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Structural reliability and performance evaluation of symmetric and asymmetric multi-storey buildings subjected to lateral wind forces

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Abstract. Lately there has been enormous enhancement of buildings architecturally. Most of the buildings are designed and constructed with diverse variations like soft–storey, torsional irregularity, asymmetrical layout of walls, irregularities in plan and elevation and thus overall building configuration. Any such variation result in challenging implications in terms of structural reliability and appropriate design of structural members. Calculation of lateral forces on these structures is an essential process in case of high– rise structures and structural performance of these aesthetically appealing asymmetric irregular shaped buildings especially when subjected to heavy wind forces need to be carefully assessed by structural engineers. The present work intends at performance evaluation by studying structural reliability of symmetrical and asymmetrical regular square, L, C and T–shaped reinforced concrete multi–storey buildings subjected to wind loads. The wind load analysis on these buildings is carried out in line with ASCE 7–10 design code. A comparative evaluation of critical parameters like fundamental period, natural and circular frequency of building, maximum joint displacement, storey drift ratio, inter–storey drift, internal forces in structural members, storey response and storey stiffness determines that difference in shape of a particular storey (or building) influence overall structural performance of building.

1. Introduction

A building is usually considered as asymmetric in plan or in elevation based on the distribution of its mass and stiffness along each storey throughout the height of the building. Asymmetric nature of building may cause interruption of force flow and stress concentration when especially subjected to lateral loads. Buildings in general are subjected to different type of loadings such as superimposed dead loads, live loads, and lateral loads etc. Lateral loads are typically of two types i.e., wind loads and seismic loads. This study emphasize on wind loads since they are one of the most critical loads in tall structures like multi–storey buildings and it must be accounted when designing any such structure. Present study conducts a comparative structural reliability and performance evaluation of symmetrical and asymmetrical buildings subjected to wind loads using ETABS. The study compares significant parameters such as fundamental period, maximum deflection, story drifts, story stiffness, story response and storey internal forces obtained by modelling structural members of buildings with different plan configurations such as regular square shape, L-shape, C-shape and T-shape.

Fundamental period of a building is defined as amount of time a displaced point takes to get to its original position due to lateral force. Maximum deflection is the farthest displacement any point on the structure can reach due to different loading types, and in this case it is due to wind loading. Story drift is the lateral displacement of a floor level related to the floor above or below. Story response is a graph to represent the relationship between the story displacement and the story height of each building. As for the story stiffness, it is the story shear per story displacement. All such wind load and relevant parameters calculations for these four different shapes of buildings were done in accordance with ASCE 7–10 wind load provisions.

2. Methodology

The present work can be considered as a comparative and quantitative structural reliability and performance evaluation of four buildings with different plan configurations when subjected to wind 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 for resisting the wind loads 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 the structural members including shear walls dimensions and locations are modelled identical to have a through comparison and collection of numerical data for parameters such as fundamental period, natural and circular frequency of building, other general parameters like maximum joint displacement, storey drift ratio, inter–storey drift, internal forces in structural members, storey response and storey stiffness affected due to wind loads as specified by ASCE 7–10. The following figures 1 (a), (b), (c) and (d) show plan configurations of buildings modelled using ETABS.

