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ORIGINAL RESEARCH PAPER

Evaluation of plan configuration irregularity effects on seismic response demands of L-shaped MRF buildings

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Abstract Damage assessments after past earthquakes have frequently revealed that plan configuration irregular buildings have more severe damage due to excessive torsional responses and stress concentration than regular buildings. The plan configuration irregularities introduce major challenges in the seismic design of buildings. One such form of irregularity is the presence of re-entrant corners in the L-shaped buildings that causes stress concentration due to sudden changes in stiffness and torsional response amplification; hence causes early collapse. A constructive research into re-entrant corner and torsional irregularity problems is essentially needed greater than ever. Therefore, the focus of this study is to investigate structural seismic response demands for the class of L-shaped buildings through evaluating the plan configuration irregularity of re-entrant corners and lateral–torsion coupling effects on measured seismic response demands. The measured responses include story drift, inter-story drift, story shear force, overturning moment, torsion moment at the base and over building height, and torsional irregularity ratio. Three dimensional finite element model for nine stories symmetric buildings as reference model is developed. In addition, six L-shaped building models are formulated with gradual reduction in the plan of the reference building model. The results prove that building models with high irregularity are more vulnerable due to the stress concentration and lateral torsional coupling behavior than that with regular buildings. In addition, the related lateral shear forces in vertical resisting elements located on the periphery of the L-shaped buildings could be significantly increased in comparison with the corresponding values for a symmetric building.

Keywords Plan configuration irregularity · L-shaped buildings · Seismic design demands · Torsional irregularity ratio

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1 Introduction

Although, the occurrence of earthquakes cannot be predicted and prevented, the building structures should be designed to resist earthquake forces. The code requirements serve to define the minimum mitigation requirements for life safety and serviceability. But compliance with regulations in building design is not always sufficient to guarantee an adequate performance when impacted by the earthquake forces for which it was designed. The building should possess main attributes to accomplish the desired performance in earthquake excitation, such as the regular configuration with satisfactory lateral strength, stiffness and ductility. So, selection of the building's plan configuration in the conceptual design plays a critical role in the structural design for resisting earthquake ground shaking. Structural requirements for seismic resistance can become an integral part of the design process (Lindeburg and Baradar 2011; Abdel Raheem et al. 2010). The structural designer has a main responsibility to create a safe structural design for the irregular buildings constructed in an active seismic zone, hence the structural engineer's role becomes challenging (Solomon and Hemalatha 2013). Recently, most of the buildings are involved with an architectural importance and it is highly unfeasible to plan with regular profiles; with such complex configuration irregularities. Accordingly, the prediction of the potential structural collapse under earthquake becomes one of the most challenging tasks. The asymmetric distribution of the mass, stiffness and strength due to the plan configuration irregularity in L-shaped buildings are the main source of severe damages due to excessive floor rotations and translations. Moreover, the plan configuration irregularity of re-entrant corners and lateral–torsional coupling could significantly amplify the seismic response demands of buildings. So, the design of irregular buildings needs special care and enhancement of member sizes at regions of irregularity. Earthquake field investigations repeatedly confirm that irregular structures suffer more damage than their regular counterparts (Jeong and Elnashai 2006). Plan irregularities affect the distribution of stiffness and in turn affect capacity, hence cause non-uniform damage states among the columns within a single floor. The torsional response of non-symmetric buildings under earthquake excitations makes their design for earthquake actions substantially more complicated than the design of symmetric buildings whose response is purely translational (Anagnostopoulos et al. 2015).

For higher and unsymmetrical buildings, the response spectrum method should be utilized for structural analysis and design, while for the symmetric building; the lateral load equivalent method could be used. The use of simple methods is restricted by code regularity limits that lack proper analytical justifications. Simple analysis methods such as Equivalent Static Load (ESL) method could underestimate the actual demands and produce unsafe design for irregular buildings (Sadashiva et al. 2010; Abdel Raheem 2013; Abdel Raheem et al. 2015). Regular structures tend to dissipate the earthquake's energy uniformly throughout the building structure, resulting in relatively light but well-distributed damage. In an irregular structure, however, the damage can be concentrated in one or a few locations, resulting in extreme local damage and a loss of the structure's ability to survive the shaking. Figure 1 shows the anchorage high school and the olive view hospital, as irregular structures that were damaged in the 1964 Alaska earthquake and in the 1971 San Fernando earthquake, respectively. Damages to west anchorage high school clearly illustrate the damages to buildings with re-entrant corners. There are two problems created in L–shape buildings: The first problem is the differential motions between different wings of the building that, result in local stress concentrations at the re-entrant corner. The second problem is the lateral–torsional coupled response that is caused by the non-coincidence of

Fig. 1 Earthquake induced damage of L-shape building due to high shear stresses combined with a stress concentration. **a** Anchorage high school in the 1964 Alaska earthquake, **b** olive view hospital in 1971 San Fernando earthquake

the center of mass and the center of rigidity. This coupled lateral–torsional response and the resulting forces are very difficult to analyze and predict (FEMA 2006, 2010). Therefore, irregular structures need a more cautious structural analysis to determine an appropriate behavior during a devastating earthquake (Alavi and Rao 2013). L-shaped buildings have two wings that could oscillate out-of-phase. Movement of the wings during an earthquake results in high shear stresses combined with a stress concentration at the re-entrant corner causing damage in the building. This damage is aggravated by torsional effects which develop since the center of mass and the center of rigidity cannot coincide in this form as shown in Fig. 2. Irregularities in the MRF buildings adversely affect its seismic performance. Also the seismic behavior of irregular structures involves excessive torsional response relative to regular structures, which can lead to severe local damage (Tezcan and Alhan 2001; Seo et al. 2012; Abdel Raheem et al. 2017). Unpredicted load paths and overstress of components can cause significant adversative effects. To prevent critical failure modes, a suitable conceptual design is required at an early stage. In addition, thorough evaluation of the structural configuration effect of the response demands is vital to attain a satisfactory seismic performance (Elnashai and Di-Sarno 2008). Further, the structures with irregular geometry, particularly with re-entrant corners, exhibit undesirable vibration modes. Moreover pure translational modes convert to lateral–torsional coupled vibration modes as seen in Fig. 3.

Based on the above raised issues, an extensive research is essentially needed to achieve an efficient seismic performance for MRF buildings even with poor configuration. Therefore, the focus of this study is to investigate structural seismic design demands for the class of L-shaped MRF buildings through the evaluation of the plan configuration irregularity of re-entrant corners and lateral–torsional coupled behavior effects on measured

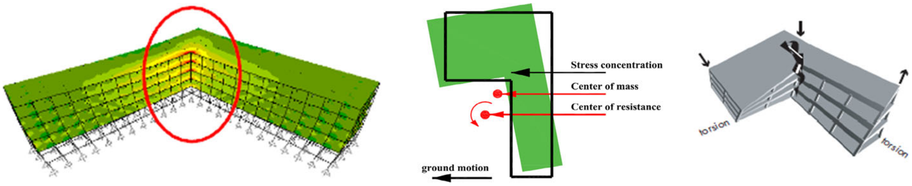


Fig. 2 Potential damage mechanisms of L-shaped buildings under earthquakes

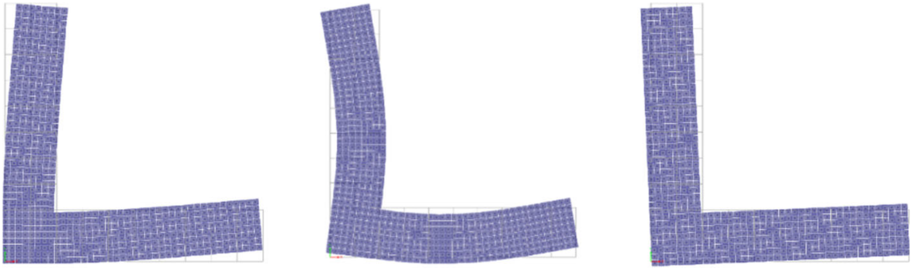


Fig. 3 Significant modes of vibration for L-shaped buildings

seismic response demands. The plan configuration irregularity which is recognized in most of the seismic design codes varies depending on a number of factors including plan geometry, dimensions and positions of structural elements, and story numbers. This research work evaluates of the effects of the plan configuration irregularities on the global response demands of L-shaped MRF building for the assessment of potential damages. The seismic performance in terms of lateral story displacement, inter-story drift ratio, shear force, overturning moment, torsion moment along building's height and torsional irregularity ratio for irregular L-shaped building models is investigated and compared to that of reference model. The outcomes results confirm the significant effects of the plan configuration irregularity on the seismic demands that necessitate an integrated cooperation between the architect and structural engineer from the earliest planning phase of building to guarantee structural safety and reduce vulnerability.

2 Code provisions for plan configuration irregularity

The structural irregularity is widely observed in buildings as a result of the architectural and service requirements in the design process (Mwafy and Khalifa 2017).Configuration irregularity defines how building mass and structure integrated to achieve seismic lateral resistance (Charleson 2009). The majority of the buildings have irregular configurations which can be either in plan or elevation or both; the plan configuration irregularity could be a major contributor to the building failure. The irregularities introduce a major challenge in the seismic behavior of buildings. One such form of plan configuration irregularity is the presence of re-entrant corners and lateral–torsional coupling in the L-shaped buildings due to discontinuity in the lateral force resisting system out of its plane, which causes torsion and stress concentration due to sudden changes in stiffness. The evaluation of torsional provisions in different buildings codes based on computed responses of asymmetric-plan systems has been the theme of several studies (Goel and Chopra 1992; Petti and De-Iuliis 2008; Lin et al. 2012).

