Torsional Behavior of Plan Asymmetric Shear Wall Buildings under Earthquake Loading

Archana J Satheesh*, Jayalekshmi B.R** and Katta Venkataramana***
*Research Scholar, Department of Civil Engg, NITK Surathkal
*archana.satheesh247@gmail.com
**Associate Professor, Department of Civil Engg NITK Surathkal
***Professor, Department of Civil Engg NITK Surathkal

Abstract: Multi-storey buildings with irregular geometry and structural systems have become prevalent due to various possibilities offered by modern materials and construction methods. However, damage from past earthquakes shows that strong torsional effects are responsible for the collapse of asymmetric buildings. Torsional irregularity depends on a number of factors like plan geometry, dimensions or position of structural elements and number of storeys. Torsional irregularity in plan, induced due to change in position of the lateral load resisting elements (shear walls) in reinforced concrete shear wall buildings of varying aspect ratios is studied in this paper. Initially symmetric buildings with L-shaped shear walls on diagonally opposite corners, and on all four corners are considered. A stipulated amount of eccentricity is introduced in these building configurations by changing the positions of the structural walls along the plan. Time history analysis is carried out to evaluate the torsional behaviour of the asymmetric buildings in terms of variation in base shear, fundamental time period, roof deflection and floor rotation. The results show that change in the dynamic eccentricity of the shear wall buildings causes variations in floor rotation and torsional response of both the building configurations.

Keywords: Asymmetric buildings, torsion, shear wall buildings, transient analysis.