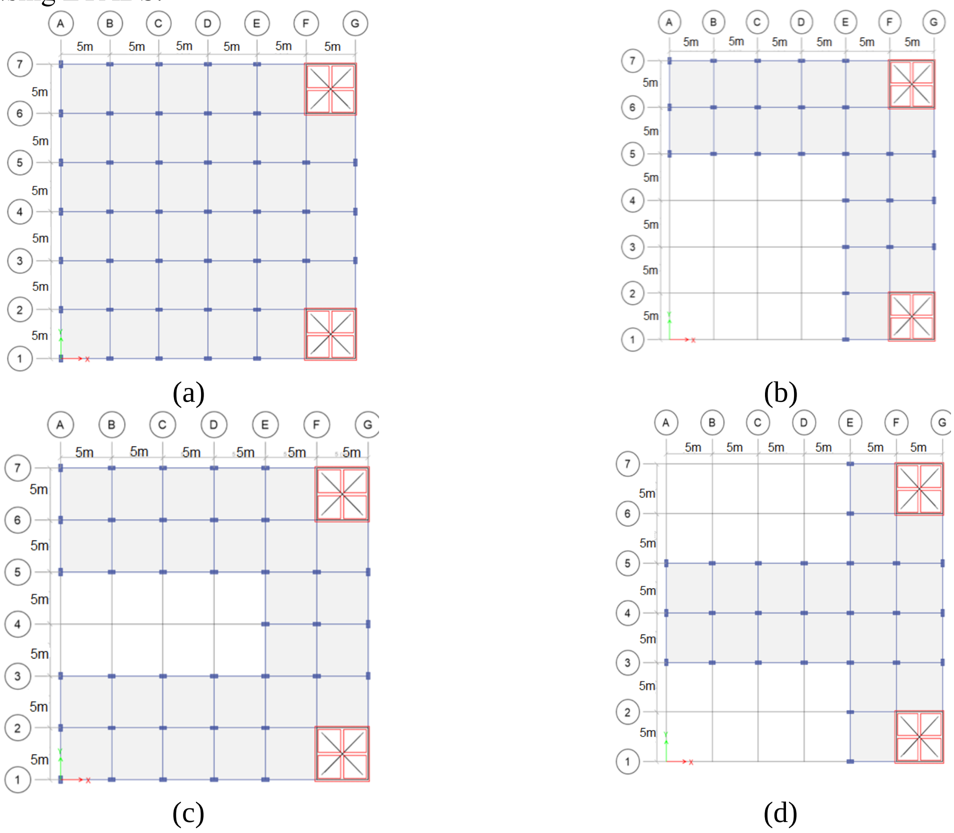
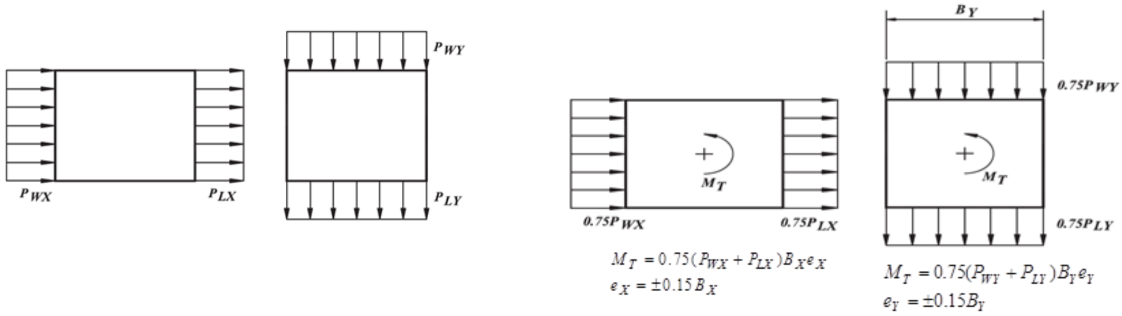


Figure 1. Building Plans (a) Regular Symmetrical Square (b) Asymmetrical L (c) Asymmetrical C (d) Asymmetrical T–Shape Buildings.

The purpose of analysis was to collect relevant data for structural reliability and performance evaluation of these four building models when subjected to wind loading case 1 and case 2 shown in figure 2 with a prevailing average wind speed of 100 mph in Abu Dhabi and a structure exposure class of B category using ETABS.



Case I Case II

Figure 2. Wind load cases considered in present analysis [1].

3. Results and Discussion

A comparative analysis of lateral load specific parameters like fundamental period, natural and circular frequency of building and some other general parameters like maximum joint displacement, storey drift ratio, inter–storey drift, internal forces in structural members, storey response and storey stiffness due to change in plan configuration of a building is carried out and discussed below.

