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Seismic Analysis of Torsional Irregularity in Multi-Storey Symmetric and Asymmetric Buildings

Manish A Kewalramani[1], Zubair I Syed[2]
[12]College of Engineering, Abu Dhabi University, Abu Dhabi (UAE)

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Abstract: *The torsion–induced failures are catastrophic for multi–storey buildings because torsional response of structure not only changes the uniform translational seismic floor displacement but also cause stress concentration and therefore it demands higher strength and ductility for structural members. A structure demonstrates weakness primarily due to discontinuous geometry, mass and/or stiffness and becomes prime source of failure during earthquake. The objective of present work is aimed at comprehensive understanding of the torsional behavior of building structural systems for symmetric and asymmetric buildings with plan irregularity. In symmetric structures center of mass and rigidity usually coincide with each other, hence torsion effect for such structures is due to accidental eccentricity; whereas asymmetric structures have irregular distribution of mass and stiffness that results in torsion and becomes most critical factor influencing the seismic damage of the structure. In present study, the performance of such structures is evaluated as per procedures described in prevailing codes of practice for significant parameters such as storey drift, base shear, maximum lateral displacement, natural time-period, frequency and modal mass participating ratio to have a comprehensive review on structural response for involved torsional irregularities.*

Index Terms: *base shear, seismic analysis, storey drift, torsional irregularity.*

INTRODUCTION

Damage reports on recent earthquakes have indicated that torsional motions often cause significant damage to buildings varying from visible distortion to structural collapse and earthquake field investigations repeatedly confirm that irregular structures suffer more damage and distortion compared to regular and symmetric structures. Moreover, earthquakes are the most unpredictable and devastating among all natural disasters. Hence, it is very essential to understand torsional behavior of buildings during an earthquake. During earthquake ground motions, structures encounter torsional vibration besides lateral oscillations most of the time. Torsion occurs under the action of earthquake forces when the center of mass of a building does not coincide with its center of rigidity. Some of the reason that can lead to this situation in the building plan are positioning the stiff elements asymmetrically with respect to the center of gravity of the story; placement of large masses asymmetrically with respect to stiffness. A combination of the two, mass as well as stiffness distribution results in the situations mentioned above.

In the event of an earthquake building rotates about its center of rigidity. This increases magnitude of both lateral forces and displacements; demanding lateral load resisting structural members proportionate to their distance from the center of rotation. The conventional analysis for torsion simply gives the force due to moment produced by an eccentric static force. It takes no account of the torsional vibrations and the associated accelerations. Quantitatively, an eccentricity between the centers of mass and stiffness is considered significant when it exceeds 10% of the horizontal plane dimensions under study. In such cases, corrective measures should be taken in the structural design of the building. Torsion may become even more complicated when there are vertical irregularities, such as setbacks. In effect, the upper part of the building transmits an eccentric shear to the lower part, which causes downward torsion of the transition level regardless of the structural symmetry or asymmetry of the upper and lower floors. Asymmetric or torsionally unbalanced buildings are prone to earthquake damage due to coupled lateral and torsional movements producing non-uniform displacement demands in building elements and concentrations of stresses and forces on structural members. Current codes fall short of providing recommendations for irregular structures. Thus, there is an apparent need to develop a simple analysis procedure based on rigorous analytical and experimental information on the inelastic seismic response of irregular structures [1]. Asymmetric building structures are almost unavoidable in modern construction due to various functional and architectural requirements.

Based on intensive studies by many researchers, the important governing parameters of the torsional responses of asymmetric structures include the ratio of the uncoupled torsional to translational frequency of the structure, the eccentricity between the centre of mass and the centre of stiffness, the uncoupled vibration frequencies and the damping ratio. These parameters have been intensively studied over the last couple of decades and some general observations have been made on elastic torsional responses of structures to earthquake ground motions [2]. Many researchers have also performed inelastic torsional response analyses, and made observations based on the results they obtained. However, unlike elastic torsional response, there is no general conclusion that can be made about the inelastic behavior of the asymmetric buildings and the governing parameters. This is because the parameters governing the torsional response change during the plastic deformation since the stiffness, radius of gyration, the location of the centre of rigidity, and the eccentricities change constantly. Hence, the objective of present work aimed at better understanding of the torsional behavior of building structural systems for both symmetric and asymmetric buildings with plan irregularity. In present study, the performance of such structures is evaluated as per procedures described in prevailing codes of practice for significant parameters such as storey drift, base shear, maximum lateral displacement, natural time-period, frequency and modal mass participating ratio to have a comprehensive review on structural response for involved torsional irregularities.

