Parametric Study of Multi-Storey R/C Building with Plan Irregularity

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Abstract: ***The response of the structure during an earthquake depends essentially on its size, shape and geometry. Regular and symmetric buildings with simple geometry in plan and properly designed have performed well during past earthquakes than assymetric buildings whereas the response of asymmetric buildings are unpredictable and to take in artistic and functional requirements, designers have to compromise with structural regularity. As a result, asymmetric buildings with u, v, h, I etc. shaped in plan have sustained widespread damage repeatedly in past major earthquakes. Therefore, the parametric study in the proposed thesis attempts to evaluate irregular plan structures like L - shape, H – shape and U- shape. Lateral length ratio is varied for each shape plan configuration and the assessment of each plan is done on the basis lateral length ratio. Buildings are analysed for Dead loads, Live loads and Wind loads are set as described in IS 875 part 1, 2 and 3 respectively. Modelling and analysis of the structure is done using "ETABS" software. Based on the results and the graphs plotted for design eccentricity, internal forces, Storey shear, Storey displacement, Overturning moments and storey drift versus lateral length ratios for different shapes, conclusion for the most stable structure is drawn.***

Keywords: lateral length ratio, ETABS, design eccentricity, storey shear

1. Introduction

In 21st century, most of the countries are developing economies across the globe, there is a faster rate of growth in the cities. Due to huge population, the number of areas in units are insufficient to meet the demand and are decreasing day by day. To overcome this insufficiency of land, people need to grow in vertical system which includes tall building structures and these building structures are affected by lateral loads in more than one way. Heavy moments and forces are caused at the base of the buildings due to the direct action of the lateral loads such as seismic and wind loads. Seismic loads (Earthquakes) are one of the greatest natural threats to life as the devastation caused by the seismic activities. Therefore, to avoid the collapse and no loss of life in the most severe possible earthquake, the structure should be designed with an optimum engineering approach.

The structures show torsional and translational motions to the earthquake ground motion input if their centre of resistance and their centre of floor mass do not coincide. Torsional motions may occur in nominally symmetrical buildings due to accidental eccentricity. The difference between the assumed and actual distribution of mass and stiffness, differences in coupling of the footing with supportive soil, non-linear forms of force-deformation relationships, and asymmetric yielding strength are the sources giving rise to accidental eccentricity. The design of the symmetric and regular buildings is far more straightforward to predict and these buildings have much higher capacity to endure a strong seismic activity than an asymmetric buildings. However, the response of irregular buildings is more random and unpredictable, engineers still have to compromise structural symmetry to accommodate serviceable and aesthetic needs. And thus serious and widespread destruction associated with structural asymmetry has been witnessed repeatedly in earlier major earthquakes.

2. Torsional Effects in Buildings

The most critical factor leading to torsional motions in buildings is structural asymmetry caused by mass, stiffness or strength distribution. Buildings exhibit coupled torsional and translational response to lateral ground motion if their centres of mass CM do not coincide with their centres of rigidity CR calculated at floor levels. The building's centres of rigidity are defined as the set of points at floor levels through which the set of applied lateral forces does not produce rotation of the floor slabs. The earthquake ground motion $\ddot{u}_g$ (t) excites the structural model in the lateral direction, acting through CM and loads the structure with an inertial force of magnitude m $\ddot{u}_g$ (t), where m is the mass of the floor diaphragm. This lateral inertial force is resisted by the structural elements, which induce an equal, but opposite, resisting force acting through CR, which is equivalent to the centre of stiffness CS and the shear centre SC for single-storey systems.

The structure is assumed to possess a uniform mass distribution when CM is located at the geometric centre GC whereas an asymmetric stiffness distribution exists when CR is located away from GC. In this case, the earthquake induced inertia force and the structural resisting force are separated by the stiffness eccentricity or static eccentricity. Thus, such a configuration induces a torsional moment that in turn invokes torsional rotation of the floor diaphragm. This onset of an earthquake-induced torque may also eventuate from mass asymmetry or strength asymmetry.