3.1 Fundamental Period

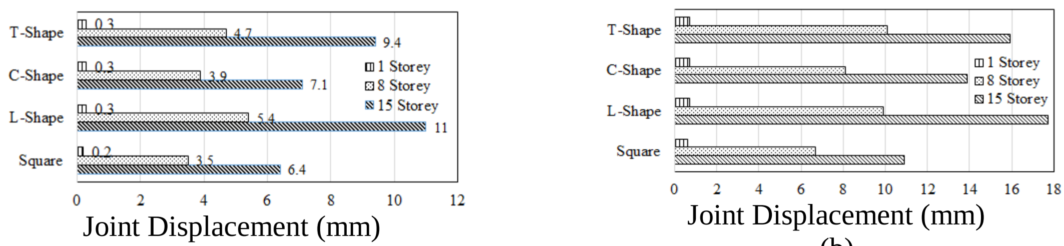
Modal analysis of buildings is carried out to measure and analyze dynamic response of buildings when subjected to wind loads. Generally, the first mode of vibration is of primary interest as it has the largest contribution to the structure's motion. The natural frequencies of the structure are frequencies at which the structures naturally tend to vibrate when subjected to some kind of disturbance i.e. wind loads in present case. Every building has its own frequency and it is dependent on stiffness and mass of the building. A building with greater mass will have lower natural frequency [2]. A square shape building with higher plan area is found to have lower values of natural frequency, circular frequency and eigen value compared to other plan configurations as seen in Table 1.

Table 1. Modal periods and frequencies of buildings with different plan configuration

Parameters	Square Shape		L–Shape		C–Shape		T–Shape	
	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2
Period (sec)	1.4	1.159	1.241	1.088	1.368	1.099	1.235	1.093
Freq. (cyc/sec)	0.714	0.863	0.806	0.92	0.731	0.91	0.809	0.915
Cir. Freq. (rad/sec)	4.4878	5.4228	5.0638	5.7776	4.5921	5.7172	5.0861	5.7504
Eigen Value (rad^2/sec^2)	20.1403	29.407	25.6424	33.3806	21.0869	32.6863	25.8688	33.0676

3.2 Joint Displacement due to Wind Loads

In general joint displacement at the top of stories of asymmetric plan configuration buildings is observed to be more in all the three directions compared to a square shape building. Joint displacements of C and T–shape buildings are however less than L–shape building as it is not symmetric about both *X* and *Y* axes. At the top story of building, a minimum joint displacement of 6.77×10^{-12} mm is observed for a C–shape building for wind load case 1 and a maximum joint displacement of 17.7mm is observed for a L–shape building for wind load case 2 which can be clearly seen in following figure 3 (a) and (b).



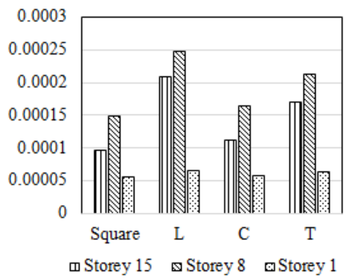
(a) (b)

3.3 Story Drift

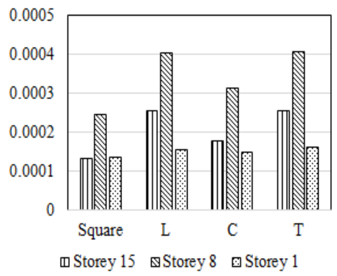
Storey drift or inter–storey drift is one of the particularly useful engineering response quantity and indicator of structural performance, especially for high-rise buildings when subjected to lateral loads [3]. Lateral deflection and drift have three primary effects on a structure; the movement can affect the structural elements (such as beams and columns); the movements can affect non–structural elements (such as the windows and cladding); and the movements can affect adjacent structures. Table 2 summarizes story drift (mm) and story drifts ratio of the first, eight and top storey relative to the base due to both cases of wind loads for various plan configurations.

Table 2. Storey Drift Ratio and Drift (mm) for various plan configurations due to two cases of wind loads

Storey	Max. Drift	Square Shape		L–Shape		C–Shape		T–Shape	
		Wind 2	Wind 1	Wind 2	Wind 1	Wind 2	Wind 1	Wind 2	Wind 1
15	*Max. Drift Y*	0.000132		0.000255		0.00018		0.000255	
	Max. Drift X		0.000097		0.000209		0.000112		0.000171
	X	29.2	25	0	25	0	25	0	25
	Y	25	2.5	30	0	30	27.5	20	2.5
8	*Max. Drift Y*	0.000246		0.000404		0.000315		0.000409	
	Max. Drift X		0.000148		0.000248		0.000164		0.000213
	X	0	27.5	0	29.2	0	27.5	0	27.5
	Y	30	2.5	30	0	30	27.5	20	2.5
1	*Max. Drift Y*	0.000137		0.000156		0.000148		0.000161	
	Max. Drift X		0.000055		0.000066		5.80E-05		6.30E-05
	X	0	29.2	0	29.2	0	29.2	0	29.2
	Y	30	0	30	0	30	30	20	0



(a)



(b)

Figure 4. Maximum storey drift ratio (a) in X-direction and (b) in Y-direction

Figure 4 (a) and (b) above show maximum storey drift ratio in X and Y direction at storey 15, storey 8 and storey 1 of different plan configuration buildings. It can be clearly seen that a square shape building has minimum storey drift in both directions for all the three stories considered followed by C-shape and T-shape buildings.

