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Setback Building, Fundamental Period, Regularity Index, Correction Factor.

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ABSTRACT

The motion of the ground during earthquake do not damage the building by impact or by any external force, rather it impacts the building by creating an internal inertial forces which is due to vibration of building mass. The magnitude of lateral force due to an earthquake depends mainly on inertial mass, ground acceleration and the dynamic characteristics of the building. To characterize the ground motion and structural behaviour, design codes provide a Response spectrum. Response spectrum conveniently describes the peak responses of structure as a function of natural vibration period. Therefore it is necessary to study of natural vibration period of building to understand the seismic response of building. The behaviour of a multi-storey framed building during strong earthquake motions depends on the distribution of mass, stiffness, and strength in both the horizontal and vertical planes of the building. In multi-storeyed framed buildings, damage from earthquake ground motion generally initiates at locations of structural weaknesses present in the lateral load resisting frames. In some cases, these weaknesses may be created by discontinuities in stiffness, strength or mass between adjacent storeys. Such discontinuities between storeys are often associated with sudden variations in the frame geometry along the height.

INTRODUCTION

The magnitude of lateral force due to an earthquake depends mainly on inertial mass, ground acceleration and the dynamic characteristics of the building. To characterize the ground motion and structural behaviour, design codes provide a Response spectrum. Response spectrum conveniently describes the peak responses of structure as a function of natural vibration period, damping ratio and type of founding soil. The determination of the fundamental period of structures is essential to earthquake design and assessment.

Seismic analysis of most structures is carried out using Linear Static (Equivalent Static) and Linear Dynamic (Response Spectrum) methods. Lateral forces calculated as per Equivalent Static Method depends on structural mass and fundamental period of structure. The empirical equations of the fundamental period of buildings given in the design codes are function of building height and base dimension of the buildings. Theoretically Response Spectrum Method uses modal analysis to calculate the natural periods of the building to compute the design base shear. However, some of the international codes (such as IS 1893:2002 and ASCE 7:2010) recommend to scale up the base shear (and other response quantities) corresponding to the fundamental period as per the code specified empirical formula, so as to improve this base shear (or any other response quantity) for Response Spectrum Analysis to make it equal to that of Equivalent Static Analysis. Therefore, estimation of fundamental period using the code empirical formula is in evitable for seismic design of buildings.
Setback in buildings introduces staggered abrupt reductions in floor area along the height of the building. Figs 1.1 to 1.2 show typical examples of setback buildings. This building form is becoming increasingly popular in modern multi-storey building construction mainly because of its functional and aesthetic architecture. In particular, such a setback form provides for adequate day light and ventilation for the lower storey in an urban locality with closely spaced tall buildings.

REVIEW LITERATURE

The literature review is conducted in two major areas. These are: (i) Response of setback buildings under seismic loading, effect of vertical irregularity on fundamental period of building and the quantification of setback and (ii) the recommendations proposed by seismic design codes on setback buildings. The first part of this chapter is devoted to a review of published literature related to response of irregular buildings under seismic loading. The response quantities include ductility demand, inter-story drift, lateral displacement, building frequencies and mode shapes. The second half of this chapter is devoted to a review of design code perspective on the estimation of fundamental period of setback building. This part describes different empirical formulas used in different design codes for the estimation of fundamental period, and the description and quantification of irregular buildings.

Experiment on Setback Building

The seismic response of vertically irregular building frames, which has been the subject of numerous research papers, started getting attention in the late 1970s. Vertical irregularities are characterized by vertical discontinuities in the geometry, distribution of mass, stiffness and strength. Setback buildings are a subset of vertically irregular buildings where there are discontinuities with respect to geometry. However, geometric irregularity also introduces discontinuity in the distribution of mass, stiffness and strength along the vertical direction. Majority of the studies on setback buildings have focused on the elastic response. Following is a brief review of the work that has been done on the seismic response of setback structures.

Humaret. al. (2014) studied the dynamic behavior of multi-storey steel rigid-frame buildings with setback towers. The effects of setbacks upon the building frequencies and mode shapes were examined. Then the effects of setbacks on seismic response are investigated by analysing the response of a series of setback building frame models to the El Centro ground motion. Finally, the computed responses to the El Centro earthquake are compared with some code provisions dealing with the seismic design of setback buildings. The conclusions derived from the study include the following: The higher modes of vibration of a setback building can make a very substantial contribution to its total seismic response; this contribution increases with the slenderness of the tower. Some of the important response parameters for the tower portion of a setback building are substantially larger than for a related uniform building. For very slender towers, the transition region between the tower and the base may be subjected to very large storey shears.