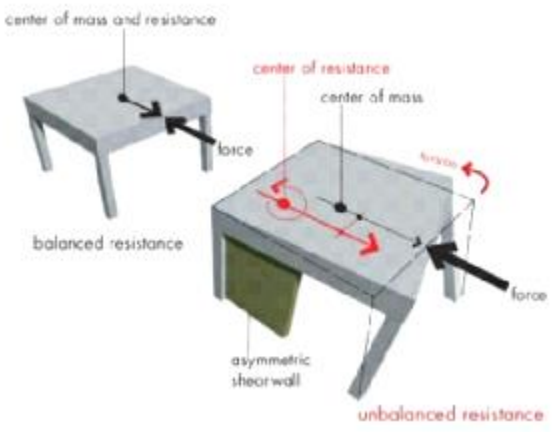


Figure 1 Torsional effects develop in a building

3. Literature Review

It is found that research on this topic started way back in 1958. Surveys and analyses following the 19th September 1985 Michoacán, Mexico earthquake conducted by Chandler (1986), Rosenblueth (1986) and Goel (2001), Bhuj, Gujarat Earthquake, it is determined that almost 50% of the failures were due to structural irregularity.

Al-Ali et al. [1] Evaluated the effects of vertical asymmetry by considering height-wise deviations of earthquake demands. The vertical irregularities in the distributions of toughness, strength and mass were taken individually and in combinations and the elastic and inelastic dynamic analyses was carried out to assess the seismic response of irregular structures. They concluded that the influence of strength asymmetry was higher than the influence of toughness asymmetry, and the effect of mass irregularity was minimum whereas the influence of combined-strength-and-stiffness asymmetry was maximum and the vertical irregularity does not affects the roof displacement.

Chintanapakdee et al. [2] considered the effects of stiffness and strength irregularities on floor displacement responses and storey drift demands. 3 kinds of asymmetries in the vertical system of structure were taken: strength asymmetry, stiffness irregularity, and both strength and stiffness asymmetry. A time history analysis was done to compare the median seismic demands of symmetric and asymmetric frames. It was concluded that the story drift demands were increased in the adjacent stories by allowing a soft storey whereas the drift demands were decreased in the other stories. On the other hand, allowing a strong storey, there drift demands were decreased in the adjacent stories and were increased in the other stories. A very small impact on the floor displacement was observed due to irregularity in upper stories. But, whereas irregularity in lower stories showed a serious impact on the vertical distribution of floor displacements.

Dhiman Basu et al. [3] performed seismic analysis of asymmetric buildings with flexible floor diaphragms. In this paper, the centre of rigidity was studied considering unsymmetrical buildings with flexible floors extended to rigid floor diaphragm. A process was projected to apply codal torsional requirements for erections with flexible floor diaphragms. The proposed process reflects the significance of static eccentricity as well as accidental eccentricity. Results of the analysis of a structure considered simply shows the importance of the torsional requirements of codal provisions for irregular flexible diaphragm structures. It was noticed that significant error may be caused when the diaphragms of such buildings are considered as rigid for torsional study. Also, the significance of contribution of accidental torsion as well as the torsional amplification terms are illustrated by an example.

Wakchaure M.R et al. [5] performed Seismic Analysis of Tall Building with and without in filled Walls. The linear dynamic analysis was carried out in this work to study the influence of masonry infill walls on of R.C.C. tall building. 10 storey building with in filled and bare frames were analysed and compared. It was concluded that base shear was increased from 2.5 to 8% considering infill walls in building. The top story displacements for in filled wall model for single strut was reduced from 0.8% to 0.4%. Storey drift of the building with infill's wall is within allowable limit. Storey drift was decreased from 0.003% to 0.02%.

