Seismic Analysis and Design of Vertically Irregular RC Building Frames

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Abstract: ***The objective of the paper is to carry out Response spectrum analysis (RSA) and Time history Analysis (THA) of vertically irregular RC building frames and to carry out the ductility based design using IS 13920 corresponding to Equivalent static analysis and Time history analysis. Three types of irregularities namely mass irregularity, stiffness irregularity and vertical geometry irregularity were considered. According to our observation, the storey shear force was found to be maximum for the first storey and it decreases to minimum in the top storey in all cases. The mass irregular structures were observed to experience larger base shear than similar regular structures. The stiffness irregular structure experienced lesser base shear and has larger inter-storey drifts. The absolute displacements obtained from time history analysis of geometry irregular structure at respective nodes were found to be greater than that in case of regular structure for upper stories but gradually as we moved to lower stories displacements in both structures tended to converge. Lower stiffness results in higher displacements of upper stories. In case of a mass irregular structure, time history analysis gives slightly higher displacement for upper stories than that in regular structures whereas as we move down lower stories show higher displacements as compared to that in regular structures. When time history analysis was done for regular as well as stiffness irregular structure, it was found that displacements of upper stories did not vary much from each other but as we moved down to lower stories the absolute displacement in case of soft storey were higher compared to respective stories in regular structure. If a high rise structure (low natural frequency) is subjected to high frequency ground motion then it results in small displacements. Similarly, if a low rise structure (high natural frequency) is subjected to high frequency ground motion it results in larger displacements whereas small displacements occur when the high rise structure is subjected to low frequency ground motion.***

Keywords: Response spectrum analysis, Time history Analysis, vertical geometry irregularity

1. Introduction

During an earthquake, failure of structure starts at points of weakness. This weakness arises due to discontinuity in mass, stiffness and geometry of structure. The structures having this discontinuity are termed as Irregular structures.Vertical irregularities are one of the major reasons of failures of structures during earthquakes. Height-wise changes in stiffness and mass render the dynamic characteristics of these buildings different from the ‘regular’ building.

IS 1893 definition of Vertically Irregular structures:
The irregularity in the building structures may be due to irregular distributions in their mass, strength and stiffness along the height of building. There are two types of irregularities-
1. Plan Irregularities
2. Vertical Irregularities.

Vertical Irregularities are mainly of five types-
1) **a) Stiffness Irregularity** — Soft Storey-A soft storey is one in which the lateral stiffness is less than 70 percent of the storey above or less than 80 percent of the average lateral stiffness of the three storeys above.
   b) Stiffness Irregularity — Extreme Soft Storey-An extreme soft storey is one in which the lateral stiffness is less than 60 percent of that in the storey above or less than 70 percent of the average stiffness of the three storeys above.
2) **Mass Irregularity**-Mass irregularity shall be considered to exist where the seismic weight of any storey is more than 200 percent of that of its adjacent storeys. In case of roofs irregularity need not be considered.
3) **Vertical Geometric Irregularity**- A structure is considered to be Vertical geometric irregular when the horizontal dimension of the lateral force resisting system in any storey is more than 150 percent of that in its adjacent storey.
4) **In-Plane Discontinuity in Vertical Elements Resisting Lateral Force**-An in-plane offset of the lateral force resisting elements greater than the length of those elements.
5) **Discontinuity in Capacity** — Weak Storey-A weak storey is one in which the storey lateral strength is less than 80 percent of that in the storey above.

As per IS 1893, Part 1 Linear static analysis of structures can be used for regular structures of limited height as in this process lateral forces are calculated as per code based fundamental time period of the structure. Linear dynamic analysis are an improvement over linear static analysis, as this analysis produces the effect of the higher modes of vibration and the actual distribution of forces in the elastic range in a better way.

Buildings are designed as per Design Based Earthquake(DBE), but the actual forces acting on the structure is far more than that of DBE. So, in higher seismic zones Ductility based design approach is preferred as ductility of the structure narrows the gap. The primary objective in designing earthquake resistant structures is to ensure that the building has enough ductility to withstand the earthquake forces, which it will be subjected to during an earthquake.

1.1 Seismic Analysis

Seismic analysis is a major tool in earthquake engineering which is used to understand the response of buildings due to seismic excitations in a simpler manner. In the past the buildings were designed just for gravity loads and seismic analysis is a recent development. There are different types of earthquake analysis methods. Some of them used in the project are-
I. Response Spectrum Analysis
II. Time History Analysis

1.1.1 Response Spectrum Analysis

This approach permits the multiple modes of response of a building to be taken into account.The structural response can be defined as a combination of many modes. Computer analysis can be used to determine these modes for a structure. For each mode, a response is obtained from the design spectrum, corresponding to the modal frequency and the modal mass, and then they are combined to estimate the total response of the structure. In this the magnitude of forces in all directions is calculated and then effects on the building is observed. The result of a RSM analysis from the response spectrum of a ground motion is typically different from that which would be calculated directly from a linear dynamic analysis using that ground motion directly, because information of the phase is lost in the process of generating the response spectrum.

1.1.2 Time History Analysis

Time history analysis techniques involve the stepwise solution in the time domain of the multi degree of freedom equations of motion which represent the actual response of a building**.**Its solution is a direct function of the earthquake ground motion selected as an input parameter for a specific building. This analysis technique is usually limited to checking the suitability of assumptions made during the design of important structures rather than a method of assigning lateral forces themselves.

1.2 Ductility based design method

Ductility in the structures results from inelastic material behavior and reinforcement detailing such that brittle fracture is prevented and ductility is introduced by allowing steel to yield in a controlled manner. Thus the chief task is to ensure that building has adequate ductility to withstand the effects of earth quakes, which is likely to be experienced by the structure during its lifetime. Ductility of the structure acts as a shock absorber and reduces the transmitted forces to the structure. Ductility is the capability of a material to undergo deformation after its initial yield without any significant reduction in yield strength[4]. IS 13920[1] was followed for ductility based design.