3.4 Internal forces in structural members

Maximum and minimum values of internal forces like shear force, bending and torsional moments, deflection for a particular beam and axial force and torsional moment for a particular column most affected by the shape of building were considered for analysis as shown in Table 3 (for beam B67 in 8th Storey) and Table 4 (for column C5 in 8th Storey).

Table 3. Internal forces in Beam B67 in 8th Story due to Wind Loads

Internal forces	Square		C-Shape		L-Shape		T Shape	
	Max	Min.	Max	Min.	Max	Min.	Max	Min.
Shear (kN)	8.35	-0.125	8.31	-0.483	10.922	-1.22	10.94	1.54
Bending Moment (kN-m)	12.06	-13.45	14.61	-15.44	19.35	-20.35	19.32	-20.3
Torsional Moment (kN-m)	4.75	-3.68	4.29	-3.176	5.545	-4.537	5.55	-4.59
Deflection (mm)	-0.2	8.56×10^{-3}	-0.5	0.2	-0.6	0.3	-0.6	0.5

Location of these values within the member vary in some cases, however in most of the cases the location of maximum and minimum value remains same due to the similar nature of load considered for this part of structural reliability analysis. It can be seen from the table 3 and table 4 that the internal forces and deflection are more in case of asymmetrical shapes (L shaped building, in particular).

Table 4. Internal forces in Column C5 in 8th Story due to Wind Loads

Internal forces	Square		C-Shape		L-Shape		T Shape	
	Max	Min.	Max	Max	Min.	Min.	Max	Min.
Axial Force (kN)	74.09	-7.95	98.68	-81.85	114.29	-52.5575	152.51	-40.99
Torsion (kN-m)	0.443	-0.443	0.563	-0.563	0.914	-0.782	0.8703	-0.872

3.5 Story Response

Storey response is analyzed in terms of maximum storey displacement as shown in Figure 5. Storey displacement is the lateral displacement of the storey relative to the base. There is a maximum permissible limit of storey displacement specified in design codes [4]. It can be seen that a fifteen storey square shape building has lesser value (6.4 mm) of storey displacement compared to C and T – shaped building, while L shape building showed maximum storey displacement of 11.9 mm at the top of the building when subjected to wind loads.

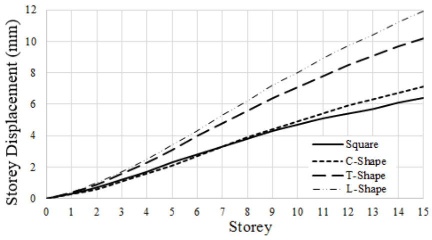
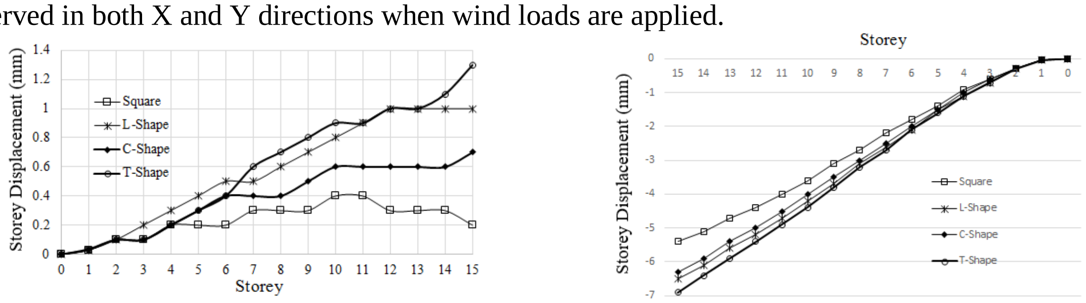


Figure 5. Storey Displacement (mm) measured for fifteen stories of different shaped buildings

Storey response is also studied in terms of minimum displacement in X and Y direction at all stories of different shaped buildings as shown in figure 6 (a) and (b). A similar behavior of displacement can be observed in both X and Y directions when wind loads are applied.