Methodology

The present work can be considered as quantitative study mainly based on collecting numerical data for four different plan configurations of buildings when subjected to seismic loads. The analysis was conducted on symmetrical and asymmetrical reinforced concrete buildings with uniform panel dimensions of 5m×5m in order to find more suitable asymmetrical structure to resists applied seismic forces efficiently. These four plan configurations of buildings consists of 15 typical stories, with typical story height of 3.5m and base story height of 4.5m. All structural members including location and dimensions of shear walls are modelled identical. Seismic load analysis factors such as building occupancy category, basic and design ground motion parameters (S_s, S_1, S_{ds}, and Sd_1), soil type, site classification and site coefficient adjustment factors, and seismic design category are also kept constant for all structural systems under consideration to have a through comparison of factors affected due to seismic loads [3]. The effect of seismic forces on lateral load specific parameters like storey drift, base shear, maximum lateral displacement, natural time period, frequency and modal mass participating ratio due to change in plan configuration of a building are studied.

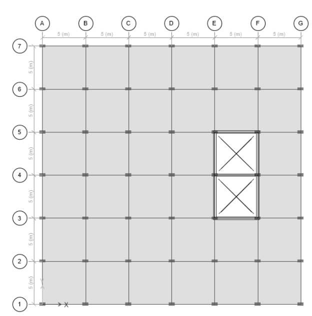

Fig 1: Regular Symmetrical Square Shape Building Plan

Fig. 1– Fig. 4 show plan configurations of buildings along with unified position of shear walls modelled using ETABS considered in present study. Every structure is subjected to earthquake forces in both directions (i.e. E_x and E_y as base shear), but applied one at a time. As per clause 12.8.4.3 of ASCE 7–10 [4]

the accidental lateral load eccentricities of ±5 % throughout the service life of the structure are amplified by the factor.

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

where δ_{max} and δ_{avg} are the maximum displacement at level *x* and the average of the displacements at the extreme points of the structure at level *x* respectively computed by assuming A_x=1. This factor should not be less than 1 and is not required to exceed 3.0. Another parameter known as torsional irregularity coefficient as defined by equation 2 is a prerequisite for all crucial calculations of depending parameters such as storey drift and lateral displacement carried out in present study.

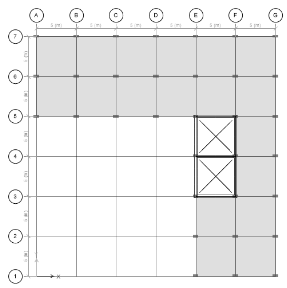

Fig 2: Asymmetrical L–Shape Building Plan

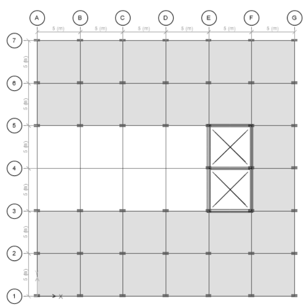

Fig 3: Asymmetrical C–Shape Building Plan

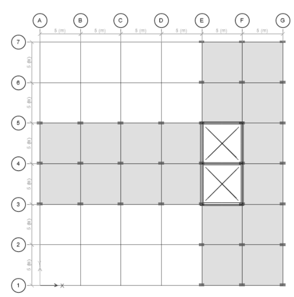

Fig 4: Asymmetrical T–Shape Building

$$\eta_t = \frac{\delta_{max}}{\delta_{avg}} \quad (2)$$

ASCE 7-10 basic load combinations were used for structural analysis purpose, however earthquake effect E was considered as described below in line with codal requirements.

$E=E_h \pm E_v$ (3)

$E_h=\rho Q_E$ and $E_v=0.2S_{ds}D$ (4)

where ρ is redundancy factor, Q_E is defined as the effects of horizontal seismic forces from V (total design lateral force or shear at the base of structure), S_{ds} is design spectral coordinate and D is the dead load of the structure.

Results and discussions

A comparative analysis of lateral load (specifically seismic loads) parameters such as storey drift, base shear, maximum lateral displacement, natural time-period, frequency and modal mass participating ratio due to only change in plan configuration(s) of a building is carried out and discussed.

