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Effect of Vertical Irregularity on Performance of Reinforced Concrete Framed Buildings

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***Abstract*— Indian standard codes (IS 456:2000, IS 13920: 1993) have not given particular attention for the design of setback buildings. This paper addresses the effect of irregularities in elevation on the seismic performance of reinforced concrete (RC) framed buildings with infill brick walls. The seismic parameters such as fundamental time period, inter storey drift ratio, base shear and top displacement of irregular buildings are compared with that of a regular building. The nonlinear static analysis, using user defined hinges, is used to assess the buildings with irregularities introduced at different storey levels and with different setback ratios. Nonlinear version of SAP 2000-12 is used for analysis. It is observed that the performances of these irregular buildings when designed according to the provisions of IS codes are inferior compared to that of regular building.**

***Keywords:* Vertical geometric irregularity, Infill, User defined hinges, Pushover analysis**

I. Introduction

Now a days, complex shaped buildings are becoming very popular mainly because of its functional and aesthetic architecture. A common type of irregularity provided in the buildings is vertical geometric irregularity, known as setback. In the case of setback buildings, the length of the building gets reduced along its height. The setback buildings are usually provided when a relatively narrow road separates two multistorey buildings, as it permits adequate sunlight and ventilation to the lower storeys. This type of building form also provides for compliance with building bye-law restrictions related to 'floor area ratio' which is a common practice in India. Setback buildings are also characterized by staggered abrupt reductions in floor area along the height of the building, with consequent drops in mass, strength and stiffness, which will consequently change its dynamic characteristics. In the latest version of IS 1893: 2002 [1], definitions of various types of irregularities and the need for the dynamic analysis of these type of buildings are incorporated. Fig. 1 shows different types of vertical geometric irregularities. Setback can be provided either in one side or in two sides. Several studies have been reported on stepped buildings (buildings with setback on one side), as torsion will play an important role in its behaviour. The lower part of a setback building with the largest floor area is termed the base, while the upper part with the smallest floor area is called the tower. Being a symmetric building, a tower building (buildings with setback on both sides) is expected to perform well under the action of seismic forces; but in contrast to this, a few studies in this area show an inferior performance of these buildings during strong earthquake motions.

Analytical studies by Costa et al. [2] and experimental studies conducted by Wood [3] pointed out that, ductility demands of setback buildings are more compared to regular buildings of similar characteristics. The Uniform building code was critically evaluated by Valmundsson et al. [4] by conducting analytical studies and proposed new formula for calculating fundamental time period for mass irregular structures. Athanassiaduo [5] conducted analytical studies to evaluate the effect of ductility on cost of building designed to the provision of high and medium ductility demand as per Eurocode 8, 2004 and found that performance of irregular buildings are equally satisfactory. Inel et al. [6] studied the possible differences in the results of pushover analysis due to default and user-defined nonlinear component properties and it was found that user defined hinges are more effective in representing the nonlinear behavior of materials.

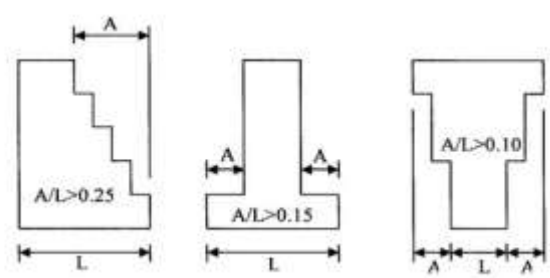

Figure 1 Vertical geometric irregularity as per IS 1893:2002

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Studies on seismic performance of RC frames with vertical irregularity and having masonry infill walls is not addressed. Hence, the present study focus on evaluating the seismic performance of twelve storey RC framed setback buildings with infill brick walls, designed according to the provisions of IS code 456: 2000 [7] and IS 13920: 1993 [8]. The different seismic parameters such as fundamental time period, inter storey drift ratio, base shear and roof top displacement of these buildings are computed and compared with that of a regular building.