Arandaet. al. (2014) studied the ductility demands of RC Frames irregular in height. The study focuses in inelastic behavior of RC Frames irregular in height when subjected to earthquake motion. For the numerical analysis static methods with different ductility factors were used. Two RC buildings of 30 m overall height was studied. One is the regular building with three bays of 5m each in both the horizontal direction. And the other one is irregular building with a tower of 5m bay width in both horizontal directions starting at mid height of the building and located centrally. It was concluded that for both the models the ductility demand in the exterior beams are larger than in the interior beam. Also the ductility demand is more in the interior columns of irregular frame as compared to the exterior ones as shown in Fig.2.2. It is observed that ductility demands for setback structures is higher than that for the regular ones and this increase is more pronounced in the tower portions

Moehleet. al. (2013) carried out an experimental and analytical study for the response of strong base motions of reinforced concrete structures having irregular vertical configurations. For the purpose of study two small scales multistory reinforced concrete test structure was used. First test structure was named as FFW and it was a nine storey three bay frame with nine storey prismatic wall. The second test structure was identical to FFW except that the prismatic wall extended only up to the first floor level, this structure was named as FSW. Thus the test structures FFW and FSW represent the buildings having regular and irregular distributions of stiffness and strength in vertical planes. The response of these test structures were examined using four different analysis methods, those are: 1) Inelastic dynamic response history analysis, 2) Inelastic static analysis, 3) Elastic modal spectral analysis, and 4) Elastic static analysis. The study concluded that the dynamic analysis methods provides an indication of the maximum displacement response whereas the static method alone is not capable of indicating displacement amplitudes for a given seismic events. Inelastic analysis methods seem to be advantageous over elastic methods in recognizing the severity of the discontinuity in the structure with discontinues wall. They concluded that the main advantage of dynamic 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 and dynamic methods are superior to the elastic methods in interpreting the structural discontinuities.

Material Used

M-20 grade of concrete and Fe-415 grade of reinforcing steel are used for all the frame models used in this study. Elastic material properties of these materials are taken as per Indian Standard IS 456 (2000). The short-term modulus of elasticity (Ec) of concrete is
taken as:

$$\mathbf{E_e = 5000\sqrt{f_{ck}}\,MPa} \qquad \mathbf{(3.1)}$$

Where f_{ck} = characteristic compressive strength of concrete cube in MPa at 28-day(20 MPa in this case). For the steel rebar, yield stress (fy) and modulus of elasticity (Es) is taken as per IS 456 (2000).

Structural Elements

Beams and columns are modelled by 2D frame elements. The beam-column joints are modelled by giving end-offsets to the frame elements, to obtain the bending moments and forces at the beam and column faces. The beam-column joints are assumed to be rigid (Fig. 1). The column end at foundation was considered as fixed for all the models in this study.

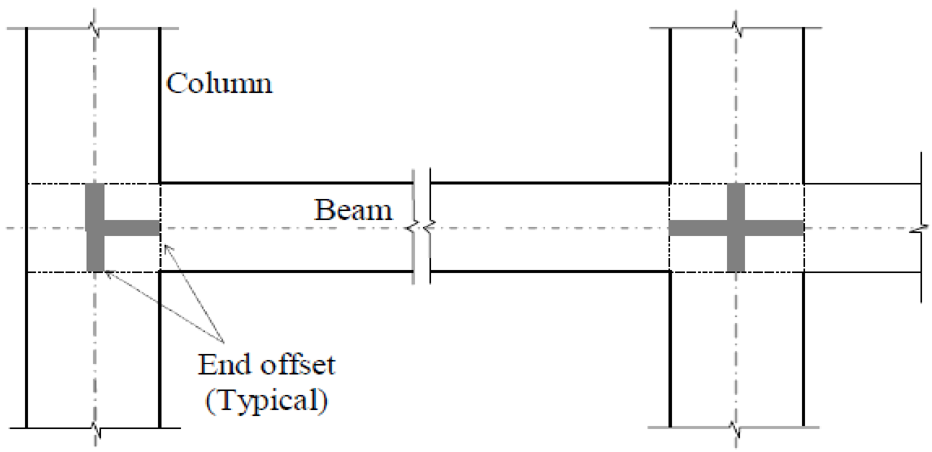

Fig. 1: Use of end of fsets at beam- column joint

The structural effect of slabs due to their in-plane stiffness is taken into account by assigning 'diaphragm' action at each floor level. The mass/weight contribution of slab is modelled separately on the supporting beams.