Abhay Guleria et al. [9] studied structural analysis of a multi-storeyed building using ETABS for different plan configurations, In this study, the results of analysis of the multi-storey structure shows that the storey overturning moment was decreasing with increase in story height. And almost a similar response was observed in L-shape, I-shape type buildings against the overturning moment. Storey drift was increased with storey height up to 6th storey reached to a maximum value and then started decreasing with increase in story height. Mode shapes were generated from dynamic analysis, and it can be concluded that asymmetrical plans experience more deformation than symmetrical plans. Asymmetrical plans should be adopted considering into gaps and asymmetrical plans undergo more deformation and hence symmetrical plans must be followed.

Sakshi A. Manchalwar et al. [10] performed Seismic Analysis of RC Frame – A Parametric Study, In this study the analysis of multistoried building (upto14 story) subjected to earthquake force was carried. Effect of column stiffness, effect of number of bays, and building height etc. is studied. This building assumed to be located in Mumbai. The earthquake load analysis is carried out using software namely SAP2000. It was concluded that as the stiffness of column increases the moment in the same floor level beam decreases. However if 14 story frame is considered, the beam moment increases up to certain floor, in middle portion moment nearly constant and then again reduced up to top story. As the stiffness of column increases the moment in same floor level column increases continuously from negative value towards positive value. However if 14 story frame is considered, the column moment decreases up to certain floor, then again increases up to top story.

4. Response Spectrum Analysis

The actual time history curves are required for a particular location to perform the seismic analysis and design of a structure. However, it is impossible to have these records for each and every location. Also, the response of the structure depend upon its own dynamic properties and the frequency content of ground motion therefore, the seismic analysis of structures cannot be carried out simply based on the peak value of the ground acceleration. To overcome such obstacles, the most popular tool for the seismic analysis of structures is the earthquake response spectrum. There are other computational advantages such as prediction of displacements and member forces by using the response spectrum method of analysis. The process includes the calculation of only the extreme values of the displacements and member forces in each mode of vibration by means of design spectra that are the average of various seismic ground motions.

Response Spectra

The interaction between ground acceleration and structural systems through response spectrum were first purposed by Biot and was later popularised by Housner. Response spectra are the set of ordinates describing extreme response of SDOF system subjected to a prescribed ground motion. The response spectrum is presented as a curve of maximum response of SDOF system subjected to a ground motion as ordinate and corresponding time period (or the natural frequency) as abscissa.

The base dimension of the building at the plinth level along the direction of lateral forces is represented as d (in meters) and height of the building from the support is represented as h (in meters). The response spectra functions can be calculated as follows:

For Type I soil (rock or hard soil sites):

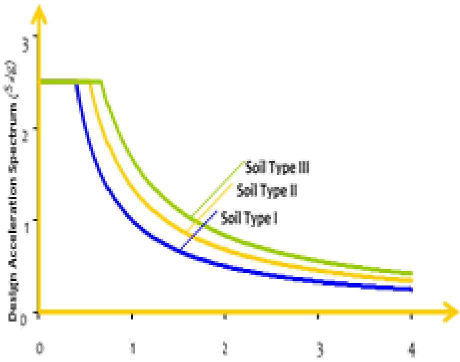
$$\frac{S_a}{g} = \begin{Bmatrix} 1 + 15T & 0.00 \le T \le 0.10 \\ 2.5 & 0.10 \le T \le 0.40 \\ \frac{1}{T} & 0.40 \le T \le 4.00 \end{Bmatrix}$$

For Type II soil (medium soil):

$$\frac{S_a}{g} = \begin{Bmatrix} 1 + 15T & 0.00 \le T \le 0.10 \\ 2.5 & 0.10 \le T \le 0.55 \\ \frac{1.36}{T} & 0.55 \le T \le 4.00 \end{Bmatrix}$$

For Type III soil (soft soil):

$$\frac{S_a}{g} = \begin{Bmatrix} 1 + 15T & 0.00 \le T \le 0.10 \\ 2.5 & 0.10 \le T \le 0.67 \\ \frac{1.67}{T} & 0.67 \le T \le 4.00 \end{Bmatrix}$$



Fundamental Translational Natural Period T (s)

Graph 1 Response spectra for 5 percent damping (IS 1893: 2002)

In a single degree of freedom system, the maximum response is determined by a frequency domain analysis or time domain analysis and maximum response is picked for a given time period of system.