II. Methodology

Response spectrum (multi mode) analysis is carried out on the models using non linear version of SAP 2000-12[9]. For the area of steel obtained, ductile detailing of different structural members is done as per IS codes [7-8]. Point plastic hinges are used for representing non linear material behavior. Infill walls are modelled as single diagonal strut [10]. For developing the backbone curve for beams and columns the method proposed by Panagiotakos et. al [11] is used. For developing force-deformation curve of infill walls, method proposed by Panagiotakos et al. [12] is adopted. The calculated hinge properties are assigned to the corresponding members near to column beam connection for beams and columns, and at the middle of the diagonal strut representing infill walls. An initial force controlled nonlinear static case with gravity loads is first applied on the models. Then a displacement controlled pushover with lateral load pattern corresponding to fundamental mode shape is carried out starting from the end of the gravity load case. In this study the monitored displacement is kept as 1.33% of the building height as per IS code[1]. The Capacity Spectrum Method (CSM) according to ATC-40 [13] is used for comparing the performance of buildings selected for the study. From the capacity spectrums, the performance point and various stages of hinge formation are studied. In Fig.2, the range AB is elastic range, B to IO is the range of Immediate Occupancy, IO to LS is the range of Life safety, LS to CP is the range of collapse prevention. If all the hinges are within the CP limit, the structure will be safe.

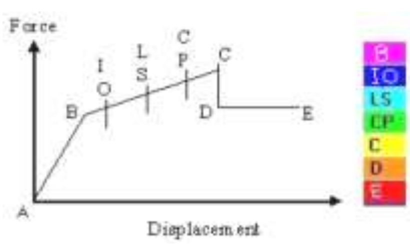
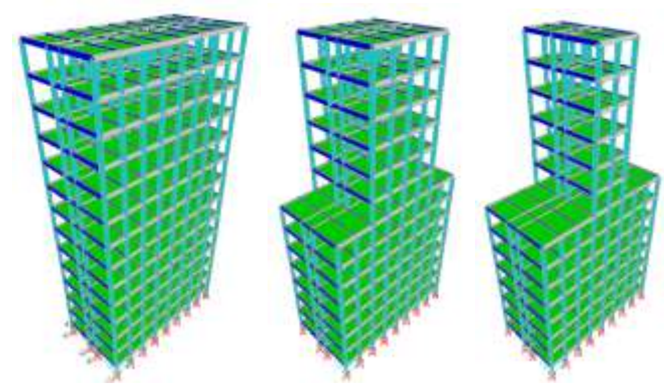


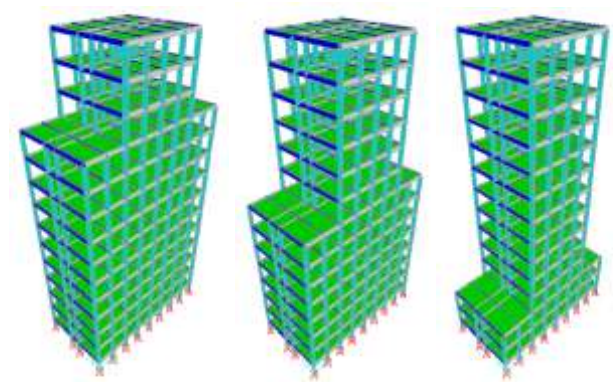
Figure 2 Force displacement relations along with different hinge stages

III. Details of Analysis

A twelve storey RC framed building with masonry infill wall is considered in the present study. The building has overall dimension of 24m × 12m, with 8 bays in the larger direction and 3 bays in the smaller direction. Fig. 3 shows the 3D view of building models with and without setbacks, generated using SAP 2000-12. The details of the buildings, setback ratio (A/L) and storey level of irregularity are given in Table 1.



Case (i) (a) R (b) IR1 (c) IR2



Case (ii) (a) IR3 (b) IR1 (c)IR4

Figure 3 Three dimensional view of building models

Two different cases are studied, (i) the effect of irregularity introduced at the same storey level with different setback ratios, (ii) the effect of irregularity introduced at different storey levels with same setback ratio. The setback ratios are selected depending on the building geometry. M30 concrete and Fe 415 and Class II bricks with compressive strength 3.5 MPa is used. The building is located in zone III (Z = 0.36) and considered to be special moment resisting framed building (R = 5). The importance factor (I) is taken as 1.5.

