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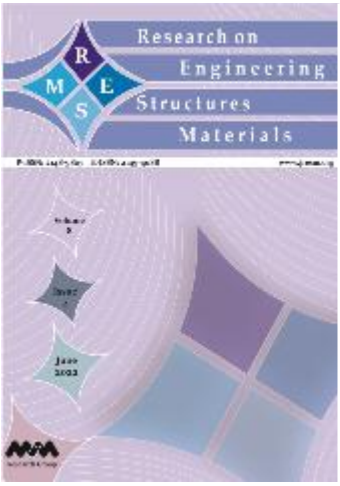

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Research Article

Seismic behaviour of re-entrant dominant RC frame buildings

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Abstract

Reinforced Concrete (RC) building stocks with plan and/or vertical irregularities are built routinely world-wide, despite being vulnerable to seismic forces. Irregular RC buildings with asymmetry, mass and stiffness irregularities have been well researched, however, seismic behaviour of RC building with re-entrant corner type plan irregularity is given relatively less attention. In the present study, a total of 104 re-entrant corner dominant plan irregular RC building models (C-, L-, T- and PLUS-shaped) are developed along with one regular rectangular building. Plan Irregularity Descriptors (PIDs) are summarized with their limit of regularity and are evaluated for building models. Building models have uni-directional and bi-directional re-entrant corner of A/L ratio ranging between 0.1 to 0.8 in the X-direction and between 0.2 to 0.8 in the Y-direction. Seismic response quantities; peak displacement, peak storey drift, normalized base shear and normalized overturning moments are evaluated using the equivalent static method and response spectrum method specified by the Indian seismic code. It has been found that building models yield amplified peak displacement responses in the direction perpendicular to that of applied seismic forces. Other seismic response parameters for all re-entrant RC building models fall well within code based permissible limits. A/L ratio limit specified by the Indian seismic code is found to be conservative. Out of various building models considered, C-shaped building models perform well under seismic forces, while PLUS-, L- and T-shaped RC building models with A/L ratio $\geq$ 0.4, in both directions, overshoot torsional irregularity descriptor, $\frac{\Delta_{max}}{\Delta_{avg}}$.

1. Introduction

Buildings with simple and regular configurations offer good seismic behaviour due to uniform lateral stiffness and strength distribution. However, building with irregular configurations becomes inevitable for various reasons like natural ventilation & illumination, limited availability of land, rapid urbanization and aesthetics [1,2]. Irregular buildings are broadly classified as plan and vertical irregulars, suffering substantial damage under seismic excitation has been a cause of concern for the research fraternity and is an active area of research for the past few decades [3]. Real buildings are mostly irregular due to either unsymmetric distribution of mass, stiffness, strength or a combination thereof or the presence of plan and/or vertical irregular configuration. Irregular buildings are prone to structural damage due to torsion, diaphragm deformation and stress concentration under seismic forces. Since the early 1970s, experimental and analytical research studies, have been conducted to understand the impact of irregularities on the seismic response of the building. Studies have revealed that strength and stiffness

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eccentricities modify building behaviour, leading to unsatisfactory seismic performance. Owing to complexities in modelling and the involvement of a large number of parameters, research efforts to understand the seismic behaviour of irregular buildings have been limited. Therefore, seismic design codes, worldwide, have limited guidelines with detailed discussion missing on irregularities. Prescribed limits of various types of irregularities in seismic design codes are by and large conservative and exceedance of limit is not permitted, else they recommend altering the structural configuration and/ or architectural planning. The design of irregular buildings becomes more complicated than regular buildings due to the presence of torsional response under earthquake excitation. And has been given attention in the past several decades. It is still an open area of research due to, varied provisions across seismic design codes. Seismic design codes have introduced provisions of accidental eccentricity as an additional loading condition primarily for irregular buildings.

Initial investigations on torsional response were through simplified single-storey rigid deck structures with two or three Degrees of Freedom (DoFs) supported on vertical shear-type elements. A comprehensive review paper by Anagnostopoulos et al. [4] has a detailed discussion on the torsional response of buildings from early 1938 to the time of its publication that provides a well-laid foundation. Goel and Chopra [5] studied the elastic and inelastic seismic response of plan asymmetric one-storey systems to show that the seismic response of an inelastic system is affected less by plan asymmetry compared to an elastic system. Single storey model designed by different seismic code criteria was investigated considering the nonlinear behaviour, random stiffness & strength of the structural elements and uncertain location of the Centre of Mass (CM) on the performance of a symmetric building using, deterministic and probabilistic approaches [6]. Elastic analysis of a single-storey building under a set of seismic excitations showed that the lateral-torsional response of the building is sensitive to both structural and ground motion characteristics [7]. Stathopoulos and Anagnostopoulos [8] examined shear beam type and plastic hinge type single-storey models for a set of seismic excitations to find that ductility demands of the stiff side increase while no effect on the flexible side of the shear beam type models. Peter and Iztok [9] have performed a parametric study of a single-storey asymmetric building to determine inelastic seismic response under bi-directional earthquake ground motions. Preliminary results based on a limited number of test models revealed that maximum response quantities can be obtained by performing uni-directional analyses and results can be combined by the Square Root of the Sum of Square rule though more investigations are needed. Influence of bi-directional seismic excitations on inelastic behaviour of in-plane irregular one-storey models with one symmetry axis showed that orthogonal elements always remain elastic while parallel elements undergo inelastic deformation under uniaxial analysis leading to a minor change in inelastic response of the models [10].

3D idealized buildings representing more realistic characteristics of the building as compared to the single-storey models were investigated for torsional effects under seismic excitations. Pinho et al. [11] have applied four Nonlinear Static procedures (NSPs); Capacity Spectrum Method (CSM), N2, Modal Pushover Analysis (MPA), Adaptive Capacity Spectrum Method (ACSM) on 3D SPEAR building tested in full scale under pseudo-dynamic conditions under bi-directional seismic loadings. It has been found that all NSPs yield satisfactory results while ACSM showed better capacity in capturing response under involved intensity. Bhasker and Menon [12] studied various torsional irregularity indices for capturing torsional effects under various intensity levels of seismic excitations using Multiple Strip Analysis (MSA). It has been shown that no scalar index of irregularity correlates well with seismic demand at all intensities, however, $\Delta_{max}/\Delta_{min}$ index is the most effective for low-intensity levels. Very limited research is conducted to understand the difference between rigid and flexible floor analysis of 3D building models. Ju and Lin [13] studied L- and U-shaped FE-based 3D building models using Response Spectrum Method (RSM) with rigid and flexible floors and found that building models with shear walls are more sensitive to flexible floor analysis. Fang and Leon [14] studied the torsional behaviour of braced frames of a 3D steel structure with rigid and semi-rigid floor and showed that the ultimate strength of the structure is higher with a rigid diaphragm than a semi-rigid diaphragm. Research on plan irregular buildings with re-entrant corners is in its initial phase. Khanal and Chaulagain [1] have studied plan irregular L-shaped buildings with re-entrant corners under varying angles of the input response spectrum. It has been found that a 135-degree angle yields a significant increase in seismic response demand.

Several reconnaissance studies performed during various earthquakes; Japan (1978), Athens (1999), Bhuj (2001), Bam (2003), Nepal (2015) and Imphal (2016) have reported damages to buildings due to symmetry and predominantly irregularity [1,3,7]. One of the worth studies conducted at the National Autonomous University of Mexico (UNAM) in Mexico City for the 1985 Mexico earthquake, reveals that out of 331 surveyed severely damaged and collapsed buildings, about 8 % were soft-story structures, 42 % were corner buildings, 15 % had story stiffness eccentricities and 40 % had experienced middle and top storey collapse [2]. It has been realized from the literature review that most of the research efforts have been made to understand the seismic behaviour of asymmetric structures and relatively fewer efforts towards other types of irregular buildings, especially, buildings with plan irregularity [3]. Fig. 1 shows the research contributions, up to the paper published, in different domains of irregular structures. It is realized that seismic behaviour of plan irregular buildings with re-entrant corners of geometrical shape C-, L-, T-, PLUS-, etc. are less researched and thus, identified as a research gap.

The present paper aims to study the seismic behaviour of re-entrant dominant plan irregular ten-storey RC frame buildings of geometrical shapes, i.e., C-, L-, T- and PLUS-. PIDs defined by seismic design codes of various countries are studied, summarized and computed to establish that RC buildings possess dominant uncoupled re-entrant corner type plan irregularity. Total 32 nos. of 3D building models are developed with A/L ratio ranges between 0.1 to 0.8 in X- direction and 0.2 in Y-direction for each geometrical shape.