Consider a single degree of freedom system subjected to ground motion acceleration,

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = -m\ddot{x}_g(t)$$

Substituting,

$$\omega_o = \sqrt{\frac{k}{m}},\ \xi = \frac{c}{2m\omega_o} \text{ and } \omega_d = \omega_o\sqrt{1-\xi^2}$$

The equation of motion associated with the response of a structure to ground motion can be rewritten as

$$\ddot{x}(t) + 2\xi\omega_o\dot{x}(t) + \omega_o^2 x(t) = -\ddot{x}_g(t)$$

Where,

ω_o is an undamped natural frequency of the system and ξ is the damping ratio

For a specified ground motion $\ddot{x}(t)$ and damping value and values of ω, the above equation can be solved using Duhamel's integral. A maximum displacement of the system can be found and a curve of maximum peak response $x(\omega)_{MAX}$ known as Displacement Response spectrum for earthquake ground motion is plotted. For different damping values, a different curve will exist.

A plot of $\omega x(\omega)_{MAX}$ and $\omega^2 x(\omega)_{MAX}$ is termed as the pseudo-velocity spectrum and pseudo-acceleration spectrum respectively. Actually, the pseudo values are not an necessary part of the response spectrum and therefore, the true values of maximum velocity and acceleration are calculated from the above equations. The total acceleration of the unit mass, SDOF system by a mathematical relationship given by,

$$\ddot{x}(t)_T = \ddot{x}(t) + \ddot{x}(t)_g$$

Therefore, the absolute acceleration response spectrum, S_a is expressed as,

$$S_a(\xi, \omega_o) = |\ddot{x_a}(t)|_{max} = \left|\ddot{x}(t) + \ddot{x_g}\right|_{max}$$

$\ddot{x}(t)$ from first equation is substituted in the above equation which yields,

$$\ddot{x}(t)_T = -2\xi_n \omega \dot{x}(t) - \omega^2 x(st)$$

And in a case where damping, ξ=0, from the above equation, for an undamped system, maximum acceleration response equals to the pseudo acceleration response. The standardise method to present the curve is in terms of $S(\omega)_n$ vs a period T in seconds.

Where,

$$S(\omega)_n = \left(\frac{2\pi}{T}\right)^2 x(\omega)_{MAX}$$

The pseudo-acceleration spectrum, $S(\omega)_n$ curve has units of acceleration vs period which has certain physical importance for zero damping only. All the three spectra are crucial in understanding the nature of the earthquake and its effect on the design. A specific response spectrum curve is selected after estimation of linear viscous damping properties of the structure for a specific site as well as the seismic properties of the particular site.

Response Spectrum analysis is the linear dynamic analysis. In this approach, response of each single degree of freedom system is combined to compute the total response of the multi degree of freedom system. The estimate of total response of the structure is computed by combining the response read from the design spectrum. Combination methods include the following:

- Maximum Absolute Response (ABS) – sum of the maximum absolute value of the response associated with each mode
- Square Root of Sum of Squares (SRSS) – A more reasonable method of combining two-dimensional structural system exhibiting well separated frequencies is the square root of the squares.
- Complete Quadratic Combination (CQC) - A method for three dimensional system that is a development on SRSS for tightly spaced modes shall be combined as per CQC method.

Non-linear static or dynamic analysis are preferred for the structures which are either too irregular or significant to a community as the analysis is more complex for which the RSA is no longer suitable.

