A simplified procedure for the seismic analysis of RC moment resisting setback frames

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Abstract. Irregularity in elevation of buildings is increasingly popular in modern urban construction. One of the prominent forms of vertically irregular frames is the setback building frames. The seismic performance of buildings with irregular distribution of mass, stiffness, and strength along the height may be significantly different from that of regular buildings. The present paper focuses on quantification of irregularity and studying the effect of irregularity on the seismic performance of setback building frames. An index namely Geometric Regularity Index (GRI), calculated based on the geometric parameter of the building frame, is proposed in the study to quantify the vertical irregularity of setback building frames. 55 numbers of 3 bay frames with stories 5, 7, 9, 11 and 13, with varying levels of irregularity, are considered in the study. Linear dynamic analysis of the frames is performed in ETABS using response spectrum method. The proposed index is correlated with the actual seismic response of the structure such as base shear and overturning moment. Based on the results of analysis, a simple method which employs the GRI of the frame is proposed to estimate the seismic responses such as base shear and overturning moment at the base. The proposed method is found to estimate the seismic response of setback frames with reasonable accuracy.

1. Introduction
Majority of urban structures are irregular in nature. Irregularity causes interruptions in the flow of forces and stress concentration when subjected to seismic excitation. Irregularity may be broadly classified as horizontal irregularity and vertical irregularity. Setback is one of the major forms of vertical geometrical irregularity [1]. Setback buildings are inevitable in modern building construction. Setback shapes may be introduced for aesthetic appearance or for day lighting purpose.

Setback causes non uniform distribution of mass and stiffness in vertical direction which may have significant influence on seismic response [2, 3]. Indian Seismic building code IS1893-2016 [4] restricted the use of ‘equivalent static method’ procedure for the analysis of building with vertical irregularity. Some research studies suggest that the static procedure should not be restricted on the basis of inter-storey stiffness, strength, and mass ratios [5 - 7]. Most of the seismic design codes did not account quantification of vertical irregularity. Efforts were made by many researchers to quantify the irregularity using some indices. Methods of quantification of irregularity for setback building frames are mainly proposed by Karavasilis et al. [8] and Varadharajanet al. [9]. The approach proposed by Karavasilis et al. [8] uses geometric properties of the building frames such as number of
bays, number of storeys, width of bays and height of stories from base. The irregularity index proposed by Varadharajan et al. [9] is based on the natural frequency of the frame.

The quantification of irregularity (irregularity index) becomes meaningful, if the severity of seismic response is correlated with irregularity index. The existing irregularity indices are not found to be well correlated with the seismic risk associated with the building [2, 10, 11]. In the present work an index, calculated based on the vertical profile of the building, is proposed for quantifying the irregularity of setback frames. The proposed index is correlated with the actual seismic response of the structure such as base shear and overturning moment. Finally, a simple procedure to estimate the seismic response of setback building frames is suggested.

2. Building models

The design of the building frames are carried out in such a way that it should not be failed under seismic loading. The design of the building is carried out as per IS 456:2000 [12] and IS 1893:2016 [4]. The bay width and height of the building is taken as 4 m and 3.5 m respectively. In the analytical study, 3 bay frames with stories 5, 7, 9, 11 and 13 are considered. The configuration of building used for the present study is shown in figure 1.

![Building configurations of frames considered for analysis: (i) 5storey 3bay, (ii) 7storey 3bay, (iii) 9storey 3bay, (iv) 11storey 3bay and (v) 13storey 3bay](image-url)
3. Geometric regularity index
For quantifying the effect of vertical irregularity in building frames, a simple index namely ‘geometric regularity index (GRI)’ is introduced which is defined as,

\[
GRI = \frac{\text{Panel area of irregular building frame}}{\text{Panel area of regular frame}}
\]  

(1)

The GRI values of various frames considered in the study (figure 1) are given in Table 1.