2. Results and Discussion

2.1 Response Spectrum Analysis

Response Structure analysis was performed on regular and various irregular buildings using Staad-Pro. The storey shear forces were calculated for each floor and graph was plotted for each structure.

2.1.1. Structural Modelling

Table 1: Specifications of the structure.

Live Load	$3kN/m^2$
Density of RCC considered	$25kN/m^3$
Thickness of slab	150mm
Depth of beam	400mm
Width of beam	350mm
Dimension of column	400x400mm
Density of infill	$20kN/m^3$
Thickness of outside wall	20mm
Thickness of inner partition wall	15mm
Height of each floor	3.5m
Earthquake Zone	IV
Damping Ratio	5%
Importance factor	1
Type of Soil	Rocky
Type of structure	Special Moment Resisting Frame
Response reduction Factor	5

Four types of Irregular buildings were considered, Regular structure, Mass irregular structure, structure with ground storey as the soft storey and vertically geometric irregular building. The first three structures were 10 storeyed.

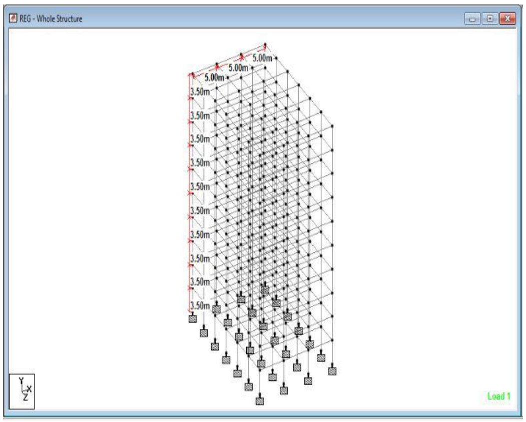


Figure 1: 3D view of regular structure (10 storeys).

2.2 Mass Irregular Structure(10 storeys)

The structure is modeled as same as that of regular structure except the loading due to swimming pool is provide in the fourth and eighth floor. Height of swimming pool considered- 1.8m. Loading due to swimming pool -$18kN/m^2$.

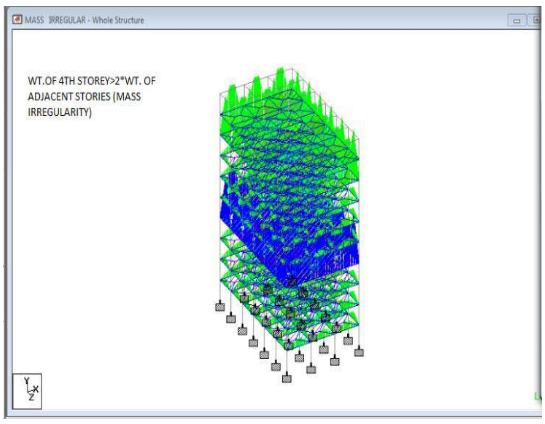


Figure 2: 3-D view of mass regular structure (10 storeys) with swimming pools on 4th and 8th storeys

2.3Stiffness Irregular Structure (Soft Storey)

The structure is same as that of regular structure but the ground storey has a height of 4.5 m and doesn‘t have brick infill.
Stiffness of each column= $12EI/L^3$
Stiffness of ground floor/stiffness of other floors= $(3.5/4.5)^3$ =0.47<0.7
Hence as per IS 1893 part 1 the structure is stiffness irregular.

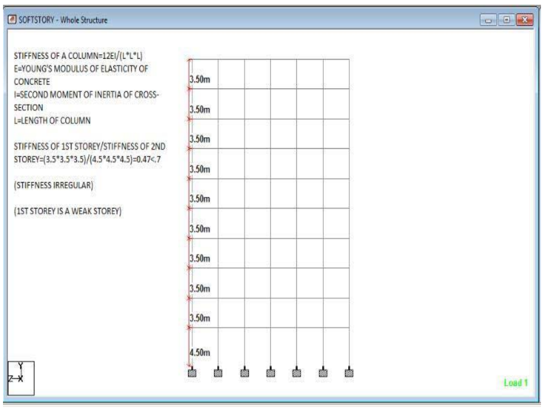


Figure 3: Stiffness irregular structure (10 storeys).

2.4 Vertically Geometric Irregular

The structure is 14 storeyed with steps in 5th and 10th floor. The setback is along X direction.
Width of top storey= 20m
Width of ground storey=40
40/20=2>1.5
Hence, as per IS 1893[2], Part 1 the structure is vertically geometric irregular structure.

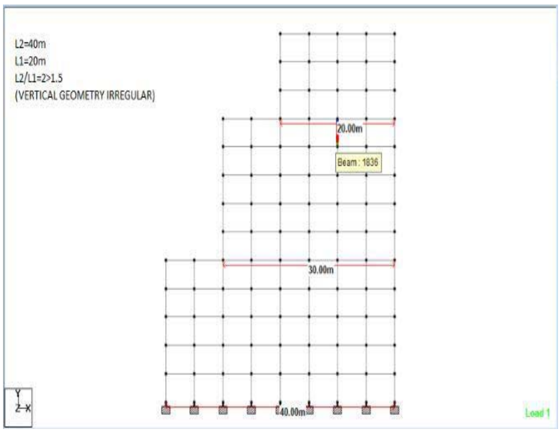


Figure 4: Vertical Geometric irregular structure (14 storeys)

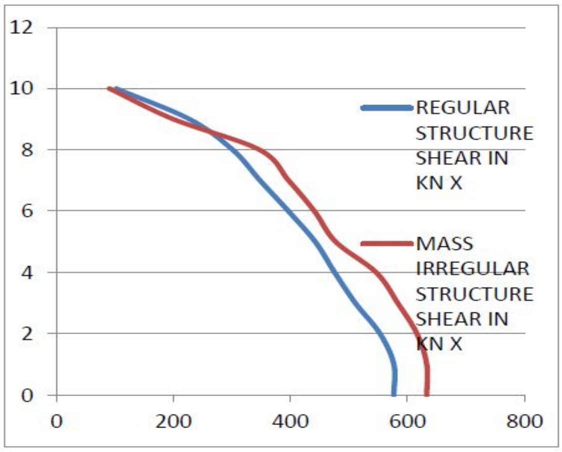


Figure 5: Comparison of Peak storey shear forces of regular and mass irregular structure in X direction.