For L-shaped buildings; reentrant corner irregularity is defined to exist where both plan projections of the structure beyond a re-entrant corner are greater than 15% of the plan dimension of the structure in the given direction (ICBO 1997; ASCE 2010). Torsional irregularity is defined in ASCE7-10 and UBC97 to exist where the maximum story drift, computed including accidental torsion with $A_z = 1.0$ 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; $\eta_t > 1.2$ (ICBO 1997; ASCE 2010). The extreme torsional irregularity exists for $\eta_t > 1.4$ (ASCE 2010). Torsional irregularity of building diaphragms leads to amplified structural responses including bending moments and drifts and should be accounted for in the computational model. To avoid structural failures and building pounding effects; the accidental lateral load eccentricities of ± 5% should be amplified by the amplification factor; A_z

$$A_z = \left(\frac{\delta_{\max}}{1.2\delta_{\mathrm{avg}}}\right)^2 \quad \text{and} \quad \eta_t = \frac{\delta_{\max}}{\delta_{\mathrm{avg}}} \tag{1}$$

where $\delta_{\max}$ and δ_{avg} are the maximum displacement and the average of the displacements at the extreme points of the structure at Level z as shown in Fig. 4. η_t is the torsional irregularity coefficient. The torsional amplification factor A_z should not be less than 1 and is not required to exceed 3.0. A building can be classified as irregular if the structure exceeds the limits as prescribed by different seismic design codes (Varadharajan et al. 2012). Table 1 summarizes plan configuration irregularity limits from different codes for L-shaped buildings.

Where R_i is the re-entrant corner irregularity that could be defined as the ratio of plan projections beyond a reentrant corner of the plan dimension of the building. e_{0j} is the distance between the centre of stiffness and the centre of mass along the x- and y-direction. r_j is the square root of the ratio of the torsional stiffness to the lateral stiffness. I_s is the radius of gyration of the floor mass in plan.

3 Seismic analysis of building structures

Both EC8 and ASCE 7-10 (ECS 2004; ASCE 2010) make the response spectrum analysis mandatory for design of tall buildings or buildings with significant structural irregularities. The total base shear from response spectrum analysis should be adjusted to equal at least 85% of the lower value of base shear corresponding to a period c_uT, where c_u ranges from 1.7 for low buildings to 1.4 for tall buildings, T is an empirically determined period. The main difference between the equivalent static procedure and dynamic analysis procedure lies in the magnitude and distribution of lateral forces over the height of the buildings. In the dynamic analysis procedure, the lateral forces are based on characteristics of the natural vibration of the building, which are determined by the distribution of mass and stiffness

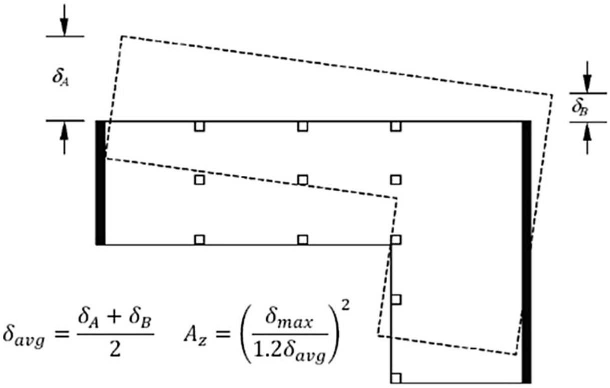


Fig. 4 Sketch for torsional irregularity ratio

Table 1 Plan configuration irregularity limits for L-shaped buildings in international seismic design codes

Plan irregularity/design code	UBC97 (ICBO 1997)	EC8 (ECS 2004)	NBCC (1995)	TEC (2007)	ASCE 7 (2010)
Re-entrant corners	$R_i \leq 15\%$	$R_i \leq 5\%$	–	$R_i \leq 20\%$	$R_i \leq 15\%$
Torsional irregularity	$\eta_t \leq 1.2$	$r_j \leq 3.33\ e_{0j}$, $r_j > l_s$	$\eta_t \leq 1.7$	$\eta_t \leq 1.2$	$\eta_t \leq 1.2$
Extreme torsional irregularity	–	–	–	–	$\eta_t \leq 1.4$

over height. While, in the equivalent lateral force procedure, the magnitude of forces is based on the estimation of the fundamental period and the distribution of forces is given by a simple formula that is appropriate only for regular buildings. The total design lateral force is given in terms of design horizontal seismic coefficient and weight of the structure, which in term depends on the site zone factor, building importance factor, response reduction factor of the lateral load resisting system and the fundamental period. According to the EC8 (ECS 2004) and ECP-201 (ECP 2008), the seismic base shear force, F_b could be determined as follows:

$$F_b = S_d(T_1) \times \lambda \times W \tag{2}$$

where $S_d(T_1)$ is the ordinate of the design spectrum at the fundamental period of vibration of the building T_1; W is the total weight of the building; λ is the effective modal mass correction factor.

The response spectra analysis procedure is based on the assumption that the dynamic response of a structural model can be approximated as a summation of the responses of the independent vibration modes of the model. The response spectra method enjoys wide acceptance as an accurate method for predicting the response of any structural model to any arbitrary base excitation of earthquakes; and satisfies the dynamics requirement of building codes. The horizontal design forces are defined in Eurocode 8 from the maximum response acceleration "acceleration spectrum" of the building under the expected earthquake (ECS 2004). The design acceleration spectrum comes from the elasticity spectrum with a depreciation of 5%, by dividing the spectral accelerations by the behavior factor q. Eurocode 8 suggests two different design spectrums, type 1 for the more seismically active regions of earthquake sizes close to M7, while type 2 for the less seismic regions of earthquakes up size M5.5. Figure 5 presents average spectral ordinate values from the equations of seismic motion prediction of the European territory for rock locations distanced 10 km from small and middle sized earthquakes, in comparison with the spectrum for rock types 1 and 2 of Eurocode 8, based on the average prediction values of the maximum soil acceleration (Ambraseys et al. 1996; Elghazouli 2009).For the design of the building the design response spectrum is used, where the elastic response spectrum reduced by the behaviour factor q. Determination of the behaviour factor q, depends on the type of the structural system, regularity in elevation and plan, and ductility class. The design spectrum for elastic analysis was defined using expressions in EN 1998-1/3.2.2.5 (ECS 2004). The elastic response spectrum and the design response spectrum are plotted in Fig. 5.

The seismic response of different models is studied for unidirectional input earthquake excitation (x-direction), to quantify the effect of lateral–torsional coupled vibration

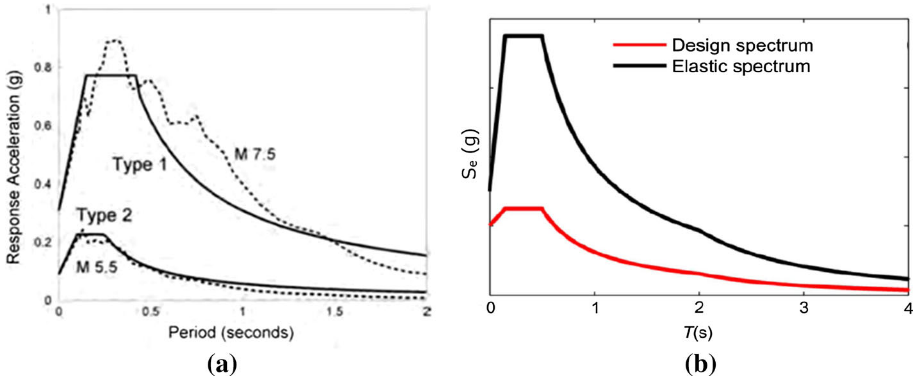


Fig. 5 Design response spectrum. **a** Average spectral ordinate in comparison with EC8, **b** elastic and design response spectrum

characteristics on the response demands in both *x*-direction and *y*-direction; without the orthogonal effect of bi-directional input. Seismic demands are dependent on the direction of applied earthquake forces on the structure. The real accelerograms show that the major principal axis of a ground motion points in the general direction of the epicenter. Therefore, the direction of applied earthquake forces can be determined if the location of an earthquake epicenter is known. But in reality, the location of the epicenter is not known in advance and a structure has to be designed so that it can resist the earthquake forces in any possible attacking angles. For complex three-dimensional structures, the use of the 100/40 or 100/30 percentage rule will produce member designs that are not equally resistant to earthquake motions from all possible directions. The numerical results by Sesigur et al. (2004) support the combination rules given in the design codes (ATC 1996; ICBO 1997; ICC 2003; ECS 2004); and report that a safe value of 0.20–0.25 seems reasonable for regular structures, higher values is required for irregular structures, but the codified combination rules are essentially deficient to seismic response demands of irregular structures.

