[Anwar, 3(10): October 2016]
DOI- 10.5281/zenodo.163596

ISSN 2348 – 8034
Impact Factor- 4.022

GLOBAL JOURNAL OF ENGINEERING SCIENCE AND RESEARCHES

STUDY ON PUSHOVER ANALYSIS OF RC FRAMES WITH VERTICAL IRREGULARITY

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ABSTRACT

The aim of the study is to compare and evaluate structural response obtained from nonlinear static analysis that is Pushover analysis procedures recommended in ATC 40. Three-dimensional low-rise moments resisting RC buildings with vertical irregularity are investigated. Two types of vertical irregularities, that is, mass and stiffness, as specified in the IS 1893- 2002 are considered in this study. In order to determine nonlinear behavior of the buildings under lateral loads, the base shear-roof displacement relationships i.e. capacity curves are obtained by Pushover analysis. The effects of mass irregularity (MI) and stiffness irregularity (KI) were investigated and discussed in terms of the height-wise distribution of story drift, storey shear, Storey Displacements. The performance point and structural performance level of mass and stiffness irregularities were determined using Pushover analysis. The mass irregular buildings were observed to experience larger storey shear whereas stiffness irregular buildings experienced lesser storey shear force than regular counterpart. The storey shear is increased by 25% at fifth floor for mass irregular structure compared to regular counterpart, whereas the stiffness irregular building experience lesser storey shear. Storey drifts were maximum for the stiffness irregular buildings; the drifts were increased by 94% than regular building. The storey displacements were decreased for mass irregular structures at the floor of irregularity, but the storey displacements were increased at bottom storey. The displacements at bottom storey were increased by 40%. The storey displacement for stiffness irregular buildings is increased by 97% compared to regular structure. The capacity curve of regular building is found less than mass irregular buildings, but the capacity curves of regular building is more than stiffness irregular buildings. The structural performance level of mass irregular building was found under "collapse" level, where as the structural performance level of stiffness irregular structure was under "Life of Safety "level.

Keywords: Pushover analysis, structural vertical irregularity, storey drifts, storey shear, storey displacements, structural performance level.

I. INTRODUCTION

Recent earthquakes in the Indian subcontinent, India-Pakistan earthquake on October 8, 2005 with a magnitude of 7.4 on Richter scale, Gujarat earthquake on January 26, 2001 with a magnitude of 7.6 on Richter scale have led to an increase in the seismic zoning factor over many parts of the country. Also, ductility has become an issue for all those buildings that were designed and detailed using earlier versions of the codes. Under such circumstances, seismic qualification of existing buildings has become extremely important. Seismic qualification eventually leads to retrofitting of the deficient structures. Pushover analysis and evaluation of performance of building using Capacity Spectrum Approach or Displacement Coefficient Method are increasingly used for this purpose.

Buildings are designed as per the building code regulations, aptly termed as prescriptive based design. It is methodology based upon meeting all of the specific requirements of the code. In prescriptive based design, the normal engineering practice is to assume linear-elastic behavior for structural members, which fails to account for redistribution of forces due to member non-linear behavior and dissipation of energy due to material yielding. Because of this, considerable damage has been observed and life safety goals were not achieved from the major Earthquakes in recent decades in residential and commercial buildings. During high seismic excitation the building generally responds well beyond its elastic and linear capacity. There are two non-linear options available for assessing the performance of the structure subjected to earthquake load; namely Pushover analysis and inelastic non-linear time history analysis.

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. Irregular structures contribute a large portion of urban infrastructure. Vertical irregularities are one of the major reasons of failures of structures during earthquakes. For example structures with soft storey were the most notable structures which collapsed. So, the effect of vertically

ISSN 2348 – 8034
Impact Factor- 4.022

irregularities in the seismic performance of structures becomes really important. Height-wise changes in stiffness and mass render the dynamic characteristics of these buildings different from the _regular building.