TABLE 1. DETAILS OF BUILDING MODELS ANALYSED

Building specification	**Setback ratio(A/L)**	**Storey level at which irregularity is introduced**
R	-	regular
IR1	0.27	7
IR2	0.40	7
IR3	0.27	10
IR4	0.27	2

Frame elements are used for modelling beams and columns, and membrane elements for slabs. Single diagonal strut is used for modelling infill. Dead loads and live loads are as per IS 875 (Part I & II):1987 [14] and earthquake loads along positive and negative X and Y direction and using the load combinations as per IS code [1] are considered in the analysis.

IV. Results and Discussion

A. *Effect of variation in setback ratio*

The dynamic responses of buildings with two different setback ratios introduced at same storey level are compared with that of a regular building.

1) Fundamental time period

According to IS code[1], the approximate time period of vibration (T_a) for moment resisting frames with brick infill walls is estimated by the empirical expression

$$T_a = {(0.09\,h)}\Big/{\sqrt{d}} \qquad (1)$$

where *h* is the height of the building, and *d* the base dimension of the building. Fig. 4 compares the fundamental time period obtained from modal analysis of different buildings. It can be seen that even though the height and base width of all the buildings considered are same, natural period for the buildings are not same as specified by (1); but varies depending upon the irregularity. As the setback ratio increases, the period of vibration decreases which may be attributed to the decrease in seismic weight due to irregularity.

2) Inter storey drift ratio

The inter storey drift ratio is defined as the inter-storey displacement divided by the storey height. The lateral displacement of each storey is obtained from response spectrum analysis. From this the inter storey drift ratio for each model is calculated manually. Fig. 5 compares the storey drift ratio of different buildings. For irregular buildings, the bottom storey drift ratios are less but the top storey drift ratios are more compared to regular buildings. As setback ratio increases, the storey drift ratio also increases. Sudden increase in storey drift ratio near to the storey level of irregularity may be due to the sudden reduction in stiffness at that level.

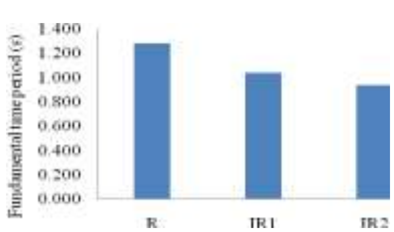


Figure 4 Variation of fundamental time period with setback ratio

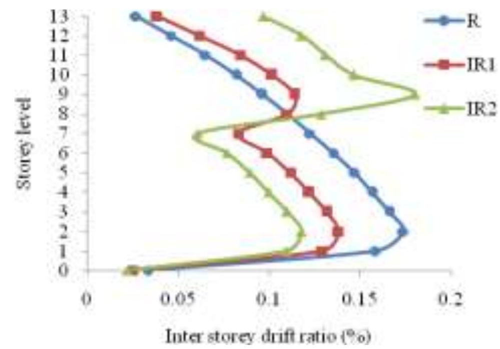


Figure 5 Distribution of inter storey drift ratio along storey height (Different setback ratios, irregularity at same level)

3) Storey shear

Fig. 6 shows the storey shear obtained from response spectrum analysis. It can be observed that, there is an abrupt change in the storey shear (i.e., slope of the curve) at the level where irregularity is introduced. It is found to be more pronounced as setback ratio is increased.

4) Performance point

The performance point obtained from the capacity spectrum of pushover analysis is presented in Fig. 7. It can be seen that, as the setback ratio increases, the base shear decreases whereas the roof top displacement increases. Top displacement is greater for building with greater setback ratio and is found to be more compared to regular building.

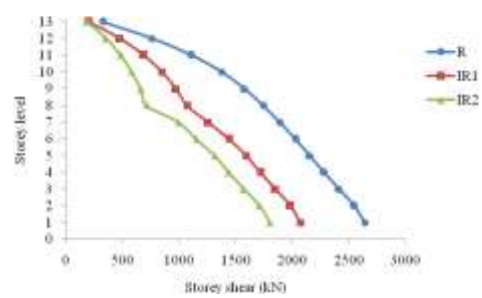


Figure 6 Distribution of storey shear along storey height (Different setback ratios, irregularity at same level)