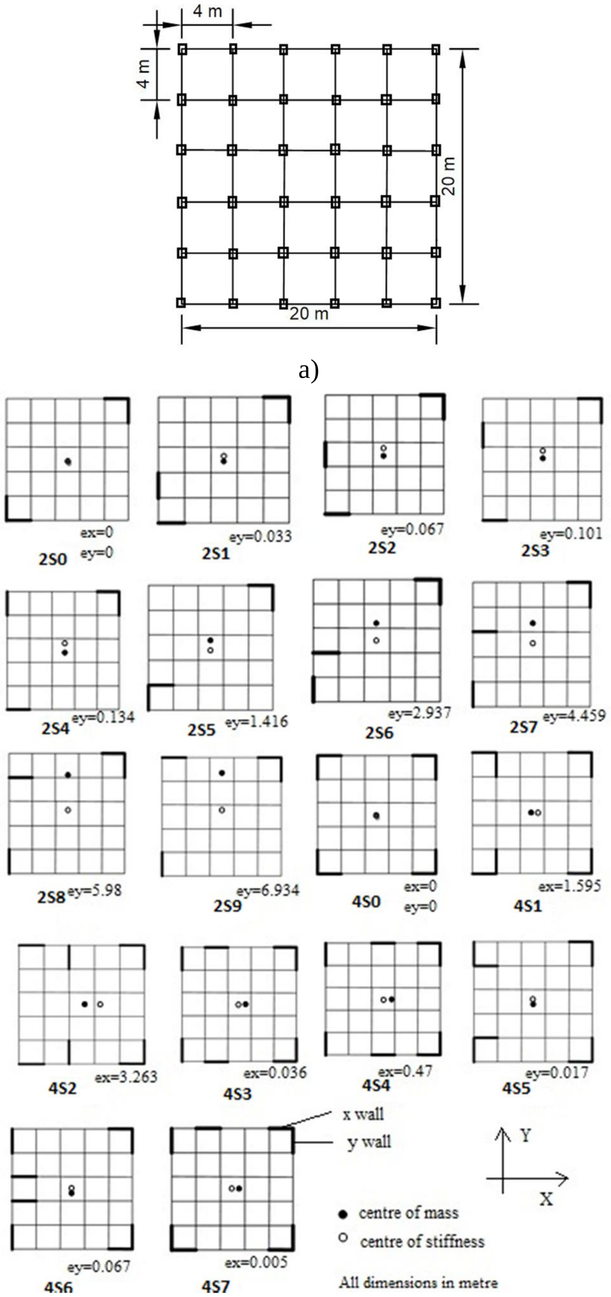
Introduction

For a building to be classified as symmetric it must possess, coincident centers of mass and stiffness lying on a common vertical axis, at each floor level [1]. In practice, this criterion is rarely achieved and most buildings are unsymmetrical to varying degrees, in plan, elevation, distribution of vertical members or mass distribution on the floors. Building with asymmetric distribution of stiffness and strength in plan undergo coupled lateral and torsional motions during earthquakes [2]. Torsional irregularity depends on a number of factors like plan geometry, dimensions or position of structural elements and number of storeys. Shear walls are the major lateral load resisting system of a building which provides adequate strength and stiffness to a building in the advent of earthquake or wind forces[3]. A shear wall is defined as an element within a building which has the specific function of resisting the lateral loads during earthquake or wind excitation of the structure. A shear wall element may be in the form of walls, elevator shafts, stairwells etc. The related lateral shear forces in vertical resisting elements located on the periphery of the structure may be significantly increased in comparison with the corresponding values for a symmetric building [4]. The effect of torsional irregularity in plan, induced due to change in position of shear walls, is studied in this paper. The variation in the torsional seismic response of the building as a result of progressive change in the position of the shear walls along the frame of RC building is considered here. Two standard shear wall building configurations, one with L shaped shear walls on all four corners and one with shear walls along the only two diagonally opposite corners are considered. The variation in their seismic response due to the induced torsional coupling when the position of the walls is altered is evaluated.

Idealisation of structure

Three dimensional (3D) idealized building frames with plan dimensions of and 20m x 20m were considered in the study. Beams were modeled using two-node beam element with three longitudinal and three rotational degrees of freedom at each node. Slabs at different story level, shear wall and the slabs of raft foundation were modeled with four-node shell elements with adequate thickness. The story height and length of each bay of all the building frames were chosen as 3m and 4m respectively. The thicknesses of floor slab and the raft slab was taken as 0.15m and 0.5m respectively. The beam dimensions were taken as 0.3 x 0.4m and column dimensions were taken as 0.5m x 0.5m with reduction to 0.4m x 0.4m after a height of three storeys. Shear walls of thickness 0.25m were provided throughout the height of the building frames. Concrete of M_{25} grade and steel of Fe 415 grade were considered as the material for the structural elements. L shaped shear walls were provided at diagonally opposite corners, and all four corners in the building frames and denoted as 2S0 and 4S0 respectively.

The bare frame building without shear walls is indicated as BF0. In this paper, seismic torsional responses of five, ten and fifteen storey reinforced concrete buildings with shear walls placed on diagonally opposite corners as well on all four corners is evaluated. It is assumed that centers of gravity of stories are at the geometric centers of floor plans. The shear walls along x direction (x walls) and shear walls along y direction (y walls) are relocated perpendicularly and successively to the consecutive bays so as to introduce asymmetry in the plan of the building along either x or y direction. The shear wall positions are changed only along one side of the building termed as the flexible side, whereas the wall positions are kept unchanged on the other side being the stiff side. A total of 18 different building configurations were thus generated as shown in Fig. 1 and analyzed to determine the effect of torsional irregularity in the seismic behavior of the buildings.



a)

b)

Figure 1. a) Bare frame building b) Building configurations

The eccentricity values of all the building configurations were calculated as per IS 1893: 2002[5].

$$e_{di} = 1.5\, e_{si} + 0.05b \quad \text{or } e_{si} - 0.05b$$

where e_{si} is the static eccentricity, e_{di} is the dynamic eccentricity and b is the floor plan width of the building in the direction perpendicular to the applied earthquake force. All the configurations have asymmetry about a single axis due to change in position of either the x directional wall or the y directional wall along the x or y axis. Out of the different configurations considered buildings with dynamic eccentricity values higher than three were considered for further analysis and study of response parameters. Therefore the configurations 2S5-2S9, 4S1 and 4S2 as observed in Table 1 were studied in comparison with the BF0, S0 buildings in detail to examine their torsional behavior.