Definition of vertical irregular building as Per IS 1893-2002

The irregularity in the building structures may be due to irregular distributions in their mass, strength and stiffness along the height of building. When such buildings are constructed in high seismic zones, the analysis and design becomes more complicated. There are two types of irregularities-

1. **Plan Irregularities**
2. **Vertical Irregularities**.

Vertical irregularities are of five types:

i) 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 storey's 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 storey's above.

ii) 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.

iii) 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.

iv) 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.

v) Discontinuity in Capacity also called as Weak Storey-A weak storey is one in which the storey lateral strength is less than 80 percent of that in the storey above.

Earthquake design philosophy

The earthquake design philosophy may be summarized as follows :

- Under minor but frequent shaking, the main members of the building that carry vertical and horizontal forces should not get damaged. However, building parts that do not carry load may sustain some repairable damage.
- Under moderate but occasional shaking, the main members may sustain some repairable damage, while the other parts of the building may be damaged such that they even have to be replaced after the earthquake ; and
- Under strong but rare shaking, the main members may sustain severe damage, but the building should not collapse.

Figure Performance objectives under different intensities of ground shaking

Thus, after minor shaking, the building will be fully operational within the short period of time and repair cost is less. And, after moderate shaking the building may be operational once the repair and strengthening of the damaged members is completed. But, after a strong earthquake the building may become disfunctional for further use, but will stand so that the people can be evacuated and the immovable and valuable things can be recovered.

The consequences of damage should be kept in mind in the design philosophy. For example, important buildings such as hospitals and fire stations play a critical role in post earthquake activities and must remain functional immediately after the earthquake. These structures must sustain very little damage and should be designed for a higher level of earthquake protection.

Importance of seismic design codes

Ground vibrations during earthquakes cause forces and deformations in structures. Structures need to be designed to withstand such forces and deformations. Seismic codes help to improve the behavior of structures so that they may withstand the earthquake effects without significant loss of property and life. Countries around the world have procedures outlined in seismic code to help design engineers in the planning, designing, detailing and constructing structures. Seismic codes are unique to a particular region or country. They take into account the local seismology. Accepted level of seismic risk, building types and materials and methods are used in construction. Further, they are indicative of the level of progress a country has made in the field of earthquake. The first Indian earthquake design code was published in the year 1962 as IS 1893:1962. Today the Bureau of Indian Standards (BIS) has the following seismic codes.

- IS 1893(Part 1):2002 (Fig. 2) - Indian Standard criteria for earthquake resistant design of structures (5^{th} revision).
- IS 4326:1993 - Indian Standard code of practice for earthquake resistant design and construction of buildings (2^{nd} revision).
- IS 13827:1993 - Indian Standard guidelines for improving earthquake resistance of earthen buildings.
- IS 13828:1993 - Indian Standard guidelines for improving earthquake resistance of low strength masonry buildings.
- IS 13920:1993 - Indian Standard code of practice for ductile detailing of reinforced concrete structures subjected to seismic forces.
- IS 13935:1993 - Indian Standard guidelines for repair and seismic strengthening of buildings.

These codes do not ensure that the structures suffer no damage during the earthquakes. But to an extent possible, they ensure that the structures are able to respond to earthquake shakings of moderate intensities without damage and of heavy intensities without total collapse. Countries with a history of earthquakes have well developed earthquake codes. Thus, counties like Japan, New Zealand and United States of America, have detailed seismic code provisions. Development of building codes in India started early. Today, India has fairly good range of seismic codes covering a variety of structures, ranging from low strength masonry houses to modern buildings. However the key to ensuring earthquake safety lies in having a robust mechanism that enforces and implements these design codes provisions in actual constructions.