5. Methodology Adopted

The methodology adopted was to determine the response of multi-storeyed buildings under the action of seismic and other loads. 3 cases were adopted by assuming the horizontal plan in different shapes keeping the area of construction same for all the structures for the respective shapes as listed below:

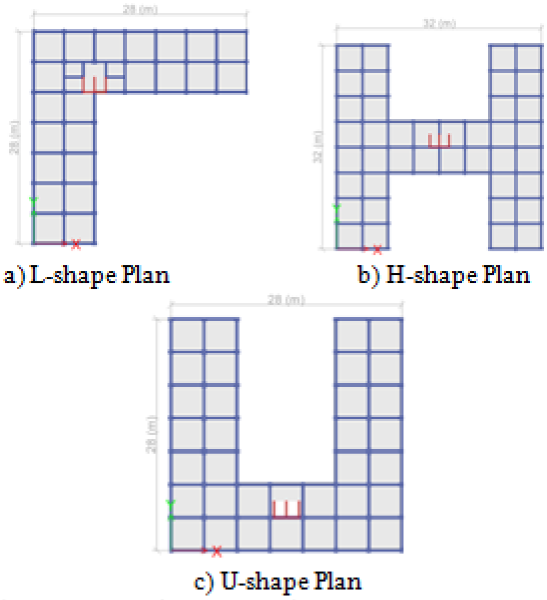


Fig 2 L, H & U Shape Plan

An 11 storey structure having 4m X 4m bays is considered for the above mentioned different shapes for the study. The building with column spaced at 4m centre to centre is assumed. Modelling and analysis of the structure is done using “ETABS” software. The height of each storey is taken as 3m and bottom storey height taken is 4m, making the total height of the structure 34m. Assessment is done on the basis of lateral length ratio for each shape. Lateral length ratio is varied for every shape. For L-shape, lateral length ratio is varied from 0.5 to 2.5, for H-shape, it is varied from 0.75 to 1.5 and for U-shape lateral length ratio is varied from 0.5 to 1.5. Buildings are analysed for Dead loads, Live loads, Seismic loads and Wind loads are set as described in IS 875 part 1, 2 and 3 respectively. Buildings are analysed considering design eccentricity and the design eccentricity at each floor is calculated according to IS 1893 (Part-1): 2002. Response quantities such as internal forces, Storey shear, Storey displacement and storey drift are considered for the assessment. Based on the results and the graphs plotted for internal forces, Storey shear, Storey displacement and storey drift versus lateral length ratios for different shapes, conclusion for the most suitable structure is drawn.

5.1 Structural Modelling

It is very important to develop a computational model on which linear/non-linear, static/dynamic analysis are performed. An assemblage of beam, column, slab and footing associated with each other as a unit is basically considered as a reinforced concrete framed structure. The load is transferred in these structures is from slabs to beams, from beams to columns, and then ultimately from columns to the footing, which in turn passes the load to the soil. In the present study, three cases are adopted by assuming the horizontal plan configuration in different shapes keeping the area of construction same for all the structures for the respective shapes.

5.1.1 L-shape Plan

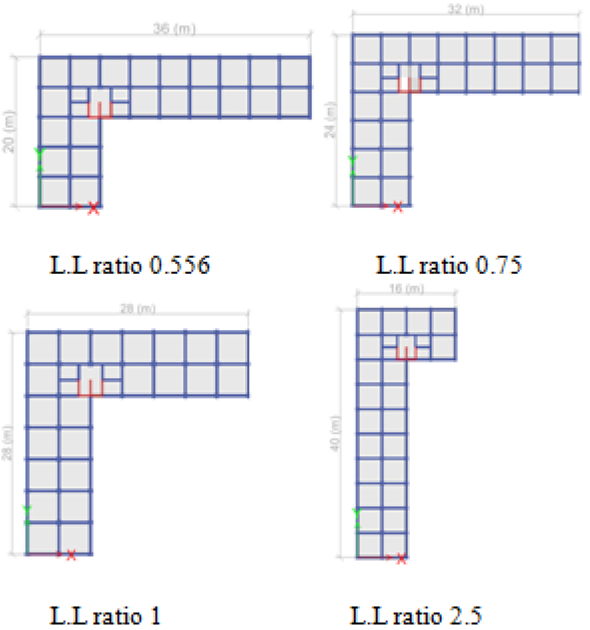


Figure 3 L-Shape Plans

5.1.2 H-shape Plan

For the assessment of the more stable structure, the lateral length ratios for H-shape plans are varied from 0.5 to 1.5.