4 Description and seismic design of studied buildings

The asymmetric plan for L-shaped buildings are very disposed to earthquake induced damage due to lateral torsional coupling, and the re-corners of these buildings suffer heavy damage due to stress concentration during earthquakes. Therefore, it is essential to investigate the seismic response of L-shaped irregular buildings. The structural elements have been designed (ECS 2004; ECP 2008). The studied building models consist of ten equal bays in both directions; each bay has a width of 5 m. All models have nine stories with total height of 28 m. The dimensions of the structural elements are determined using a preliminary design process. The dead loads include the self-weight of the building: 1.5 and 3.5 kN/m^2 for typical floor and roof finishing; respectively; 1.5 kN/m^2 equivalent distributed load for partitions walls at typical floor. A live load of 2.5 kN/m^2 is considered at typical floor and 1.0 kN/m^2 at roof. The used materials in the structural design are C400 for concrete and steel types St40/60 for longitudinal rebar and Steel St24/35 for transverse rebar. Three-dimensional model are constructed by ETABS software (CSI 2016) for analysis and design of structural elements. In addition, SAFE software (CSI 2009) is used to design, check of long-term deflection and punching for slabs. The safe design for column cross section is completed to satisfy the Eurocode and Egyptian codes requirements (ECS 2004; ECP 2007, 2008). Beams of 25 × 60 cm dimensions are used as marginal beam for flat slab system, flat slab thicknesses of 0.16 m are determined. Column dimensions vary between 60 × 60 cm^2 for the lower three stories to 60 × 60 cm^2 for the upper three stories.

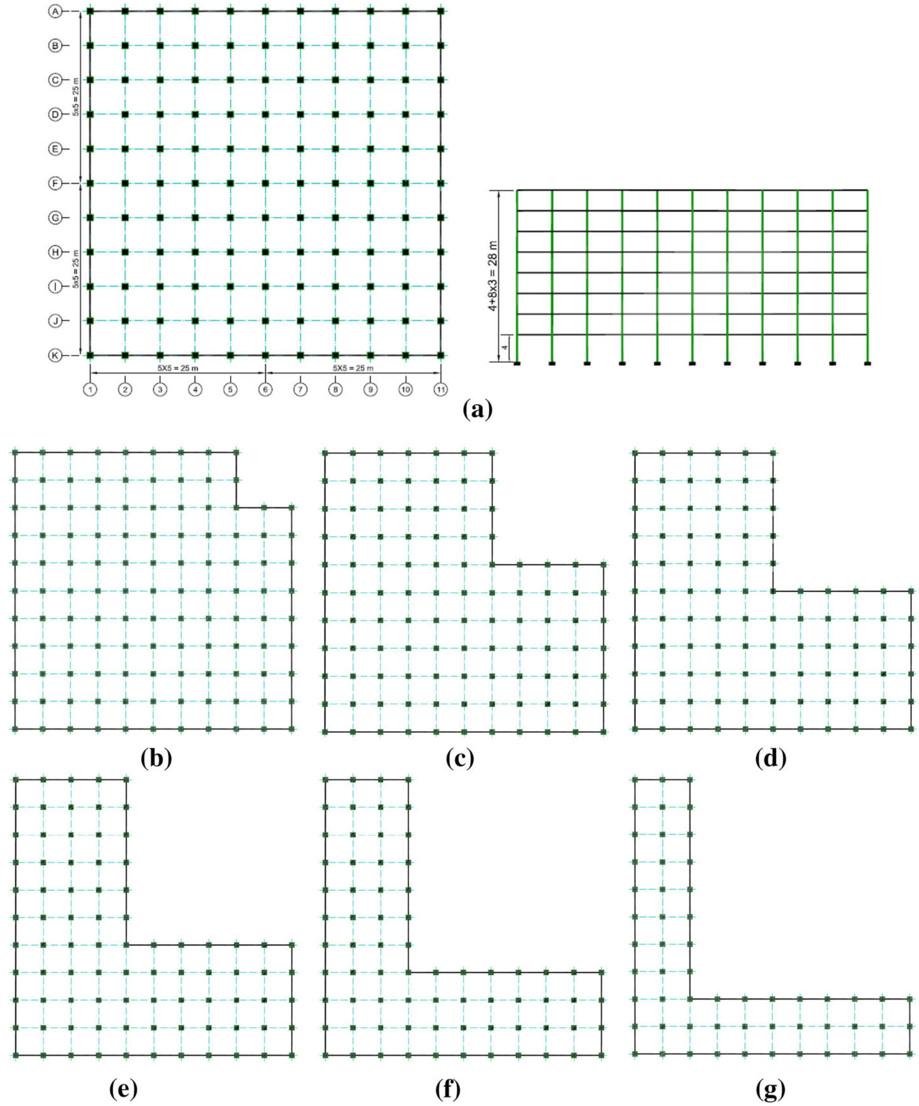
The seismic design of studied building models takes into account the effect of cracking while evaluating the stiffness of reinforced concrete elements; hence affect size of seismic forces and lateral displacements demands (ECP 2008). The seismic design has been done with assumption of: soil class ‘C’ as per referring to dense and stiff soil; importance factor is equal to 1.0; Seismic zone factor = 0.15 g; damping ratio 5% and the shape of the spectrum is type (1) as per Egyptian zoning system. Furthermore, a total seismic mass including dead loads (DL) plus 50% of live load (LL) is considered. For response spectrum method, Square Root of Sum of Squares (SSRS) is used as directional combination method, Complete Quadratic Combination (CQC) for modal combination method. Based on the FE model, the number of vibration modes is defined to achieve more than 90% from mass participation as response spectra condition in the response direction.

5 Numerical modeling and analysis findings

The performance of irregular buildings under seismic effects is a problem unless precautionary measures are taken. As a result of floor shape irregularity, the coupled lateral–torsional motions and the lateral forces experienced by various resisting elements would differ from those experienced by the same elements if the building had symmetric plan. So the main objective is to evaluate seismic response demands for irregular buildings with re-entrant corner in forms L-shaped buildings compared to the reference regular building model “RM”. Mathematical modeling and finite element simulation are introduced for the seismic analysis of the MRF buildings. Where the seismic demands of six horizontal irregularity L-shaped in plan buildings (Li models) are investigated and compared to that of regular building as reference model (RM model) as shown in Fig. 6. The L-shaped building models are generated through gradual reduction in the plan of regular reference building model. Significant measured response demands are investigated: code and analytical vibration period and mode shapes, story lateral displacements, story drift ratio, torsional irregularity ratio, diaphragm torsional rotation, normalized base shear, normalized base shear versus top displacement and normalized overturning and torsional moment responses.

5.1 Free vibration analysis

In most structural design, empirical building period formulas are used to initiate the design process (Kwon and Kim 2010). The vibration periods and modal direction factor as dominated from the structural analysis using analytical models are indicated in Table 2; in addition, the fundamental period of vibration based on empirical equations in different international codes are introduced. In both regular and L-shaped irregular buildings, the computed periods from empirical expressions are significantly shorter than those computed from structural models. The fundamental period based on ECP-201 (2008) is 0.913,



(a)

(b) (c) (d)

(e) (f) (g)

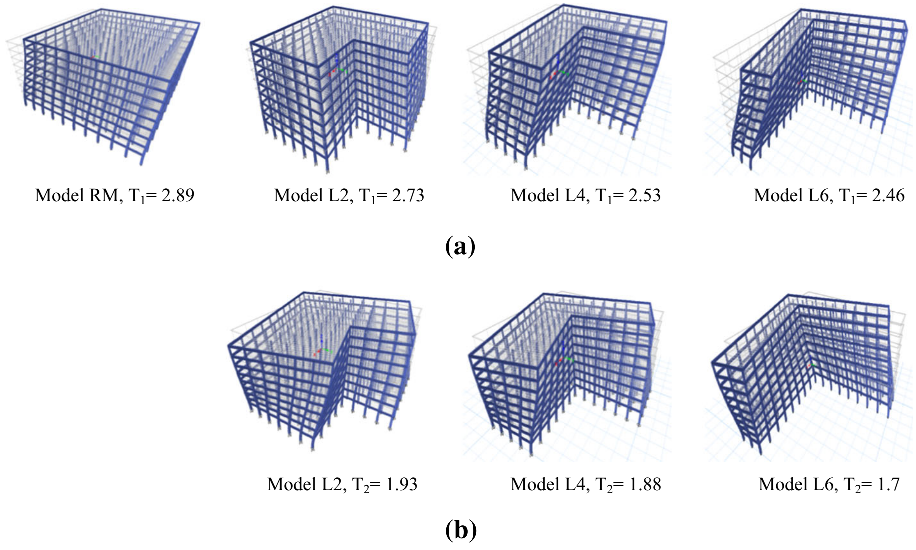
Fig. 6 Reference regular building model "RM" and irregular L-shaped building models. **a** Plan of reference regular/symmetric building model "RM", **b** model L1, **c** model L2, **d** model L3, **e** model L4, **f** model L5, **g** model L6

whereas the fundamental period of the RM, L-Models based on FE approach ranges from 2.89 to 2.46 s, which reaches 316–269% for regular and irregular configuration that introduced in the code provisions. Hence it is clear that the code formulas have a significant defect in the calculation of vibration period which is considered the main parameter for lateral force procedure. Moreover, the vibration modes could be pure *x*- or *y*-translational or rotational mode for the reference symmetric buildings without re-entrant/torsional irregularity. However, irregular L-shaped buildings exhibit special coupled lateral–torsional vibration modes as in Fig. 7. The phenomenon of torsional coupling occurs due to

Table 2 Vibration characteristics of the reference building model “RM” and L-shaped building models