Table 1. Eccentricity values

Building	e_x (m)	e_y (m)	e_{dx} (m)	e_{dy} (m)
BF0	**0**	**0**	**1**	**1**
2S0	**0**	**0**	**1**	**1**
2S1	0	0.03	1	1.050
2S2	0	0.06	1	1.101
2S3	0	0.10	1	1.152
2S4	0	0.13	1	1.201
2S5	**0**	**1.41**	**1**	**3.124**
2S6	**0**	**2.93**	**1**	**5.406**
2S7	**0**	**4.45**	**1**	**7.689**
2S8	**0**	**5.98**	**1**	**9.970**
2S9	**0**	**6.93**	**1**	**11.401**
4S0	**0**	**0**	**1**	**1**
4S1	**1.59**	**0**	**3.393**	**1**
4S2	**3.26**	**0**	**5.895**	**1**
4S3	0.03	0	1.054	1
4S4	0.47	0	1.705	1
4S5	0	0.01	1	1.026
4S6	0	0.06	1.000	1.101
4S7	0.00	0	1.008	1

Results and Discussions

Base Shear

Base shear a very important parameter in the seismic analysis of buildings and it directly implies the vulnerability of the building to earthquake loading. From Fig. 2, it can be observed that the shear wall buildings have lower base shear in comparison with the bare frame ones. This decrease in base shear which is more distinct in the 5 and 10 storey buildings is significant due to the stiffening effect of the shear walls. In the considered building configurations, base shear values decreases with increase in the height of the building. Increase in base shear ratio can be observed with increase in the eccentricity values with 2S9 having the highest base shear ratio which is 15.6% higher with respect to 2S0. 4S2 has a value which is 40% higher with respect to 4S0. It can also be observed that buildings with smaller eccentricities have lower base shear in comparison to the S0 buildings.

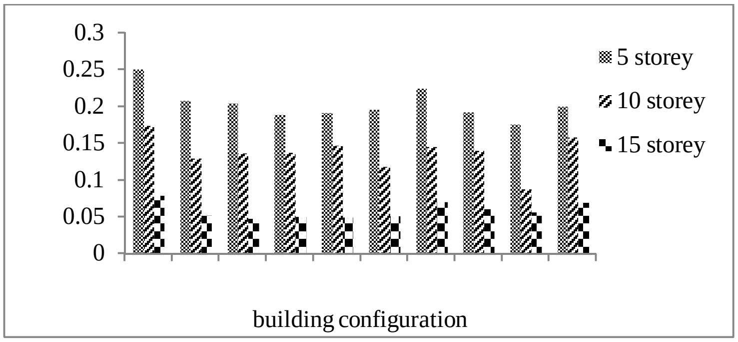


Figure 2. Variation in base shear

Fundamental Time Period

The fundamental time period of the buildings show similar variation in all the cases and configuration with increase in height of the buildings. The highest fundamental period is observed in the BF buildings. With the incorporation of shear walls, the stiffness of the buildings increases and consequently the fundamental period decreases. Eccentricity of the shear walls also causes considerable changes in the time period values. The 2S0 buildings have lower time period in comparison with the BF configuration as shown in Fig. 3, which is due to the stiffening effect of shear walls. 2S9 configuration with 12.55% higher values with respect to 2S0 has the highest fundamental period due to the highest y direction eccentricity. The lowest time period is obtained in the 4S0 symmetric configuration and highest in the 4S2 configuration in all the three height variants. 4S2 with the highest eccentricity in the 4S configuration buildings has its time period 8.4% higher in comparison with 4S0.