A. Maximum Storey Drift

It is defined as ratio of displacement of two consecutive floor to height of that floor. Storey drift is usually interpreted as inter–storey drift; the lateral displacement of one level relative to the other level above or below. It is one of the particularly useful engineering response quantity and indicator of structural performance for high–rise buildings when subjected to lateral loads. The maximum storey drift values along X and Y direction for various plan configurations considered in the study along with location are tabulated in Table 1. A considerable reduced storey drift can be observed for T shape building in both X and Y directions.

Table 1: Maximum Storey Drift (mm) along X and Y Direction

Plan	X direction		Y direction	
Square	1.093	Storey 8	1.209	Storey 6
L	0.905	Storey8	0.898	Storey 8
C	0.944	Storey 8	0.965	Storey7
T	0.895	Storey 8	0.718	Storey 8

Fig. 5 (a) and (b) show storey drift due to E_x in X–direction and due to E_y in Y–direction respectively for all four types of plan configurations considered. The variation in the storey drift for different shapes due to earthquake forces in both x and y directions can be clearly observed with high values of drift at mid-height of the building. A square shape building producing higher values of inter-storey drift, while T-shape building producing the least values of inter-storey drift due to earthquake forces in both x and y directions.

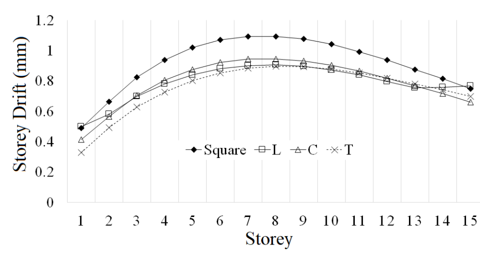

Fig 5(a): Storey drift along x-direction due to E_x

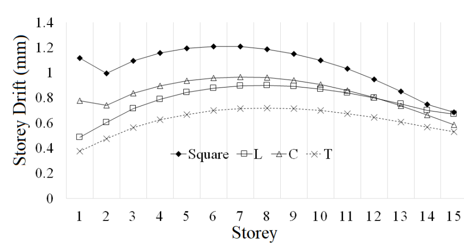

Fig 5(b): Storey drift along y-direction due to E_y

B. Base Shear

Base shear is an estimate of the maximum expected lateral force that will occur due to seismic ground motion at the base of a structure. Higher value of base shear is indicates that structure is stiff under earthquake ground motions and vice versa. The base shear values for various plan configurations considered in the study are listed in Table 2. It is desired that structure should be stiffer for seismic response as seen for the square shape building [5].

Table 2: Base Shear (kN) along X and Y Direction

Plan	X direction	Y direction
Square	8423.22	8423.22
L	4681.53	6859.79
C	7061.41	6924.13
T	5017.20	5241.09

C. Maximum lateral displacement

Maximum lateral displacement values in x, y and z direction for various plan configurations considered in the study are listed in Table 3 when seismic forces are applied in both X and Y directions. It can be clearly observed that a T-shape building has least values of lateral joint displacement, while a square shape building has higher values of lateral joint displacement.

Table 3: Maximum Joint Lateral Displacement (mm)

Table 3: Maximum Joint Lateral Displacement (mm)

Plan	X			Y		
	Ux	Uy	Uz	Ux	Uy	Uz
Square	48.308	6.559	2.544	13.99	55.737	3.599
L	40.91	9.759	2.378	6.632	41.01	3.564
C	41.784	5.772	2.298	10.064	44.679	3.046
T	39.721	5.521	2.148	4.628	32.751	2.726

The storey–wise maximum joint displacement is plotted in Fig. 6 (a) and (b) for different shapes of building due to earthquake force in x and y direction. It can be seen that a square shape building producing higher values of joint displacement at all storeys compared to other plan configurations, while T-shape building producing least values of joint displacement as distribution of earthquake forces depends on the exposed area.