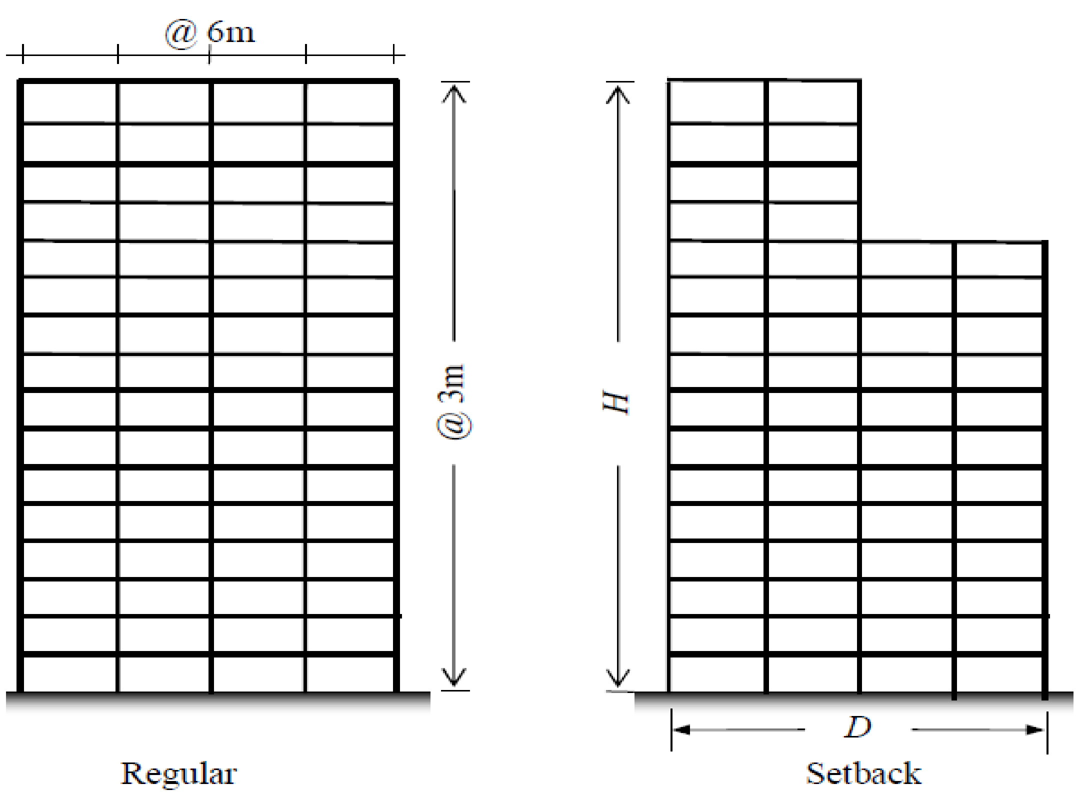

Fig. 2: Typical structural models used in the present study

Building Geometry

The study is based on three dimensional RC building with varying heights and widths. Different building geometries were taken for the study. These building geometries represent varying degree of irregularity or amount of setback. Three different bay widths, i.e. 5m, 6m and 7m (in both the horizontal direction) with a uniform three number of bays at base were considered for this study. It should be noted that bay width of 4m – 7m is the usual case, especially in Indian and European practice. Similarly, five different height categories were considered for the study, ranging from 6 to 30 storeys, with a uniform storey height of 3m. Altogether 90 building frames with different amount of setback irregularities due to the reduction in width and height were selected. The building geometries considered in the present study are taken from literature (Karavasisiset. al., 2008). The regular frame, without any setback, is also studied shown in Fig. 2.