ISSN 2348 – 8034
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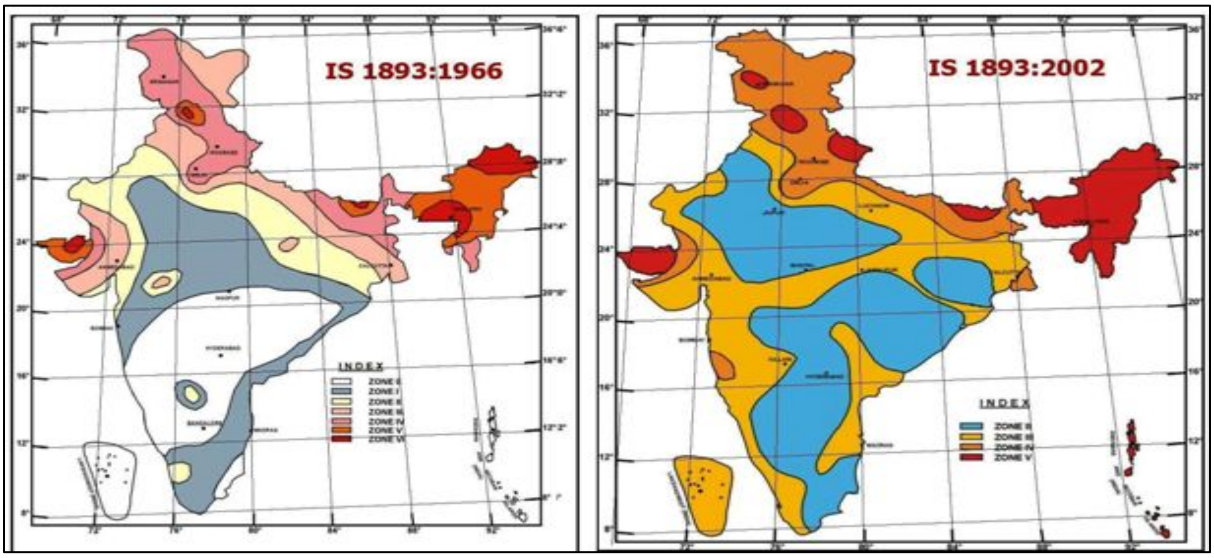


Figure Seismic zoning maps of India IS 1893:1966 and IS1893:2002

Need for thesis work

Real structures are almost always irregular as perfect regularity is an idealization that very rarely occurs. The increasing number of damage statistics after seismic events has provided strong evidence that irregular buildings exhibit inadequate behavior, though they were designed according to the current state of knowledge existing in seismic codes. This inferior seismic performance has been attributed to the combined action of structural irregularities, i.e., to the combined non-uniform distributions of mass and stiffness along the height of buildings.

The study aimed to understand the influence of vertical irregularities on the seismic performance of moment resisting RC frames. An extensive parametric study on the seismic response of moment-resisting RC frames with vertical mass and stiffness irregularity is presented.

Aims and objective of the study

The main objectives of the study are as follows

- To study the seismic behavior of regular and vertical irregular structure on storey drifts, storey shear and storey displacements using Pushover analysis.
- To generate capacity curves and evaluate performance point and structural performance level using Pushover analysis as per ATC-40**.**

Scope of the study

1. The Present work is focused on the study of Seismic demands of different irregular R.C buildings using analytical techniques (Pushover analysis) for the seismic zone V (medium soil) of India.
2. The configuration involves vertical irregularities such as mass and stiffness. The performance was studied in terms of storey shear, storey drifts in Non linear analysis. Whereas the performance point and hinge status are obtained in Non linear analysis using ATC40.
3. The Pushover analysis is carried out on three dimensional vertical irregular RC frames which contain eight storeys. The building has four bays in both longitudinal and transverse direction
4. The mass and stiffness Irregularity are considered at 1st, 5th and 8th floors.
5. The entire modeling, analysis was carried out by using ETABS 9.2 nonlinear version software.

