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Fundamental time period of RC Setback Buildings

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Abstract

The buildings with the presence of setback irregularity are now being increasingly used in the urban areas. The present work proposes an irregularity index for quantifying the setback irregularity based on the dynamic characteristics of the buildings. This paper also proposes a modified equation for the fundamental period of vibration, for building frames with setback irregularity. Furthermore, the equations for estimating the maximum inter storey drift ratio (I_r) and maximum displacement ductility (μ_{max}) are also proposed. These equations are proposed on basis of the regression analysis conducted on the seismic response databank of 305 building models with different types of setback irregularity for each height category. The proposed equations are represented as a function of the irregularity index, and are validated for 2D and 3D building models with setback irregularity.

***Keywords**:* Setback irregularity; Vertical geometric irregularity; Fundamental period of vibration; irregular buildings.

1. Introduction

The setback irregularity is one of the most common types of irregularity in the modern buildings. The functional and aesthetic requirements are the main reasons for preference of these structures. These buildings are very useful in urban areas, where the buildings are closely spaced. In such areas, these buildings provide the adequate sunlight and ventilation for the bottom stories, in addition; it approves with the building bye law restrictions of ‘Floor area ratio’ as per building code of India.

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The presence of a setback in the building results in abrupt reductions of the floor area, which in turn results in change of mass and stiffness along the building height. The past earthquake records indicate that, the buildings with setbacks experience greater damage as compared to the regular buildings. This poor seismic behaviour may be attributed to the inadequacy of current codes, based on which these buildings were designed. The change of mass and stiffness of the stepped building along its height results in the difference in their dynamic characteristics, as compared to the regular buildings and this aspect is ignored by design codes. This may be due to the scarcity of literature works available regarding this aspect.

The procedures prescribed by the design codes like EC 8 2004 and FEMA 356 for estimating the deformation demands are formulated considering the single degree of freedom systems. So, the prescribed procedures are unsuitable for design of real structures. Also, the current seismic codes imply restrictions on method of analysis used for irregular structures, and prescribe the dynamic analysis for seismic evaluation of such structures. In addition, a 20 % reduction on value of behaviour factor is prescribed for such structures. The maximum displacements and interstorey drifts are calculated by equal displacement rule as shown in Eq. 1

$$\mu = q \tag{1}$$

Where, μ = displacement ductility

q = Behaviour factor

The displacements and inter-storey drift ratio are calculated by the following expressions

$$D = D^{'} \times q \tag{2}$$

$$d = d^{'} \times q \tag{3}$$

Where D = maximum displacement

D’ = yield value of maximum displacement under reduced design lateral forces

d = maximum inter-storey drift

d’ = yield value of maximum inter-storey drift under reduced design lateral forces

The above rules as stated in Equations 1-3, assume uniform profile of D’ and d’ during the seismic excitation. This is contradictory to the observations of previous research works (Athanassioudu 2008; Karavasilis *et al.* 2008a; Varadharajan *et al.* 2012a; Varadharajan *et al.*, 2012b; Varadharajan *et al.* 2013a; Varadharajan 2013b Varadharajan *et al.* 2014).

In the present study, some of the important aspects regarding the setback irregularity are discussed. This paper, proposes an approach to quantify the mass and stiffness changes due to the setback in the form of a parameter called as the 'Irregularity index'. The proposed approach is found to be more effective as compared to the existing measures in quantifying the setback irregularity. Furthermore, the empirical equations suggested by the seismic design codes for evaluation of the fundamental period of vibration, are heavily depended on the building height. Therefore, a modified equation, based on the results of time history analysis of 305 different building frames is proposed to make it applicable to the buildings with setback irregularity. Furthermore, the empirical equations to estimate the deformation demands like maximum interstorey drift ratio and displacement ductility are also proposed. The proposed equations are validated for 2D and 3D building models.

2. Literature review

The research works regarding setback irregularity started in early 1970s with Humar and Wright, who conducted analytical studies on buildings with a setback, and observed higher drift demand at the upper portion of the setback. ***Moelhe (1984)*** conducted both experimental and analytical study on R.C. frames with setbacks. Based on results of his analytical studies, it was observed that damage concentration was greater near vicinity of the setback ***Aranda (1984)*** also observed greater ductility demand at the tower portion of the setback, as compared to the base portion. However, ***Wood (1992)*** observed similar seismic behavior of building frames, with and without setbacks.