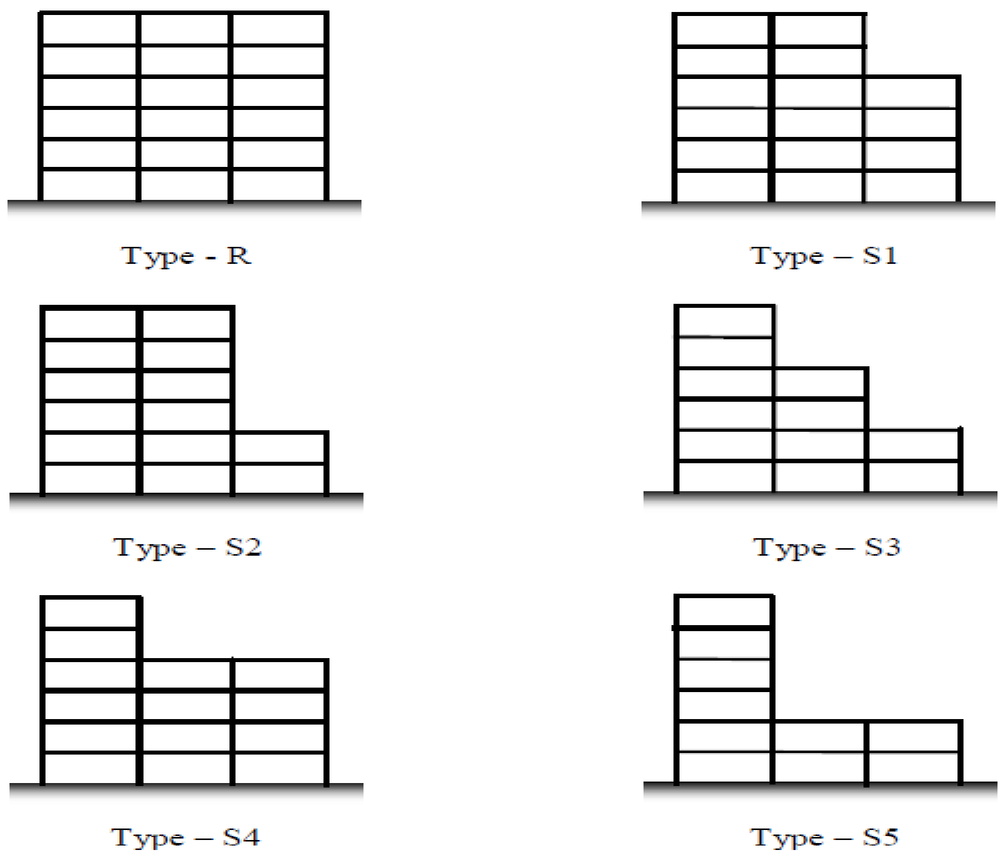

Fig 3: Typical building elevations for six-storey building variants (R, S1 to S5)

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The exact nomenclature of the buildings considered are expressed in the form of S-X-Y, where S represents the type of irregularity (i.e., S1 to S5 or R). X represents the number of storeys and Y represents the bay width in both the horizontal direction. For example S3-18-6 represents the building with S3 type of irregularity, having 18 numbers of stories and bay width of 6m in both the horizontal direction. The slab thickness is considered to be 120mm for all the buildings, Infill walls in the exterior faces of all the buildings are assumed as of 230mm thickness and of 120mm thickness for all the inner infill walls. The parapet wall is assumed to be of 230 mm thickness and of 1000mm height for all the selected buildings. There are altogether six different building geometries, one regular and five irregular, for each height category are considered in the present study. Fig .3 presents the elevation of all six different geometries of a typical six storey building. The buildings are three dimensional, with the irregularity in the direction of setback, in the other horizontal direction the building is just repeating its geometric configuration. Setback frames are named as S1, S2, S3, S4 and S5 depending on the percentage reduction of floor area and height as shown in the Fig. 3.