Procedures		Studied building models						
		RM	L1	L2	L3	L4	L5	L6
3D model natural vibration analysis								
1st fundamental vibration mode shape, T_1		2.89	2.85	2.73	2.63	2.53	2.46	2.46
Modal direction factor, Ux		0.70	0.50	0.50	0.49	0.47	0.39	0.28
Modal direction factor, Uy		0.30	0.50	0.50	0.49	0.47	0.39	0.28
Modal direction factor, Rz		0.00	0.00	0.00	0.02	0.06	0.22	0.44
2nd vibration mode—Torsional mode, T_2		N/A	1.93	1.93	1.94	1.94	1.88	1.7
Fundamental vibration period by code empirical equation								
ECP-201 (2008)	$T = 0.075H^{0.75}$	0.913						
ECP-201 (1993)	$T = 0.1\ N$	0.900						
ASCE 7-10 (2010)	$T = 0.028H^{0.80}$	1.047						
UBC97 (ICBO 1997)	$T = 0.049H^{0.75}$	0.596						
IS (2002)	$T = 0.09H/\sqrt{D}$	0.360						
EC8 (ECS 2004)	$T = 0.075H^{0.75}$	0.913						
NBCC (1995)	$T = 0.05H^{0.75}$	0.608						

H is considered the overall height of the building above the foundation, *N* is the number of the stories and *D* is the directional dimension of building under study


Model RM, T_1= 2.89 Model L2, T_1= 2.73 Model L4, T_1= 2.53 Model L6, T_1= 2.46

(a)

Model L2, T_2= 1.93 Model L4, T_2= 1.88 Model L6, T_2= 1.7

(b)

Fig. 7 3D view of vibration mode shapes of studied building models. **a** 1st vibration mode shape, **b** 2nd vibration mode shape

interaction between lateral loads and resistant forces generate greater damage in the buildings. The more irregular the structure, the larger number of modes is needed for accurate determination of the dynamic response of the structure (Liang et al. 2012).

5.2 Seismic response demands

Although in the seismic design of structures the directions of ground motion incidence are usually applied along the fixed structural reference axis, it is known that for most world tectonic regions the ground motion can act along any horizontal direction; therefore, this implies the existence of a possible different direction of seismic incidence that would lead to an increase of structural dynamic response. The maximum structural response associated to the most critical directions of ground seismic motions has been examined. For all models, the variation with incident angle of seismic response demands of the L-shaped buildings is being investigated. The results are compared with that of reference model of symmetric building “RM”. Three cases of incidence angle (0°, 45° and 135°) for the input response spectrum are investigated and compared. The response spectrum is applied along the *x*-direction “case I”; and along the principal directions of equal wing L-shaped buildings 45° direction “case II: stiff direction” and 135° direction “case III: flexible direction”. The building models are analyzed to calculate the peak dynamic responses.

5.2.1 Deformation response demands

The horizontal displacement of tall buildings is one of the most important response demands in tall building design that depends on the dynamic characteristics of the building during earthquake (Wada 1991). The amplification of lateral deformations could change the performance level of the building models. In addition, the lateral deflection and drift could affect the entire building performance and design of nonstructural elements (Abdel Raheem et al. 2015). Lateral deflection and drift have three primary effects on a structure; the movement can affect the structural and non-structural elements plus the movements can affect adjacent structures. Without accurate consideration during the design process, large deflections and drifts can have negative effects on structural elements, nonstructural elements, and adjacent structures (Searer and Freeman 2004; Abdel Raheem et al. 2010). The nonstructural elements should be designed to allow the expected movement of the structural system. Thus, to evaluate the realistic performance level of a structure, a comprehensive dynamic analysis should consider the effects of floor-shape irregularity on the lateral displacement demands. The story lateral displacements over the buildings’ height for different models are introduced in Fig. 8.

Figure 8a show that maximum story displacement distribution along models heights under unidirectional input spectrum (case I: *x*-direction). Models L4 and L5 display the highest top displacement response demand of equal or more than 0.186 m, which is more than 31.5% over of that RM model. The lateral displacement response demands increase with configuration regularity, have values of 0.154 m (108.9%), 0.163 m (115.9%), 0.174 m (123.0%), 0.187 m (132.4%), 0.186 m, (131.5%), 0.159 m, (131.5%) for models through L1–L6 models, respectively. An associated displacement response is developed in the perpendicular direction to input earthquake load “*y*-direction” as shown in Fig. 8b. The *y*-direction story displacement response demand increases with the gradual development of configuration irregularity of the L-shaped building model due to lateral–torsional vibration coupled behavior. The displacement response gets its maximum value of 0.144 m for L6 model, which closely equal to 91% of that in *x*-direction. The seismic performance level could be significantly affected due to configuration irregularity, hence leads to additional displacement demands compared to the reference model. As shown Fig. 8c, the reference regular model “RM” displays an absolute story displacement response demand of 0.141 m

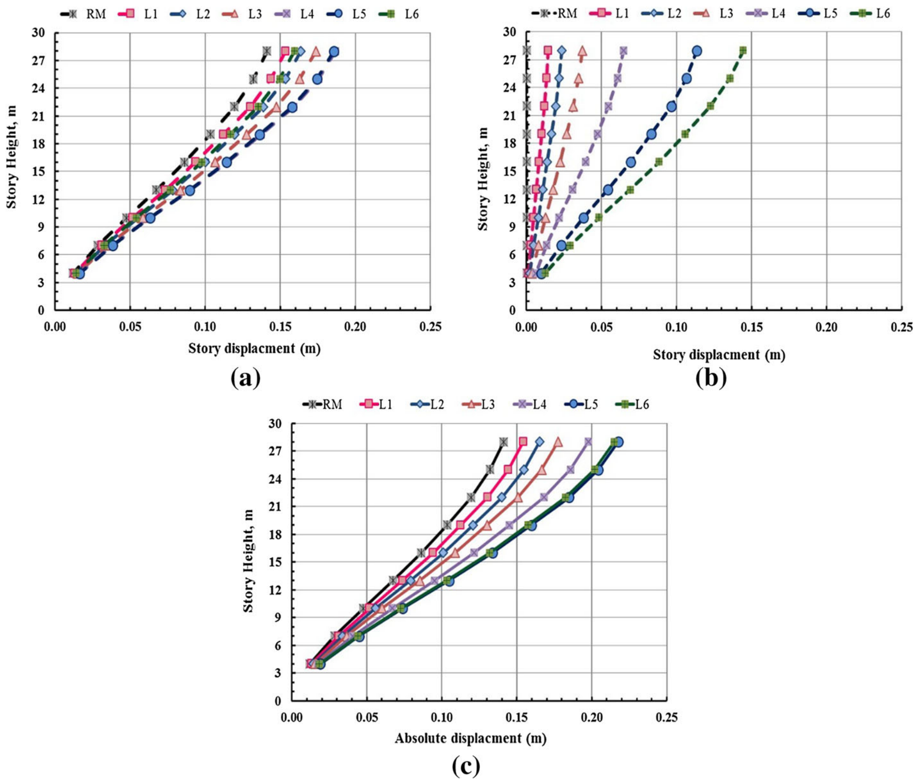
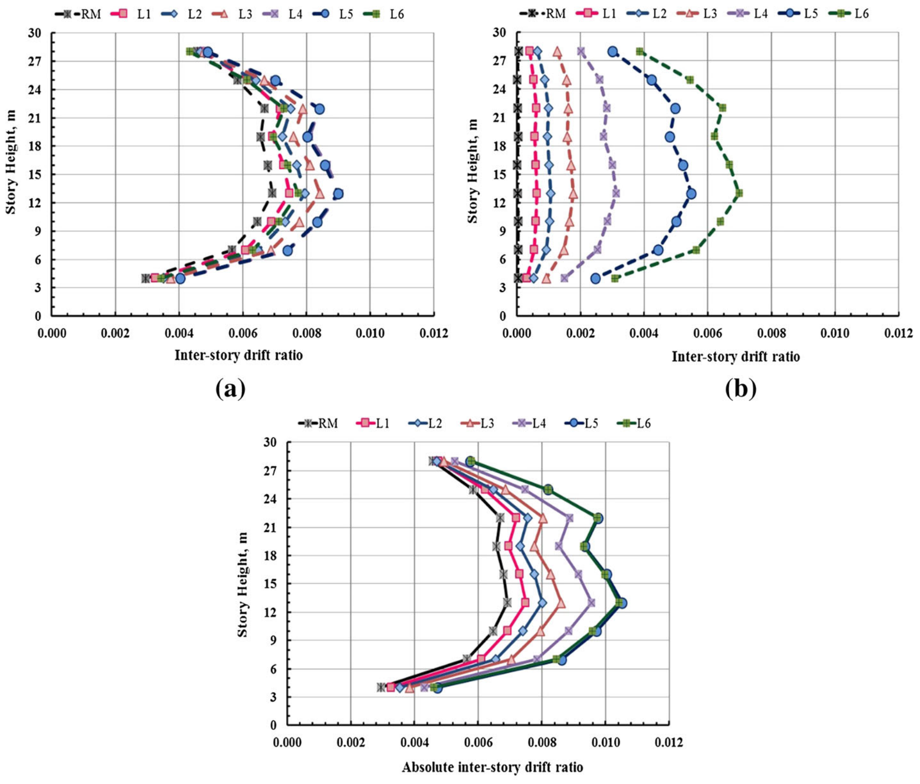


Fig. 8 Story displacement responses for different models-case-I. **a** *X*-direction response, **b** *y*-direction response, **c** absolute story displacement based on SSRS

based on SSRS of both bi-directional responses, while the absolute lateral displacement demands are 0.154 m (109.3%), 0.165 m (117.1%), 0.178 m (125.8%), 0.198 m (140.1%), 0.218 m (154.2%), 0.215 m (152.4%) for models L1–L6, L5 compared to that of RM, respectively. The absolute lateral displacement response demands that are developed due to incremental eccentricity of plan irregularity, could strike structural sustainability with destitute code calculation depending only on the direct response spectrum analysis for unidirectional lateral displacement response in earthquake direction, the actual absolute lateral displacement demand could be significantly amplified due to lateral–torsional coupled behavior.