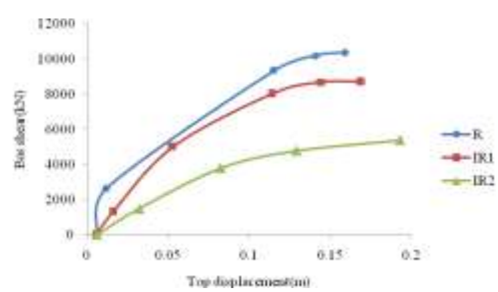


Figure 7 Pushover curve up to performance point for models with various setback ratios

5) Hinge pattern at yielding

Fig. 8 represents the hinge pattern at yield state obtained from pushover analysis. For all the models considered, at yield state, hinges are formed within Immediate Occupancy (IO) level and hence the buildings are safe. It can be observed that for regular buildings, hinges are well distributed and are formed only on beams. For irregular buildings hinges are concentrated on base of the tower region and also hinges are formed on columns which show'Weak column' behaviour. It is noted that the number of column hinges formed increased with increase in setback ratio.

B. *Effect of irregularity at different storey levels*

For studying the effect of level of irregularity, a constant setback ratio (0.27 for this study) is considered and irregularity is introduced at three different storey levels. The variations in different seismic parameters are compared with that of regular building.

1) Fundamental time period

Fig. 9 shows the fundamental time period of buildings with same setback ratio, irregularity introduced at different storey levels. The time period varies based on the storey level at which irregularity is introduced, even though the setback ratio is kept same. It is emphasized that natural period computed as per (1) is not valid for irregular buildings.

2) Inter storey drift ratio

Fig. 10 shows the inter storey drift ratio of the buildings with same setback ratio, with irregularity introduced at different storey levels. It can be observed that in vicinity of the irregularity, there is an abrupt increase in storey drift ratio. It shows that the members in this region need to be strengthened.

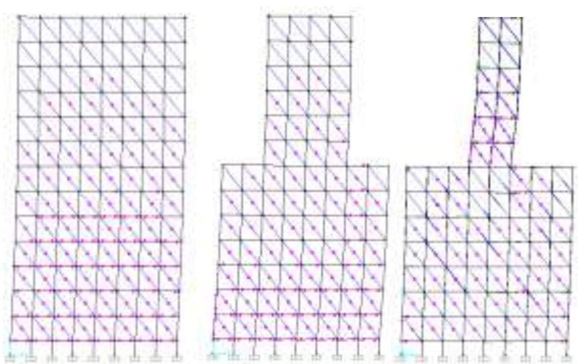


Figure 8 Hinge pattern at yielding for (a) R, (b) IR1, (c) IR2

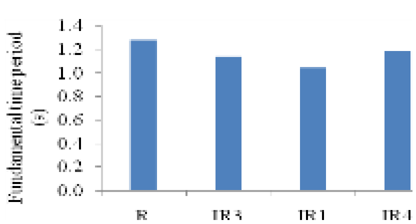


Figure 9 Variation of time period for irregularity at different storey level

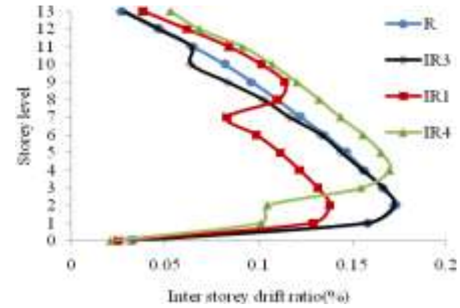


Figure 10 Distribution of inter storey drift ratio along storey height (same setback ratio and irregularity at different levels)

3) Storey shear

From Fig. 11 it can be observed that, there is a sudden change in the storey shear at the level where irregularity is introduced as seen earlier.

4) Performance point

Fig. 12 shows the performance point obtained from pushover analysis. As against case(1), here it is observed that only base shear depends upon the storey height at which irregularity is present and roof top displacement is independent of this. Roof top displacement depends mainly on setback ratio, rather than the storey height at which setback is provided.