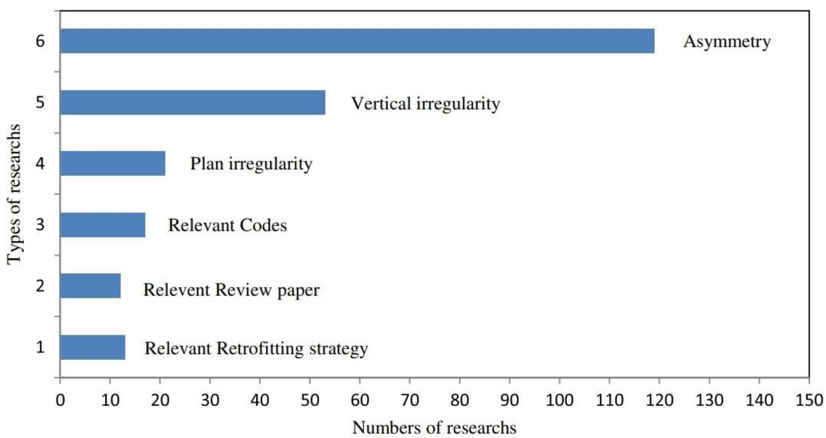


Fig. 1 Research on asymmetric/ irregular structures [3]

Seismic response parameters; peak displacement, peak storey drift, normalized base shear and normalized overturning moment are evaluated. Total of 72 nos. of 3D re-entrant dominant RC building models with an A/L ratio, which varies between 0.4 to 0.8 in the

Y-direction are developed to study the seismic behaviour of these models with bi-directional re-entrant corners. The study is extended to include the effect of rigid and flexible (semi-rigid) diaphragms on the seismic behaviour of plan irregular re-entrant dominant RC building models.

2. Plan Irregularity Descriptors (PIDs)

Seismic design codes worldwide define irregularity, both plan and vertical, for buildings with limits on regularity. Physical parameters like; projection ratio, static eccentricity, torsional radius, mass-radius of gyration, floor displacement, fundamental period of torsional mode, area of cut-outs, out-of-plane offsets, etc. with specific limits have been used by the seismic design code to quantify types, and degree of irregularity exists in the building. Stringent recommendations on irregularities are imposed to ensure the good seismic performance of a building. Table 1 summarizes various PIDs along with their definition and limits of regularity prescribed by the seismic design code of representative countries of seismically active regions. RC buildings are routinely encountered with torsional irregularity type of plan irregularity mostly due to plan asymmetry and/or stiffness asymmetry of the lateral load-resisting structural system. Thus, most PID definitions are associated with torsional irregularity while the other four types of irregularity have a single PID definition as shown in Table 1. Thus, it is evident that plan irregularities other than torsional irregularity are relatively less researched.

Table 1. Plan Irregularity Descriptors; their definition and limits of regularity for buildings

Types of Irregularity	Plan Irregularity Descriptor (PID) with description and limit of Regularity (Seismic Design Code of the Country)
Re-entrant Corner	$\frac{A}{L}$ ratio where, A= projection length and L= Plan dimension
	> 0.15 (India [15], Bangladesh [16], Pakistan [17], Philippines [18], Nepal [19], Korea [20], EL Salvador [21]); > 0.2 (Peru [22], Turkey [23]); > 0.25 (Algeria [24], Iran [25]); >0.3 (China [26])
Torsional Irregularity	Normalized static eccentricity ratio, $\frac{e_{kx}}{L}$ or $\frac{e_{ky}}{B}$ $e_{kx} = x_r - x_m$; $e_{ky} = y_r - y_m$ where, e_k = Static eccentricity; x_m & y_m= Distance of centre of mass in X- and Y-direction, respectively; x_r & y_r= Distance of centre of rigidity in X- and Y-direction, respectively; L & B = Plan dimension in X- and Y-direction, respectively
	≥ 0.1 (EL Salvador, Mexico [27]); ≥ 0.15 (Portugal [12], Algeria); ≥ 0.2 (Egypt [12], Iran [12])
	(i) Static eccentricity (e_k) to torsional radius (r_k) ratio, $\frac{e_{kx}}{r_{kx}}$ or $\frac{e_{ky}}{r_{ky}}$ where, $r_{kx}=\sqrt{\frac{\Sigma(k_{xi}(y_i-y_r)^2)+\Sigma(k_{yi}(x_i-x_r)^2)}{\Sigma k_{yi}}}$; $r_{ky}=\sqrt{\frac{\Sigma(k_{xi}(y_i-y_r)^2)+\Sigma(k_{yi}(x_i-x_r)^2)}{\Sigma k_{xi}}}$ where, r_m= Mass radius of gyration; k_{xi} & k_{yi} = stiffness of an element in X- and Y-direction, respectively and x_i & y_i = distance of an element with respect to reference axis in X- and Y -direction, respectively
	≥ 0.15 (Japan [12]); > 0.3 (Europe [28])
	(ii) Torsional radius (r_k) to Mass radius of gyration (r_m) ratio, $\frac{r_{kx}}{r_m}$ or $\frac{r_{ky}}{r_m}$, where, $r_m=\sqrt{\frac{\Sigma m_i d_i^2}{\Sigma(m_i)}}$ where, m_i= lumped mass and d_i= redial distance from CM
	≤ 0.8 (Italy [12]); < 1 (Europe); $\frac{r_{kx,CM}}{r_m}$ or $\frac{r_{ky,CM}}{r_m}$ ≤ 1 (Greece [12])

	(iii) Maximum to the minimum or average floor displacement, $\frac{\Delta_{max}}{\Delta_{min}}$ or $\frac{\Delta_{max}}{\Delta_{avg}}$ where, $\Delta_{max}, \Delta_{min}$ and Δ_{avg}= Maximum, minimum and average floor displacement, respectively
	$\Delta_{max}/\Delta_{min}$: > 1.5 (India, Nepal); $\Delta_{max}/\Delta_{avg}$: ≥ 1.2 (Bangladesh, China, India, Iran [12], Pakistan, Philippines, Taiwan [12], Turkey, USA [12]); ≥ 1.3(Peru); $\Delta_{max}/\Delta_{avg}$ ≥ 1.4(New Zealand [29], Bangladesh-extreme); ≥ 1.7 (Canada [30]); $\Delta_2 - \Delta_1 \geq 0.002H$ (Chile [31], $\Delta_2 - \Delta_1$=max relative displacement between two consecutive floors and H=storey height); $\left(\frac{\Delta_{max}}{\Delta_{avg}}\right)_{drift}$ > 1.2 (EL Salvador, Korea)
	(iv) The ratio of fundamental torsional to translational modes time period, $\frac{T_\theta}{T_x}$ and $\frac{T_\theta}{T_y}$, where, T_x and T_y= Fundamental time period of translational mode in X- and Y-direction, respectively and T_θ= Fundamental time period of torsional mode
	> 1 (India)
Floor Slabs having excessive Cut-outs or Openings	Opening located anywhere in the slab
	> 0.1 opening edge (India); >0.15 (Algeria); >0.3 (China) ;>1/3 (Turkey); > 0.5 (Bangladesh, EL Salvador, India, Iran, Korea, Nepal, Pakistan, Peru, Philippines)
Out-of-plane offsets in Vertical Elements	Structural walls or frames are moved out of a plane in any storey along the height of the building
	India, Bangladesh, Canada, EL Salvador, Korea, Pakistan, Philippines, Nepal
	(i) In addition to (i), (a) For any single column j, the tangent of the offset angle, $\frac{a_j}{b_j} > 0.4$ (b) Average of the absolute values of the tangent of the offset angle, $\frac{\sum^{N_c}\left\lvert\frac{a_j}{b_j}\right\rvert}{N_c} > 0.1$ where, a_j = the horizontal offset at column j b_j = the vertical distance between the base of the upper column and the top of the lower column j N_c = number of columns at the level under consideration
	New Zealand
Non-parallel Lateral Force System	Vertical structural systems resisting lateral forces are not oriented along the two principal orthogonal axes in the plan
	India, Bangladesh, Canada, EL Salvador, Korea, Pakistan, Philippines

3. Re-entrant Dominant Irregular Building Models

A regular ten-storey RC building of plan dimension $50\ \text{m} \times 50\ \text{m}$ with a square module of $5\ \text{m} \times 5\ \text{m}$ each, placed symmetrically in both directions is considered as a basic plan configuration. Irregular RC buildings of various C-, L-, T- and PLUS-shaped geometrical shapes are derived by removing nos. of square modules appropriately from the basic plan configuration of a square regular building. Fig. 2 shows regular RC buildings along with C-, L-, T- and PLUS-shaped irregular RC buildings derived from regular RC building to have re-entrant corners.

