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

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Abstract:
In buildings with multiple stories, one of the significant problems that continue to be documented involves torsion-induced failures. Particularly, structural torsion responses cause stress concentration and also alter the otherwise uniform translational seismic floor. In so doing, structural members require higher ductility and strength. Indeed, weaknesses in structures arise from factors such as stiffness and discontinuous geometry, a common source of failure especially when earthquakes are experienced. In this study, the central purpose is to examine building structural systems in relation to the impact of torsional behavior, especially in asymmetric and symmetric buildings constituting irregular plans. In situations where symmetric structures are present, the rigidity and mass center tends to coincide with one another. The eventuality is that for these structures, the torsion impact is attributed to accidental eccentricity. On the other hand, when asymmetric structures are present, stiffness and mass are distributed irregularly, with the resultant torsion causing structural seismic damage significantly. In this investigation, the objective is to evaluate the performance of each form of structure relative to various codes' procedures regarding building practice. Some of the variables to be investigated include modal mass and frequency participating ratio, natural time-period, maximum lateral displacement, base shear, and storey drift. The motivation is to ensure that a comprehensive review is achieved regarding the targeted torsional irregularities' structural response.

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I. INTRODUCTION

From the damages arising from earthquakes experienced recently, it is evident that most of the buildings tend to be destroyed due to torsional motions. The impact can be traced from structural collapse to visible distortions. Also, additional studies confirm that the most damage is felt in irregular structures, with symmetric and regular structures experiencing less damage. Of the natural calamities responsible for these destructions, earthquakes remain the leading cause. The eventuality is that there is a need to examine buildings' torsional character when earthquakes occur. Specifically, when earthquakes occur, lateral oscillations and torsional vibrations are likely to be felt. Specifically, earthquake forces cause torsion because they cause a failure of balance between a building's mass and the center of rigidity. Major factors attributed to the imbalance include asymmetrical positioning of stiff elements in relation to a storey building's center of gravity and placing large masses asymmetrically. When these two variables combine, which include the distribution of stiffness and that of the mass, coupled with an earthquake, torsional behavior is likely to occur.

Also, if an earthquake occurs, there tends to be a rotation of buildings about their centers of rigidity. The rotation causes a notable increase in the displacement magnitude, as well as that of lateral forces. Hence, torsion behavioral analysis yields

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forces associated with eccentric static force-produced moments. Notably, the parameter does not account for accelerations and vibrations linked to the torsion. From a quantitative perspective, an eccentricity that exceeds 10% while occurring between the centers of stiffness and mass is acknowledged as being significant. In such situations, the buildings' structural designs require corrective steps. In situations with vertical irregularities, torsion poses more complications. In particular, such situations imply that eccentric shears are likely to be transmitted by structures to their lower sections, translating into translation level downward torsion, with the lower and upper floors' structural asymmetry or symmetry playing an insignificant role. The emerging trend is that when buildings are torsionally imbalanced or asymmetric, they are likely to be damaged by earthquakes, with torsional and lateral movements exacerbating the adverse outcomes. The eventuality is that non-uniform displacements occur. In the current codes, there is a gap regarding the specification and implementation of relevant recommendations, especially those that regard irregular structures. The implication is that the need to establish simpler steps informed by experimental and analytical data could not be overstated, especially in situations involving irregular structures because they are associated with inelastic responses [1]. Notably, the current state of construction holds that asymmetric structures are unlikely to be avoided because architectural and functional requirements vary significantly.

From the majority of previous research studies, situations involving asymmetric structures have the magnitude of torsional response determined by different variables. Some of these variables include the damping ratio, uncoupled vibration frequencies, eccentricities between the center of stiffness and the mass, and the ratio between the structure's translational frequency and uncoupled torsional impact. With comprehensive literature documenting the impact of these parameters, more attention has been directed at the structures' elastic torsional response to ground vibrations associated with earthquakes [2]. Also, more research has been conducted relative to inelastic torsional responses. Despite this effort, however, inelastic behaviors and the associated governing parameters linked to asymmetric buildings are yet to receive an in-depth analysis. This lack of comprehensive examination is attributed to significant changes that torsional responses' governing parameters exhibit, including the eccentricities, center of rigidity location, the radius of gyration, and the stiffness. Therefore, this study sought to give insight into building structural systems' torsional behavior, considering both asymmetric and symmetric buildings associated with irregular plans. It is also notable that the evaluation of the structures' performance was made based on the prevailing practice codes governing major variables such as the modal mass participating ratio, the frequency, the natural time-period, the maximum lateral displacement, the base shear, and the storey drift. The motivation was to gain insight into the affected torsional irregularities' state of structural response.

II. METHODOLOGY

This study is quantitative because it seeks to collect and analyze numerical data. Four types of building configuration plans will be considered and analyzed regarding how they could respond to seismic loads. It is also notable that reinforced concrete buildings, asymmetrical and symmetrical, were considered. The dimensions of the panels were uniform and set at 5mx5m. these experimental conditions were meant to ensure that a relevant and asymmetrical structure that could efficiently resist any seismic forces applied onto it is established. The height of the base storey was 4.5 m, the typical storey being 3.5 metres high, and 15 typical stories considered for examination. Similarly, the dimensions and locations of shear walls and other structural features were identical. Factors that were examined included site coefficient adjustment factors, site classification, soil type, design ground motion variables, occupancy category, and location. Indeed, it is important to keep these factors constant, alongside the seismic design type in

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the structures under examination, especially due to the need for outcome validity and reliability [3]. The correlation that was investigated included the impact of seismic forces on the parameters of modal mass and frequency participating ratio, natural time period, maximum lateral displacement, base shear, and storey drift.