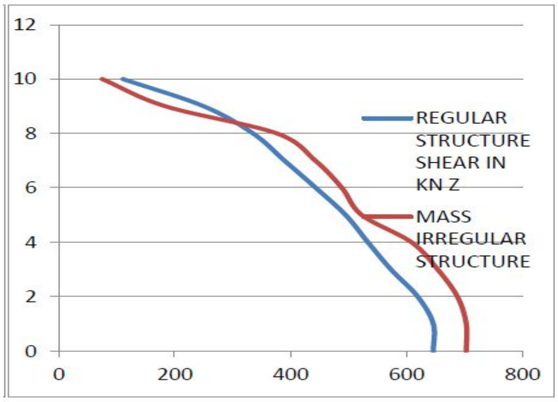


Figure 6: Comparison of Peak storey shear forces of regular and mass irregular structure in Z direction.

The storey shear force is maximum in ground storey and it decreases as we move up in the structure. Mass irregular storey shear force is more in lower storeys as compared to regular structure. The graph closes in as we move up the structure and the mass irregular storey shear force becomes less than that in regular structure above 8th storey.

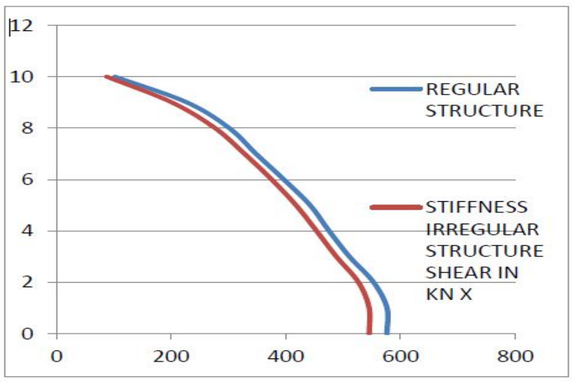


Figure 7: Comparison of Peak storey shear forces of regular and stiffness irregular structure in X direction.

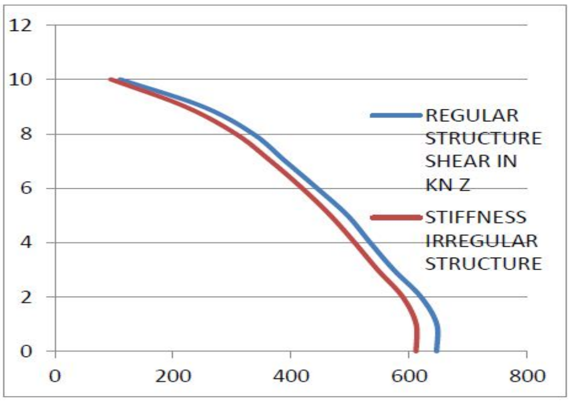


Figure 8: Comparison of Peak storey shear forces of regular and stiffness irregular structure in Z direction.

The Stiffness Irregular structure has a ground storey height of 4.5m(more than height of the above storeys). This makes the building less stiff than regular structure. And hence, the storey shear force is more in regular structure as compared to stiffness irregular structure.

2.5 Time History Analysis

Regular and various types of irregular buildings were analyzed using THA and the response of each irregular structure was compared with that of regular structure for IS code Ground motion.

2.5.1 Specification:

Table 2: Specifications of the structure[3].

Live Load	3kN/m^2
Density of RCC considered	25kN/m^3
Thickness of slab	150mm
Depth of beam	400mm
Width of beam	350mm
Dimension of column	400x400mm
Density of infill	20kN/m^3
Thickness of outside wall	20mm
Thickness of inner partition wall	15mm
Height of each floor	3.5m
Force Amplitude factor	9.81

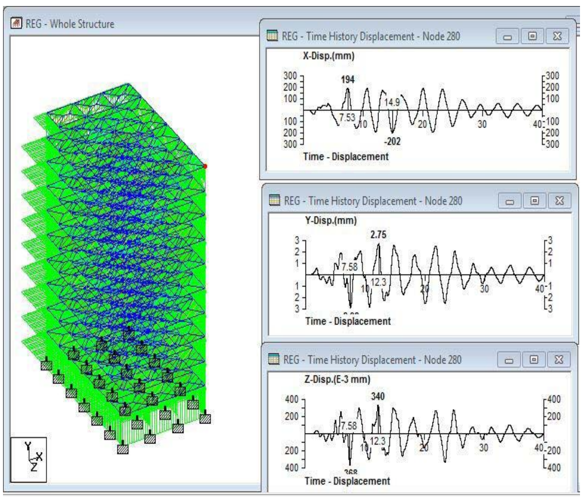


Figure 9: Time history displacement of the highlighted node of regular structure.

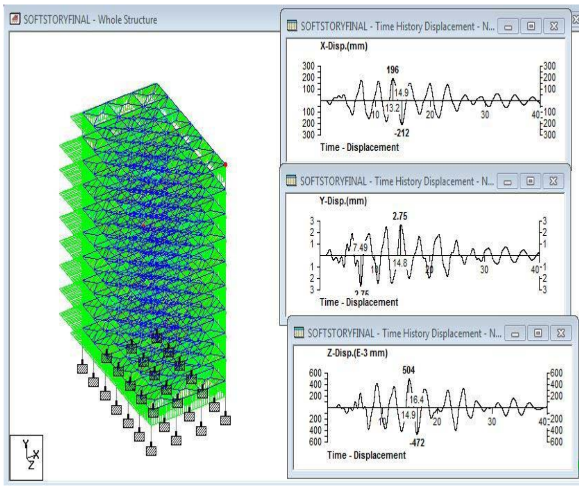


Figure 10: Time history displacement of the highlighted node of stiffness irregular structure.