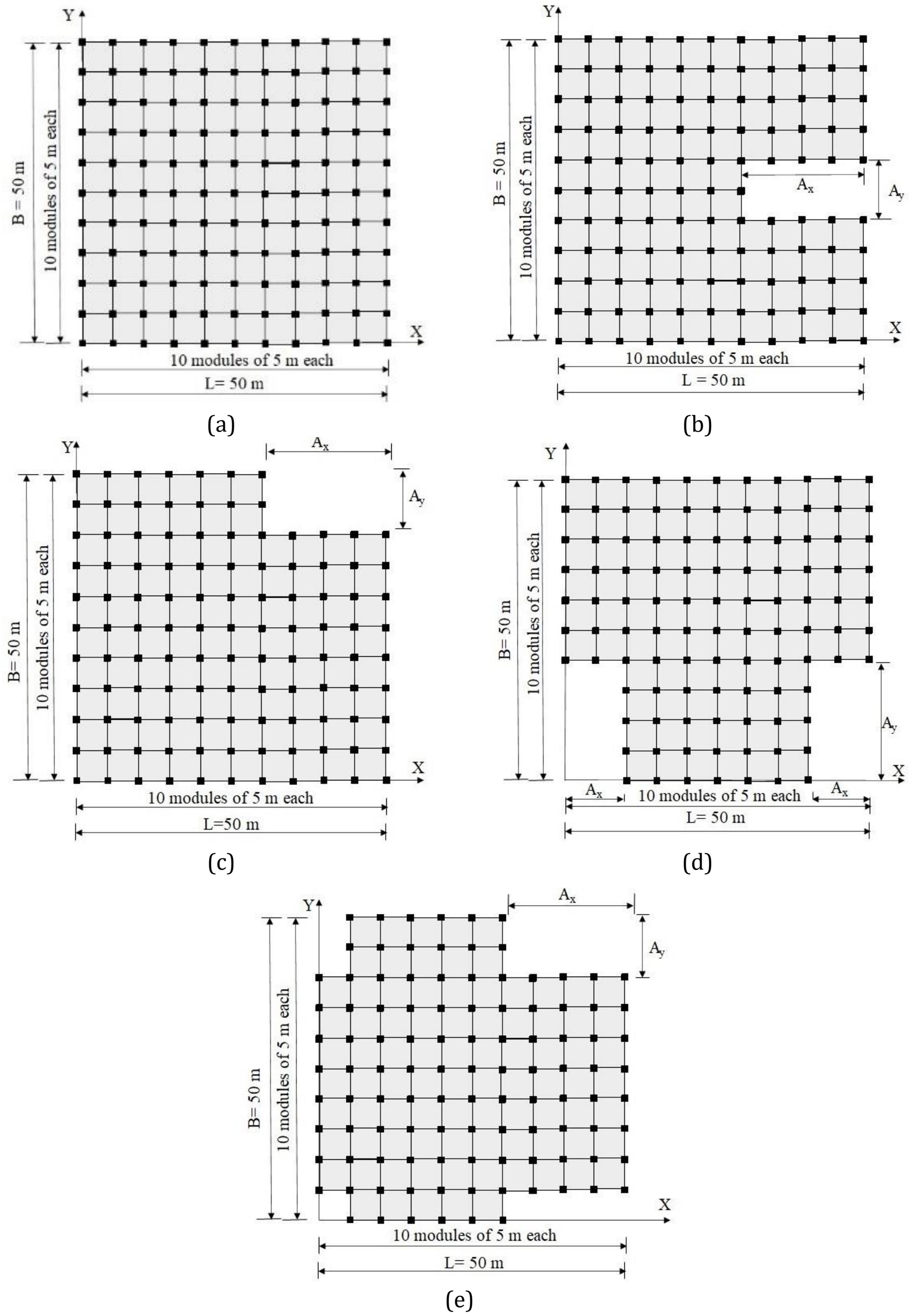


Fig. 2 Regular and plan irregular RC building models with A/L ratio 0.4 in the X-direction and 0.2 in the Y-direction, (a) Regular; (b) C-shaped; (c) L-shaped & (e) PLUS-shaped with A/L ratio 0.4 in the X direction and 0.2 in the Y-direction and (d) T-shaped with A/L ratio 0.2 in the X-direction and 0.4 in the Y-direction

Two categories of re-entrant dominant plan irregular RC building models developed are, (i) uni-directional re-entrant models having A/L ratio ranges between 0.1 to 0.8 in

X-direction with A/L ratio of 0.2 in Y-direction for C-, L- and PLUS-shaped RC building models. In T-shaped RC building models- A/L ratio of X-direction is 0.2 and in Y-direction it ranges between 0.1 to 0.8; (ii) bi-directional re-entrant models having A/L ratio ranges between 0.1 to 0.8 in X-direction with A/L ratio ranges between 0.2 to 0.8 in Y-direction for C-, L- and PLUS-shaped RC building models. In T-shaped RC building models A/L ratio varies from 0.1 to 0.8 in Y- direction with A/L ratio ranges between 0.2 to 0.4 in X-direction. RC building stocks with relatively high A/L ratio, both, uni-directional and bi-directional are practiced due to one or other reasons as discussed earlier.

Building models are analyzed and designed by, the Limit State Method (LSM) following Indian design code IS 456:2000 [32] for, gravity and lateral loading. IS 875 (Part-1, 2) [33,34], and IS 1893 (Part-1) codes are used for defining gravity and seismic loading definition, respectively.

Table 2. Geometric and design inputs for regular and irregular RC buildings

Geometric Details of RC Building	
Structural system	Moment Resisting Frame (MRF)
Shape of the building	C, L, T and PLUS
Centre-to-centre distance between frames in each direction	5 m
Typical floor height	3 m
Slab thickness	150 mm
Beam size	300 mm × 450 mm
Column sizes	600 mm × 600 mm (Typical floor nos. 1 to 3)
	500 mm × 500 mm (Typical floor nos. 4 to 6)
	400 mm × 400 mm (Typical floor nos. 7 to 10)
Diaphragm type	Semi-rigid, Rigid
Design Inputs of RC Building	
Gravity Loading Definition	
Impose load (Live load)	3 kN/m² for a Typical floor 1.5 kN/m² for Roof floor
Floor finish	1 kN/m²
Seismic Loading Definition	
Seismic zone factor	0.36 (∵ seismic zone-v)
Importance factor	1.2
Response reduction factor	5 (∵ SMRF)
Soil type	Medium stiff
Damping	5 % of critical damping
Time period estimation	Code-based formula; Programme calculated
Seismic Analysis Method	
Equivalent Static Method (ESM)	---
Response Spectrum Method (RSM)	
Nos. of participating modes	Up to mass participation ≥ 90%
Participating modes	$\left[\{\emptyset_{ik}\}_x \ \{\emptyset_{ik}\}_y \ \{\emptyset_{ik}\}_\theta\right]$ at the floor i in mode k Where, x, y = Translational degrees of freedom θ = Rotational degree of freedom
Material Definition	
Concrete	f_{ck} = 25 MPa for $M25$ grade
Steel	f_y = 415 MPa for HYSD

The highest seismic zone is considered to have maximum seismic demand on plan irregular building models. The floor of the regular RC building models is modelled as rigid diaphragm while plan irregular building model have flexible floor diaphragms following recommendations by the seismic design codes for seismic analysis of irregular buildings. Table 2 summarizes geometrical and design inputs for the analysis and design of various structural elements of the RC building models.

Computational 3D models of regular and irregular RC buildings are created using commercial ETABS software ($V18$) by CSI corporation, USA [35]. Masonry walls are not modelled in the 3D model as; (i) non-uniform distribution of walls may lead to accidental eccentricities which increase seismic demand and (ii) Stiffness contribution of masonry wall is generally not considered in practice as walls are treated as nonstructural element. The study aims to investigate the seismic behaviour of re-entrant dominant RC buildings. RC building models are analyzed by ESM and RSM as per Indian seismic design code. Both seismic analysis methods are required to be performed for each RC building models as per Indian seismic design code as base shear and seismic response parameters are required to be scaled up by a scaling factor, $\left(\frac{\overline{V_B}}{V_B}\right)$ where $\overline{V_B}$ is the base shear by ESM and V_B is the base shear by RSM when base shear and seismic response parameters obtained by RSM are lesser than those from ESM.