5.1.3 U-shape Plan

For the assessment of the more stable structure, the lateral length ratios for H-shape plans are varied from 0.5 to 1.5.

6. Results and Discussion

6.1 Design Eccentricity

The eccentricity between the centre of mass and centre of stiffness of the storey that cause the torsion in the building are determined and then the design eccentricities are calculated as follows:

According to IS-1893 (Part-1):2002, the design eccentricity e_{di} to be used at the floor i shall be taken as:

$$e_{di} = \begin{cases} 1.5e_{si} + 0.05b_i \\ or\ e_{si} - 0.05b_i \end{cases}$$

Where

e_{di} = static eccentricity at floor i defined as the distance between the centre of mass and centre of rigidity.

b_i= Floor plan dimension of floor I, perpendicular to the direction of force.

Table 1: Equivalent Design Eccentricity for L-Shape Buildings

DESIGN ECCENTRICITY				
	L.LRatio-0.556	**L.LRatio-0.75**	**L.LRatio-1**	**L.LRatio-2.5**
Story	**Dsi**	**Dsi**	**Dsi**	**Dsi**
Story11	4.66	3.82	3.86	6.125
Story8	4.98	3.70	3.66	6.90
Story5	5.64	3.92	3.56	8.05
Story1	8.19	4.98	3.78	10.01

Where,

Dsi - Design eccentricity

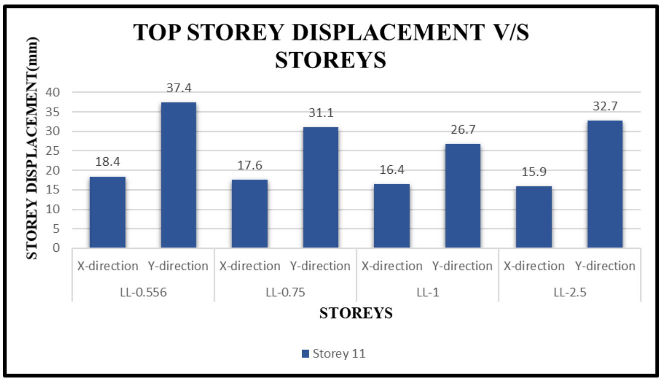
6.1.1 Design eccentricity is calculated knowing the centre of mass and centre of stiffness of all the stories of the building and it is compared for all the structures in the L-shape. From the table, we come to know about the design eccentricity for the building with lateral length ratio 1 is coming out to be minimum comparing both the directions whereas building with lateral length ratio 2.5 is showing maximum design eccentricity for the first floor.

6.1.2 For H-shape building, the design eccentricity for the building with lateral length ratio 1.2 is coming out to be minimum comparing both the directions whereas building with lateral length 1.42 is showing maximum design eccentricity for the first floor.

6.1.3 For U-shaped buildings, the design eccentricity for the building with lateral length ratio 0.81 is coming out to be minimum comparing the design eccentricity in both the directions whereas building with lateral length 1.25 is showing maximum design eccentricity for the first floor.

6.2 Lateral Displacements

The lateral storey displacement of the 11th storey are shown in the following bar graph plotted for top storey displacements v/s Storeys for all L-shaped buildings of different lateral length for the worst combination in y-direction:



Graph 2: Storey Displacements vs Storeys for L-shape Plan

6.2.1 For L-shaped Plans, plan with lateral length ratio 1 is showing the minimum lateral displacement of the 11th storey in x and y direction i.e. 16.4 and 26.7 mm respectively, of all other plans with different lateral length ratios whereas the plan with lateral length ratio 0.556 is showing maximum lateral displacement of the 11th storey in x and y directions i.e. 18.4 and 37.4 mm respectively. And the buildings with lateral length ratios 0.75 and 2.5 are showing top storey displacement of 31.1, 32.7 mm in y direction, respectively.