Wong and Tso (1994) used elastic response spectrum analysis to determine the response of structures with setback irregularity and observed higher modal masses in setback buildings, resulting in different seismic load distributions as compared to the regular structures. ***Pinto and Costa (1995)***, based on their study, concluded structures, with and without setbacks exhibited similar seismic behavior, and the same result was observed by **Mazzolini and pilso (1996)** from the analytical study on setback structures. ***Duan and Chandler (1995)***, used static and modal spectral analysis to conduct analytical studies on building systems with setback irregularity. Results of study suggested the inefficiency of both analysis procedures in preventing the damage concentration in structural members near the level of setbacks.

Kappos and Scott (1998), compared static and dynamic analysis methods for evaluating the seismic response of R.C. building frames with the setbacks. On comparison, the difference in results of both methods was observed. The authors ignored the irregularities in mass, strength and stiffness in their study.

Khoure et al. (2005) performed seismic analysis and design of a nine storey steel frame with the setbacks as per provisions of Israeli steel code SI 1225(1998). Results of analytical study indicated higher torsion in the tower portion of the setback.

Trembley and poncet (2005) conducted analytical study on building frames with vertical mass and setback irregularity. These frames were designed in accordance with NBCC code provisions. The static and dynamic analysis was used to evaluate the seismic response of these buildings. Results of analytical study confirmed the inefficiency of both static and dynamic analysis procedures in predicting the seismic response of irregular structures.

Basu and Gopalakrishnan (2007) proposed an alternative method for evaluation of seismic response of building frames with horizontal setbacks. The proposed method was assessed by applying it on four building models. From results of analytical study it was found that the proposed procedure yielded accurate results of natural frequency for building systems in which the scattering of centre of mass is less than 50%. However, for other building models the proposed procedure yielded inaccurate results.

Karavallis et al. (2008) conducted parametric study on the multistorey steel frames with setback irregularity. These frames were designed in accordance with EC 8 seismic code provisions. The time history analysis method was employed to create a seismic response databank consisting of parameters like number of stories, irregularity index, and beam to column strength ratio. Based on the results of the analytical study four different performance levels were identified namely a) occurrence of first plastic hinge b) Maximum inter-storey drift ratio (IDR_{max}) equal to 1.8 % ; c) IDR_{max} equal to 3.2% d) IDR_{max} equal to 4.0%. Further, results of analytical study suggested that the inter-storey drift (IDR) ratio increased with increase in storey height and tower portion of setback experienced maximum deformation as compared to the base portion.

Athanassiadou (2008) determined the seismic response and capacity of RC building frames with setbacks. Three types of building frames were modelled. Two of these three frames contained two to four setbacks in upper floors and the third frame contained setback along its full height from top to bottom. These frames were designed as DCH and DCM frames as per low ductility class of Euro code 2008.For analytical study these frames were subjected to an ensemble of 30 different ground motions. From the results of analytical study, it was observed that the frames designed as per EC 8 provisions exhibited adequate seismic performance.

Kappos and Stefanidou (2010) proposed a new deformation based method for evaluation of inelastic seismic response of the 3d R.C. building models with setback irregularity. The proposed method uses the advance analysis technique. The authors have used partial inelastic model in their methodology. The main aim of the proposed method was to reduce the design forces thereby economize the design process. The 3D irregular setback building models were designed as per EC 8 provisions and by the proposed method. On comparison of the results, it was found that the proposed method yielded accurate results as compared to the EC 8 code especially with respect to the detailing of transverse reinforcement in the members.

Sehgal et al. (2011) conducted analytical studies on R.C. frames with a setback on one side and on both sides. The authors also, studied the variation of setback length on seismic response. Based on the analytical study, the authors found higher torsional response near setbacks, and increase in setback length is found to aggravate the response.

Georgoussis (2011) investigated the effect of irregular variation of stiffness in the setback structures. For investigating the setback structures, a new indirect method based on the modal stiffness was suggested. The proposed procedure was applied to the setback building models and the results of the proposed procedure were compared with that of three-dimensional analysis. Results of both methods were found to be comparable and accuracy of the proposed procedure was verified.