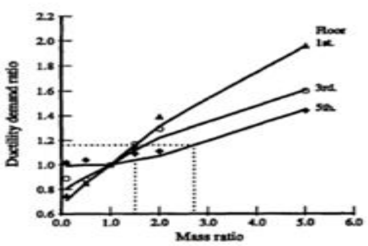
II. LITERATURE REVIEW

Moehle and Alarcon (1986)[1]carried out an experimental response study on two small scale models of reinforced concrete frame-wall structures subjected to strong base motions by using shake table. One of the test structures, designated as FFW, had three-bay frames and a nine-story, prismatic wall. The other structure, designated as FSW, was identical to FFW except that the wall extended only to the first floor level. Thus the test structures FFW and FSW represent the buildings having "regular" and "irregular" distributions of stiffness in vertical plane respectively. They compared the measured response with that computed by the elastic static analysis and inelastic static analysis. They compared maximum floor displacements obtained by the experiments and by elastic, inelastic analysis methods. Thus they concluded that the main advantage of inelastic methods is that those are capable of estimating the maximum displacement response, whereas the static methods cannot be used for this purpose. Further, they inferred that the inelastic static analysis is superior to the elastic methods in interpreting the structural discontinuities.

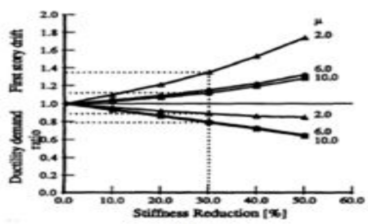
Ruiz and Diederich (1989)[2] studied the seismic performance of buildings with weak first story in case of single ground motion. They studied the influence of the lateral discontinuity on ductility demand at the first story under the action of the acceleration record with largest peak ground acceleration, as obtained on soft soil in Mexico City during the Mexico earthquake of September 19, 1985. A parametric study was carried out for 5- and 12-story buildings with weak first story, and with brittle infill wall in upper stories in some cases and ductile in others. The fundamental periods of these buildings were 0.67 and 1.4s respectively. They noted that the behavior of weak first story buildings greatly depends on the dominant periods of response, the resistances of upper and first stories.

Nassar and Krawinkler (1991)[3] Evaluated seismic demand of 3-, 5-, 10-, 20-, 30-, and 40-story heights and 0.217, 0.431, 0.725, 1.220, 1.653 and 2.051 s fundamental periods, respectively. The three models studied were: (a) BH (beam hinge) model, in which plastic hinges form in beams only (b) CH (column hinge) model, in which plastic hinges form in columns only, and (c) WS (weak story) model, in which plastic hinges form in columns of the first story only. They used 36 strong ground motions, recorded during single earthquake, namely, the Whittier Narrows earthquake of October 1, 1987, in and around Los Angeles, California. They concluded that weak first story leads to large ductility and overturning moment demands.

Valmudsson and Nau (1997)[4] focused on evaluating building code requirements for vertically irregular frames. The earthquake response of 5-, 10-, and 20-story framed structures with mass and stiffness distributions was evaluated, the structures were modeled as two-dimensional buildings. The response



(a)



(b)

calculated from the time-history analysis was compared with the ELF analysis.

They concluded (see Figure (a)) that when the mass of one floor increases by 50%, the increase in ductility demand is not greater than 20%. Figure (b) shows by Reducing the stiffness of the first story by 30%, increases the first story drift by 20-40%.

[Anwar, 3(10): October 2016]
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ISSN 2348 – 8034
Impact Factor- 4.022

III. METHODOLOGY

Pushover analysis

Pushover analysis is a form of non-linear analysis where the magnitudes of the lateral loads incrementally increased, maintaining a predefined distribution patterns along the height of the building, until a collapse mechanism develops in the building. With the increase in the loads, non-linear responses of the members are captured.

The pushover analysis can determine the lateral load verses deformation behavior of the building corresponding to the incremental loads. Programs supporting pushover analysis provide elegant visualization of the damage state for each load step and the redistribution of the internal forces in the members. At each step, the base shear and the roof displacement can be plotted to generate the capacity curve or pushover curve. It gives an idea of the lateral strength and the maximum inelastic drift the building can sustain. For regular buildings it can also give a rough estimate of the lateral stiffness of the building. Fig. 5 illustrates shows the way to plot the force deformation curve.