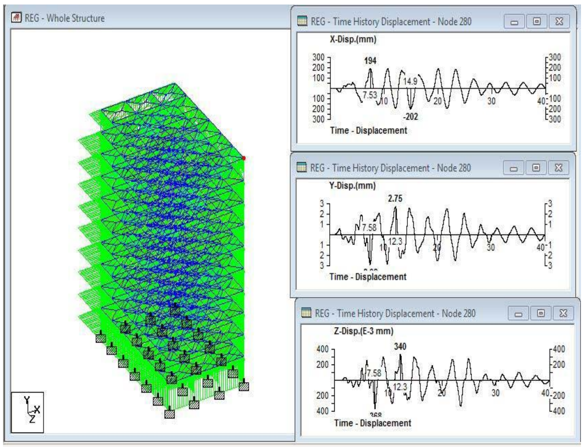


Figure 11: Time history displacement of the highlighted node of mass irregular structure.

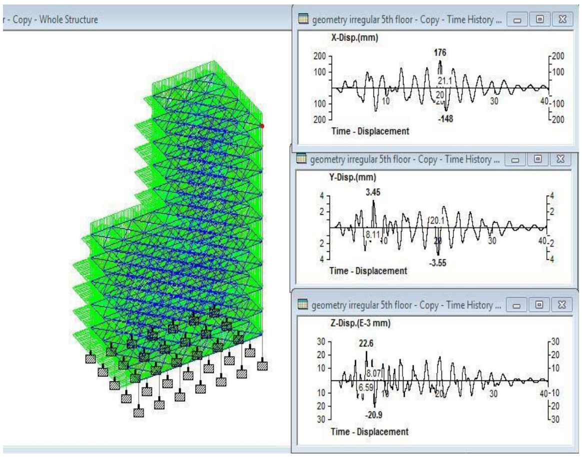


Figure 12: Time history displacement of the highlighted node of geometry irregular structure.

The above figures show the Time history displacements of the topmost node of regular, stiffness irregular and geometry irregular structure respectively. Similarly time history displacements were obtained for other floors in the structure and the maximum displacement was plotted in the graph.

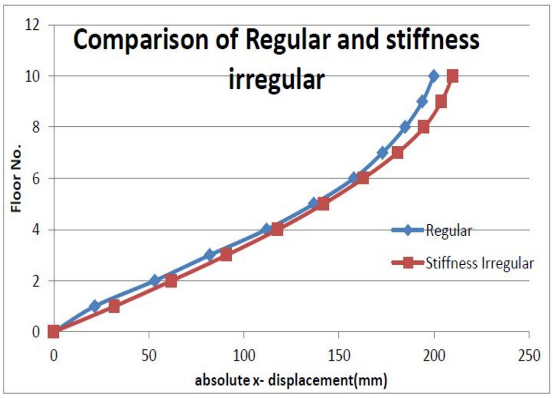


Figure 13: Comparison of displacements along x-directionof different floors of regular and stiffness irregular structure.

Due to less stiff ground storey the interstorey drift is found to be more in stiffness irregular structure. Hence, the floor displacement is more in stiffness irregular structure than regular structure.

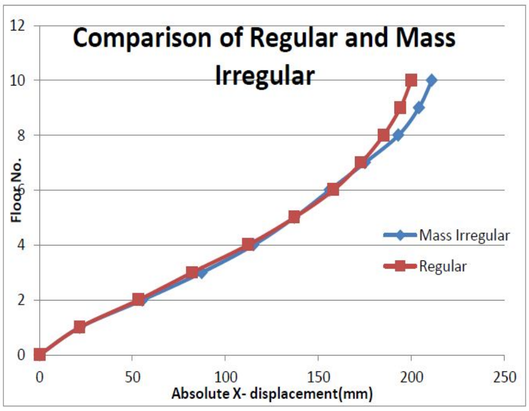


Figure 14: Comparison of displacements along x-direction of different floors of regular and mass irregular structure.

Mass irregular structure has swimming pool in 4th and 8th floor hence the 4th storey displacement is more in mass irregular structure. The effect of extra mass is found to be more in 8th storey where higher inter storey drift is observed. Higher the position of extra mass the moment of the inertial force is more leading to larger displacement.

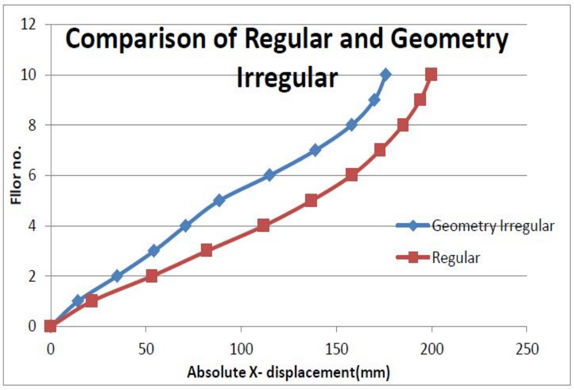
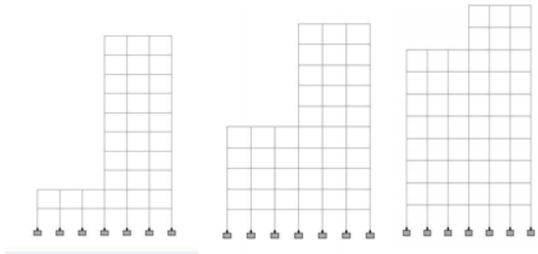


Figure 15: Comparison of displacements along x-direction of different floors of regular and geometry irregular structure.

In geometry irregular structure the stiffness upto 5th storey is far more than that of regular structure. So the displacement in lower storeys of geometry irregular structure is very less as compared to regular structure. But at 5th storey due to setback there is a sudden increase in the displacement and hence there is decrease in slope of the graph.