The story drift ratio response demand is investigated for L-shaped irregular building models and compared to the reference regular building model. The story drift ratios over the building's height for different models are introduced in Fig. 9. The inter-story drift ratio distribution of 9-story models in input earthquake direction "x-direction" increases gradually over building's height and reaches its maximum value in the 4th story level then decreases at the higher levels, Fig. 9a. The story drift response increase as the degree of building configuration irregularity increases from RM model to L5 model. The story drift response gets it maximum value for models L4 and L5 and reaches more than 30% over, compared to that of reference model RM. The story drift responses are 0.0075 (8%), 0.0079 (15%), 0.0084 (22%), 0.0091 (31%), 0.0090 (30%), 0.0077 (12%) for models L1–



(a) (b)

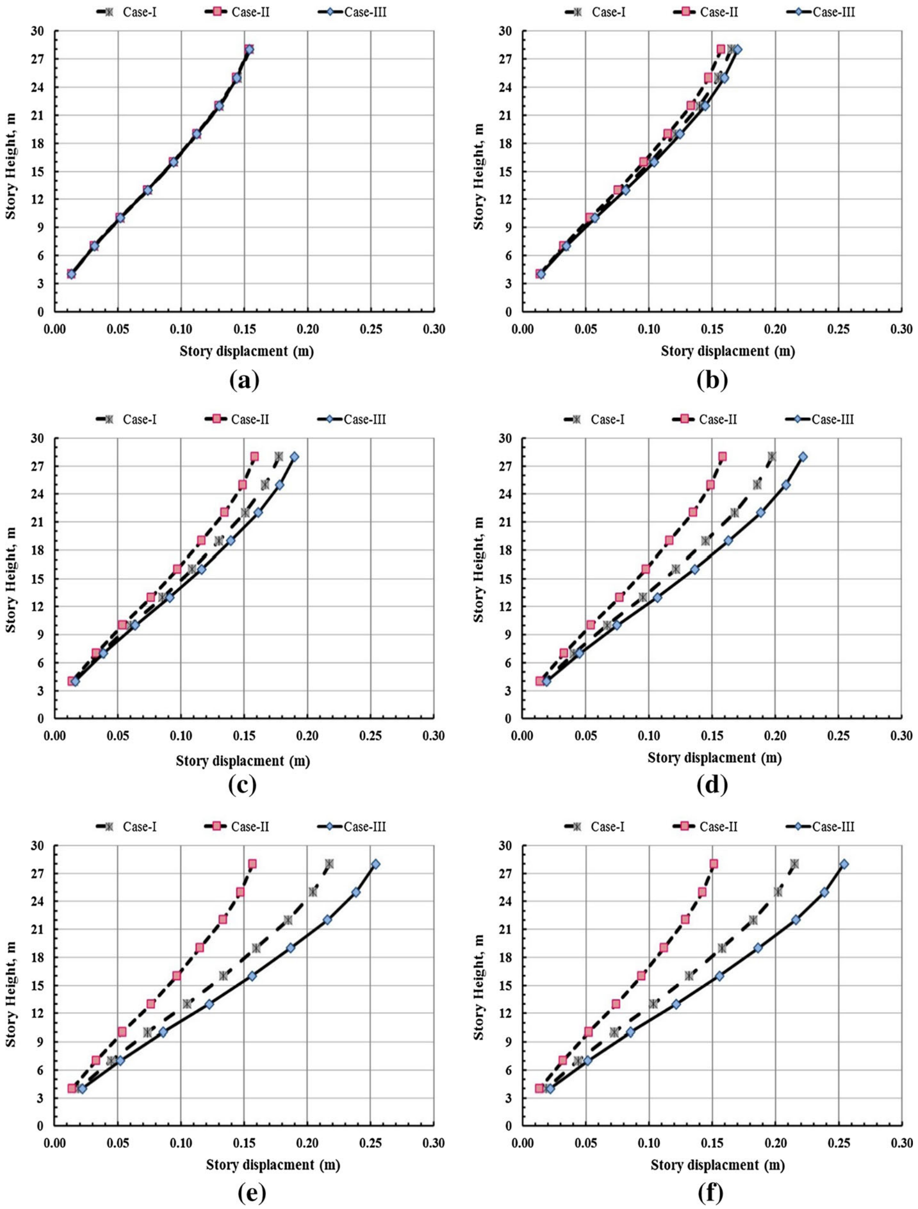
(c)

Fig. 9 Inter-story drift ratio response demands for different models, case-I. **a** *X*-direction response, **b** *y*-direction response, **c** total inter-story drift ratio based on SSRS

L6, respectively. These response values confirm the significant effects of floor shape irregularity. Figure 9b shows the inter-story drift ratio response distribution along models' height that is additionally induced in the perpendicular to input earthquake direction (*y*-direction). Inter-story drift response increases and get significant values through model L1–L6 as plan irregularity effects increase. The *y*-direction inter-story drift ratio response gets a maximum value of 0.007 for L6 model due to lateral–torsional vibration coupled behavior. Figure 9c shows the absolute inter-story drift ratio response calculated based on SSRS approach. The absolute inter-story drift ratio reach 108.3, 116.0, 124.4, 138.3, 152.2, 150.7% for models L1–L6 compared to that of RM model, respectively. It is clear that the torsional coupling induces a significant amplification to seismic drift demands that should be accounted for in the plan configuration irregular building design.

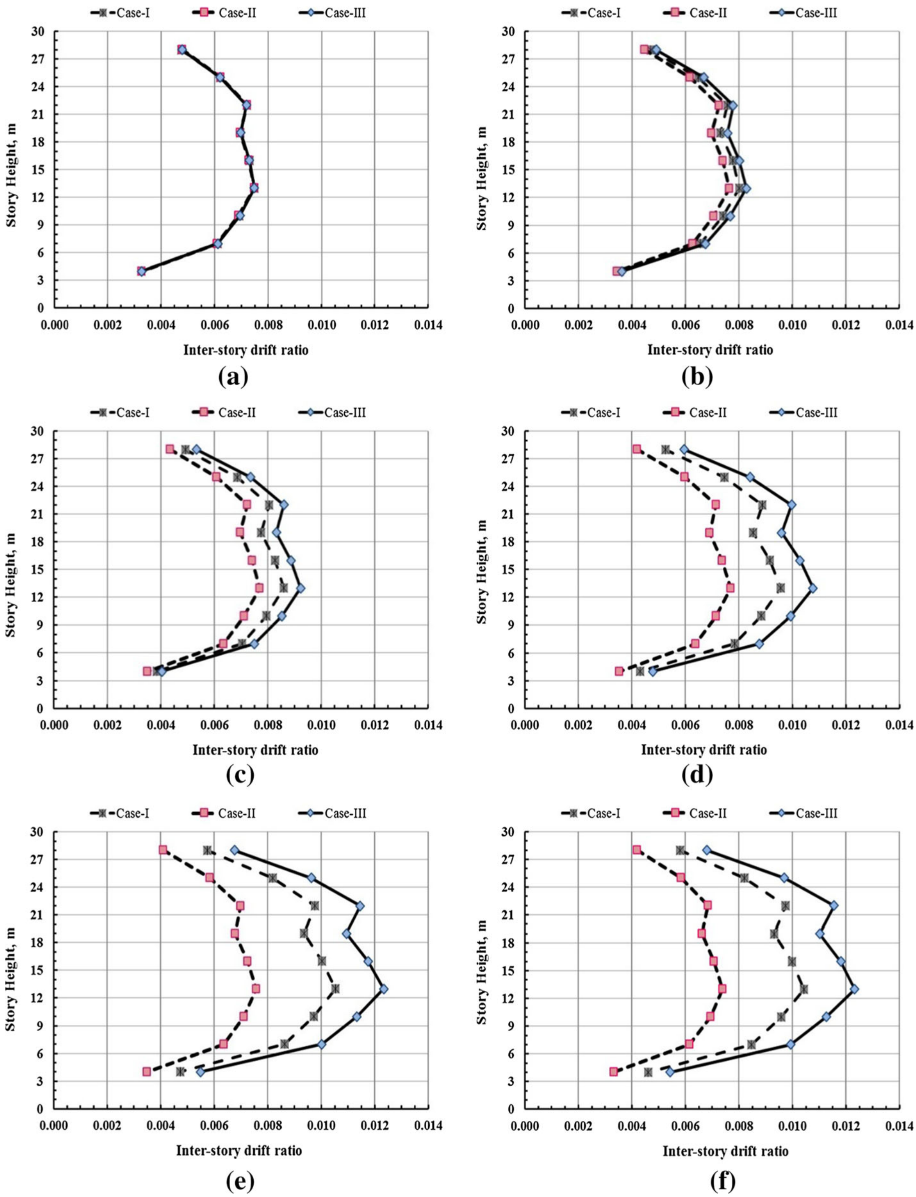
The present study refers to the investigation of the effect of the seismic incident angle on structural response using the response spectrum method. The results from the spectrum analysis show that the value of critical angle that yields the maximum responses almost does not depend on the seismic excitation, depends though on the structure characteristics and the type of the response quantity itself. For RM model with two-way plan symmetry, the critical angle is either 0° or 90°, while for L-shaped building models, the critical angles are 45° and 135° that are the principal directions of the L-plan foot print.