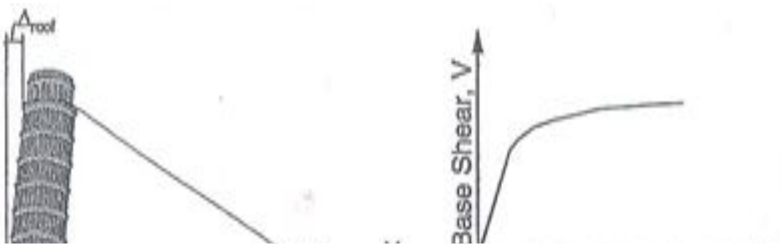

Figure A typical capacity curve (Courtesy: ATC-40)

Analytical data of a building

A three dimensional symmetrical building in plan and vertical irregular building was considered. The plan dimension of regular and irregular structure 16m x 16m in X and Y directions. The length and width of each bay is 4mx4m respectively. The floor height of regular structure is 3m**.**

Sl.no	Variable	Data
1	Type of structure	RCC frame
2	Number of Stories	8
3	Floor height for regular building Floor height for irregular building	3m 4.5m
4	Live load	3KN/m^2
5	Materials	Concrete (M25) and Reinforced with HYSD bars (Fe415)
6	Size of Columns	500mmx500mm
7	Size of beams	230mmx300mm 230mmx450mm for MI
8	Dead load on walls	12kN/m
9	Importance Factor	1
11	Type of soil	Medium
12	Zone	v
13	Response Reduction Factor	5

Regular buildings pushover analysis

After modeling the structure, a push of 0.96 m is given to the structure and the pushover curve is generated i.e., curve plotted with the base shear and roof displacement values as shown in Fig 13. From Fig13 for a roof displacement of 0.395 m a maximum base shear of 1918 kN was observed. After a displacement of 0395 m the capacity of the structure is observed to be declining.

The details of base shear, roof displacement and the number of elements falling in different performance zones like immediate occupancy, life safety and collapse prevention. It is clearly observed that the hinges were in the elastic region (i.e. A to B) up to a displacement of 0mm and further increase in the displacement leads to formation of 222 hinge as the structure enters into non-linear stage (i.e. B to IO). The structure remains in "Life Safety" performance level till the displacement reaches 86.54 mm and further increase in the displacement

increases the number of hinge formation to 280 at which the performance level changes to "Life Safety". With further increase in displacement beyond 397 mm, more number of hinges is formed forcing the performance level change to "Collapse Prevention". At 404.12 mm displacement, the structure performance level enters into "Collapse Stage" and further increase in displacement leads to significant loss of strength due to abundant number of hinge formations.

Capacity spectrum curve

The capacity spectrum curve for a drift of 0.96 m, obtained by the intersection of pushover curve with response spectrum curve. Firstly both these curves are converted in terms of spectral acceleration and spectral displacement, and then they are superimposed to give the performance point of the structure. The green colour curve seen is the pushover curve and the curve in yellow color is the response spectrum curve in terms of spectral acceleration and spectral displacement. At the intersection of the performance point a base shear is 1405 kN at a displacement of 78.86mm, which was obtained between steps 1th and 2th, we can observe that the hinges have entered into "Life Safety" level as seen in 2th step and still the hinges are in the state of "Collapse "level.

ISSN 2348 – 8034
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Storey shear of regular and mass irregular building

Table Storey shear of regular and mass irregular building in X-direction

Story	Regular building	MI 1floor	MI 5floor	MI 8floor
8	318.16	350.91	228.01	365.47
7	634.3	695.93	455.22	592.68
6	918.02	1001.89	662.49	796.67
5	1158.98	1256.74	1197.65	969.27
4	1348.17	1450.56	1108.09	1104.19
3	1479.7	1578.1	1217.93	1197.61
2	1552.94	1642.28	1279.94	1249.46
1	1581.2	1681.23	1300.01	1266.07