2.5.2 Comparison of absolute displacement of setback structures with setback at different floors:



Setback in 2nd floor 5th floor 8th floor

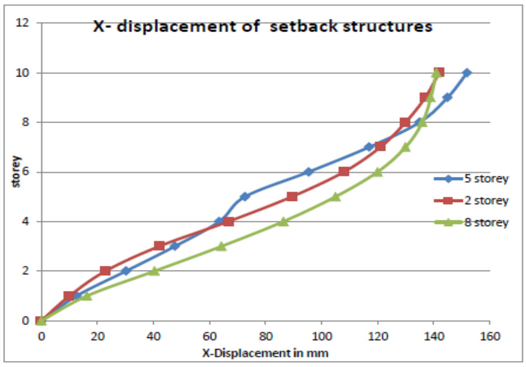


Figure 16: Comparison of displacements along x-direction of 5,2 and 8 storey setback structures.

It shows that in setback structures due to setback the stiffness and mass of the structure both decreases. In setback structure with offset at 8th storey at lower storeys the displacement is more than the other two. This behaviour may be attributed to the increase mass of the structure. In setback structure with offset at 5th floor there is a sudden change in slope of the curve due to offset. But the most conspicuous behavior is that its top node displacement is more than the former structure. This can be attributed to less stiffness in the upper stories of the structure. The behavior of setback structure with offset at 2nd floor is similar to second setback structure. The difference is the fact that the curve is smoother in this case.

2.5.3 Introduction to the ground motion used :

THA can be used to get a time response of a structure due to particular earthquake excitation. The earthquake data considered for analysis was IS code earthquake (Intermediate frequency).The IS code ground motion used for the analysis had PGA of 0.2g and duration of 40 seconds.

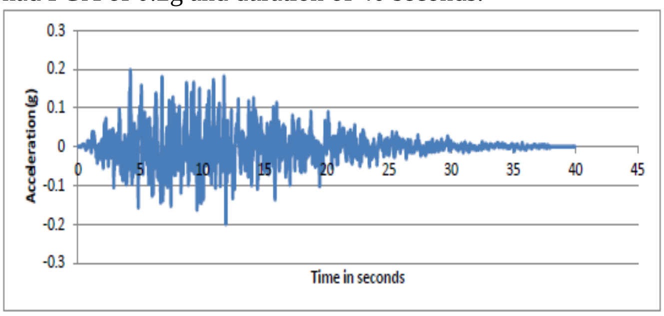


Figure 17: IS code ground motion (Intermediate frequency).

The earthquake excitation was provided to following structures 1.Regular structure of 2 storeys, 6 storeys and 20 storeys.
1. Stiffness Irregular structure of 20 storeys.
2. Three mass Irregular structures of 20 storeys with swimming pools in 19th storey.
3. Three Geometry Irregular structure with steps in 2nd, 5th and 8th storey respectively.

2.5.3.1 Time History Displacement Of Structures Due To Ground Motions.

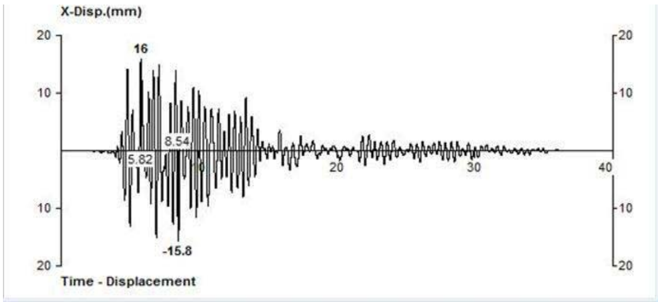


Figure 18: X-displacement of peak storey node of regular 2 storey building subjected to IS code ground motion.

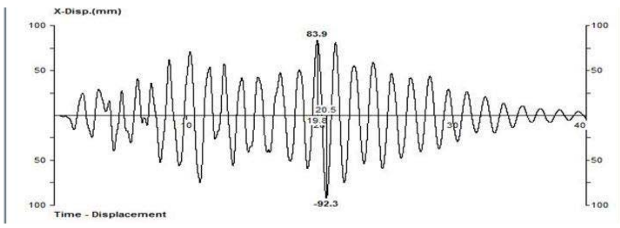


Figure 19: X-displacement of peak storey node of regular 6 storey building subjected to IS code ground motion.

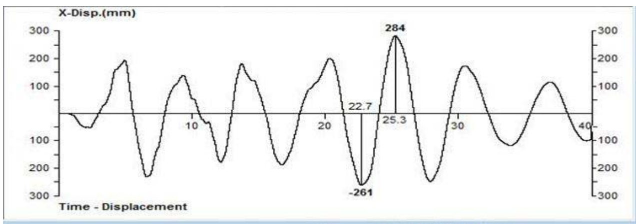


Figure 20: X-displacement of peak storey node of regular 20 storey building subjected to IS code ground motion.

It has been observed that low storeyed structures (<5 storey) show large displacements in high frequency ground motion and small displacements in low frequency ground motion. This is because low storeyed structures have high natural frequency (frequency is proportional to $(k/m)^{1/2}$). So, in a high frequency earthquake there response is larger due to resonance. Similarly, high rise structures have low natural frequency and hence undergo large displacements in low frequency ground motion and small displacements in high frequency ground motion.

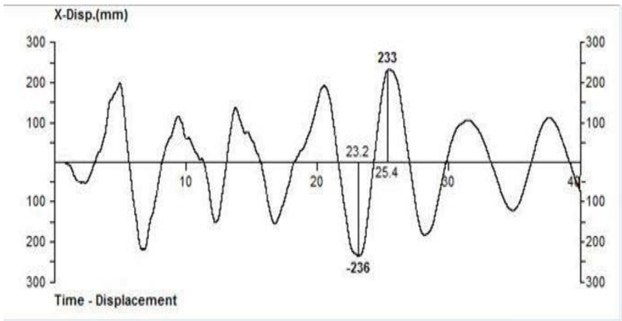


Figure 21: X-displacement of highlighted node of mass irregular 20 storey building with swimming pool on 19th floor subjected to IS codeground motion.

