Seismic Response of Vertical Irregular Structures in Setback and Stepped Buildings

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Abstract

Vertical irregular building are frequently constructed across the globe for functional as well as aesthetic purpose. However post-earthquake reconnaissance survey reports revealed high seismic vulnerability of the building with vertical irregularities. Consequently it is very important to explore the reason behind the high seismic vulnerability and the poor performance of irregular structures during the earthquake. A humble effort is under taken considering several case studies comprising different configuration of vertical irregular structures, so as to comprehend the seismic behavior of vertical irregular structure using response spectrum and pushover analysis has been attempted in finite element software ETABS 16.2.1 version. The results of the analysis indicate the irregular structures have ample chance of higher stress concentration as well as higher displacement demand at the vicinity of irregularity. Member strength enhancement at the vicinity of vertical irregularity may improve the overall seismic performance of the building. Also, this research checks the adequacy of fundamental mode properties for the quantification of vertical irregularity. Furthermore, pushover analysis has been done to observe the hinge formation pattern and also the plastic hinge rotation for observing the performance level of building.

Keywords: *Hinge formation pattern, Irregularity index, Setback buildings, Stepped buildings, Vertical irregularity*

Introduction

A structure is “regular” if the distribution of its mass, strength, and stiffness is such that it will sway in a uniform manner when subjected to ground shaking –that is, the lateral movement in each story and on each side of the structure will be about the same. Regular structures tend to dissipate the earthquake’s energy uniformly throughout the structure, resulting in relatively light but well distributed damage.

Structures may have plan and elevation irregularities, which depend on geometry lateral stiffness and strength distributions, mass ratios along the height, mass- resistance eccentricity and discontinuity in diaphragm stiffness. In an irregular structure, however, the failure of the structural component is concentrated in one or a few locations, this results the extreme failure at the localized points in the structure to survive the shaking (Varadharajan et al., 2012). Real structure are always irregular as regular structures is just an idealization. Structural irregularities may vary dramatically in their nature, and, in principle, the concept of irregularity is a fuzzy one. Because of the complex behavior of such structures under earthquake excitations, it is not surprising that, in spite of the large research efforts in irregular building structures dating back to the 1970s, even in recent years, many papers have been devoted to a better understanding of seismic response both of simplified one-storey and of multi-storey building models.

This research mainly comprise of the vertical irregularity of setback building and shows how the irregularity are dealt in the setback and stepped buildings in reference to the various codes and literature. The setback irregularity is one of the most common form of irregularity. Setbacks in the building is provided not only for the aesthetic reason, but also for complying with the floor area ratio as per building byelaws restriction. Setback is provided, where there is space constraints and closer proximity of the building is required. In this research, both single side setback and double side setback building has been considered.

Objective of the study

The main aim of this research work is to analyze the seismic performance of the various irregular building and compare the response parameter with the regular building. The specific objectives are:

- To quantify the irregularity for setback buildings as suggested by the various building codes and researches.
- To check the stress concentration at the critical members in irregular buildings.
- To observe the hinge formation pattern in the regular and irregular buildings. And also to check the level of performance from plastic hinge rotation with reference to FEMA 365 (*The Seismic Rehabilitation of the Buildings*, 2000)

Methodology

Irregularity index

Quantification of irregularity index for the vertical irregular structures:

Karavasilis et al., 2008 proposed an alternative approach to calculate the irregularity in a building due to the presence of steps. The paper define the two regularity indices for stepped building φs and φb for story-wise and bay-wise irregularity respectively.

$$\varphi_s = \frac{1}{n_s}\sum_{1}^{n_s-1}\frac{L_i}{L_i+1}$$

$$\varphi_s = \frac{1}{n_b}\sum_{1}^{n_b-1}\frac{H_i}{H_i+1}$$

n_s = number of story H_i = height of i^{th} story

n_b = number of bays L_i = width of i^{th} story

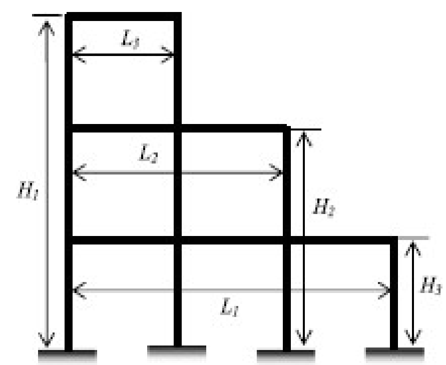


Figure 1: Irregularity index (Karavasilis et al., 2008)