Figures 10 and 11 illustrate the variation of the absolute lateral displacement and inter-story drift ratio responses for different incidence angles of input spectrum for different L-shaped models. While the responses for the reference symmetric model, RM are independent from the incidence angle of the input spectrum, they are sensitive to the changes in the angle of excitation for L-shaped models. The more irregular building structure through



(a) (b) (c) (d) (e) (f)

Fig. 10 Effect of lateral torsional coupled vibration on the absolute story lateral displacement response demands. **a** Model L1, **b** model L2, **c** model L3, **d** model L4, **e** model L5, **f** model L6



(a) (b) (c) (d) (e) (f)

Fig. 11 Variation of absolute inter-story drift ratio demands for different incidence angles of input spectrum. **a** Model L1, **b** model L2, **c** model L3, **d** model L4, **e** model L5, **f** model L6

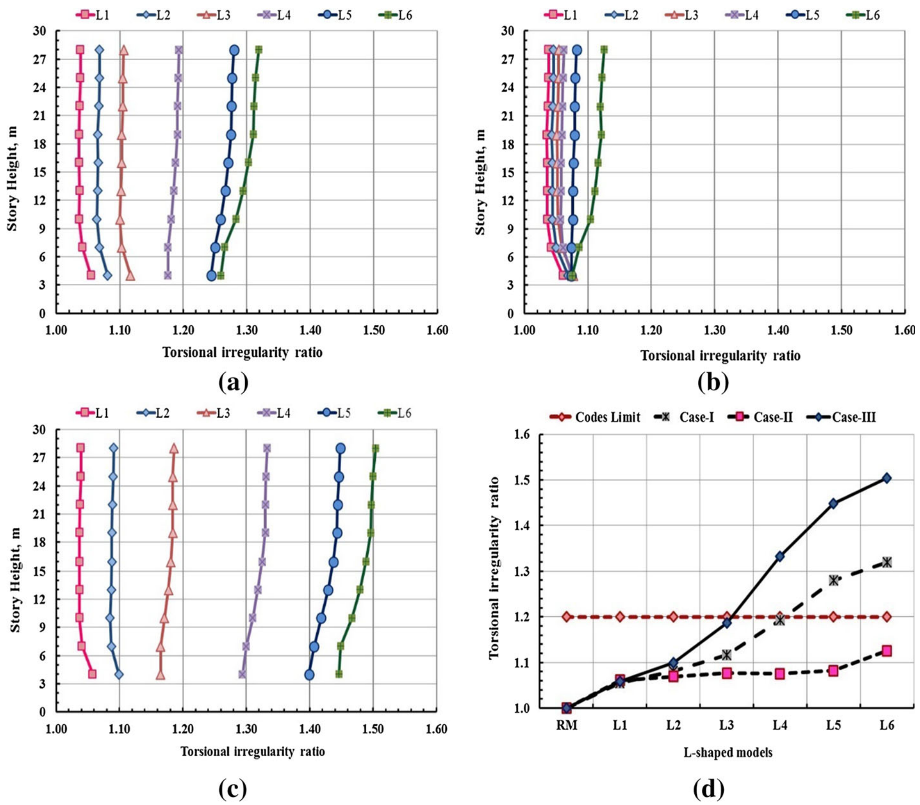
models L1–L6, the larger lateral displacement response and inter-story drift response demands are induced.

The developed absolute lateral displacement and inter-story drift ratio demands are significantly decreased for the input spectrum along the stiff direction “Case II”, the responses values reach 100, 95, 89, 80, 72, 71% for models L1–L6 compared to that of conventional design direction “case I”, respectively. The low response with lower limit could be attributed to the disappearance of the eccentricity due to plan configuration irregularity, hence minimization of torsional behavior effect. While, the developed absolute lateral displacement and inter-story drift ratio demands are significantly increased for the input spectrum along the flexible direction “Case III”, they reach 100, 103, 107, 113, 117, 118% through models L1–L6 compared to that of conventional design direction “case I”, respectively. The high response with upper limit could be attributed to the maximization of the eccentricity due to plan configuration irregularity, and associated torsional behavior effects. Although in the seismic design of structures, the direction of ground motion incidence is usually applied along the fixed structural reference axis (Case I: *x*-direction), the maximum structural response could be associated to the most critical directions of input seismic force. For the model L6 with the most severe plan configuration irregularity, the developed absolute lateral displacement and inter-story drift demand display the lowest reduction of 29% under response spectrum in the stiff direction “Case II”, while the highest increase of 18% under response spectrum in the flexible direction “case III”.

5.2.2 *Torsional irregularity ratio*

Torsional irregularity is one of the most important factors that cause severe damage to the building structures. Torsional irregularity ratio is an analytical index derived based on response characteristics, and accounts for the multi-directional response as well as the asymmetry of the structure; hence, it captures the true 3D effects that govern the response of building structures whereas it recognizes the differential deformation in plan, hence ability of vertical resisting element to withstand anticipated lateral forces. The torsional irregularity ratio limit in different international design codes (IS 2002; ASCE 2005; Herrera and Soberón 2008; Özmen et al. 2014) is 1.2, when the calculated torsional irregularity ratio exceeds this value means that building is affected by differential deformation in plan and further significantly affect the seismic performance level for building, therefore the design procedure for resisting element should be carefully formulated to reduce the torsional effects.

Figure 12a shows the torsional irregularity ratio for L-shaped building along models' height; torsional irregularity ratio is slightly changed over the building model heights, but grows up with the increase of model eccentricity. For models with small eccentricity, the lower stories exhibit large torsional deformation more than upper stories in contrary to models with large eccentricity models display more torsional deformation at upper stories. The maximum torsional irregularity ratios for the unidirectional spectrum applied along the fixed structural reference axis (Case I: x-direction) are 1.06, 1.08, 1.12, 1.19, 1.28 and 1.32 for L-shaped models L1–L6, respectively. Figure 12b–d illustrate the effects of incidence angles of input spectrum for different L-shaped models on the calculated torsional irregularity ratio. The calculated torsional irregularity ratio are underestimated for the input spectrum along the stiff direction “Case II”, the responses values reach 1.06, 1.07, 1.08, 1.08, 1.08, 1.13 for models L1–L6 compared to that of conventional design direction “case I”, respectively. The low response with lower limit could be attributed to the disappearance of the eccentricity due to plan configuration irregularity, hence minimization of torsional behavior effect. While, the developed torsional irregularity ratio demands are significantly increased for the input spectrum along the flexible direction “Case III”, they reach 1.06, 1.10, 1.19, 1.33, 1.45, 1.50 through models L1–L6 compared to that of conventional design direction “case I”, respectively. The high response with upper limit could be attributed to the maximization of the eccentricity due to plan configuration irregularity, and associated



(a) (b)

(c) (d)

Fig. 12 Torsional irregularity ratio for different models. **a** Torsional irregularity ratio; case-I, **b** torsional irregularity ratio; case-II, **c** torsional irregularity ratio; case-III, **d** maximum torsional irregularity ratio

torsional behavior effects. For the model L6 with the most severe plan configuration irregularity, the calculated torsional irregularity ratio is more sensitive the incidence angle of the input spectrum; especially for highly irregular model, L6. It has 1.32 for the conventional case-I; but displays a lower value of 1.13 for case-II and a higher value of 1.50 for Case-III.

5.2.3 Diaphragm torsional rotation

The torsional seismic effects caused by the irregularity of plan layout of building structures have been emphasized for seismic design in many codes (Jinjie et al. 2008). The effect of this detrimental action causes twisting the building accompanying translation displacement for building with complex seismic configuration. Torsional diaphragm rotation is considered significant parameter to evaluate torsion moment plus probability of local failure for outer element threatening the robustness of a structure that is highly dependent on the performance of the diaphragms (Diamantidis 2009). The floor system that experiences twisting due to differential movement of slab edges undergoes in-plane bending. The relative stiffness of the horizontal to vertical structural systems affects the torsional resistance of the frames and the in-plane rotation of the slabs (Al-Harash et al. 2011).