PIDs for re-entrant dominant RC building models are determined and are compared with those of regular RC building model. Table 3 summarizes PIDs for all RC building models conducted for the study and are limited to re-entrant corner and torsional irregularity types of plan irregularity only since other types of plan irregularity are absent in the RC building models. It is evident from Table 3 that all irregular RC building models are re-entrant dominant only since PIDs associated with torsional irregularity are well within prescribed limits of regularity defined by various seismic codes.

Table 3. Plan Irregularity Descriptors for regular and re-entrant dominant plan irregular RC buildings

Building Models	Plan Irregularity Descriptors (PIDs)											
	$\left(\frac{A}{L}\right)$		$\left(\frac{e_k}{B}\right)$		$\left(\frac{e}{rkcs}\right)$		$\left(\frac{rkcs}{rm}\right)$	$\left(\frac{rkcm}{rm}\right)$	$\frac{T_\theta}{T_X}$	$\frac{T_\theta}{T_Y}$	$\left(\frac{\Delta_{max}}{\Delta_{avg}}\right)$	
	X	Y	X	Y	X	Y	-	-	-	-	X	Y
Regular	0	0	0	0	0	0	1.062	1.062	0.930	0.930	1.064	1.064
C1* (0.1,0.2) #	0.1	0.2	0.004	0.004	0.009	0	1.033	1.033	0.935	0.931	1.064	1.065
C2 (0.2,0.2)	0.2	0.2	0.007	0.007	0.015	0	1.040	1.040	0.938	0.931	1.065	1.066
C3 (0.3,0.2)	0.3	0.2	0.009	0.009	0.020	0	1.034	1.034	0.942	0.931	1.064	1.067
C4 (0.4,0.2)	0.4	0.2	0.011	0.011	0.024	0	1.035	1.035	0.948	0.932	1.064	1.068
C5 (0.5,0.2)	0.5	0.2	0.011	0.011	0.025	0	1.038	1.038	0.953	0.933	1.063	1.069
C6 (0.6,0.2)	0.6	0.2	0.011	0.011	0.024	0	1.021	1.021	0.957	0.933	1.063	1.071
C7 (0.7,0.2)	0.7	0.2	0.009	0.009	0.020	0	1.010	1.010	0.962	0.932	1.062	1.062
C8 (0.8,0.2)	0.8	0.2	0.007	0.007	0.014	0	1.017	1.017	0.964	0.930	1.061	1.076
L1 (0.1,0.2)	0.1	0.2	0.001	0.000	0.001	0.001	1.063	1.063	0.930	0.929	1.065	1.065
L2 (0.2,0.2)	0.2	0.2	0.001	0.001	0.002	0.002	1.023	1.023	0.931	0.930	1.066	1.066
L3 (0.3,0.2)	0.3	0.2	0.001	0.002	0.003	0.004	1.064	1.064	0.931	0.930	1.068	1.068

L4 (0.4,0.2)	0.4	0.2	0.001	0.002	0.002	0.005	1.064	1.064	0.931	0.931	1.069	1.071
L5 (0.5,0.2)	0.5	0.2	0.001	0.003	0.001	0.007	1.064	1.064	0.932	0.932	1.069	1.073
L6 (0.6,0.2)	0.6	0.2	0.000	0.004	0.000	0.009	1.064	1.065	0.932	0.932	1.072	1.077
L7 (0.7,0.2)	0.7	0.2	-0.001	0.005	-0.003	0.011	1.066	1.066	0.931	0.930	1.076	1.082
L8 (0.8,0.2)	0.8	0.2	-0.003	0.006	-0.007	0.013	1.069	1.069	0.929	0.928	1.08	1.088
T1 (0.2,0.1)	0.2	0.1	0	-0.001	0	-0.003	1.065	1.065	0.929	0.929	1.066	1.066
T2 (0.2,0.2)	0.2	0.2	0	-0.002	0	-0.005	1.066	1.066	0.930	0.930	1.069	1.069
T3 (0.2,0.3)	0.2	0.3	0	-0.003	0	-0.007	1.067	1.067	0.930	0.930	1.074	1.071
T4 (0.2,0.4)	0.2	0.4	0	-0.003	0	-0.007	1.066	1.067	0.932	0.932	1.083	1.073
T5 (0.2,0.5)	0.2	0.5	0	-0.002	0	-0.006	1.066	1.066	0.934	0.934	1.092	1.074
T6 (0.2,0.6)	0.2	0.6	0	-0.001	0	-0.002	1.032	1.032	0.934	0.935	1.103	1.074
T7 (0.2,0.7)	0.2	0.7	0	0.001	0	0.003	1.026	1.026	0.933	0.934	1.116	1.075
T8 (0.2,0.8)	0.2	0.8	0	0.005	0	0.012	1.021	1.021	0.927	0.930	1.133	1.077
PLUS1(0.1,0.2)	0.1	0.2	0.000	0.000	0.000	0.001	1.066	1.066	0.929	0.929	1.069	1.068
PLUS2(0.2,0.2)	0.2	0.2	0.001	0.001	0.001	0.001	1.064	1.064	0.928	0.928	1.071	1.071
PLUS3(0.3,0.2)	0.3	0.2	0.001	0.001	0.002	0.002	1.068	1.068	0.929	0.929	1.073	1.075
PLUS4(0.4,0.2)	0.4	0.2	0.001	0.001	0.002	0.003	1.068	1.068	0.930	0.930	1.074	1.079
PLUS5(0.5,0.2)	0.5	0.2	0.000	0.002	0.000	0.004	1.068	1.068	0.930	0.930	1.075	1.084
PLUS6(0.6,0.2)	0.6	0.2	-0.001	0.002	-0.003	0.005	1.069	1.069	0.930	0.931	1.076	1.091
PLUS7(0.7,0.2)	0.7	0.2	-0.003	0.003	-0.007	0.007	1.071	1.071	0.929	0.929	1.077	1.100
PLUS8(0.8,0.2)	0.8	0.2	-0.006	0.004	-0.014	0.009	1.076	1.076	0.924	0.926	1.079	1.113

*Re-entrant RC building Model No., # (A/L ratio in X-direction, A/L ratio in Y-direction)

4. Results and Discussion

The seismic behaviour of RC building models with C-, L-, T- and PLUS- type geometrical shapes are presented in four parts; (i) unidirectional re-entrant RC building models; (ii) bi-directional re-entrant RC building models; (iii) Stress concentration in re-entrant RC building models and (iv) Diaphragm modelling of re-entrant RC building models. A three-dimensional seismic analysis of each RC building models is performed by considering both, rigid and flexible diaphragm using ETABS. Seismic response parameters; peak displacement, peak storey drift, normalized base shear $\left(\frac{V_B}{\sum W}\right)$-ratio of base shear to seismic weight of the building and Normalized Overturning Moment $\left(\frac{M_0}{\sum w_i h_i}\right)$ - ratio of overturing moment with product of weight and height of the building are evaluated. PIDs evaluated for each RC building models are re-evaluated to ascertain coupling of torsional irregularity with re-entrant corner type irregularity, especially for higher unidirectional and bi-directional A/L ratio. Shear stress distribution in the diaphragm of RC building models is studied with greater emphasis on RC building models with re-entrant corners. The effect of diaphragm modelling on the seismic behaviour of re-entrant dominant RC building models are investigated.

4.1. Uni-directional Re-entrant RC Building Models

Effect of increasing A/L ratio in a uni-directional direction is studied first with a constant A/L ratio of 0.2 in orthogonal direction. 28 out of 32 plan irregular RC building models are re-entrant dominant only since they exceed limit of regularity; A/L ratio of 0.15 as per the Indian Seismic code in X-direction. A/L ratio of 0.2 in Y-direction is considered to understand the immediate impact of re-entrant corner PID exceedance in Y-direction on seismic behaviour. Peak displacement of RC building models in X- and Y-directions due to seismic force are plotted in Fig. 3(a) and Fig. 3(b). It is evident that peak displacement response of plan irregular RC building models increases w.r.t. to regular RC building model except C-shaped re-entrant corner RC models. This is because C-shaped RC building models are symmetric about the horizontal axis with MR frames resisting lateral loads.