Sarkar et al., 2010 [3] proposed the irregularity index to quantify the irregularity index as

$$\eta = \frac{\tau_1}{\tau_{1,ref}}$$

Where, Ʈ1 is the mode participation factor for the stepped building and Ʈ1, is the first mode participation factor for the similar regular building frames without steps (R). Approximate values of these two factors can be obtained from simple static analyses, using the concept of Rayleigh as follows.

$$\tau_1 = \frac{\{d_j\}[M]\{1\}}{\{d_j\}^T[M]\{1\}} = \frac{\sum m_j\, d_j}{\sum m_j\, d_j^{\,2}}$$

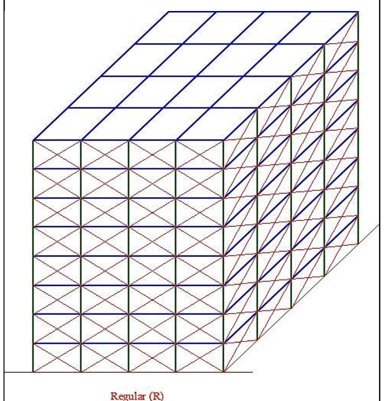
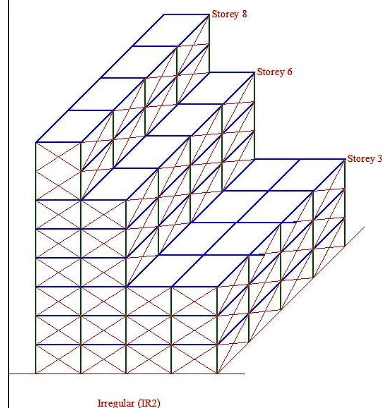
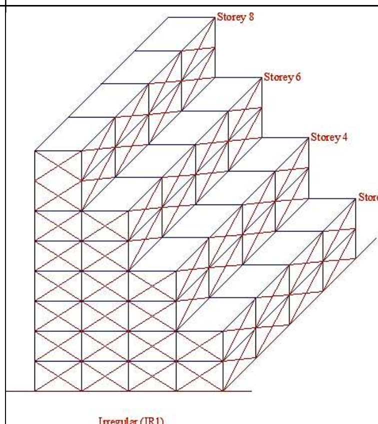
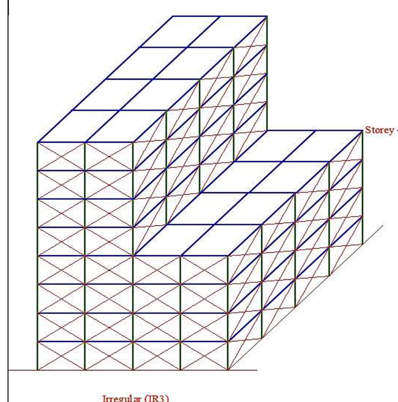
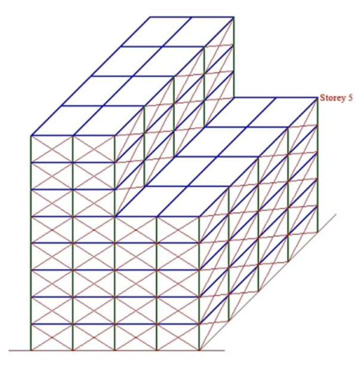
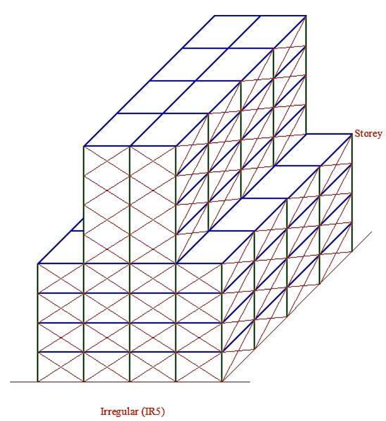
Where dj is the floor displacement at j^{th} floor when the seismic weight, m_j applied as lateral loads at the corresponding floor levels. These displacement values are normalized or scaled with respect to the mass matrix such that:

$$\{d_j\}[M]\{d_j\} = \sum m_j d_j^2 = 1$$

Modeling of the Regular and irregular buildings

Setback buildings are characterized by staggered, abrupt reductions in the floor area along the height of the building, with corresponding drops in mass, strength, and stiffness. Buildings with both single and multiple setbacks are popular in urban areas, and both of these forms separately received attention in the research. Therefore, two building models, one with a single setback (SB) where a narrow tower projects from a wide base) and the other with multiple setbacks [popularly known as stepped building (ST)] are considered in this study.