2.6 DUCTILITY BASED DESIGN: Comparison of Design Based on ESA AND THA

2.6.1 Regular Structure

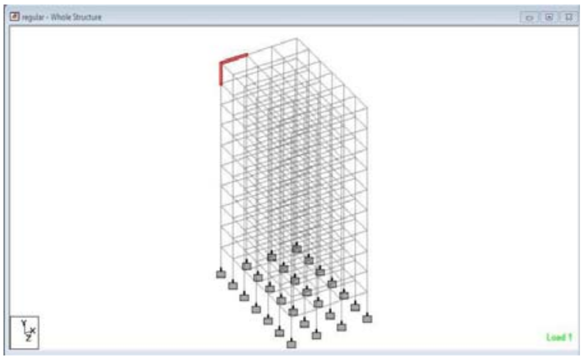
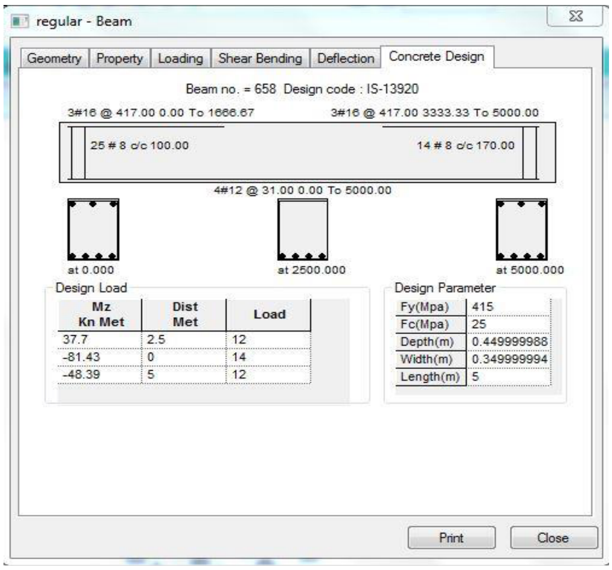
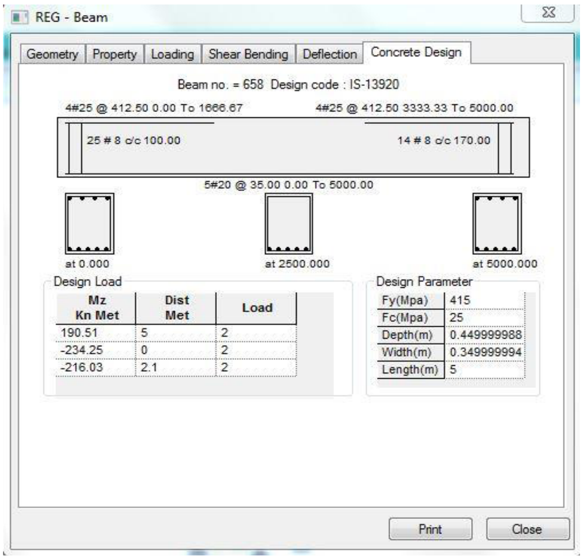


Figure 22: 3-D view of a 10-storey regular structure with highlighted beam and column.

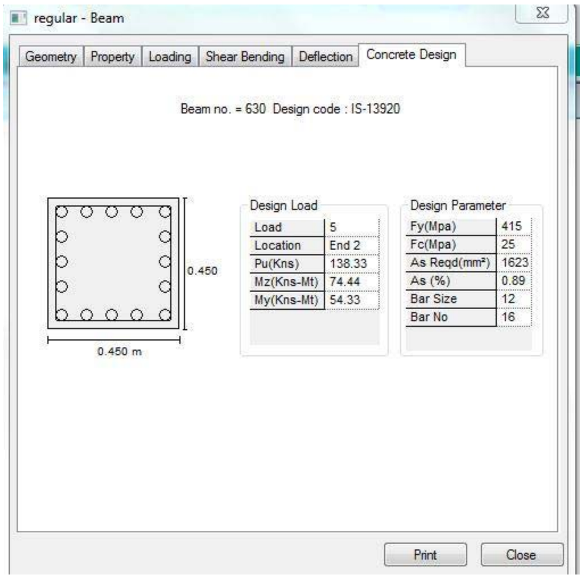


Beam design as per ESA

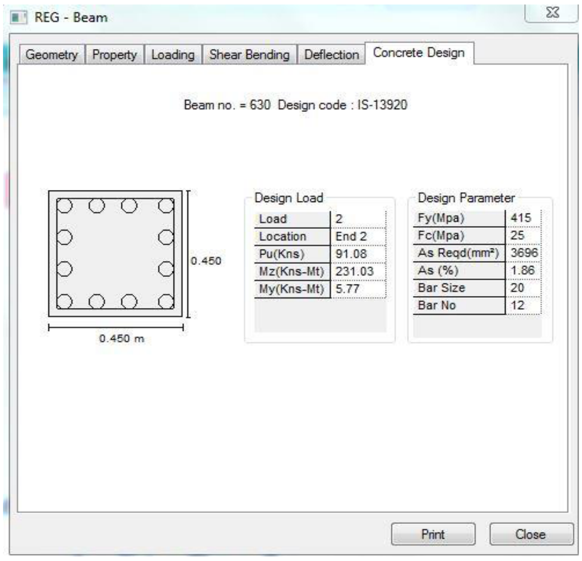


Beam design as per THA

Figure 23: Results of Design of beam as per ESA and THA.



Column design as per ESA



Column design as per THA

Figure 24: Results of Design of column as per ESA and THA.