Most of the other types of re-entrant dominant RC building models show marginal increase of ~6 % in peak displacement response. T-shape building models; T5(0.2, 0.5); T6(0.2, 0.6); T7(0.2, 0.7) and T8(0.2,0.8) show an increase in peak displacement of 6.11 %; 8.02 %; 10.5 % and 13.98 %, respectively. It has been observed that peak displacement in Y-direction due to applied seismic force increases marginally ~5.44 % for all re-entrant corner RC building models, except PLUS type RC building models. PLUS-shaped RC building models; PLUS6(0.6,0.2), PLUS7(0.7,0.2) and PLUS8(0.8,0.2) response increase by 6.01 %, 7.9 % and 10.55 %, respectively vis-a-vis regular RC building models. C-, L- and PLUS-shaped building models with A/L ratio > 0.15 yield maximum increase of 4.75 %, 25 % and 35.04 %, respectively in Y-direction peak displacement due to X-direction seismic force.

However, this response shows maximum increase of 173 % for T-shape building models. X-direction peak displacement response due to seismic force in Y-direction of C-, L- and PLUS-shaped building models vary between 8.37 % – 48.91 %, 9.79 % – 98.15 % and 18.06 % – 161.21 %, respectively. However, this response varies between 16.75 % – 34.69 % for T-shaped building models. Fig. 3(c) and Fig. 3(d) show peak displacement response of re-entrant dominant RC building models in orthogonal directions to the applied seismic force, i.e., peak displacement in X-direction due to seismic force applied in Y-direction and vice-versa. Peak displacement of re-entrant dominant RC building models is found to be amplified for models with A/L ratio > 0.15. This is due to coupling between re-entrant type plan irregularity with a torsional response. Re-entrant dominant RC building models of C-, L- and T-shaped show almost identical peak displacement response for A/L ratio of 0.1. However, PLUS- shape re-entrant dominant RC building models yield ~10 % increase in peak displacement response in orthogonal directions to applied seismic loads in both X- and Y-direction. Therefore, seismic code limit of A/L ratio < 0.15 seems to be underrated and such type of plan irregular RC building should be avoided. It has been observed that re-entrant corner results in to torsional displacement and thus beyond certain value of A/L ratio re-entrant plan irregularity converted to torsional irregularity.

Peak storey drift ratio of all building models is evaluated as shown in Table. 4. It has been observed that almost all building models have peak storey drift value well within permissible limit of 0.004 times height of the storey i.e., 0.012(1.2 % drift ratio). Maximum peak storey drift value obtained for T8(0.2,0.8) building model is 0.0063 (0.63 % drift ratio) only.

Fig. 4(a) and Fig. 4(b) shows normalized base shear and normalized overturning moment for all building models in the direction of applied seismic forces, i.e., X- and Y-direction. These response quantities in orthogonal directions of the applied seismic force direction are plotted in Fig. 4(c) and Fig. 4(d). It is evident from these figures that normalized base shear in the direction and orthogonal direction of applied seismic forces have similar trend and so as for normalized overturning moment. This is due to the fact that seismic response quantities are governed by ESM over RSM and these quantities are scaled up by the ratio of quantities by ESM to RSM as per Indian seismic design code. Therefore, a general term "seismic forces" is used to indicate seismic forces obtained by seismic analysis using ESM and RSM leading to identical values owing to scaling up of the value obtained by later. Detailed analysis of building models reveals that re-entrant corner with increasing A/L ratio leads to torsional response as these models had non-exceeding PIDs related to torsional irregularities as tabulated in Table 1.

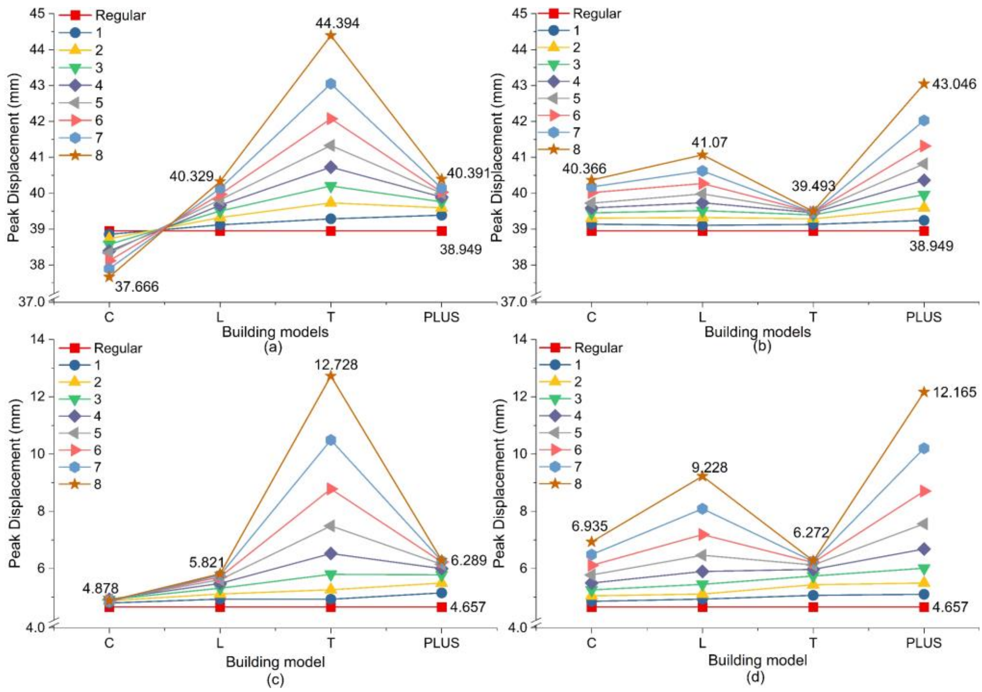


Fig. 3 Peak displacement response of regular and re-entrant dominant plan irregular RC building models, (a) Response in X-direction for seismic force RSM-X; (b) Response in Y-direction for seismic force RSM-Y; (c) Response in Y-direction for seismic force RSM-X and (d) Response in X-direction for seismic force RSM-Y

Table 4. Peak storey drift ratio of regular and re-entrant dominant plan irregular RC building models

	Peak Storey Drift								
	Regular	C1	C2	C3	C4	C5	C6	C7	C8
X-dir.	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0017
Y-dir.	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0019	0.0019	0.0019
Y ← X dir.$^{+}$	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
X ← Y dir.$^{+}$	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003
		L1	L2	L3	L4	L5	L6	L7	L8
X-dir.	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0019	0.0019
Y-dir.	0.0018	0.0018	0.0018	0.0018	0.0018	0.0019	0.0019	0.0019	0.0019
Y ← X dir.	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003
X ← Y dir.	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0004
		T1	T2	T3	T4	T5	T6	T7	T8
X-dir.	0.0018	0.0018	0.0018	0.0019	0.0019	0.0019	0.0019	0.0020	0.0021
Y-dir.	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
Y ← X dir.	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0005	0.0006
X ← Y dir.	0.0002	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003
		PLUS1	PLUS 2	PLUS 3	PLUS 4	PLUS 5	PLUS 6	PLUS 7	PLUS 8
X-dir.	0.0018	0.0018	0.0018	0.0018	0.0018	0.0019	0.0019	0.0019	0.0019
Y-dir.	0.0018	0.0018	0.0018	0.0019	0.0019	0.0019	0.0019	0.0019	0.0020
Y ← X dir.	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
X ← Y dir.	0.0002	0.0002	0.0002	0.0003	0.0003	0.0003	0.0004	0.0005	0.0005

$^{+}$-Displacement response in Y-direction due to earthquake force applied in X-direction or vice-versa.