Varadharajan *et al.* (2012a) has conducted a detailed review of different structural irregularities in the building. The authors observed a drastic change in seismic response near the vicinity of irregularities especially in case of tall structures. These results were further confirmed by **Vardaharajan *et al.* 2012 (b).**

Varadharajan 2013 (a) has determined the seismic response of short period structures with setback irregularity. From the analysis results the short period structures exhibited a strong response as compared to long period structures **(Varadharajan *et al.* 2013b)**. This shows the criticality of short period structures.

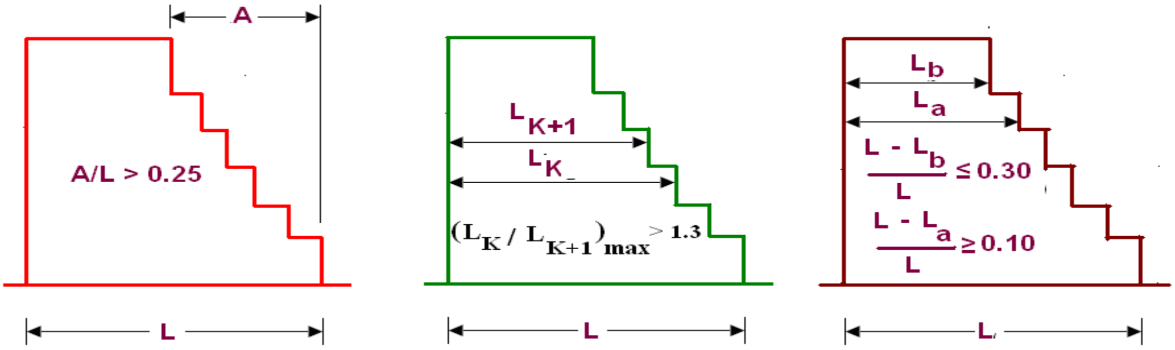
Varadharajan *et al.* (2014) determined the seismic response of setback frames designed as per EC8:2004 and IS 456 provisions. The results of analytical study showed conservativeness of EC 8 provisions in estimation of deformation demands.

3. Code provisions for setback irregularity

The setback irregularity is identified by several design codes as indicated in Table 1. As per IS 1893:2002, a building is said to be irregular when the horizontal dimension of the building frame in any storey is greater than 150 % of the adjacent storey. As per other seismic design codes, the above prescribed limit is 130 %. The setback limit as per different codes is shown in Table 1, and the pictorial representation of setback limit as per IS 1893:2002 and ASCE 7:05 is shown in Figure 1. To define the vertical setback irregularity, the codes consider the ratio of horizontal dimension of one storey to that of the adjacent storey but the gradual variation of the setback irregularity is ignored, which results in inaccurate prediction of seismic response of setback structures. The dynamic method of analysis is prescribed by several design codes [ASCE-7.05, UBC 97, EC8 and IS1893:2002], for analysis of such irregular structures.

The fundamental time period of the structure is an important parameter which represents the dynamic response of the structure under seismic excitation but, the seismic design codes specify the same expression of the fundamental time period for both regular and irregular building structures as

$$T = 0.075h^{0.75} \tag{4}$$



(a) (b) (c)

Figure 1: Code limits for vertical setback irregularity a) IS code b) ASCE code c) EC 8 code

As per code proposed equation, the fundamental time period is a function of building height only, and this equation does not account for stepped variations of building frame along the building height. However, in reality, the period decreases with the increase in the vertical setback irregularity. Hence, the Eq. 4 is inadequate in predicting the periods for the building frames with setbacks.

4. Quantification of setback irregularity

As discussed earlier, the limits of setback irregularity as prescribed by different seismic codes, does not account for gradual variation of setbacks along the building height. To address the above issue, the first main aim is to propose a parameter to quantify the setback irregularity. The proposed parameter is then compared with the parameters proposed by Karavasilis *et al.* (2008). The parameters proposed by Karavasilis *et al.* (2008) are represented in Eq. 5, and the definition of terminologies in Eq. 5 are expressed in Figure 2.

$$\phi_s = \frac{1}{n_s - 1}\sum_{1}^{n_b - 1}\frac{L_i}{L_{i+1}} \quad , \ \phi_b = \frac{1}{n_b - 1}\sum_{1}^{n_b - 1}\frac{H_i}{H_{i+1}} \tag{5}$$

Where, n_s represents the number of stories in the building model, and n_b represents the number of bays in the first storey of the building model. L_i and H_i are the width and the height of the ith storey as presented in Figure 2.

