height gives a minimum of 30% less when compared to RS and TH methods. For buildings higher than 50 m, according to ASCE/SEI 7-10, ELF is not allowed to be used in the presence of re-entrant corner irregularity of 15%. However, from results of this study, it can be concluded that the columns at the re-entrant corner locations are not largely affected for a building having a re-entrant corner of 25%. Thus, the ASCE/SEI 7-10's limitation for re-entrant corner irregularity to be considered may be acceptably increased from 15% to 25%.

It should be noted that other types of horizontal irregularity such as diaphragm discontinuity and nonparallel lateral force resisting systems irregularities might be investigated.

#### NOMENCLATURE

ELF	Equivalent Lateral Force
RS	Response Spectrum
SDC	Seismic Design category
TH	Time History
$T_s$	Transition period of vibration

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