The regular frame is named as R. The exact nomenclature of the buildings considered are expressed in the form of S-X-Y, where S represents the type of irregularity (i.e., S1 to S5 or R). X represents the number of storeys and Y represents the bay width in both the horizontal direction. For example S3-18-6 represents the building with S3 type of irregularity, having 18 numbers of stories and bay width of 6m in both the horizontal direction. For all the other setback buildings the reduction in height and reduction of width will be consistent with reductions as explained in Fig. 3. For example a S3-18-5 will have plan dimension of3 bay by 3 bay at the base and will continue up to 6th floor. Plan dimension will reduce to 2 bay by 2 bay from 7th to 12th floor, and it will further reduce to 1 bay by 1 bay from 13th floor to 18th floor. The setbacks are considered in one horizontal direction only; the building is made three dimensional by repeating these bays in other horizontal direction. The frames are designed with M-20 grade of concrete and Fe-415 grade of reinforcing steel as per prevailing Indian Standards. Gravity (dead and imposed) load and seismic load corresponding to seismic zone II of IS 1893:2002 are considered for the design. The cross sectional dimensions of beams and columns are taken as shown in Table 1. The slab thickness is considered to be 120mm for all the buildings, Infill walls in the exterior faces of all the buildings are assumed as of 230mm thickness and of 120mm thickness for all the inner infill walls. The parapet wall is assumed to be of 230 mm thickness and of 1000mm height for all the selected buildings.

Table 1: Dimensions of beams and columns for different buildings

Building Type according to number to stories	Column dimension	Beam dimension
Six-storey building	400 mm × 400 mm	300 mm × 450 mm
Twelve-storey building	600 mm × 600 mm	450 mm × 600 mm
Eighteen storey building	800 mm × 800 mm	450 mm × 600 mm
Twenty four-storey building	1000 mm × 1000 mm	450 mm × 750 mm
Thirty-storey building	1200 mm × 1200 mm	600 mm × 750 mm

The structures are modelled by using computer software SAP-2000 (v12) as explained in Section 3.2. Modal analyses were performed to check if the selected frames represent realistic building models. It is found that the selected buildings cover a wide fundamental period range of 0.95s – 3.78s. It may be noted that the fundamental period versus overall height variation of all the selected frames are consistent with the empirical relationships presented by Goel and Chopra (1997) as shown in Fig. 4. This shows that the models selected for this study can be interpreted as being representative of general moment resisting RC frame behaviour for six to thirty-storey buildings, as established by Goel and Chopra (1997).

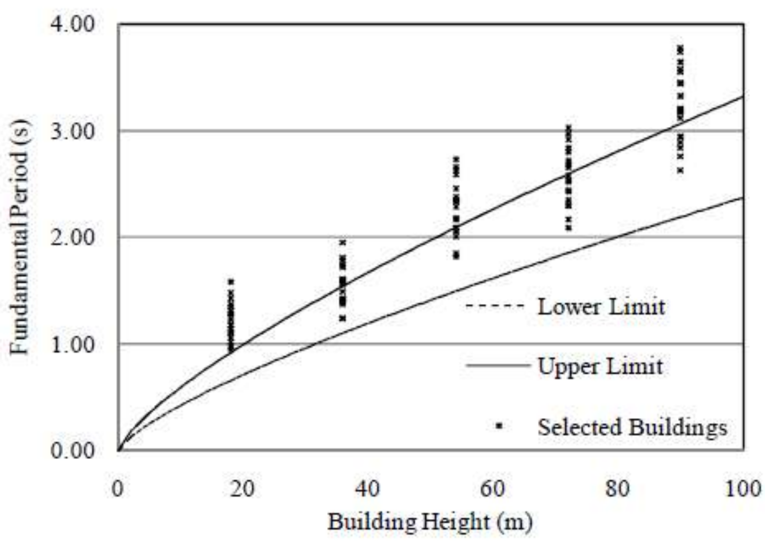

Fig. 4: Fundamental period versus overall height variation of all the selected frames

EXPERIMENT ANALYSIS

When free vibration is under consideration, the structure is not subjected to any external excitation (force or support motion) and its motion is governed only by the initial conditions. There are occasionally circumstances for which it is necessary to determine the motion of the structure under conditions of free vibration. However, the analysis of the structure in free motion provides the most important dynamic properties of the structure which are the natural frequencies and the corresponding modal shapes.