TABLE 1: SETBACK LIMITS AND EMPIRICAL EQUATIONS FOR ESTIMATING FUNDAMENTAL TIME PERIOD AS PER DIFFERENT CODES OF PRACTICE

S. No.	**Name of code**	**Year**	**Setback irregularity limit**	**Empirical Equation for T**
1	UBC	1997	Si < 130 %	$C_t h^{0.75}$
2	IS I893	2002	Si < 150 %	$0.09h/\sqrt{d}$
3	EC 8	2004	Si < 130 %	$C_t h^{0.75}$
4	NBCC	2005	Si < 130 %	0.01N
5	ASCE 7:05	2005	Si < 130 %	$T_a = C_t h_n^x$

Where Si – setback irregularity limit, C_t – constant which varies for different codes, h – total height of the building, T – Fundamental period of vibration, N- Number of stories

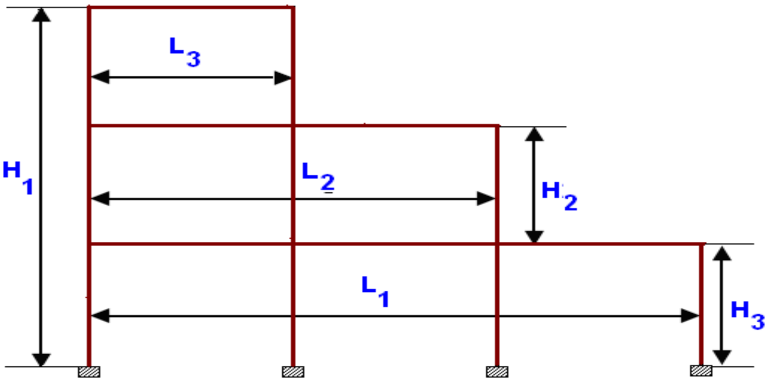


Figure 2: Frame Geometry for definition of irregularity indices proposed by Karavasilis *et al.* (2008).

The second main purpose of the present study is to propose a correction factor for code defined expression of the fundamental period of vibration, to make it suitable for building structures with setback irregularity. To achieve the above aims, 1525 (305*5) building models representing the different degree of the vertical setback irregularity and ground motions were considered for the analytical study (Tables 2 and 3).

The building models considered have the number of bays varying from one to five (in the direction of earthquake) with a bay width of 3 m and 4 m, in the direction perpendicular to the direction of the earthquake. It should be kept in mind that bay width of 4 m-6 m is the general case for RC building frames, in Indian and European codes. Moreover, from the analysis results, it was observed that the number of bays does not affect the response of the building significantly. Five different height categories, ranging from 6 to 18 stories, with a similar storey height of 3m, was considered for the present study. A total of sixty one building geometries is considered for the analytical study. Twenty-one of these are shown in Figure 4a, and rest of them are adopted from Karavallis *et al.* (2008). The geometries considered for the study consist of building models with equal and unequal step heights and widths. The geometrical configurations selected to represent building models with, a) Setbacks at bottom, middle and top storey, b) small to large setbacks at different locations along the height of the building. The geometries are selected such that, they represent the majority of the actual setback structures encountered in practice. Furthermore, the relations between the fundamental period of vibration (T) and the total building height (H) are kept in accordance with the empirical relations proposed by Goel and Chopra (1997), to ensure that the building models considered for the analytical study represent the general moment resisting RC frames. The periods of building models used, and limits proposed by Goel and Chopra (1997) as shown in Figure 3.