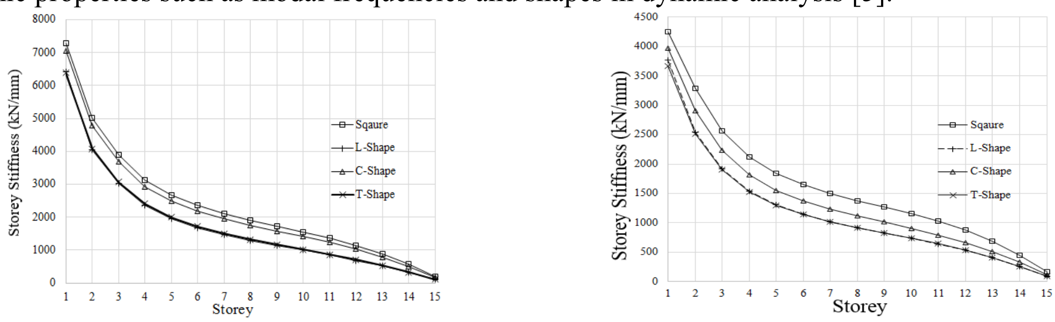


(a) (b)

Figure 6. Minimum storey displacements in (a) X- direction and (b) Y-direction

3.6 Storey Stiffness

The story stiffness is defined as inverse of inter–story drift when a unit load is applied at that particular story, in other words it is the shear force required to produce unit displacement of that storey. It is an important parameter for both static and dynamic analysis of building subjected to lateral loads, for calculation of lateral displacements in static analysis and calculation of lateral displacements and dynamic properties such as modal frequencies and shapes in dynamic analysis [5].



(a) (b)

Figure 7. Storey Stiffness (kN/mm) in (a) X-direction for wind load case I and (b) Y-direction for wind load case II

The inter–story stiffness is used as one the main damage–sensitive features of a multi-story building for detection, localization and quantification of damage caused. The distribution of lateral loads is dependent on the relative stiffness of each structure. Elements with higher stiffness resist more lateral load than elements with lower stiffness. The results of storey stiffness in X and Y direction are shown in figure 7 (a) and (b). A square shaped building has higher storey stiffness followed by C shape in both directions. However, for L and T-shaped buildings the results were quite similar as seen in Fig 7 (a) and (b).

4. Conclusions

A thorough comparison of parameters namely fundamental period, natural frequency and circular frequency, joint displacements, storey drift, internal forces in structural members, storey response in terms of maximum storey displacement, and storey stiffness of four different shaped buildings using ETABS has been carried out. From lateral load analysis of these buildings modal deflected shapes concluded that asymmetrical plans undergo more deformation than symmetrical plans.

Storey drift displacement increased with storey height up to 8th storey reaching to maximum value and then starts decreasing for wind load in X-direction while for wind load in Y-direction it increases from base till top of the building for all shapes. Relative to the square plan configuration, it can be observed that the L-shaped and T-shaped buildings have almost 48.24% increase in drift ratio in the Y-direction for storey 15, while the L-shaped have a 53.59% increase in drift ratio in the X-direction for storey 15.

Fundamental period showed relatively significant decrease in the T-shaped building of almost 11.79% compared to the square shaped building which had the highest value of 1.4 seconds. Similarly, the L-shaped building had 11.35% lower fundamental period compared to square shape. Thus, it can be said that buildings with lower mass tend to have lower fundamental period or higher frequency.

It was also noticed that the storey stiffness of these plan configurations increase as the mass of the building increase since the square-shaped building showed roughly about 34% increased stiffness in the Y-direction when compared to L-shaped and T-shaped buildings, the same storey stiffness increase in X-direction was observed to be 30%.

In general it can be concluded that plan configurations of a building has significant impact on the lateral load response of structure in terms of displacement, story drift and story shear. Large displacements were observed in L–shaped building when subjected to wind loads in both X and Y-direction due to severe irregularity in plan i.e. asymmetric about both the axes. Hence, it can be said that T–Shape and L–shape multi-storeyed buildings are more susceptible to wind loads compared to the symmetrical buildings based on criteria included in present study.

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