A bay width of 5 meter can be considered as a globally common construction practice. The building of 8 stories is considered with story height of 3.5 m. The characteristic strength of concrete and reinforcement steel are taken as 25 and 500 MPa, respectively. The size (breadth and depth) of columns and beams are taken as 400 × 400 mm and 300 × 400 mm respectively. The thickness of slab is considered as 125 mm. The Modeling has been done on the basis of IS: 1893-2002 and the building has been analyzed for the maximum peak ground acceleration (PGA) of 0.36g. The live load of 4 KN/m^2 and wall load of brick masonry has been considered. The structural and geometrical modeling of the buildings has been considered based on the literature reviews Bhosle et al., 2017.

Regular Model **R**		**Regular Model setback at 3 story each** **IR2**	
Irregular model setback at 2 story each **IR1**		**Irregular Model setback at 4 story** **IR3**	
Irregular Model setback at 5th story **IR4**		**Irregular Model Double stepping at 4th story** **IR5**	

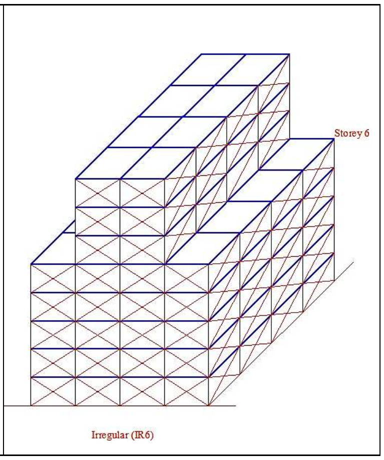
Irregular Model Double stepping at 6th story **IR6**	

Figure 2: Regular, setback and stepped building models

Analysis procedure

For this research, the structural model with vertical irregularity has been defined as presented above. The quantification and analysis of the vertical irregular structures has been proceeded as follows:

1. Irregularity index by various codes and research papers based on the time period and mode participation factor
2. Modeling of the structure in finite element tool ETABS 16.2.1 version.
3. For equivalent static and response spectrum analysis, the earthquake parameters are defined as per IS-1893:2002.
4. Compare the story displacement and story drift of the regular and irregular structures.
5. Compare the moment increase in the columns at the vicinity of the irregularity/steps of the irregular buildings with that of the regular building.
6. Assign default plastic hinge properties based on FEMA 356 guidelines.(*The Seismic Rehabilitation of the Buildings*, 2000)
7. Pushover analysis is performed to observe the hinge formation pattern and the plastic rotation of the hinge.

Results

The results have been drawn from the various analysis of all the regular and irregular buildings. Under the following sub-headings different parameter of the building has been compared and observations has been done.

Fundamental time period

The time period obtained from the ETABS 16.2.1 in the first principal mode is referred as fundamental time period in mode and the fundamental time period in first mode is given below:

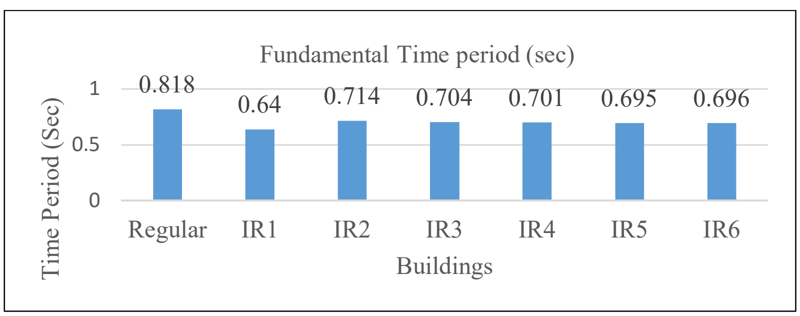


Figure 3: Time Period of regular and irregular structures in first fundamental mode.

Model mass participation ratio

The contribution of the total seismic mass of the building in the particular mode of vibration of the building is model mass participation ratio. The model mass participation ratio of the first mode has been shown in below:

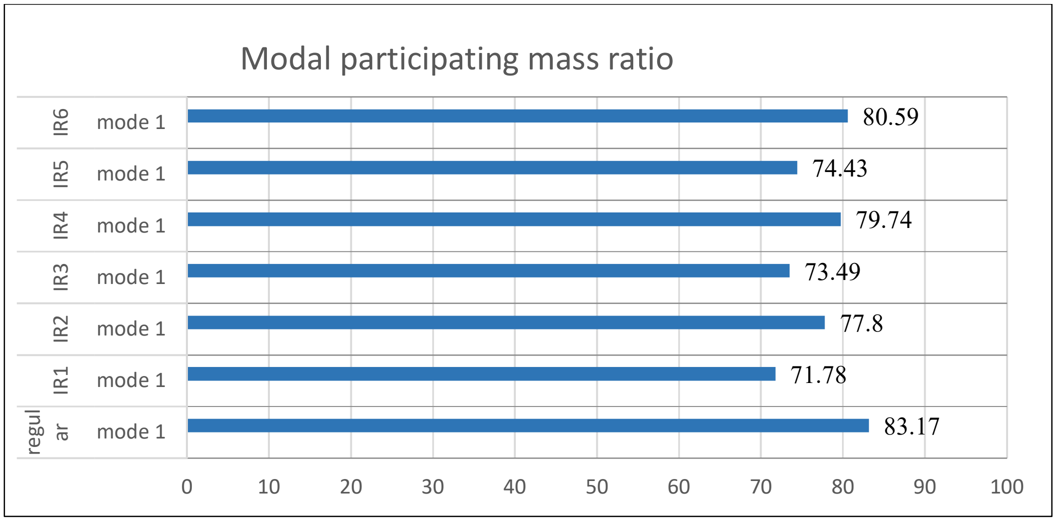


Figure 4: Model Mass participation ratio of first three modes of regular and irregular buildings

Irregularity index:

The numerical indicator used for measuring the irregularity is called irregularity index and the irregularity index calculation methods is different as per the various codes and researches, which has been tabulated below:

Table 1: Irregularity index by various codes and research papers

ID	Fundamental period	Amount of irregularity		Irregularity index (Karavasilis et al., 2008)		Irregularity index (Sarkar et al., 2010)
		IS 1893:2002	ASCE 7-10			
R	0.818	1	1	1	1	1
IR1	0.64	0.75	1.33	1.404	1.61	0.726
IR2	0.71	0.5	2	1.262	1.67	0.914
IR3	0.704	0.5	2	1.285	2	0.852
IR4	0.701	0.5	2	1.285	1.6	0.905
IR5	0.694	0.5	2	1.285	1.25	0.867
IR6	0.696	0.5	2	1.285	1.112	0.887

Table 2: Mode participation factor and Irregularity index

Building	Mode participation factor(γ1)	Irregularity η
R	54.162	1
IR1	39.345	0.726
IR2	49.503	0.914
IR3	46.155	0.852
IR4	49	0.905
IR5	46.943	0.867
IR6	48.04	0.887

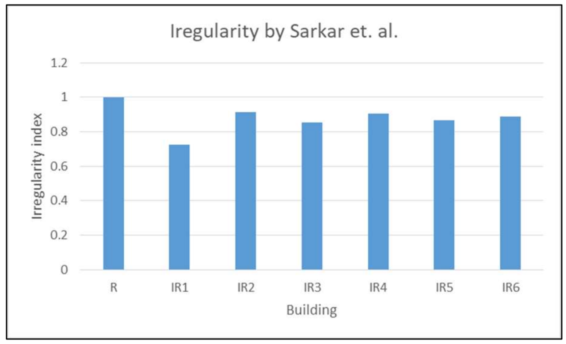


Figure 5: Irregularity Index by Sarkar et. al.

Observations:

1. From Figure 3 and Figure 5, it can be depicted that as the irregularity increases the fundamental time period decreases.
2. From Figure 4 and Figure 5, it can be observed that as the irregularity increases the mode mass participation of the first mode decreases. (Bhosle et al., 2017)

Story Displacement

The maximum displacement of a story in a building in response of the excitation due to the earthquake in principal direction is called story displacement. The comparison of the story displacement has been shown below due the earthquake load in a principal direction.

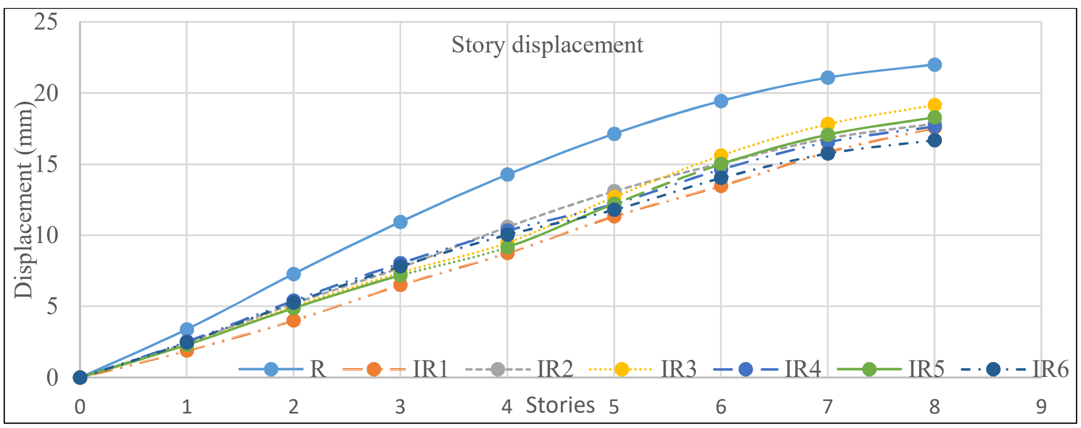


Figure 6: Comparison of displacement of various stories for different types of buildings

1. The story displacement of regular building is more than that of building with setback and stepped building on the other hand the story displacement of regular building is less than that of weak and soft story buildings and floating column buildings. Maximum top story displacement is in the order: R>IR3>IR5>IR2>IR4>IR1>IR6.
2. It has been observed that the setback at different stories doesn't create much of difference in the story displacement as shown in the Figure 6.