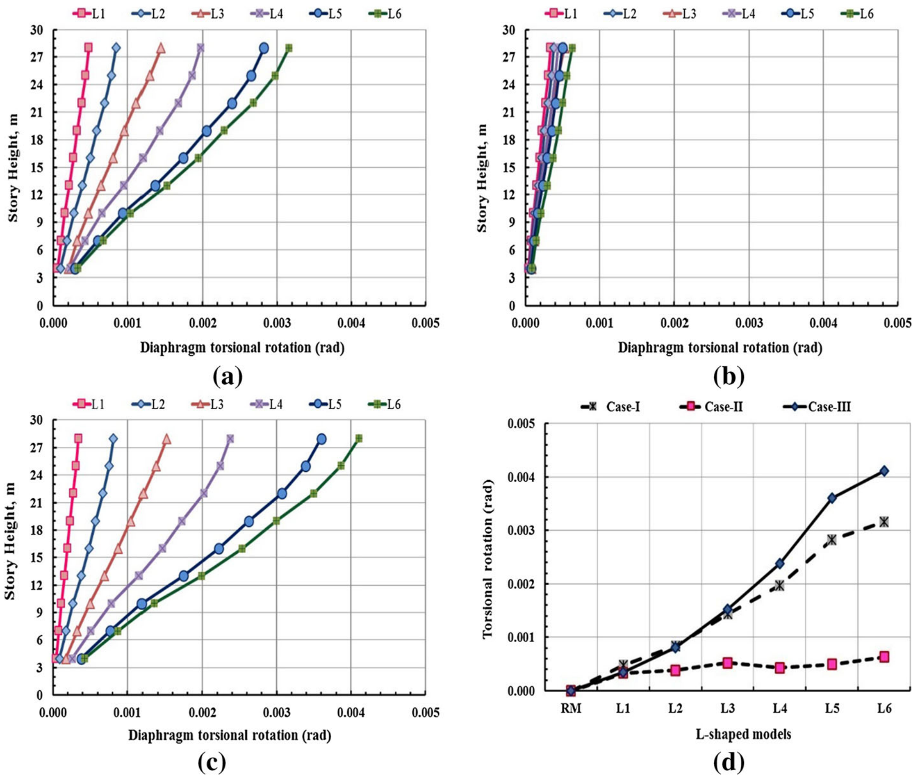


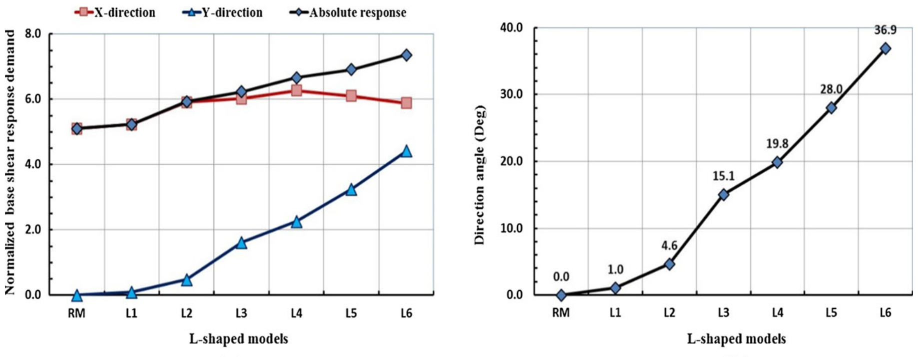
Fig. 13 Diaphragm torsional rotation response demands. **a** Torsional rotation along models' height; case-I, **b** torsional rotation along models' height; case-II, **c** torsional rotation along models' height; case-III, **d** maximum torsional rotation

Figure 13a shows the torsional diaphragm rotation for L-shaped building over models' height; with the detrimental increase in eccentricity for models, the torsional response demand will be more head strong action proceeding influence in torsional diaphragm rotation for L-shaped models. All stories undergo a rotation as well as displacements in two directions; the floor rotation angle responses significantly increase upwards reaching the maximum value at the top level of models. Whereas the torsional irregularity ratios are slightly vary along the building's height; decrease upwards for models L1–L3; while increase for models L4–L6. The maximum torsional diaphragm rotations for the unidirectional spectrum applied along the fixed structural reference axis (Case I: x-direction) are 0.0005, 0.0008, 0.0014, 0.0020, 0.0028 and 0.0032 rad for L-shaped models L1–L6, respectively. The floor rotations increase in proportion to the story numbers.

Figure 13b–d illustrate the effects of incidence angles of input spectrum for different L-shaped models on the calculated torsional rotation. The calculated torsional rotation are underestimated for the input spectrum along the stiff direction "Case II", the response values reach 0.0003, 0.0004, 0.0005, 0.0004, 0.0005 and 0.0006 for models L1–L6 compared to that of conventional design direction "case I", respectively. While, the developed torsional rotation demands are significantly increased for the input spectrum along the flexible direction "Case III", they reach 0.0003, 0.0008, 0.0015, 0.0024, 0.0036 and 0.0041 through models L1–L6 compared to that of conventional design direction "case I", respectively. The calculated torsional rotation is more sensitive the incidence angle of the input spectrum; especially for highly irregular model, L6. It has 0.0032 rad for the conventional case-I; but displays a lower value of 0.0006 rad for case-II and a higher value of 0.0041 rad for Case-III.

5.2.4 Normalized base shear force response demands

Normalized shear force presents shear force response demand at base as ratio to building's weight ($V_b/\Sigma W$); this parameter allows accurate comparison between buildings which accumulate different areas with different lumped masses. The successful comparison between regular reference model RM and L-shaped models in this manner equip real simulation for shear force is demanded according to seismic response for models. Figure 14a shows that normalized base shear force for each model in the seismic loading direction "*x*-direction", *y*-direction and absolute response, The absolute base shear force response demand significantly increases with gradually increasing in eccentricity between the center of mass and the center of rigidity due plan configuration irregularity in the L-shaped buildings. The regular model "RM" displays the lowest normalized shear force demand of 5.1%, while with the development of plan irregularity in L-shaped models; the normalized shear force demand get higher values of 5.2, 5.9, 6.2, 6.7, 6.9, 7.4% for models L1–L6, respectively. The additional shear force response demand developed in the perpendicular direction to earthquake direction could violate the safe design for resisting elements; which is attributed to lateral–torsional coupled behavior that may cause disastrous effect for lateral load resisting element. Figure 14b shows accidental angle for the absolute base shear force response generated from lateral–torsional coupling action due to significant development in eccentricity in L-shaped buildings. The regular model has fully unidirectional shear force response, while the accidental angle of absolute base shear force response for L-shaped models record maximum deviation of 36.9 degree from the reference *x*- for L6 model. The incidence angle of input spectrum has slight effect (not more than 1%) on the normalized absolute shear force response demands for L1–L4 models, while gets a significant effect for models L5 and L6, reach 4.7 and 10.1% high for input spectrum in the stiff direction "Case-II", reach 9.2 and 19.4% low for input spectrum in the



(a) **(b)**

Fig. 14 Normalized base shear force response demand and absolute response accidental angle, case I. **a** Normalized base shear force, **b** accidental angle flexible direction “Case-III”, compared to the unidirectional spectrum applied along the fixed structural reference axis (Case I: x-direction).

5.2.5 Normalized overturning and torsional moment response demands

Normalized overturning and torsional moment presents moment response demand at base with respect to multiplication building’s weight by its height equals ($M_B/\Sigma W \cdot h$); this parameter allows accurate comparison between buildings which accumulate different areas and lumped masses. The successful comparison between regular reference model and L-shaped models equip real simulation for the overturning and torsional moments’ demand according to seismic response for models. Figure 15a shows the normalized absolute overturning moment response that is created at foundation level for each model. The normalized overturning moment at base significantly increases with gradually increasing in eccentricity due to configuration irregularity, whereas regular model demand shows the lowest value 5.76%. The normalized overturning bending moment demands increase with the development of eccentricity in L-shaped models; their values are 5.96, 6.49, 6.88, 7.26, 7.54, 8.18% for models L1–L6, respectively. The seismic normalized overturning moment response exchanges safe design for resisting element to unsafe element suffering from the additional force that is induced in y-direction due to torsion action causing a disastrous effect on the lateral load resisting element. The incidence angle of input spectrum has slight effect (not more than 1%) on the normalized absolute overturning moment response demands for L1–L3 models, while gets a significant effect for models L3–L6, reach 3.8, 10.6, 15.1% high for input spectrum in the stiff direction “Case-II”, reach 3.9, 7.9, 11.9 low for input spectrum in the flexible direction “Case-III”, compared to the unidirectional spectrum applied along the fixed structural reference axis (Case I: x-direction).

Figure 15b shows the normalized absolute torsional moment response that is created at foundation level for each model. The normalized torsional moment at base significantly increases with gradually increasing in eccentricity due to configuration irregularity. The incidence angle of input spectrum has significant effect on the normalized absolute torsional moment response demands for RM and L-shaped models; the Case-II of input spectrum in the stiff direction displays the lowest values of normalized absolute torsional moment response demands, while Case-III of input spectrum in the flexible direction displays the highest response demands. As a result, the related lateral shear forces in

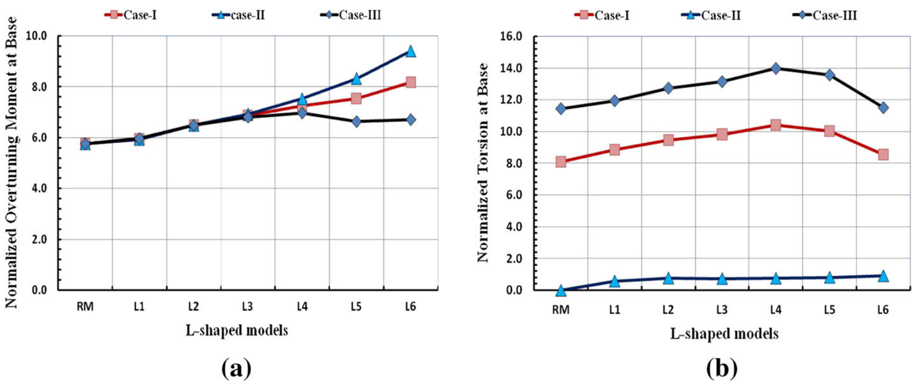


Fig. 15 Normalized moment response demands. **a** Overturning moment response, **b** torsional moment response

vertical resisting elements located on the periphery of the L-shaped buildings could be significantly increased in comparison with the corresponding values for a symmetric building. Torsion causes variations in column drift; therefore inter-story drift cannot capture the localized variation in demand because the drift of columns varies according to their in-plan positions.