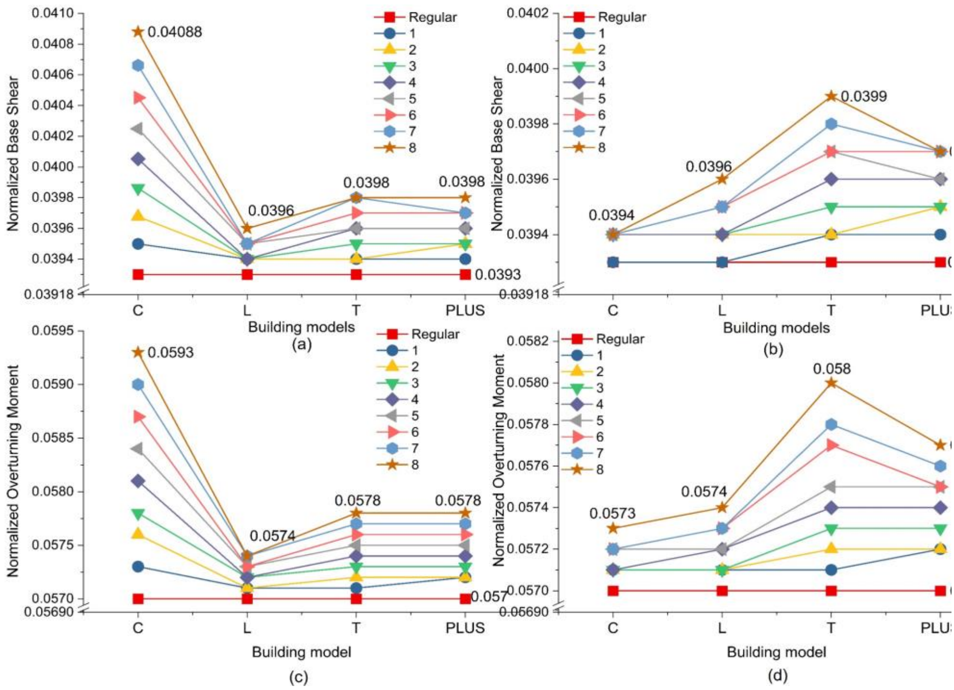


Fig. 4 (a) Normalized base shear response in X-direction for seismic force RSM-X; (b) Normalized base shear response in Y-direction for seismic force RSM-Y; (c) Normalized overturning moment response in X-direction for seismic force RSM-X and (d) Normalized overturning moment response in Y-direction for seismic force RSM-Y of regular and re-entrant dominant plan irregular RC building models

L-shaped building models; L6(0.6,0.2) to L8(0.8,0.2) as well as PLUS-shaped building models; PLUS5(0.5,0.2) to PLUS8(0.8,0.2) exceed torsional irregularity limit of 1.2 for PID; $\frac{\Delta_{max}}{\Delta_{avg}}$, at all floor levels for X-direction displacement response to Y-direction seismic force. Indian seismic code and most seismic codes world-wide have specified $\frac{\Delta_{max}}{\Delta_{avg}}$ limits under the direction of seismic force, but limit of $\frac{\Delta_{max}}{\Delta_{avg}}$ for orthogonal directions to the applied seismic direction is not specified. However, such as bi-directional torsional seismic response is typical of a re-entrant irregularity, and thus $\frac{\Delta_{max}}{\Delta_{avg}}$ limit should be specified for maximum torsional response irrespective of seismic force direction.

4.2. Bi-directional Re-entrant RC Building Models

In this section, results of seismic response studies conducted for RC building models having bi-directional re-entrant corners are reported. New building models are developed with A/L ratio in Y-direction ranges between 0.4 to 0.8 with an increment of 0.2 while A/L ratio in X-direction is between 0.1 to 0.8 as earlier building models. Building models with A/L ratio of 0.8 in Y-direction for C-shaped and ratio beyond 0.6 for T-shaped building models in the X-direction are non-realizable due to geometrical dimensions. As evident from discussion in Section 4.1 that peak displacement of orthogonal directions to applied seismic force direction shows amplification, therefore, results related to this response are reported in Table 5.

Table 5. Peak displacement response of re-entrant RC building models in orthogonal directions to the direction of seismic force

Direction of Response ← Seismic Force	$\left(\frac{A}{L}\right)_y$	$\left(\frac{A}{L}\right)_x$								
		Regular	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
						C-shaped RC Building Model				
Y←X dir.	0.2	4.65	4.79	4.88	4.92	4.93	4.91	4.87	4.85	4.87
X←Y dir.	0.2	4.65	4.85	5.04	5.25	5.49	5.78	6.11	6.49	6.93
Y←X dir.	0.4	4.65	4.92	5.09	5.18	5.18	5.12	5.02	4.92	4.92
X←Y dir.	0.4	4.65	4.97	5.26	5.61	6.04	6.57	7.25	8.06	9.05
Y←X dir.	0.6	4.65	5.08	5.38	5.57	5.63	5.56	5.42	5.29	5.35
X←Y dir.	0.6	4.65	5.09	5.49	5.96	6.55	7.29	8.27	9.51	11.05
						L-shaped RC Building Model				
Y←X dir.	0.2	4.65	4.93	5.11	5.31	5.48	5.61	5.71	5.77	5.82
X←Y dir.	0.2	4.65	4.93	5.11	5.45	5.90	6.46	7.18	8.09	9.22
Y←X dir.	0.4	4.65	5.23	5.90	6.51	7.03	7.43	7.70	7.82	7.79
X←Y dir.	0.4	4.65	5.03	5.45	6.39	7.03	8.23	9.97	12.3	15.67
Y←X dir.	0.6	4.65	5.81	7.18	8.60	9.97	11.17	12.09	12.53	12.34
X←Y dir.	0.6	4.65	5.12	5.71	6.53	7.70	9.44	12.09	16.13	22.54
Y←X dir.	0.8	4.65	6.64	9.22	12.27	15.67	19.23	22.60	24.98	26.23
X←Y dir.	0.8	4.65	5.19	5.82	6.64	7.78	9.51	12.35	17.23	26.23
						PLUS-shaped RC Building Model				
Y←X dir.	0.2	4.65	5.15	5.49	5.78	6.00	6.15	6.23	6.26	6.28
X←Y dir.	0.2	4.65	5.10	5.49	6.01	6.68	7.56	8.70	10.20	12.16
Y←X dir.	0.4	4.65	5.83	6.73	7.48	8.17	8.68	8.96	8.95	8.69
X←Y dir.	0.4	4.65	5.35	6.04	6.89	8.17	10.02	12.72	16.67	22.49
Y←X dir.	0.6	4.65	6.90	8.71	10.69	12.72	14.56	15.70	16.34	14.96
X←Y dir.	0.6	4.65	5.47	6.23	7.32	8.96	11.59	15.70	23.18	35.84
Y←X dir.	0.8	4.65	8.56	12.16	16.7	22.4	29.09	35.84	40.23	41.07
X←Y dir.	0.8	4.65	5.54	6.28	7.28	8.69	10.95	14.96	23.01	41.07
						T-shaped RC Building Model				
	$\left(\frac{A}{L}\right)_x$					$\left(\frac{A}{L}\right)_y$				
Y←X dir.	0.2	4.65	4.93	5.26	5.80	6.52	7.49	8.78	10.49	12.73
X←Y dir.	0.2	4.65	5.06	5.43	5.74	5.97	6.12	6.21	6.25	6.27
Y←X dir.	0.4	4.65	5.12	5.77	6.66	7.94	10.0	13.09	17.66	24.46
X←Y dir.	0.4	4.65	5.43	6.24	7.04	7.76	8.21	8.55	8.75	8.55

It has been observed that peak displacement response substantially increases ($\geq 137\%$) for $A/L \geq 0.6$ for C-, L- and PLUS-shaped building models and thus, re-entrant corner of such A/L ratio should not be permitted. T-shaped building model shows amplification of the order ($> 173\,\%$) in peak displacement response for both A/L 0.2 and 0.4 and therefore A/L limit of 0.15 by seismic design codes are not in agreement for such building models. Seismic analysis suggests that only C- and L-shaped building models yield reasonable peak displacement response for A/L ratio $\leq$ 0.4. PLUS-shaped building model with A/L 0.4 also yields reasonable peak displacement response. Detailed investigation reveals that building models with $A/L \geq 0.6$ result into flexible projected frames also called cantilever tails and thus peak displacement response increases substantially due to deformation of such cantilever tails.

Buildings with such flexible cantilever tail('s) result in exceeding the, $\frac{\Delta_{max}}{\Delta_{avg}}$ PID limit of 1.2 while other torsional irregularity PIDs were verified to fall within the limit. Fig. 5 shows building models with A/L ratio in X- and Y-direction with, $\frac{\Delta_{max}}{\Delta_{avg}}$ PID values. Dark line indicates that building models within have the PID value < 1.2, permissible value by seismic design codes. PID, $\frac{\Delta_{max}}{\Delta_{avg}}$ is obtained for peak displacement of building model in orthogonal directions to the applied seismic force as tabulated in Table 5. Re-entrant corner type plan irregularity defined by A/L ratio with permissible limit of regularity as 0.15 by Indian seismic design code is marked in Fig. 5 with dash-dot line. It is evident from Fig. 5 that, permissible limit of regularity is quite conservative since many building models don't exceed $\frac{\Delta_{max}}{\Delta_{avg}}$ PID for A/L ratio up to 0.4 in Y-direction for C-, L- & PLUS-shaped and X-direction for T-shaped and for A/L ratio in X-direction up to 0.6, 0.3 & 0.2 for C-, L- & PLUS-shaped, respectively and in Y-direction up to 0.4 in T-shaped building models. Few building models with A/L ratio of 0.2 in Y-direction for C-, L- & PLUS-shaped and X-direction for T-shaped show $\frac{\Delta_{max}}{\Delta_{avg}}$ PID within limit for A/L ratio in X-direction up to 0.8, 0.5 & 0.4 for C-, L- & PLUS-shaped and in Y-direction up to 0.6 for T-shaped building models.