5) Hinge pattern at yielding

From Fig. 13, it can be observed that if the irregularity is

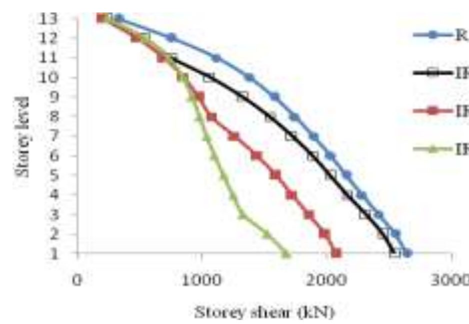


Figure 11 Distribution of storey shear along storey height (Same setback ratio, irregularity at different levels)

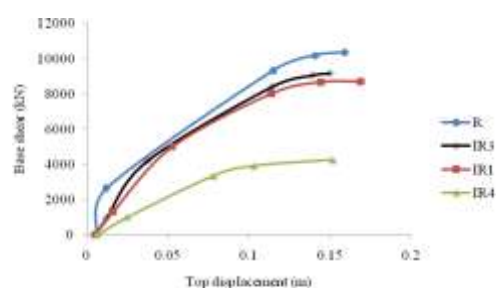


Figure 12 Pushover curve up to performance point for models with irregularity at different storey levels

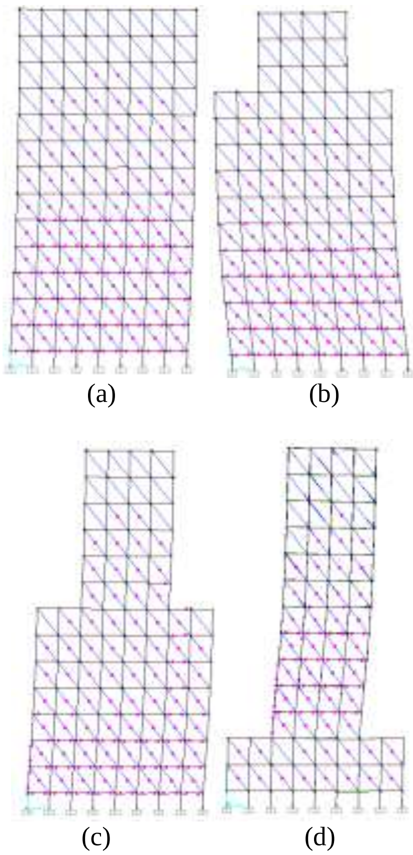


Figure 13 Hinge pattern at yielding for (a) R (b) IR3 (c) IR1 (d) IR4

introduced at top storeys, the hinge pattern is similar to that of regular building. If the setback is introduced in bottom storeys, the hinges are mainly concentrated on the tower portion and increased numbers of column hinges are also observed.

Analysing the hinge pattern, it can be observed that as the setback ratio increases, the number of hinges formed on columns also increases, suggesting that the IS code design recommendations are applicable only for regular buildings; but insufficient for irregular buildings. Thus, buildings with vertical geometric irregularity designed as per Indian Standard Codes is found to be poorly performing compared to regular buildings.

V. Summary and Conclusions

In this paper, seismic performance of RC framed buildings with setback, designed as per Indian design codes is investigated. It is observed that, the fundamental period of a framed building with irregularity is not a function of building height and base width alone as specified in IS Code [1] and it depends upon the setback ratio and storey level at which it is introduced. The formation of hinges at yield state demonstrated the poor performance of these buildings when compared to regular buildings, depending upon the setback ratio. Thus, the criteria for the design of various elements at the location of irregularity need to be improved in order to enhance the performance of setback buildings during ground motion.

The salient conclusions drawn from the present study are,

- Fundamental time period of setback buildings are found to be always less than that of similar regular buildings and it is found to depend on the setback ratio and storey level at which irregularity is introduced.
- The top storey drift increases with setback ratio; maximum storey drift is found for the building with greatest setback ratio, near to the storey where irregularity is introduced.
- It is found that the performance point changes due to the presence of irregularity. The base shear is found to decrease with increase in setback ratio. Roof top displacement depends on setback ratio of the buildings but it is found to be independent of the storey level where irregularity is introduced.
- For regular buildings the hinges are uniformly distributed; but for irregular buildings the hinges are concentrated near base of the tower region and hinges are also formed on columns. There is need for strengthening of the elements at this location.

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