| Building Configuration | GRI      |
|-----------------------|---------|
|                       | 5 storeyed frame | 7 storeyed frame | 9 storeyed frame | 11 storeyed frame | 13 storeyed frame |
| 1                     | 1.00     | 1.00            | 1.00             | 1.00              | 1.00              |
| 2                     | 0.93     | 0.95            | 0.96             | 0.97              | 0.97              |
| 3                     | 0.87     | 0.9             | 0.93             | 0.94              | 0.95              |
| 4                     | 0.80     | 0.86            | 0.89             | 0.91              | 0.92              |
| 5                     | 0.73     | 0.81            | 0.85             | 0.88              | 0.90              |
| 6                     | 0.83     | 0.90            | 0.93             | 0.94              | 0.95              |
| 7                     | 0.73     | 0.81            | 0.85             | 0.88              | 0.90              |
| 8                     | 0.60     | 0.71            | 0.78             | 0.82              | 0.85              |
| 9                     | 0.47     | 0.62            | 0.70             | 0.76              | 0.79              |
| 10                    | 0.67     | 0.81            | 0.85             | 0.88              | 0.90              |
| 11                    | 0.60     | 0.71            | 0.78             | 0.82              | 0.85              |

It may be noted that for regular frames GRI is unity. GRI values reduce as the irregularity increases.

4. Seismic response of regular and irregular frames
All the frames shown in the previous section are analysed using ETABS. In the present study linear dynamic analysis is done using response spectrum method. The design response spectrum given in IS 1893: 2016 is used for the analysis. The seismic reduction factor adopted is 5 and the seismic zone is assumed as Zone V. The peak ground acceleration is 0.36g.

Response quantities such as base shear (\(V_b\)) and overturning moment (\(OTM\)) at base are estimated. In the present study, the following non dimensional parameters are defined:

\[
\text{Base shear ratio (} V_b \text{ ratio)} = \frac{V_b}{\sum_{i=1}^{n} W_i}
\]  

(2)

\[
\text{Overturning Moment ratio (} OTM \text{ ratio)} = \frac{OTM}{\sum_{i=1}^{n} W_i h_i}
\]  

(3)

Here, \(W_i\) is the seismic weight of the \(i^{th}\) storey, \(h_i\) is the height of \(i^{th}\) storey from base and \(n\) is the number of stories. The results of seismic analysis of all frames considered in the present study are shown in figures 2 and 3.
The variation of the non-dimensional parameters $V_B$ Ratio and $OTM$ ratio with $GRI$ is represented using second order polynomials as:

$$V_B \text{ Ratio} = -0.0642 GRI^2 + 0.1352 GRI + 0.0102$$  \hspace{0.5cm} (4)

$$OTM \text{ Ratio} = -0.0479 GRI^2 + 0.0958 GRI + 0.0524$$  \hspace{0.5cm} (5)

These relations permit one to estimate the base shear and overturning moment based on the geometric parameters of the frame and seismic weights.

4.1. Comparison of seismic responses obtained using response spectrum analysis and equivalent static analysis

An attempt is made to compare the response of the frames obtained using ETABS and response obtained through equivalent static analysis as given in IS 1893:2016. For the purpose of comparison, a magnification factor is proposed which is defined as,
Magnification Factor \((MF) = \frac{\text{Response obtained by Spectrum method}}{\text{Response obtained by Equivalent Static method}}\) \hspace{1cm} (6)

4.1.1. Regular building. The variation of magnification factor for \(V_B\) ratio and \(OTM\) ratio with no. of stories are computed and shown in figure 4.

![Figure 4. Magnification factors for regular frames](image)

The magnification factor is found to be linearly increasing with number of stories for both base shear and overturning moment. It is evident that the equivalent static method underestimates the seismic responses of tall regular building frames. Hence, seismic responses obtained using equivalent static method for such frames need to be magnified to get the actual response.

4.1.2. Irregular building. The variation of magnification factor for \(V_B\) ratio and \(OTM\) ratio with \(GRI\) are computed. A straight line is fitted to the points as shown in figures 5 and 6. Mean trend and the upper bound are shown.