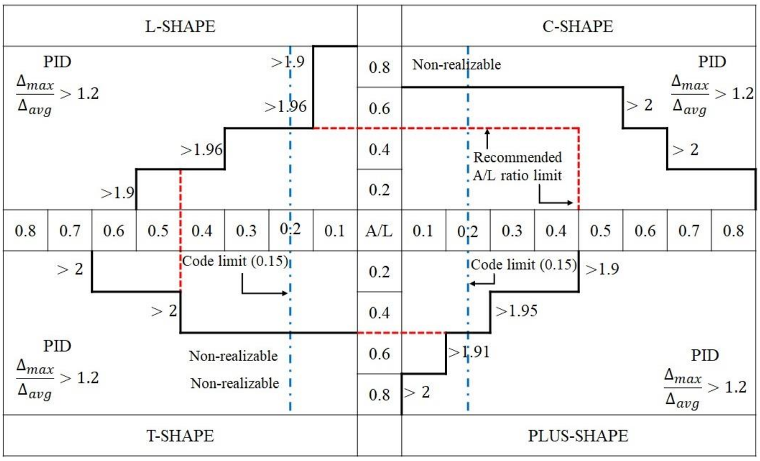


Fig. 5 Torsional response type PID, $\left(\frac{\Delta_{max}}{\Delta_{avg}}\right)$ for bi-directional re-entrant irregular RC building models

Based on this analysis, it can be recommended that the limit of regularity of A/L ratio for re-entrant corner type plan irregularity may be increased to 0.4 from present value of 0.15, as indicated by dash line in Fig. 5. Note that, school, business centre, hotel, hospital and hostel buildings typically have C-, L- and T-shaped geometry and are widely practiced world-wide. It can be realized from Fig. 5 that PLUS-shaped building models with $A/L \geq 0.6$ shows $\frac{\Delta_{max}}{\Delta_{avg}}$ PID exceeded even for A/L ratio ≤ 0.1 in X-direction. Therefore, it is not recommended to practice PLUS-shaped buildings owing to their torsional behavior with low level of re-entrant corners. Amongst various geometrical shapes of building models considered in the present study, C-shaped building models show better seismic response followed by T-shaped and L-shaped building models.

Plan irregular buildings with re-entrant corners are expected to undergo complicated deformed shapes during modal analysis [3,13]. The present study has observed such behaviour of building models when A/L ratio become ≥ 0.4 in, both, X- and Y- directions due to cantilever tail('s) (i.e., flexible projected frames). However, complicated deformed shape of these building models is associated with higher modes which have very low time period (very high frequencies). Therefore, mass participation of such complicated deformed shape is very low $(\sim \leq 1\%)$. The mass participation for re-entrant dominant building models is driven by vibration associated with high time period (low frequency) associated to fundamental translational and rotational modes.

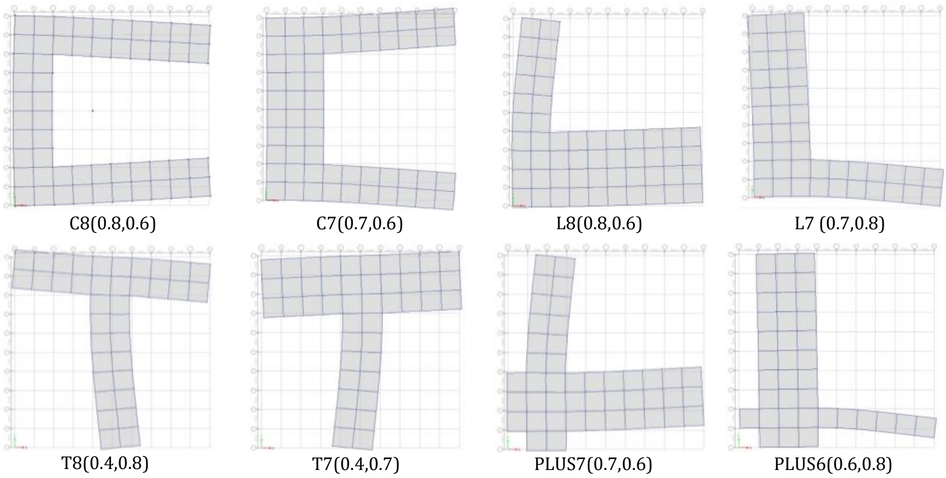


Fig. 6 Representative complicated deformed mode shapes of re-entrant RC building models

Modal analysis of building models reveal that re-entrant corner dominant building models have time period of translational mode in principal directions higher than time period of rotational mode. Though, with an increase in A/L ratio $\geq (0.7, 0.8)$ for L-shaped, $(0.4, 0.8)$ for T-shaped and $(0.8, 0.6)$ & $(0.6, 0.8)$ for PLUS-shaped in X- and Y-directions, mass participation by transitional mode decreases while it increases from rotational modes leading to translational-rotational combined modes of vibration.

Table 6 shows summary of the complicated deformed shapes of building models with their time period and mass participation ratio. It can be seen that with increasing A/L ratio, corresponding time period associated with the complicated deformed shape increases due to the flexibility of the cantilever tail('s) and reduced seismic weight of the building model. Few representatives, complicated deformed mode shapes are shown in Fig. 6 for C-, L, T- and PLUS-shaped building models

Table 6. Summary of time period and mass participation factor of complicated deformed shape of re-entrant RC building models

RC Building Model	Mode Shapes with A/L Ratio-Time period and Mass Participation Factor
C-shaped	Mode-4: (0.8, 0.2)- 0.61 sec, ~0 %, (0.8, 0.4)-0.65 sec, ~0 %, (0.8, 0.6)-0.668 sec, ~0 %
	Mode-6: (0.7, 0.6)- 0.465 sec, ~0 %
	Mode-7: (0.6, 0.2)- 0.284 sec, ~0 %, (0.7, 0.2)- 0.398 sec, ~0 %, (0.6, 0.4)- 0.308 sec, ~0 %, (0.7, 0.4)- 0.428 sec, ~0 %, (0.6, 0.6)- 0.234 sec, ~0 %
	Mode-10: (0.4, 0.6)- 0.189 sec, ~0 %, (0.5, 0.6)- 0.258 sec, ~0 %
	Mode-12: (0.4, 0.6)- 0.189 sec, ~0 %
L-shaped	Mode-7: (0.7, 0.8)- 0.296 sec, < 1 %, (0.8, 0.8)- 0.365 sec, < 1 %
	Mode-10: (0.7, 0.6)- 0.192 sec, ~0 %, (0.8, 0.6)- 0.246 sec, ~0 %, (0.5, 0.8)-0.2 sec, ~0 %, (0.6, 0.8)- 0.247 sec, ~0 %

T-shaped	Mode-10: (0.6, 0.4)- 0.204 sec, < 1 %, (0.7, 0.4)-0.232 sec, < 1 %, (0.8, 0.4)-0.25 sec, ~0 %
PLUS-shaped	Mode-4: (0.8, 0.8)- 0.561 sec, ~0 %
	Mode-7: (0.8, 0.6)- 0.36 sec, < 1 %, (0.5, 0.8)- 0.281 sec, < 1 %, (0.6 0.8)- 0.36 sec, < 1 %, (0.7, 0.8)- 0.44 sec, < 1 %
	Mode-10: (0.8, 0.4)- 0.205 sec, ~0 %, (0.7, 0.6)- 0.231 sec, ~0 %
	Mode-12: (0.6, 0.6)- 0.28 sec, ~0 %

4.3. Stress Concentration in Re-entrant RC Building Models

Re-entrant corner dominant building models are likely to have stress concentration at corner(‘s) due to torsional response resulting from combined translational-torsional modes of vibration. All building models are modelled with semi-rigid diaphragm following seismic design code stipulations related to irregular building. Such modelling approach enables seismic analysis to capture in-plane forces developed in the diaphragm due to inertia force of the building. Fig. 7 shows the in-plane stress distribution produce in the diaphragm of C-, L-, T- and PLUS-shaped building models for A/L ratio of 0.8 in X-direction and 0.4 in Y-direction. Von-mises shear stresses are evaluated for each building model which reveal that corners are subjected to higher shear stress. Additionally, it can be seen that, peripheral portion of diaphragms also suffered from shear stress concentration due to the flexibility of cantilevered tail(‘s). Most building models yield low values of shear stress at re-entrant corner (‘s) due to relatively lower value of $\left(\frac{e_x}{B}\right)$ ratio resulting to low additional shear force by the twisting moment. As discussed earlier, complicated deformed mode shapes of the building models do not contribute significantly due to low mass participation and thus, produces negligible shear stresses in the diaphragm. Shear stress concentration at re-entrant corners may become significant, if complicated deformed mode shape contribution increases significantly due to the asymmetric mass and stiffness distribution for the building model.