2.6.2 Mass Irregular Structure

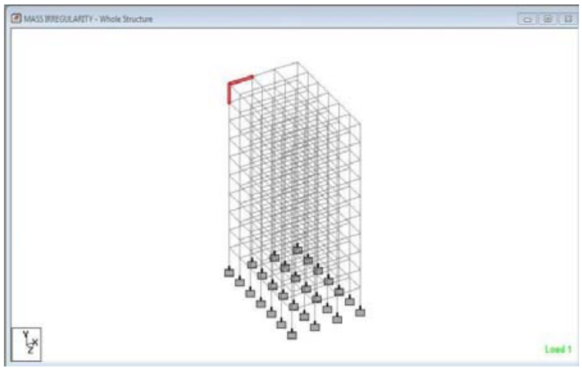
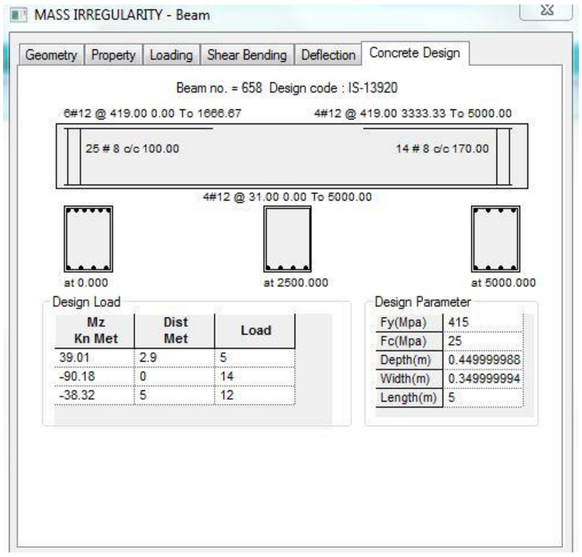
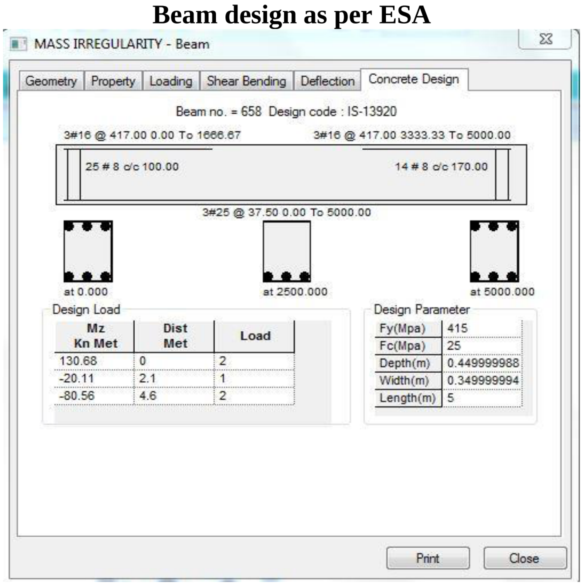


Figure 25: 3-D view of a10 storey mass irregular structure with highlighted beam and column.

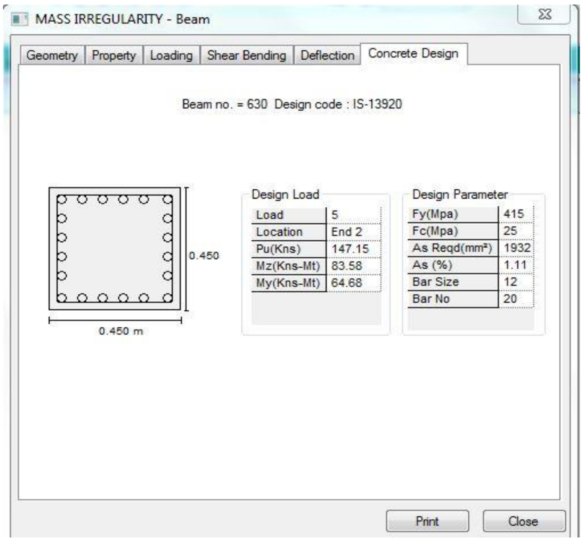


Beam design as per ESA

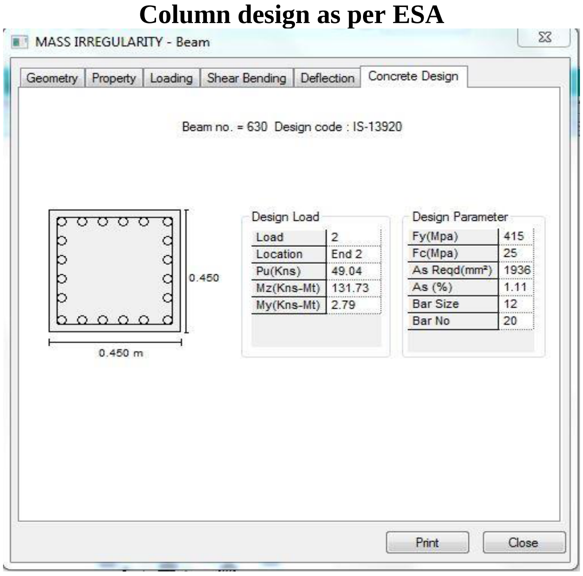


Beam design as per THA

Figure 26: Results of Design of beam as per ESA and THA.