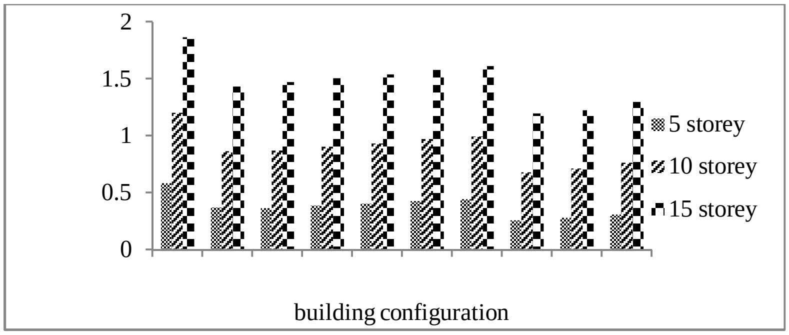


Figure 3. Variation in fundamental time period

Roof Deflection

The lateral deflection of roof of the building with reference to fixed base of the structure is referred to as roof deflection. The bare frame buildings have higher roof displacement in all three height variants due to the stiffening effect of the walls in the shear walled configurations. Further the roof deflections of the shear wall buildings undergo variation with the change in the positions of shear walls. From Fig. 4 it can be observed that 2S9 with the maximum y directional eccentricity has the highest roof deflection. The roof deflection is found to increase with increase in the eccentricities. Deflection values of 2S9 and 4S2 are 44% and 17.3% higher in comparison to 2S0 and 4S0 respectively.

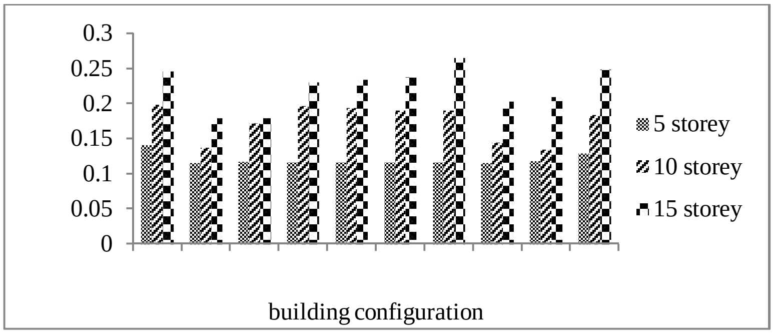


Figure 4. Variation in roof deflection

Floor rotation

The floor rotations of the buildings were estimated by considering the maximum storey drifts of the extreme corners of the top floor of each model. The displacement time histories of the corner points were considered and the highest value of the difference of the drift values gave the maximum relative displacement of the corners. Floor rotation in radians was obtained by dividing the relative displacement by the width of the considered side of the building. The floor rotation values increases with height and eccentricity of the buildings as shown in Fig. 5 and hence it can be inferred that the torsional effect becomes more significant with increase in the height and eccentricity of the building. The highest floor rotation is observed in 2S9 and 4S2, 15 storey building. 2S5 to 2S9 configurations have y directional eccentricity due to changing location of x walls and the 2S9 configuration has maximum eccentricity due to positioning of x-walls to the extreme end in the y direction. The BF0, 2S0, 4S0 has the least or minimal floor rotation which is obviously due to the absence of asymmetry. In the case of 4S configuration, 4S2 with maximum y directional eccentricity has the highest floor rotation in all the height variants. All three building heights show almost similar change in the floor rotation with the change in location of shear walls.