Story Drift

The ratio of the adjacent relative story displacement with that of the relative height difference between the adjacent stories is termed as story drift. The story drift of all the irregular buildings with that of the regular building has been compared.

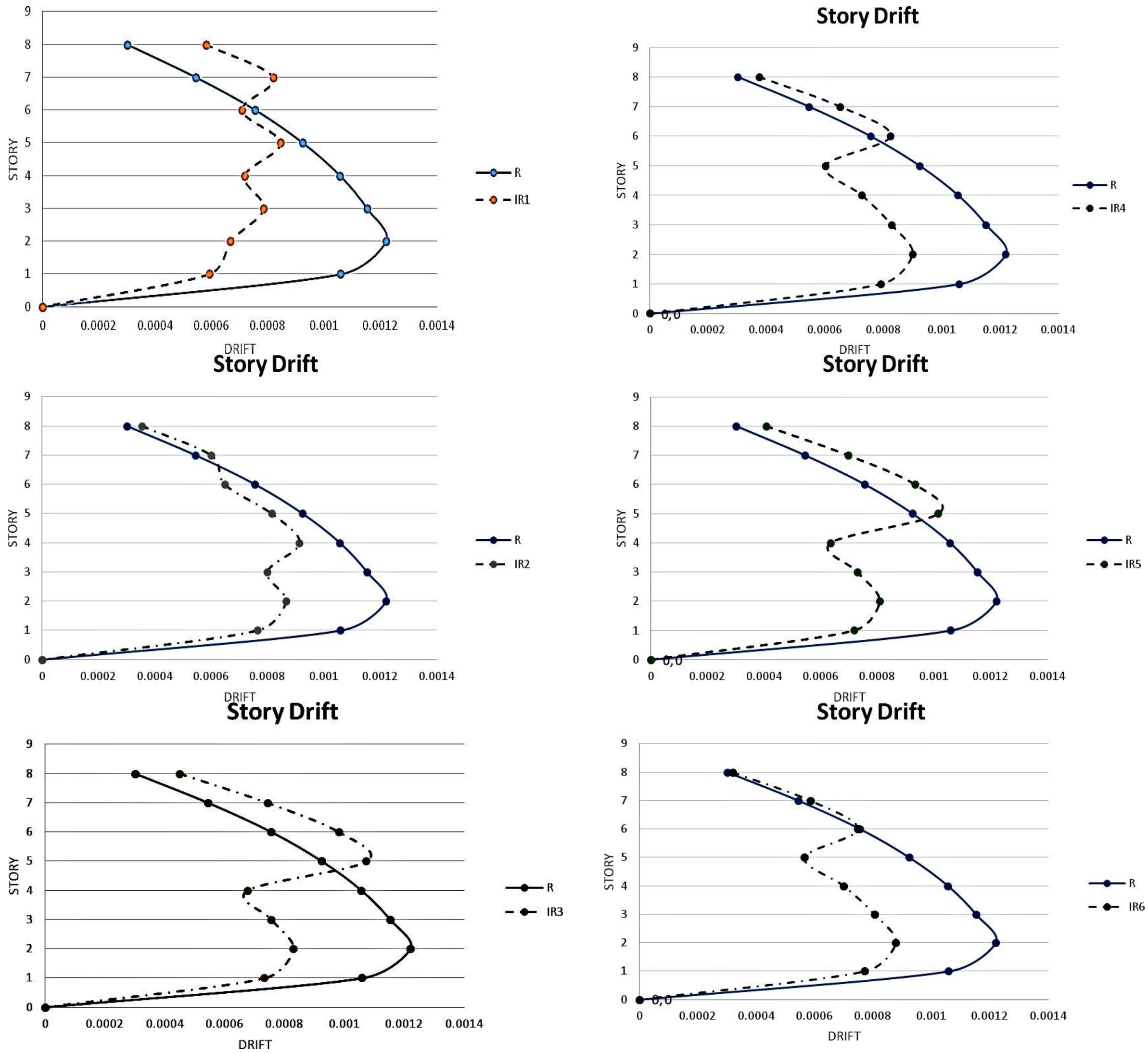


Figure 7: Story drift ratio of regular and irregular buildings

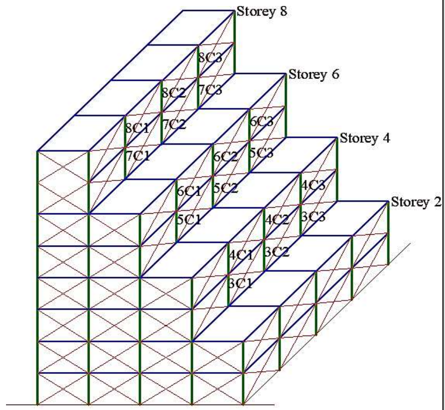
Observations:

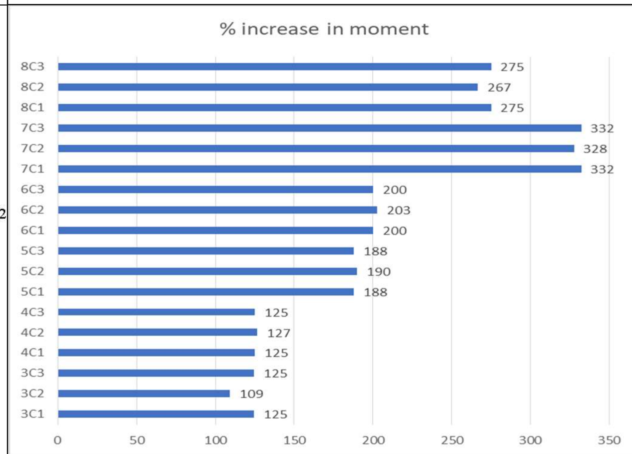
1. Maximum story drift of irregular setback and stepped building is seen less in comparison to the maximum story drift in regular building.
2. Story drift at the location of setback and steps is changing abruptly