![Figure 5. Variation of Magnification Factor - \(V_B\) ratio](image)
It may be observed that, equivalent static method is overestimating the seismic responses of setback building frames. The expressions for mean and upper bound values of magnification factors in terms of \textit{GRI} for both \textit{V}_B ratio and \textit{OTM} ratio are provided in Table 2.

| Parameter  | Expressions for Magnification Factor |
|------------|-------------------------------------|
| \textit{V}_B ratio | Mean value \(1.1304 \textit{GRI}+0.05\) |
|            | Upper bound \(1.1304 \textit{GRI}+0.25\) |
| \textit{OTM} ratio | Mean value \(1.145\textit{GRI}-0.0915\) |
|            | Upper bound \(1.145\textit{GRI}+0.39\) |

Using the above expressions of magnification factors, the actual seismic response of setback frames may be worked out from the response computed using equivalent static method.

5. **Simplified procedure for the analysis of setback frames**

Magnification factors have been derived for both \textit{V}_B ratio and \textit{OTM} ratio. The expressions for mean value and upper bound values of the magnification factor, as a function of \textit{GRI}, form the basis of the simplified procedure for the analysis of Setback frames. The actual seismic response may be obtained by multiplying magnification factor with the seismic response obtained by equivalent static method.

The mean value as well as the upper bound value of the base shear and overturning moment at base can be estimated. In order to demonstrate the applicability of the proposed procedure an 8 storey 3 bay irregular setback building frames is considered for the analysis (figure 7). The storey height and bay width of the building frame are 3.5 m and 4 m respectively. The seismic responses are computed using equivalent static method. The \textit{GRI} value can be computed from the dimensions of the frame.
Figure 7. Building Model

The magnification factors (mean and upper bound values) are worked out from the GRI value. Now, the magnification factor value is multiplied with the seismic response computed using equivalent static method to obtain the actual response.

Table 3. Performance of the proposed method

|                        | Base shear ($V_b$) | Overturning moment at base ($OTM$) |
|------------------------|-------------------|-----------------------------------|
| Equivalent static method | 163.05 kN         | 3279.85 kNm                      |
| Magnification Factor    |                   |                                   |
|                         | Mean              | 0.99                              |
|                         | Upper bound       | 1.19                              |
| Response computed using the proposed method | Mean              | 161.42 kN                         |
|                         | Upper bound       | 194.03 kN                         |
| Actual Response (ETABS) | 150.02 kN         | 2568.28 kNm                       |
| % Error in the computed mean response using equivalent static method | 8.69               | 27.71                             |
| % Error in the computed mean response using the proposed method | 7.60               | 10.45                             |

Table 3 shows the performance of the proposed method in the estimation seismic responses. It is observed that, compared to equivalent static method, the deviation of the estimated seismic force from the actual is low in the proposed method. Also, the estimated mean values of both base shear and overturning moment at the base are found to be conservative.

6. Conclusion

The present study focussed on the seismic performance of RC moment resisting setback frames. Linear dynamic analysis was conducted on 55 frames with varying levels of irregularity. A simple index, viz. Geometric Regularity Index (GRI), which is computed based on the panel area of the frame, is proposed to quantify the irregularity. Seismic response quantities such as base shear and overturning moment are expressed as non-dimensional parameters and their variation with GRI are established. A simple method is proposed to obtain the seismic effect of irregular setback buildings by magnifying the seismic effect computed from equivalent static method. The
magnification factor is expressed in terms of the GRI of the frame. The proposed method is found to match reasonably well with the effect obtained by ETABS through response spectrum method.

In the present study only linear dynamic analysis is considered. The frame is assumed to be in the elastic limit during the entire period of loading. IS method shows conservative results in the estimation of base shear and overturning moment of setback frame structures. The actual seismic response, estimated using response spectrum method, is found to reduce as the irregularity increases for setback frames. This fact is contradicting the normal belief that irregular frames attract more seismic forces. However, since setback building frames has many locations with sharp changes in geometry, nonlinear analysis would be required to get more insights into the energy absorption characteristics and seismic resistance of the structure.

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