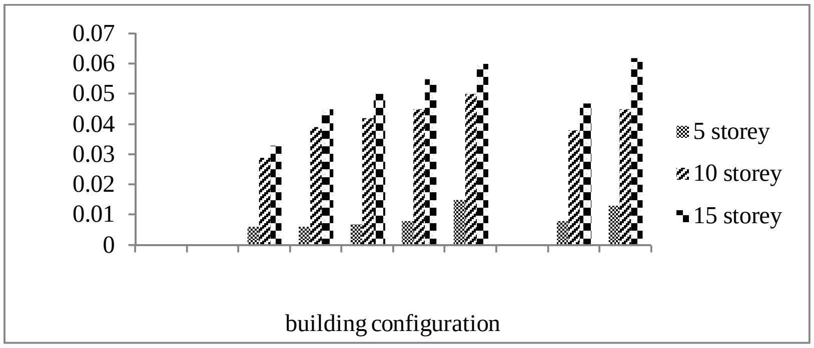


Figure 5. Variation in floor rotation

Torsion irregularity factor

As per IS 1893:2000, ASCE 7-10[6] and FEMA 450[7], torsional irregularity shall be considered to exist when the maximum storey drift, at one end of the structure transverse to an axis is more than 1.2 times the average of the story drifts at the two ends of the structure. ASCE 7-10 and FEMA 450 also states that extreme torsion irregularity exists when the maximum story drift, at one end of the structure transverse to an axis is more than 1.4 times the average of the story drifts at the two ends of the structure. The torsion irregularity factors obtained for the building configurations are as shown in Table 2 below. It can be observed that the irregularity factor increases with increase in the height of the building. As per the codal provisions, irregularity does not exist for the five storey buildings considered here. Extreme torsion irregularity exists for 2S4, 4S5 and 4S6 in fifteen storey buildings. Irregularity factor is not found to tally with the increase in the eccentricity values in 2S5 to 2S9. Highest irregularity coefficient is obtained for 2S4 and 4S6 buildings. In 2S4, the y walls is oriented on the bay at the extreme opposite end in the x direction and in 4S6, two x walls are located on inner bay in the y direction.

Table 2. Torsion irregularity coefficient values

Building	Torsion irregularity coefficient		
	5	10 storey	15 storey
BF0	1.000	1.000	1.000
2S0	1.000	1.000	1.000
21	1.019	1.112	1.289
2S2	1.019	1.115	1.306
2S3	1.019	1.120	1.329
2S4	1.026	1.138	1.425
2S5	1.015	0.883	1.283
2S6	1.016	1.113	1.346
2S7	1.019	1.124	1.371
2S8	1.020	1.170	1.335
2S9	1.021	1.172	1.319
4S0	1.000	1.000	1.000
4S1	1.014	1.016	1.036
4S2	1.023	1.025	1.044
4S3	1.014	1.222	1.272
4S4	1.006	1.093	1.092
4S5	1.015	1.187	1.423
4S6	1.019	1.234	1.456
4S7	1.006	1.098	1.128

It can be observed that torsional irregularity coefficient which is described by many of the international codes as a measure of irregularity in the buildings does not seem to accurately indicate the torsional response of the asymmetric buildings under earthquake loading. The torsion irregularity values are observed to vary with increase in height of the buildings and therefore giving negligible torsion effect on the 5 storey buildings considered here. It is also seen that, as per the results obtained, floor rotations represent the torsional behavior more realistically in comparison with the above mentioned torsion irregularity. In certain configurations the irregularity factor does not conform to the variation in eccentricity. Fig. 6 shows the scatter plot between the values of irregularity coefficient and floor rotation for all the considered configurations. The R^2 value in the correlation between the floor rotation and irregularity coefficient is 0.4324. It is also seen that, as per the results obtained, floor rotations represent the torsional behavior more realistically in comparison with the above mentioned torsion irregularity. In certain configurations the irregularity factor does not conform to the variation in eccentricity.

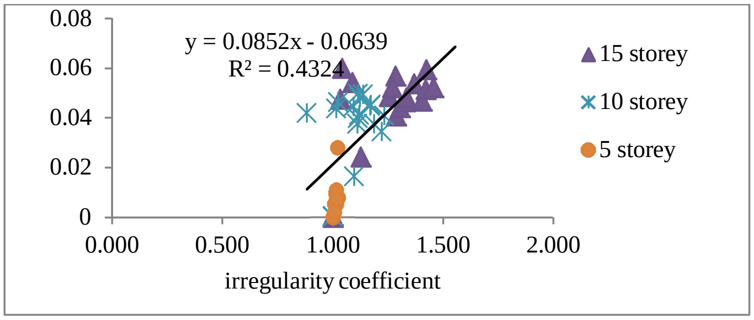


Fig. 6. Torsion irregularity coefficient versus floor rotation

The correlation coefficients between the response parameters were estimated and is given in Table 3. it can be observed that the correlation between floor rotation and irregularity coefficient was obtained as 65%. The response parameters like time period, roof deflection and base shear have higher correlation with the floor rotation values than with that of irregularity coefficient. Therefore it can be inferred that floor rotation gives a better picture of the torsional seismic response of the buildings in comparison with the irregularity coefficients in the code provisions.