Moment at the Vicinity of the irregularity

Moment due to earthquake load in the principal direction at the location of the irregularity has been looked upon as shown in the table below.

Table 3: Comparison of the moment at the location of irregularity

<table>
<tr><th>Building type</th><th>% increase in the moments</th></tr>
<tr><td>

Irregular (IR1)</td><td>
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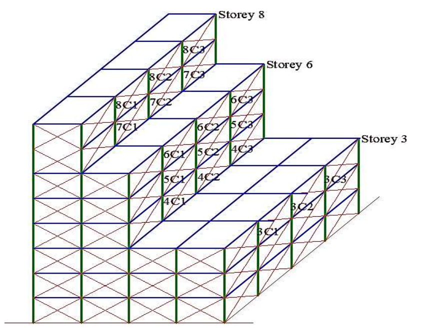
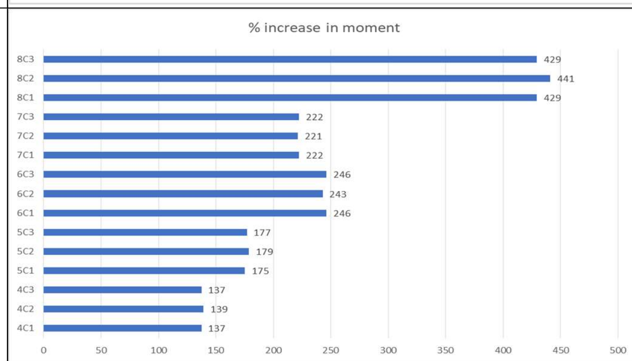
<tr><td>

Irregular (IR2)</td><td>
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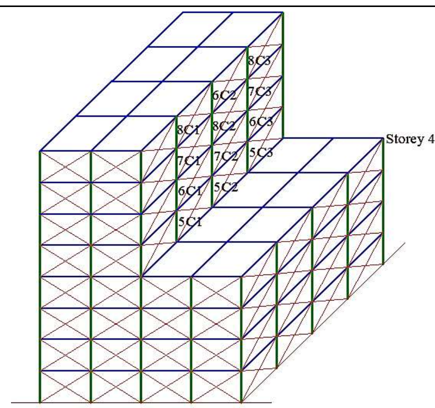
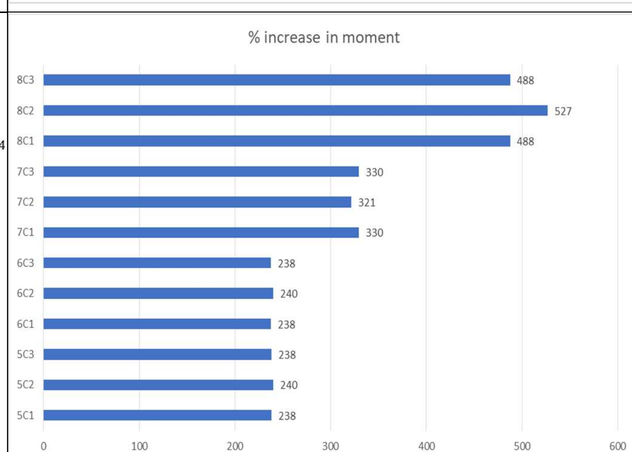
<tr><td>