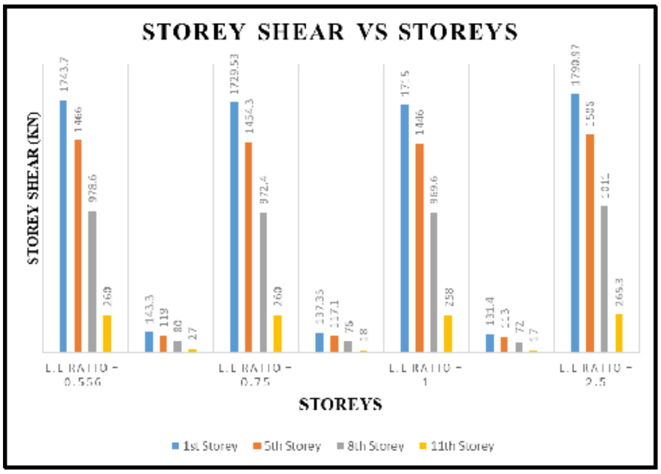
6.2.2 For H-shaped Plans, plan with lateral length ratio 1.2 is showing the minimum lateral displacement of the 11th storey in x and y directions i.e. 15.5 and 16 mm respectively, of all other plans, whereas the plan with lateral length ratio 0.82, 1 and 1.42 are showing maximum lateral displacement of the 11th storey i.e. 23.2, 21.8 and 25.7 mm in y direction respectively.

6.2.3 For U-shaped Plans, plan with lateral length ratio 0.81 is showing the minimum lateral displacement of the 11th storey in x and y directions i.e. 26 and 17.3 mm respectively, of all other plans with different lateral length ratios whereas the plan with lateral length ratio 1 is showing maximum lateral displacement of the 11th storey in x and y direction i.e. 40.6 and 21.8 mm. And the building with lateral length ratios 0.667 and 1.25 are showing storey displacement of 31.4 and 40.6 mm respectively.

6.3 Storey Shear

Storey Shear: It is the sum of design lateral forces at all levels above the storey under consideration.

Base Shear: The maximum lateral force at the base of the building is known as Base Shear.



Graph 3: Storey Shear vs Storey for L-shape Plan

6.3.1 For L-shape plan, the storey shears of the 1st, 5th, 8th and 11th storey for the buildings with different lateral length ratios and the graph clearly shows that the storey shears of all the 4 storeys in the building with lateral length ratio 1 is coming out to be the minimum of all with the base shear of 1715 kn whereas the buildings with lateral length ratio 0.556, 0.75 and 2.5 are showing larger storey shears.

6.3.2 For H-shape Plan, the storey shears of the 1st, 5th, 8th and 11th storey for the buildings with different lateral length ratios and the graph clearly shows that the storey shears of all the 4 storeys in the building with lateral length ratio 1.2 is coming out to be the minimum of all with the base shear of 2322.4 kn in y direction whereas the buildings with lateral length ratio 0.82, 1 and 1.42 are showing base shears of 2588.74, 2594 and 2472.5 Kn in y direction, respectively.

6.3.3 For U-shape plans, the storey shears of the 1st, 5th, 8th and 11th storey for the buildings with different lateral length ratios and the graph clearly shows that the storey shears of all the 4 storeys in the building with lateral length ratio 0.81 is coming out to be the minimum of all with the base shear of 2217.4 Kn in y-direction, whereas the buildings with lateral length ratio 0.667, 1 and 1.25 are showing base shears of 2876.7, 3345.4 and 2329.8 Kn respectively.