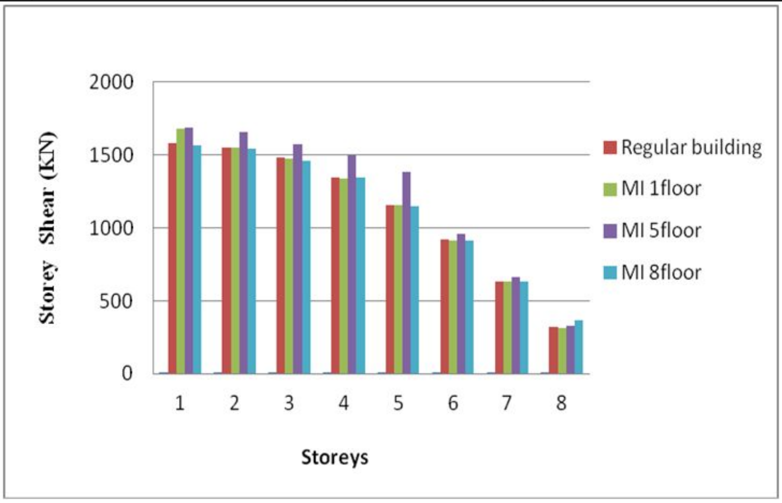

Figure Comparison of Storey Shear regular and mass irregular building in X-direction.

Table Storey shear of regular and mass irregular building in Y-direction

Story	Regular building	MI 1floor	MI 5floor	MI 8floor
8	236.83	350.91	303.73	331.4
7	472.16	695.93	606.4	537.67
6	683.35	1001.89	882.5	722.93
5	862.35	1256.74	1271.3	879.73
4	1003.54	1450.56	1476.07	1002.32
3	1101.45	1578.1	1622.39	1087.21
2	1155.97	1642.28	1705	1134.33

[Anwar, 3(10): October 2016] ISSN 2348 – 8034
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1	1177.02	1681.23	1731.71	1149.42

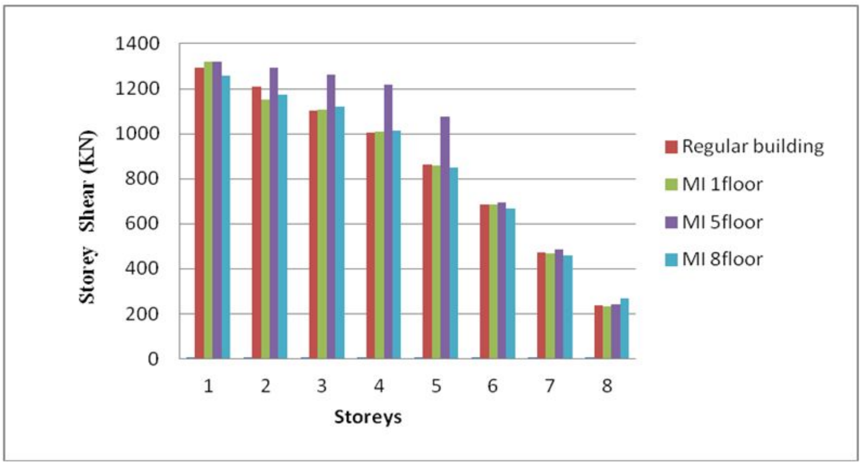

Figure Comparison of Storey shear regular and mass irregular building in Y-direction

Storey displacements of regular and stiffness irregular building

Table Storey displacements of regular and stiffness irregular building in X direction

Story	Regular bldg	KI @ 1stfloor	KI @ 5thfloor	KI @ 8thfloor
8	45.8858	39.4536	45.9438	68.7907
7	50.6698	43.7909	50.9593	49.7729
6	56.0516	49.0328	57.0194	53.6322
5	59.6489	53.7444	92.7793	55.986
4	59.2211	56.1149	58.9476	54.6311
3	54.0511	54.397	51.6185	49.0325
2	43.5429	48.1537	39.6924	38.9965
1	26.6014	49.513	21.714	23.802
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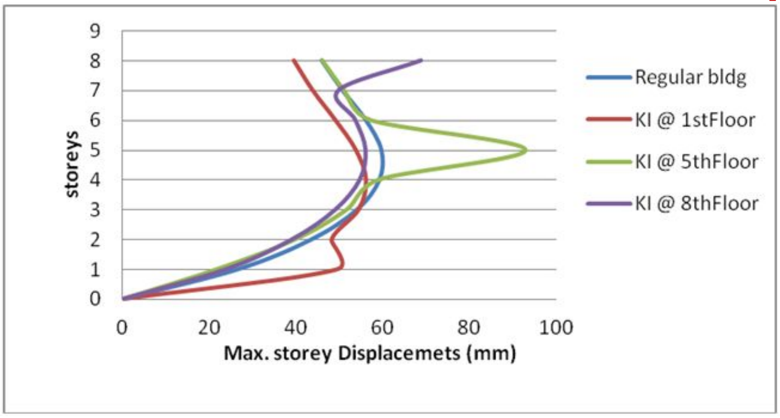