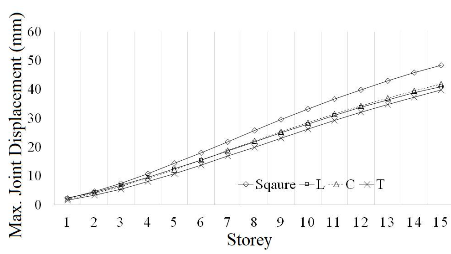

Fig 6(a): Max. Joint Displacement in *x*-direction due to E_x

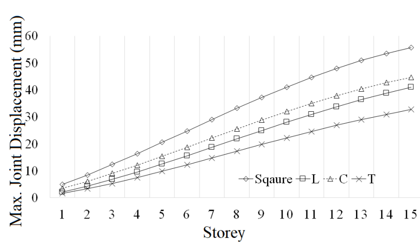

Fig 6(b): Max. Joint Displacement in *y*-direction due to E_y

D. Natural Time Period and Modal Participation

Natural time period value depends on the mass and flexibility of structure, more the flexibility and mass means longer the values of time period (T). In general tall structures are more flexible and have larger mass, and therefore expected to have longer T [6]. Table 4 shows natural time period, frequency and circular frequency for various plan configurations considered in the study. It can be observed that square shape building has longer time period compared to other structures and a wide variation in time period can be observed due to change in plan configuration. The reason for longer time period for square shape building can be attributed to asymmetric position of shear walls made building behave more flexible under seismic loads, while for a T shape building the position of shear walls can be considered appropriate in order to make it more rigid structure for seismic ground motion response.

Table 4 also includes modal mass participating ratio, which is measure of energy contained with each resonant mode since it represents the amount of system mass participating in a particular mode. For a particular structure, with a mass matrix, normalized mode shapes and ground motion influence coefficient, participation of each mode can be obtained as the effective mass participation factor. Both modal and mass participation factors are highly correlated, i.e. higher the cumulative participation factor, the higher the cumulative mass participation. The modal mass participation ratio is widely used as the metric to determine the relative significance of modes in a modal response spectrum analysis. For present study, to achieve approximately 90% of modal mass participation in vertical direction, the seismic analysis was conducted with fifteen number of modes.

Table 4: Natural Time Period and Mass Modal Participation

Plan	Mode	Time Period	Freq.	Circular Freq.	Eigen Value	Modal mass participating ratio(%)		
		(sec)	(cyc/sec)	(rad/sec)	(rad^2/sec^2)	X-trans	Y-trans	Rotation
Squr	1	1.358	0.736	4.627	21.412	0.117	0.000	0.386
	2	1.146	0.872	5.481	30.044	0.117	0.288	0.386
	3	0.814	1.228	7.717	59.545	0.316	0.288	0.844
			Sum of 15 modes			**9.625**	**9.730**	**13.003**
L	1	1.056	0.947	5.951	35.416	0.027	0.222	0.132
	2	0.931	1.074	6.745	45.500	0.125	0.316	0.453
	3	0.721	1.388	8.720	76.041	0.329	0.319	0.837
			Sum of 15 modes			**9.100**	**10.155**	**12.967**
C	1	1.233	0.811	5.094	25.950	0.108	0.000	0.450
	2	1.057	0.946	5.944	35.329	0.108	0.294	0.450
	3	0.785	1.274	8.003	64.044	0.319	0.294	0.848
			Sum of 15 modes			**9.378**	**9.746**	**13.266**
T	1	0.985	1.015	6.378	40.677	0.000	0.317	0.000
	2	0.943	1.060	6.663	44.389	0.158	0.317	0.367
	3	0.697	1.435	9.019	81.338	0.331	0.317	0.840
			Sum of 15 modes			**9.335**	**10.069**	**12.790**

CONCLUSIONS

Inter-storey drift was observed maximum for the square shape building due to inadequacy and asymmetric location of shear walls clearly indicating dependence of the stiffness and mass concentration on the structure, as in other plan configurations shear walls are adequate and relatively more symmetric compared to square shape building. Position of shear walls in a building influence the lateral displacement and storey drift due to seismic actions. The optimum location of shear wall in reducing storey drift and lateral displacement was given by L and T plan configurations.

Base shear values were obtained to be maximum for square shape building indicating that structure is stiffer for seismic response.

Natural time-period of buildings with adequate shear walls is observed to be lesser compared to square shape building with inadequate and inappropriate locations of shear walls. Moreover, modal mass participating ratio of modelled buildings in this study are within permissible limits, i.e. greater than 90% of seismic weight as per codal provisions.

From the study it is quite evident that though the outside perimeters of buildings were almost similar, a significant variation in values of torsion related parameters was observed due to plan asymmetry and presence of stiff elements within the structure.

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