By considering the fact that the damping levels are usually very small in structural systems, the equation of free vibration can be written as:

$$M\ddot{v} + Kv = 0 \qquad (3.2)$$

Looking for a solution in the form of v1q(t)□ ,i =1, 2,....N, where the dependence on time and that on space variables can be separated. Substituting for v, the equation of motion changes to the following form:

$$M\{\phi\}\ddot{q}(t) + K\{\phi\}q(t) = 0 \qquad (3.3)$$

This is a set of N simultaneous equations of the type

$$\sum_{j=1}^{N} m_{ij}\phi_j\ddot{q}(t) + \sum_{j=1}^{N} k_{ij}\phi_j q(t) = 0; i = 1,2,\ldots, N \qquad (3.4)$$

Where the separation of variables leads to:

$$-\frac{\ddot{q}(t)}{q(t)} = \frac{\sum_{j=1}^{N} k_{ij}\phi_j}{\sum_{j=1}^{N} m_{ij}\phi_j}; i = 1,2,\ldots N \qquad (3.5)$$

As the terms on either side of this equation is independent of each other, this quantity can hold good only when each of these terms are equal to a positive constant, say ω^2 . Thus we have,

$$\ddot{q}(t) + \omega^2 q(t) = 0 \qquad (3.6)$$

$$\sum_{j=1}^{N}\left(k_{ij} - \omega^2 m_{ij}\right)\phi_j = 0; i = 1,2,\ldots N \qquad (3.7)$$

The solution of Eq. 3.6 is q(□t)sin(□t - α)□ a harmonic of frequency □. Hence the motion of all coordinates is harmonic with same frequency and same phase difference α. The above equation is a set of N simultaneous linear homogenous equations in unknowns of □ .The problem of determining constant □(□2)□ for which the Eq. 3.7 has a non-trivial solution is known as the characteristic value or Eigen value problem. The Eigen value problem may be rewritten, in matrix notations as,

$$\left(K - \omega^2 M\right)\{\phi\} = 0 \qquad (3.8)$$

A non-trivial solution for the Eq. 3.8 is feasible when only the determinant of the coefficient matrix vanishes, i.e.,

$$\left|K - \omega^2 M\right| = 0 \qquad (3.9)$$

The expansion of the determinant in Eq. 3.9 yields an algebraic equation of N^{th} order in $\omega^2$2 , which is known as the characteristic equation. The roots of characteristic equation are known as the Eigen values and the positive square roots of these Eigen values are known as the natural frequencies (ω_1) □ of the MDOF system. It is only at these N frequencies that the system admits synchronous motion at all coordinates. For stable structural systems with symmetric and positive stiffness and mass matrices the Eigen values will always be real and positive. For each Eigen values the resulting synchronous motion has a distinct shape and is known as natural/normal mode shape or eigen vector. The normal modes are as much a characteristic of the system as the Eigen values are. They depend on the inertia and stiffness, as reflected by the coefficients m_{ij} and k_{ij}. These shapes correspond to those structural configurations, in which the inertia forces imposed on the structure due to synchronous harmonic vibrations are exactly balanced by the elastic restoring forces within the structural system. These eigen vectors are determined as the non-trivial solution of Eq. 3.8.

CONCLUSIONS

Fundamental period of all the selected building models were estimated as per modal analysis, Rayleigh method and empirical equations given in the design codes. The results were critically analysed and presented in this chapter. The aim of the analyses and discussions were to identify a parameter that describes the irregularity of a setback building and arrive at an improved empirical equation to estimate the fundamental period of setback buildings with confidence. However, this study shows that it is difficult to quantify the irregularity in a setback building with any single parameter. This study indicates that there is very poor correlation between fundamental periods of three dimensional buildings with any of the parameters used to define the setback irregularity by the previous researchers or design codes. However, it requires further investigation to arrive at single or multiple parameters to accurately define the irregularity in a three dimensional setback buildings. Based on the work presented in this thesis following point-wise conclusions can be drawn:

Although this is not supported theoretically this approach is found to be most conservative among other code equations.

- It is found that the fundamental period in a framed building is not a function of building height only. This study shows that buildings with same overall height may have different fundamental periods with a considerable variation which is not addressed in the code empirical equations.
- This study indicates that there is very poor correlation between fundamental periods of three dimensional buildings with any of the parameters used to define the setback irregularity by the previous researchers or design codes.

SCOPE FOR FUTURE STUDY

- ➢ This study could not conclude on the appropriate parameter defining their regularity in three-dimensional multi-storeyed setback buildings. There is a scope to investigate different parameters either geometrical or structural or combination of both to define the setback irregularity.
- ➢ The present study is limited to reinforced concrete (RC) multi-storeyed building frames with setbacks only in one direction. There is a future scope of study on three dimensional building models having setbacks in both of the horizontal orthogonal directions.

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