Figure Storey displacements for regular and stiffness irregular building in X direction

Table Storey displacements of regular and stiffness irregular building in Y direction

Story	Regular bldg	KI @ 1stFloor	KI @ 5thFloor	KI @ 8thFloor
8	44.5321	39.3762	45.923	68.6023
7	48.5615	43.6754	50.938	49.5355
6	52.9787	48.8168	56.9952	53.1596
5	55.849	53.3395	92.7344	55.5037
4	55.117	55.6889	58.9056	54.3577
3	49.9014	54.0784	51.551	48.814
2	39.8214	47.8212	39.5719	38.7091
1	24.3664	48.7476	21.4743	23.2882
0	0	0	0	0

ISSN 2348 – 8034
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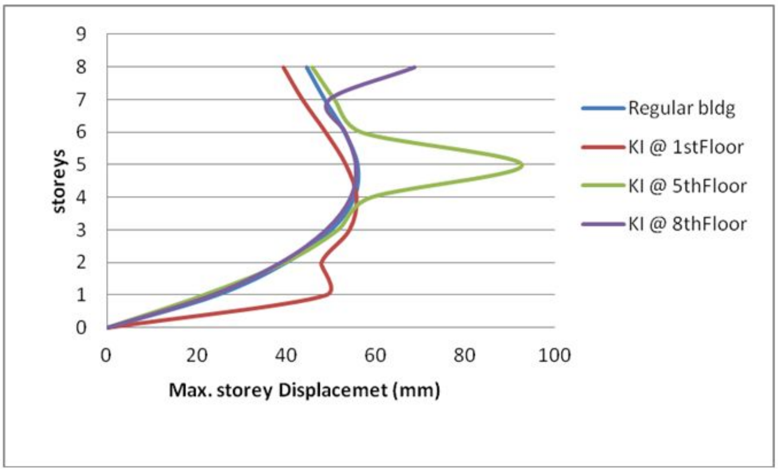

Figure Storey displacements for regular and stiffness irregular building in Y direction

IV. CONCLUSION

This work gives rise to the following particular conclusions

- The investigation indicates that the storey drifts were reduced by 35%, 10%, 14% at first, fifth and eighth floor for mass irregular buildings, but the storey drifts at bottom storey increased by 54% and 27% at fifth and eighth floor respectively.
- Storey drifts is increased by 94% for stiffness irregularity at bottom storey.
- The storey shear is increased by 6%, 25% and 15% at first, fifth and eighth floor for mass irregular structures. The heavier mass is on the middle height of building has significant effect on the storey shear.
- The storey displacements are reduced by 48%, 12% and 16% at first, fifth and eight floors respectively for mass irregular building, but the drifts at the bottom storey increased by 40% and 19%.
- Stiffness irregularity has significant effect on storey displacement. The variation is 83%, 55% and 49% for first, fifth and eighth floor respectively compared to regular RC frame.
- The storey displacements are increased by 86%, 66% and 54% for stiffness irregular structures.
- The capacity curves of mass irregular buildings were not much different of regular moment resisting frame.
- The Seismic capacity of the regular buildings falls under "Immediate occupancy" level.
- The seismic capacity of mass irregular building falls under "Collapse" level, whereas stiffness building falls under "Life of safety" level.

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