Irregular (IR3)</td><td>
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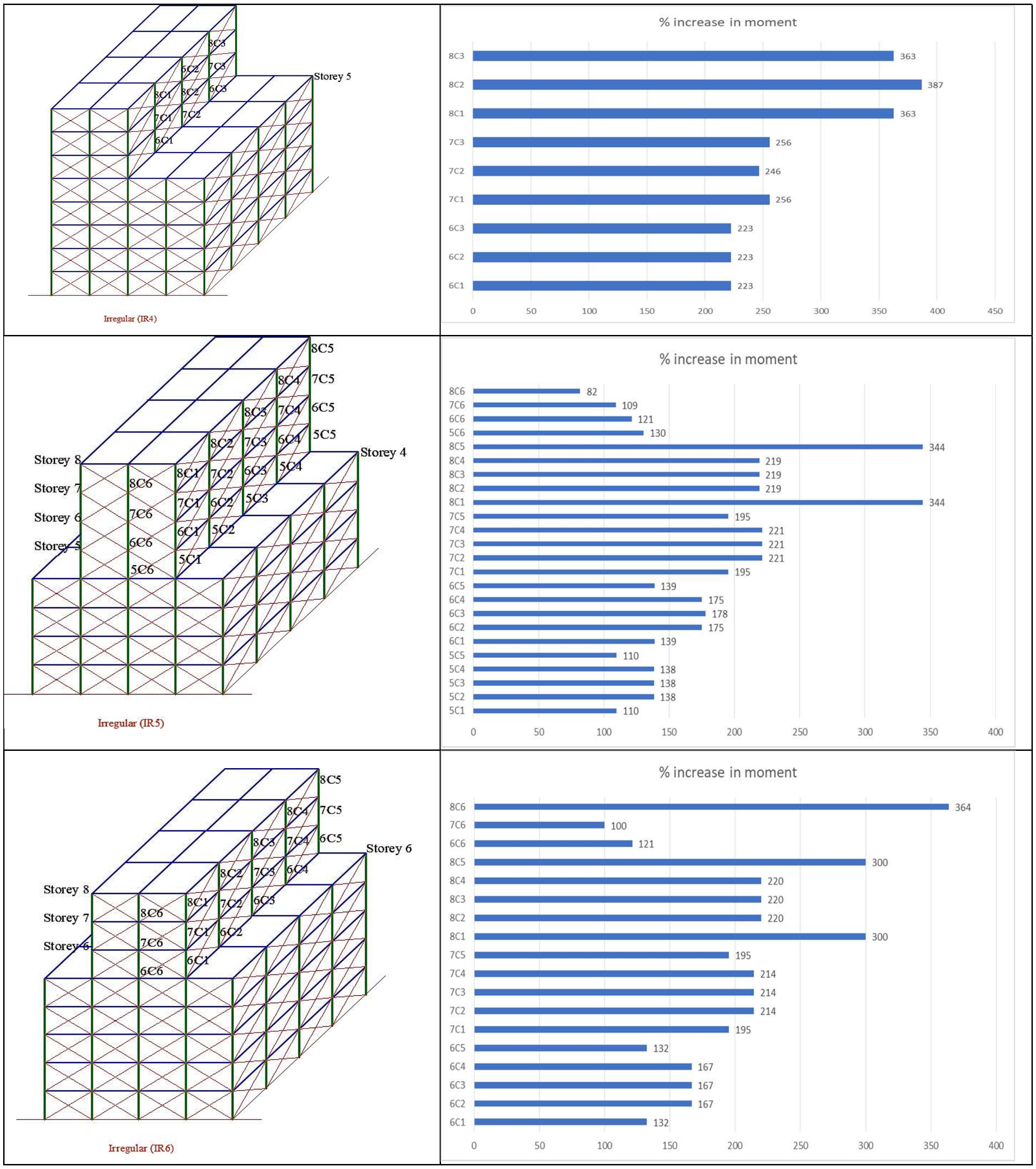
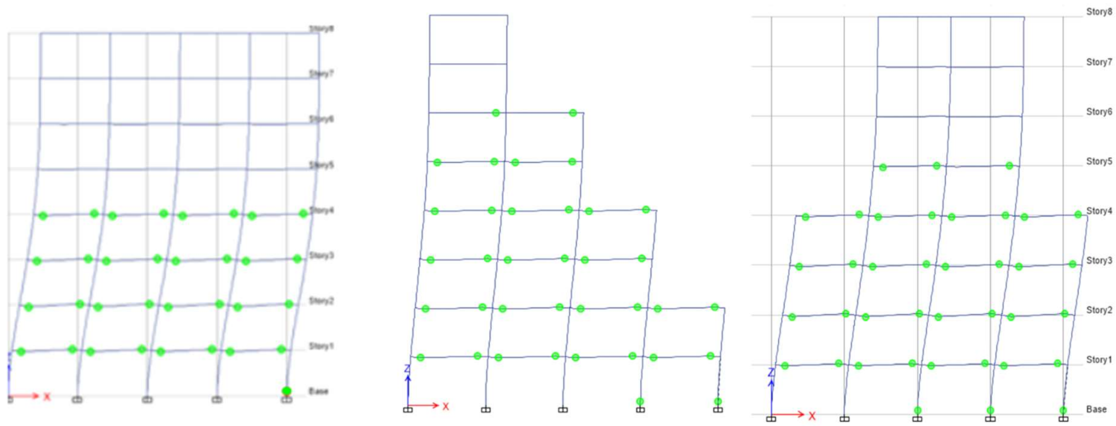