Table 3. Correlation coeffients of the response parameters

Response parameters	Correlation coefficients					
	Floor rotation	Base shear	Roof Deflection	Time period	Eccentricity	Irregularity coefficient
Floor rotation	1					
Base shear	**-0.635**	1				
Roof Deflection	**0.723**	-0.673	1			
Time period	**0.686**	-0.807	0.906	1		
Eccentricity	**0.465**	0.265	0.245	0.215	1	
Irregularity	**0.657**	**-0.558**	**0.432**	**0.428**	**0.126**	1

Examination of these observations shows that the torsional irregularity coefficient as defined in the regulations need not necessarily represent the torsional characteristics of the structure realistically. Hence code definitions of the torsional irregularity coefficients could be modified to incorporate the eccentricity parameter and floor rotation to better represent the response of the structure.

Conclusions

The torsional response of a building frame depends on the structural configuration and the orientation of the lateral load resisting elements or shear walls. The response parameters like fundamental time period, floor rotation, base shear etc. undergo variation with change in the positions and orientation of the shear walls and the following major conclusions can be arrived at:

The base shear ratio tends to decrease with incorporation of shear walls as a result of stiffening of the building. Further with addition of asymmetry, the base shear ratio increases with increase in the eccentricity. 4S2 with the highest value of x directional eccentricity among 4S configuration, has the highest base shear ratio with an increase of 43.9 % with respect to 4S0.

Fundamental time period is also found to increase with change in eccentricity and the symmetric shear wall buildings have the lowest time period. 2S9 buildings have the highest variation in time period in comparison to the other asymmetric cases which is 12.5% higher with respect to 2S0 because of the high y directional eccentricity.

The roof deflections of the bare frames buildings are comparatively higher than the symmetric shear wall buildings. With addition of shear walls, the roof deflection increases proportionally with the increase in eccentricity of the buildings. The variation in the deflection values due to asymmetry is highest in the case of 2S9 and 4S2 which are 44% and 17.3% with respect to 2S0 and 4S0.

The floor rotation of the building frames changes directly with the change in eccentricity, orientation and overall distribution of the shear walls. The movement of the walls in a direction opposite to their axial direction increases the floor rotation. 2S9 and 4S2 with the highest values of eccentricity underwent maximum floor rotation wherein the rotation values where 90 to 100% higher in comparison with the negligible values of the symmetric cases.

The floor rotation parameter gives a better representation of the irregularity in the buildings when compared to the torsion irregularity coefficient. The codal provisions based on irregularity could be modified to give a better representation of the torsional irregularity of the shear wall in terms of floor rotation.

The variation in the torsion irregularity coefficient values with respect to the floor rotation and eccentricity of the irregular buildings under the effect of seismic loading can be quantified with parameters after regression analysis on a wide range of buildings with different aspect ratios under different earthquake loading.

References

[1] Pavan Agarwal and Vinay Gupta, “Dynamic Amplification of eccentricities in seismic response of multistoreyed buildings”, European Earthquake Engineering, Vol. 1, 37-45, 1997.
[2] Rana Roy and Suvonkar Chakroborty, “Seismic Demand of Plan-Asymmetric Structures: A Revisit”, Earthq Eng & Eng Vib, Vol. 12, 99-117, 2013.
[3] Dorde Ladinovic, “Nonlinear Seismic Analysis of Asymmetric in Plan Buildings”, University of Novi Sad, Faculty of Technical Sciences, Architecture and Civil Engineering Vol. 6, No 1, 25 – 35, 2008.
[4] Ozmen, G., Girpin, K. and Durgun, Y., “Torsional Irregularity in Multi Storey Structures.” International Journal of Advanced Structural Engineering, 6, 121-131, 2014.
[5] IS 1893 (Part 1):2002 Indian Standard Criteria for Earthquake Resistant Design of Structures.
[6] American Society of Civil Engineers (2010) ASCE 7-10, Minimum Design Loads for Buildings and other Structures.
[7] NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures (FEMA 450).