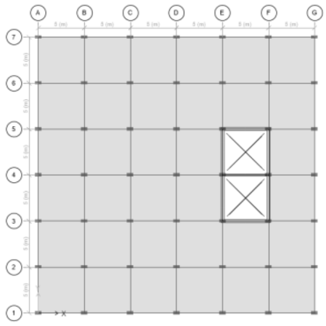

Fig. 1. Regular Symmetrical Square Shape Building Plan

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[7-12].

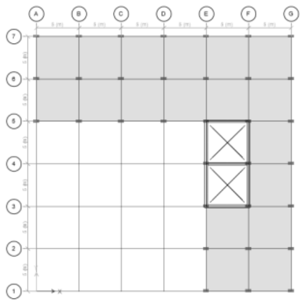

Fig. 2. Asymmetrical L–Shape Building Plan

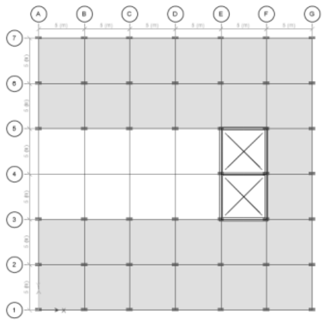

Fig. 3. Asymmetrical C–Shape Building Plan

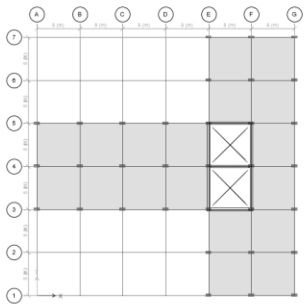

Fig. 4. Asymmetrical T–Shape Building

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

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.

$$E = E_h \pm E_v \quad (3)$$

$$E_h = \rho Q_E \quad \text{and} \quad (4)$$

$$E_v = 0.2 S_{ds} D$$

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.

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III. 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.

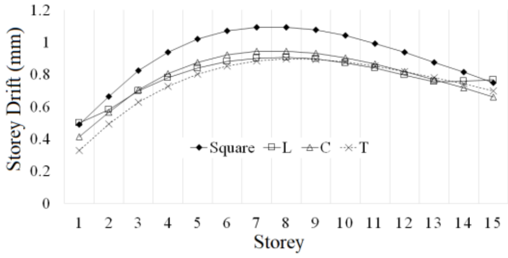

Fig. 5(a) Storey drift along x-direction due to E_x

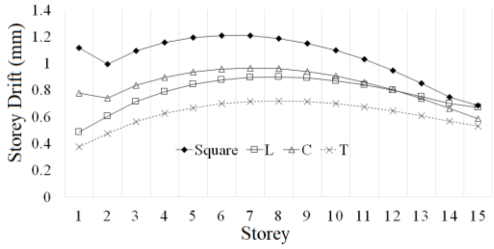

Fig. 5(b) Storey drift along y-direction due to E_y

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

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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.

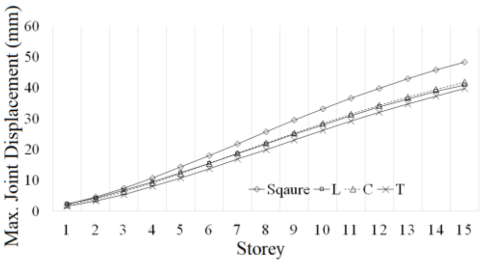

Fig. 6(a) Max. Joint Displacement in *x*-direction due to E_x

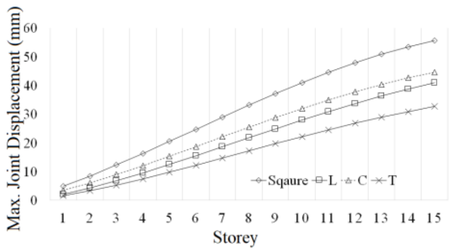

Fig. 6(b) Max. Joint Displacement in *y*-direction due to E_y

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 (sec)	Freq. (cyc/sec)	Circular Freq. (rad/sec)	Eigen Value (rad²/sec²)	Modal mass participating ratio(%) 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**

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IV. Conclusions

This study established that when the building is square in shape, there is maximum inter-storey drift because of its asymmetric nature of its shear walls. Hence, it was discerned that mass concentration and stiffness affect structural behavior. In other designs or building shapes, there were more symmetric and adequate shear walls. It was also established that in case of seismic actions, factors of storey drift and lateral displacement are influenced by a building's position of the shear walls. Particularly, T and L plan configurations were established to be better placed to achieve optimum shear wall locations through which lateral displacement and storey drift could be minimized. For buildings that were square in shape, the study established that there are maximum base shear values. Hence, the structures proved stiff and better placed to respond to seismic forces or actions.

Also, buildings exhibiting adequate shear walls had lesser natural time period. However, square shaped buildings exhibited inappropriate and inadequate shear wall locations. Furthermore, the study's modeled buildings' modal mass participating ratio was found to be within the recommended limits, standing at above 90 percent of the seismic weight. The study concluded that whereas external building variables were identical, the torsion value varied significantly because of differences in the symmetry of the structures' designs, with structural stiffness also playing a determinant role in accounting for these differences in torsion values.

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