Observations:

1. Due to abrupt change in mass stiffness and strength irregularity, the moments in the members located in the vicinity of irregularity increases up to 2 to 5 times than that of the regular counterpart.

Pushover analysis:

The pushover analysis has been carried out to observe the hinge formation pattern and the plastic rotation observed in the hinges in the regular and irregular buildings.



Regular building Irregular building IR1 Irregular building IR5

Figure 8: Hinge Formation Pattern

Plastic hinge rotation

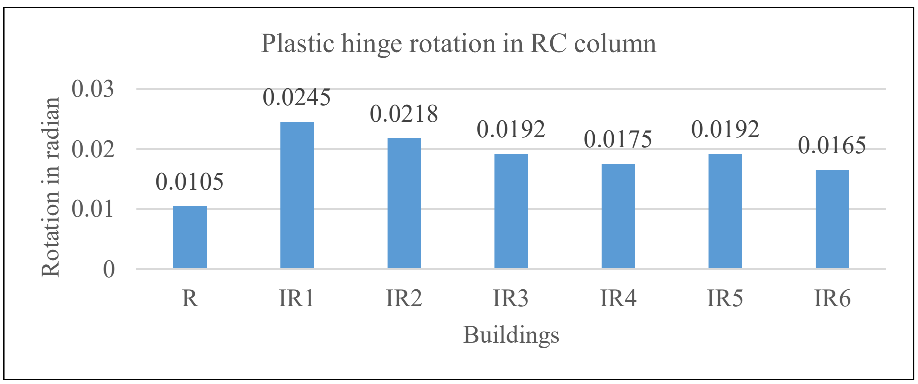


Figure 9: Plastic hinge rotation in RC column

Observations:

Hinge formation pattern has been observed for regular building, setback building and stepped building as:

1. The hinge formation pattern in regular building is found to start from 2nd and 3rd story and progressively increases to the higher stories.
2. In setback building the hinge formation is localized in a single vertical resisting frame at lower stories at the place where there is setback irregularity.
3. The hinge rotation with compared with the FEMA 365 table 6.8, the column of regular building is found to be in life safety level of performance.
4. For IR3 , IR4 , IR5 and IR6 the plastic hinge rotation signifies the performance level is in between life safety and collapse prevention
5. For IR1 and IR2 the plastic hinge rotation signifies the performance level is collapse prevention.

Conclusion and recommendation

The research work have been concluded in the followings points:

1. The formula proposed by IS 1893(part 1) 2002 for the calculation of time period holds good only for the regular building but for irregular building there is large deviation of time period as calculated from the code. (Sarkar et al., 2010)
2. Setback irregularity accounts for the lower first mode participation than that of regular structure.

3. Setback irregularity accounts for lower roof displacement and story drift than that of the regular building thus they seem to perform well than that of regular building in the case of seismic responses acting in orthogonal direction.
4. The member in the vicinity of irregularity attract larger forces thus it is recommended to locally strengthen that member at the vicinity of irregularity instead of globally strengthening the entire irregular structure. (Dutta et al., 2017)
5. The rotation of the plastic hinge in the regular and irregular building showed that the regular building is in life safety level of performance while other irregular structures are in between life safety and collapse prevention level of performance.
6. The hinge distribution pattern depicts the local hinge formation pattern at the vicinity of irregularity, which suggests local strengthening of the members in the vicinity of irregularity.

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