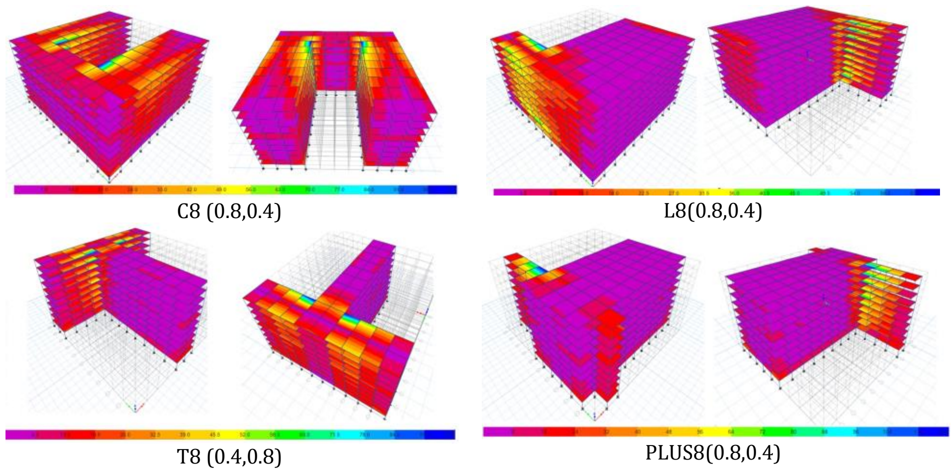
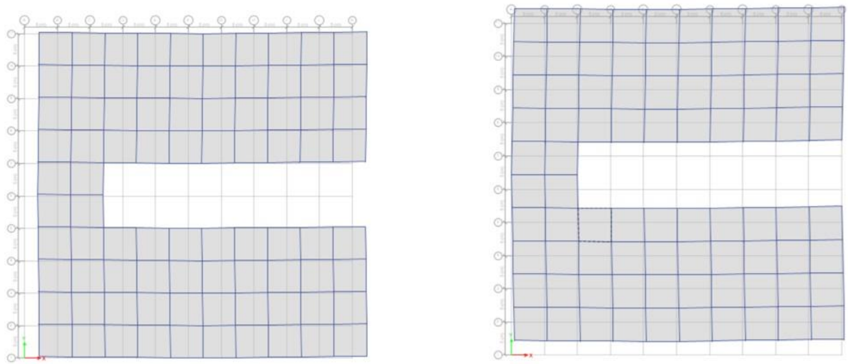


Fig. 7 In-plane stress distribution C-, L-, T- and PLUS-shaped building models

4.4. Diaphragm Modelling of Re-entrant RC Building Models

Diaphragms is an important element of the RC buildings since it transfer lateral load to vertical load resisting system. In-plane stiffness of the diaphragm relative to the stiffness of the lateral load resisting system defines rigidity or flexibility. Indian seismic design code recommends use of flexible diaphragm to perform seismic analysis of RC building with re-entrant corner as per latest version. All building models in the present study are developed using both, semi-rigid (flexible) and rigid diaphragm modelling approach to understand effectiveness of their lateral load distribution capabilities to vertical load resisting system using ETABS. It has been found that re-entrant dominant building models with semi-rigid (flexible) diaphragm yield exactly identical seismic behaviour with that of the rigid diaphragm since semi-rigid diaphragm also have relatively higher in-plane stiffness. Though, deformation of semi-rigid diaphragm is different than rigid diaphragm where later has rigid translation only. The said observations are of good agreement with result reported by other literature [14] related to semi-rigid diaphragm.



(a) (b)

Fig. 8 Displacement profile in semi-rigid diaphragm
(a) seismic force in X-direction and (b) seismic force in Y-direction

Difference between shear force results obtained for all building models with rigid and semi-rigid diaphragm are found to be $\leq 5\,\%$ only. A representative, C-shaped building model with A/L ratio 0.8 in X-direction and 0.2 in Y-direction is shown in Fig. 8 for seismic force in X- and Y-directions. Peak displacement of building models with semi-rigid diaphragm are found to be higher vis-à-vis building model with a rigid diaphragm. In semi-rigid diaphragm, floors are capable of transferring internal forces which is not possible in case of rigid diaphragm.

5. Conclusions

Irregular RC buildings have suffered damages during past earthquakes and are vulnerable. Irregularities are classified as plan and vertical irregularity by seismic design codes world-wide. Present paper aims to investigate the seismic behaviour of plan dominant with re-entrant corners irregular RC buildings of C-, L-, T- and PLUS-shaped. Total 104 building models comprising of C- (24 nos.), L- (32 nos.), T-(16 nos.) and PLUS- (32 nos.) shaped with A/L ratio ranges between 0.1 to 0.8 in X-direction and of 0.2, 0.4, 0.6 and 0.8 in Y-direction for C-, L- and PLUS- shapes and A/L ratio of 0.2 and 0.4 in X-direction and of 0.1 to 0.8 in Y-direction for T-shaped models are developed along with a regular RC building model. Plan Irregularity Descriptors (PIDs) are defined and computed to ensure developed building models are re-entrant dominant. Seismic response parameters; peak displacement, peak storey drift, normalized based shear and normalize overturning moment are determined using Equivalent Static Method and Response Spectrum Method recommended by Indian Seismic design code for all building models. Combined translational-torsional modes of vibration resulting to stress concentration at re-entrant corner and other places of the building models are studied. Recommendation by seismic design code for 3D analysis of irregular building with flexible diaphragm is investigated by modelling building models with both, rigid and flexible diaphragm approach.

The major observations of the present study are summarized as follows.
Building models show a marginal increase of $\sim 6\%$ in peak displacement due to seismic forces, except for T- and PLUS-shaped building models with A/L ratio ≥ 0.6 in the X-direction and 0.2 in Y-direction.

- Building models with an A/L ratio of 0.2 to 0.8 in the X-direction and 0.2 in the Y-direction yield moderate to substantial increase (34.68 % to 173.31 %) in peak displacement of orthogonal directions to the direction of seismic force applied.
- Peak storey drift response of all building models falls well within permissible limit of 0.4% of storey height by Indian seismic code.
- Normalized base shear and normalized overturning moment of building models are found to be at par with the regular building model.
- L- and PLUS-shaped building models with A/L ratio ≥ 0.5 in the X-direction exhibit torsion type PID, $\frac{\Delta_{max}}{\Delta_{avg}}$ exceeding the permissible limit of 1.2. Thus, such building models shall be modified in terms of geometric dimensions.
- Complicated deformed mode shapes are observed for increasing A/L ratio, however, these modes have insignificant mass participation due to low time period.
- Limit of re-entrant corner PID, A/L ratio of 0.15 defined by Indian seismic design code is found to be conservative. A/L ratio limit of 0.4 is recommended from the present study since beyond this limit PID, $\frac{\Delta_{max}}{\Delta_{avg}}$ exceeding permissible limit of 1.2.
- C-shaped building models perform well under seismic force for large range of A/L in X- and Y- direction.
- Shear stress values at the re-entrant corner of building models are found to be relatively low. Stress concentration is observed at the periphery of semi-rigid diaphragm for few building models.
- Building models with semi-rigid (flexible) diaphragm yield similar (difference $\leq 5\%$) lateral load force distribution in the lateral-load resisting system as that of building models with rigid diaphragm. However, peak displacement response of building models with semi-rigid (flexible) diaphragm is different and higher vis-à-vis rigid diaphragm building models.

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