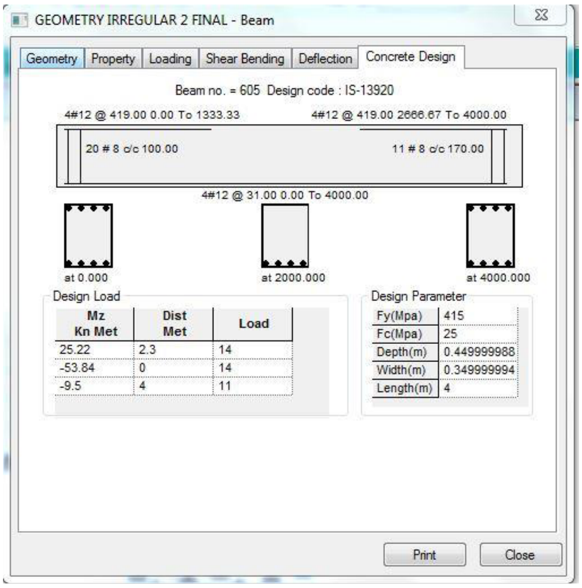


Column design as per ESA

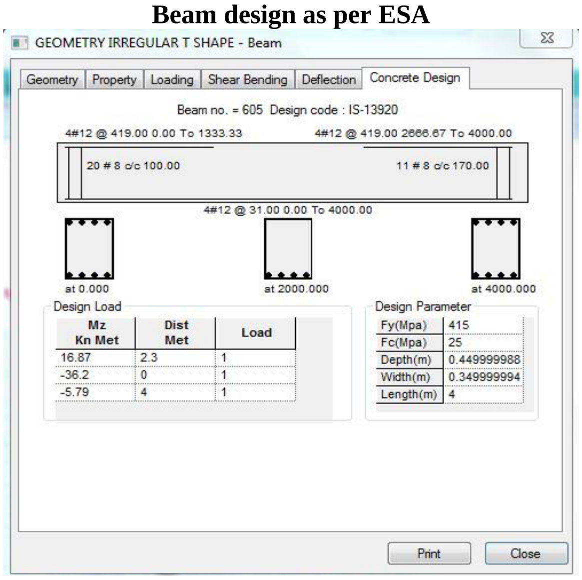


Column design as per THA

Figure 27: Results of Design of column as per ESA and THA.



Beam design as per ESA



Beam design as per THA

Figure 29: Results of Design of beam as per ESA and THA of a 10 storey geometry irregular structure.

2.6.3 Geometry Irregular Structure(T Shape):

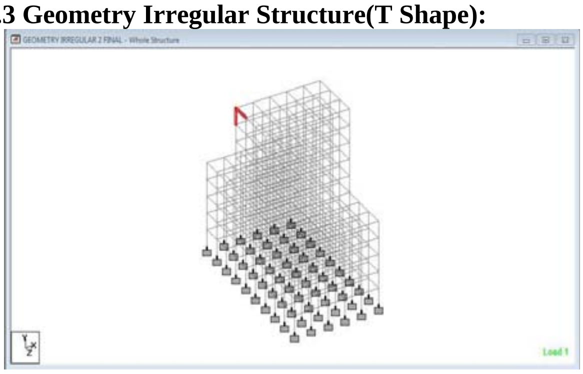
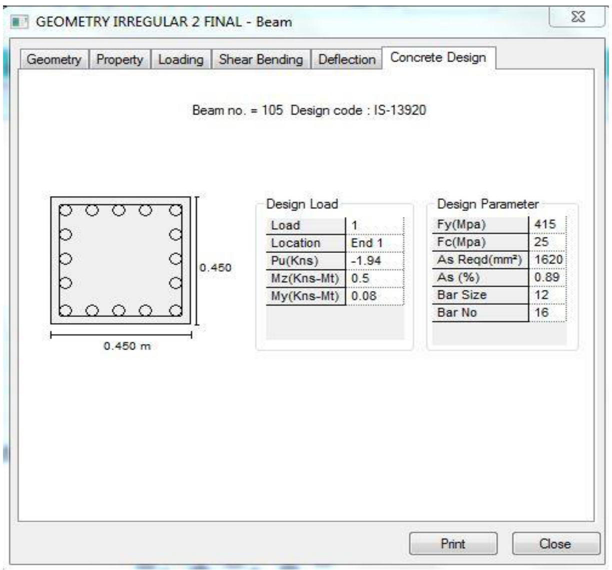
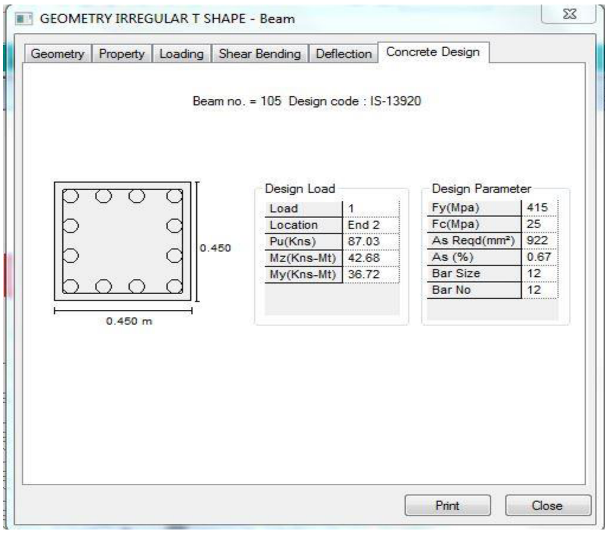


Figure 28: 3-D view of a 10 storey geometry irregular structure with highlighted beam and column.



Column design as per ESA



Column design as per THA

Figure 30: Results of Design of column as per ESA and THA of a10 storey geometry irregular structure.

3. Conclusions

According to RSA results, the storey shear force was found to be maximum for the first storey and it decreased to a minimum in the top storey in all cases. It was found that mass irregular building frames experience larger base shear than similar regular building frames. The stiffness irregular building experienced lesser base shear and has larger inter storey drifts.

In case of mass irregular structure, Time History Analysis yielded slightly higher displacements for upper stories than that in regular building, whereas as we move down, lower stories showed higher displacements as compared to that in regular structures. In regular and stiffness irregular building (soft storey), it was found that displacements of upper stories did not vary much from each other but as we moved down to lower stories the absolute displacement in case of soft storey were higher compared to respective stories in regular buildings.

References

[1] IS 13920-Ductility Design.
[2] IS 1893- Calculation of Seismic forces.
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[4] Athanassiadou C.J, 2008, Seismic performance of R/C plane frames irregular in elevation, Engineering Structures 30 (2008):1250–1261.