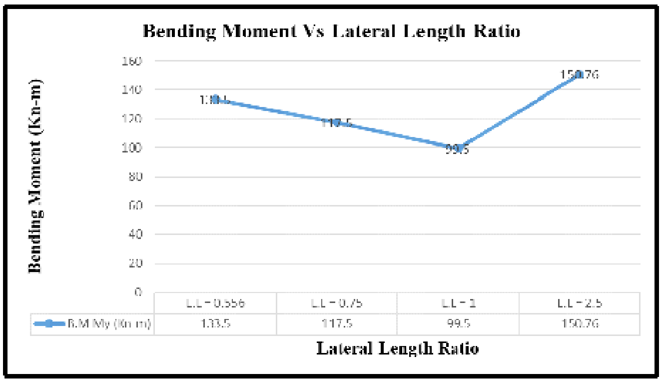
6.4 Bending Moment of the sample column

6.4.1 In L-shape plans, the bending moment of a sample column of the ground storey of the building with lateral length ratio 1 is coming out to be the minimum i.e. 99.5 kn-m, whereas, the other buildings with lateral length ratios 0.556, 0.75 and 2.5 showing higher bending moments such as 133.5, 117.5 and 150.76 kn-m respectively.

6.4.2 In H-shape plans, the bending moment of a sample column of the ground storey of the building with lateral length ratio 1.2 are coming out to be the minimum i.e. 82.25 kn-m respectively, whereas, the other buildings with lateral length ratios 0.82, 1 and1.42 are showing higher bending moments such as 90, 85.2 and 88 Kn-m respectively.

6.4.3 In U-shape plans, the bending moment of a sample column of the ground storey of the building with lateral length ratio 0.81 is coming out to be the minimum i.e. 71.76

kn-m, whereas, the other buildings with lateral length ratios 0.556, 1 and 1.25 are showing higher bending moments such as 73.10, 89.2 and 117.4 Kn-m respectively.



Graph 4: Bending Moment of sample column vs lateral length ratio graph for L-shape plan

7. Conclusion

The aim of this study was to examine the stability of multi-storey buildings with irregular plans like L - shape, H – shape and U- shape. In designing the multi-storied buildings, irregularity in structures is inevitable due to the functional requirement of the buildings. Assessment is done on the basis of lateral length ratio for each shape. Parameters like internal forces and roof displacement are used for the assessment. Following conclusion can be drawn from the analysis of the results:

7.1 For L-shape plans, based on the results obtained, it is observed that the building with lateral length ratio – 1 is showing minimum values for the parameters such as lateral displacements, storey drift, storey shear and the bending moment of the sample column of the ground storey. Hence, it can be concluded that the L-shape building plan with lateral length ratio -1 is the most suitable structure among all the plans.

7.2 While assessing the stability of the H-shape buildings, it can be observed that the building plan with lateral length ratio 1.2 is showing the minimum lateral displacement, storey drift and bending moment of the sample column of the ground storey but whereas it is showing the maximum value for the storey shear, hence, it can be concluded that U shape building plan with lateral length ratio 1.2 is the most suitable structure among all plans.

7.3 For U-shape plans, the building plan with lateral length ratio – 0.81 is showing the minimum lateral displacement, minimum storey drift, storey shears and minimum bending moment of the sample column of the ground storey plan. Hence, it can be stated that the U-shape building plan ratio – 0.81 is the most suitable structure among for all U-shape plans.

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Dr. Harpal Singh is a Professor in Department of Civil Engineering in Guru Nanak Dev Engineering College, Ludhiana. He studied B.E in civil engineering in 1984, M.E in Structures (Behavior of Skew Box Girder Bridge) in 1986 and Ph.D. (Response of Reinforced Concrete Frames with Infilled Panels under Earthquake Excitation) in 1996. His qualification reads B.E, M.E and PhD. He is a Professor in GNDEC, Ludhiana since 1998. He was Principal Guru Nanak Dev Engineering College, Ludhiana. He was Principal in Giani Zail Singh College of Engineering and Technology, Bathinda for 5 years. He was Head of civil department for 2 years, two year and two month experience in Dean academic affair and six year as a Assistant professor.