5.2.6 *Capacity ratio for columns at base*

The columns is designed and sized such that they don't fail in brittle shear prior to failing in flexure moment, and even after damage during an active earthquake, vertical elements should have sufficient capacity to withstand the imposed vertical forces. So, it is essential to evaluate the columns' safety based on the capacity ratio calculated from column axial load-biaxial moment interaction diagram. The column capacity ratio gives an indication of the stress condition with respect to the capacity of the column; it is a measure index for the demand/capacity ratio of the columns. The maximum, minimum, average and standard deviation (SD) for capacity ratio values at column base for different models are listed in Table 3. It is clear that the floor plan irregularity has significant effects on the demand/capacity ratio of the columns. The standard deviation for capacity ratio for columns at base reflects the variation in lateral load distribution due to lateral–torsional coupled behavior of the L-shaped models. Figure 16 show the variation of capacity ratio for column at base along *x*-axis for regular and L-shaped buildings; it is clear that the plan configuration irregularity has significantly effects on capacity ratio and biaxial bending moment demands. The comparison define a significant trend for a severe turn in seismic design requirements for columns due to plan irregularity, with irregularity development for L-shaped models, the capacity ratio face the torsional hazard such that several columns will be overstressed. The columns located near re-entrant corners are subjected to huge shear forces when compared to other columns, therefore such additional shear force due to torsional moments should be considered in the design of the irregular buildings.

6 Summary and conclusions

The plan configuration irregularity of L-shaped buildings have significant effects on the seismic response demands due to lateral–torsional coupled behavior and stress concentration. In the plan irregular buildings, the torsion phenomenon can induce additional force demand in structural elements at the outer perimeter of the building. This study aims to investigate structural seismic response demands for the class of L-shaped buildings through evaluating the plan configuration irregularity of re-entrant corners and lateral–torsion

Table 3 Capacity ratio of columns at base for different models

Capacity ratio	RM	L1	L2	L3	L4	L5	L6
Maximum	0.780	0.956	0.973	1.028	1.083	1.217	1.700
Minimum	0.380	0.376	0.377	0.385	0.398	0.426	0.459
Average	0.433	0.527	0.526	0.543	0.558	0.616	0.727
Standard deviation	0.082	0.135	0.136	0.141	0.155	0.183	0.304

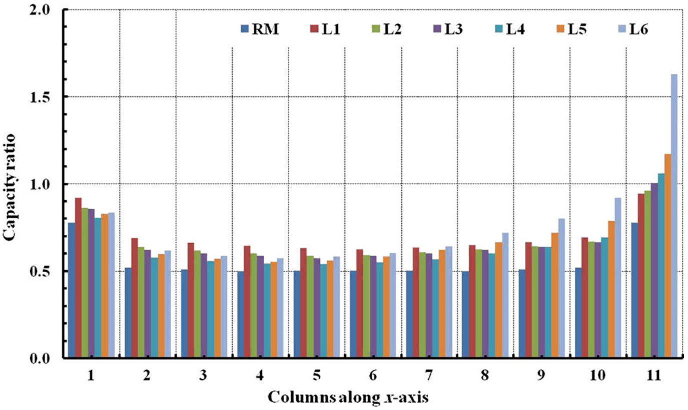


Fig. 16 Capacity ratio for columns along *x*-axis

coupling effects on measured seismic response demands. The mathematical models for the regular and irregular L-shaped buildings are developed using ETABS software to determine the seismic response demands. The measured responses include story drift, inter-story drift, story shear force, overturning moment, torsion moment at the base and over building height, and torsional irregularity ratio. Three dimensional finite element model for nine stories symmetric buildings as reference model is developed. In addition, six L-shaped building models are formulated with gradual reduction in the plan of the reference building model. The maximum structural response associated to the most critical directions of ground seismic motions has been examined. For all models, the variation with incident angle of seismic response demands of the L-shaped buildings is being investigated. The results are compared with that of reference model of symmetric building "RM". Three cases of incidence angle (0°, 45° and 135°) for the input response spectrum are investigated and compared. The response spectrum is applied along the x-direction "case I"; and along the principal directions of equal wing L-shaped buildings 45° direction "case II: stiff direction" and 135° direction "case III: flexible direction". The building models are analyzed to calculate the peak dynamic responses. The main finding results of the study are summarized as follows:

In both regular and L-shaped irregular buildings, the computed periods from empirical expressions in different codes are significantly shorter than those computed from structural models. The code formulas have a significant defect in the calculation of vibration period which is considered the main parameter for lateral force procedure. Moreover, the irregular L-shaped buildings exhibit special coupled lateral–torsional vibration modes; the more irregular the structure, the larger number of modes is needed for accurate determination of the dynamic response of the building structure. The story lateral displacement and inter-story drift ratio demands of asymmetric L-shaped models are larger than those of the corresponding symmetric buildings. The absolute story lateral displacement response increases as the plan configuration irregularity increases that could be a harmful act on non-structural elements. The absolute inter-story drift response ratio increases as the floor plan irregularity increases, the inter-story drift response along the height of the building shows that the middle stories are more affected than Lower and upper stories. The shear force demands in vertical resisting elements located on the periphery of the structure are significantly increased in comparison with that in symmetric buildings. For particular ranges of the key parameters defining the structural system irregularity, lateral–torsional coupled behavior induces a significant amplification of earthquake forces which should be accounted for in the seismic design. The absolute overturning moment response located at foundation level calculated from seismic analysis for L-shaped models are clear exemplified in effect of plan irregularity, poor configuration of structural components could harm the building's stability. Since the floor diaphragm is not stiff enough as the case of L-shaped floor, the dynamic response of the structure will be influenced significantly by the distribution of the lateral forces at its level. The lateral differential deformation and torsion action dominate the seismic behavior dominate, hence cause local damage to the outer columns threaten the building's robustness during the earthquake.

The developed absolute lateral displacement and inter-story drift ratio demands are significantly decreased for the input spectrum along the stiff direction "Case II" for models L1–L6 compared to that of conventional design direction "case I". The low response with lower limit could be attributed to the disappearance of the eccentricity due to plan configuration irregularity, hence minimization of torsional behavior effect. While, the developed absolute lateral displacement and inter-story drift ratio demands are significantly increased for the input spectrum along the flexible direction "Case III" for models L1–L6 compared to that of conventional design direction "case I". The high response with upper limit could be attributed to the maximization of the eccentricity due to plan configuration irregularity, and associated torsional behavior effects. Although in the seismic design of structures, the direction of ground motion incidence is usually applied along the fixed structural reference axis (Case I: *x*-direction), the maximum structural response could be associated to the most critical directions of input seismic force. For the model L6 with the most severe plan configuration irregularity, the developed absolute lateral displacement and inter-story drift demand display the lowest reduction of 29% under response spectrum in the stiff direction "Case II", while the highest increase of 18% under response spectrum in the flexible direction "case III".

The developed torsional irregularity ratio and diaphragm torsional rotations are more sensitive to the incidence angle of input spectrum. For the model L6 with the most severe plan configuration irregularity, the calculated torsional irregularity ratio is more sensitive the incidence angle of the input spectrum; especially for highly irregular model, L6. It has 1.32 for the conventional case-I; but displays a lower value of 1.13 for case-II and a higher value of 1.50 for Case-III. The incidence angle of input spectrum has significant effect on the normalized absolute torsional moment response demands for RM and L-shaped models; the Case-II of input spectrum in the stiff direction displays the lowest values of normalized absolute torsional moment response demands, while Case-III of input spectrum in the flexible direction displays the highest response demands. As a result, the related lateral shear forces in vertical resisting elements located on the periphery of the L-shaped buildings could be significantly increased in comparison with the corresponding values for a symmetric building. The plan configuration irregularity has significantly effects on capacity ratio and biaxial bending moment demands. Plan irregularities affect the distribution of stiffness and in turn affect capacity, hence cause non-uniform damage states among the columns within a single floor. The torsional response of non-symmetric buildings under earthquake excitations makes their design for earthquake actions substantially more complicated than the design of symmetric buildings whose response is purely translational. Moreover, Torsion causes variations in column drift; therefore inter-story drift cannot capture the localized variation in demand because the drift of columns varies according to their in-plan positions.

From the current study results, it could conclude that the floor irregularity in L-shaped buildings plays a considerable role in the seismic behavior of MRF building including a substantial increase in the lateral deflection and inter-story drift response demands, could significantly alter the performance level of the structures. The results support the combination rules given in the current codes; but higher values is required for irregular structures, hence the codified combination rules could be essentially deficient to seismic response demands of irregular structures. The seismic normalized overturning moment response exchanges safe design for resisting element to unsafe element suffering from the additional force that is induced due to torsion. The outcomes results confirm the significant effects of the plan configuration irregularity on the seismic demands that necessitate an integrated cooperation between the architect and structural engineer from the earliest planning phase of building to guarantee structural safety and reduce vulnerability.

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