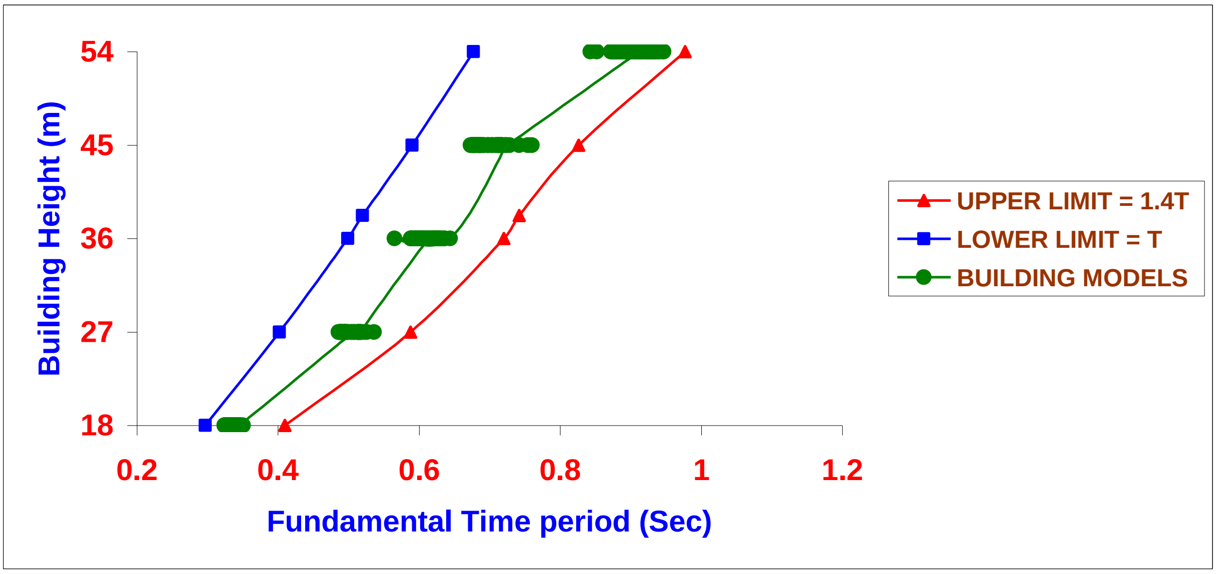


Figure 3: Fundamental Time period of building models used within limits prescribed by Goel and Chopra (1997).

TABLE 2: DETAILS OF BUILDING MODELS USED

S.No	**Model No.**	**Details of Building models**
1	A_{bg}	A indicates 6 storey building model, subscripts b indicates number of bays and subscript g indicates geometry number.
2	B_{bg}	B indicates 9 storey building model, subscripts b indicates number of bays and subscript g indicates geometry number.
3	C_{bg}	C indicates 12 storey building model, subscripts b indicates number of bays and subscript g indicates geometry number.
4	D_{bg}	D indicates 15 storey building model, subscripts b indicates number of bays and subscript g indicates geometry number.
5	E_{bg}	E indicates 18 storey building model, subscripts b indicates number of bays and subscript g indicates geometry number.

TABLE 3: DETAILS OF GROUND MOTIONS USED

Name of Earthquake and Station	**Date**	**M_u**	**D (Km)**	**PGA (m/s^2)**
Kern Country (Taft)	21/07/1952	7.7	43	1.74
San Fernado (Castaic)	09/02/1971	6.6	29	2.63
Imperial Valley (Calexico)	15/10/1979	6.6	15	2.70
Loma Prieta (Gilroy Array #4)	18/10/1989	6.9	16	4.09
Loma Prieta (SF Intern. Airport)	18/10/1989	6.9	64	3.23
Northridge (LA Nfaring Road)	17/01/1994	6.7	24	2.68
Northridge (LA City Terrace)	17/01/1994	6.7	37	3.10
Northridge (LA Wonderland Ave.)	17/01/1994	6.7	23	0.17
Northridge (Leona valley #3)	17/01/1994	6.7	38	0.11
Northridge (LA Chalon Road)	17/01/1994	6.7	24	2.21
Northridge (LA Baldwain Hills)	17/01/1994	6.7	31	1.65

where M_u = magnitude of the earthquake, D = Distance from epicenter, PGA = Peak ground acceleration, T_c = Critical time period of earthquake. For every accelogram , the scale factors were obtained from SEAOC manual. The characteristic period T_c for these ground motions have been calculated by using Riddel and Newmark (1979) algorithm. The study on these building models has been carried out by time history analysis using E-Tabs v 9.0 software.

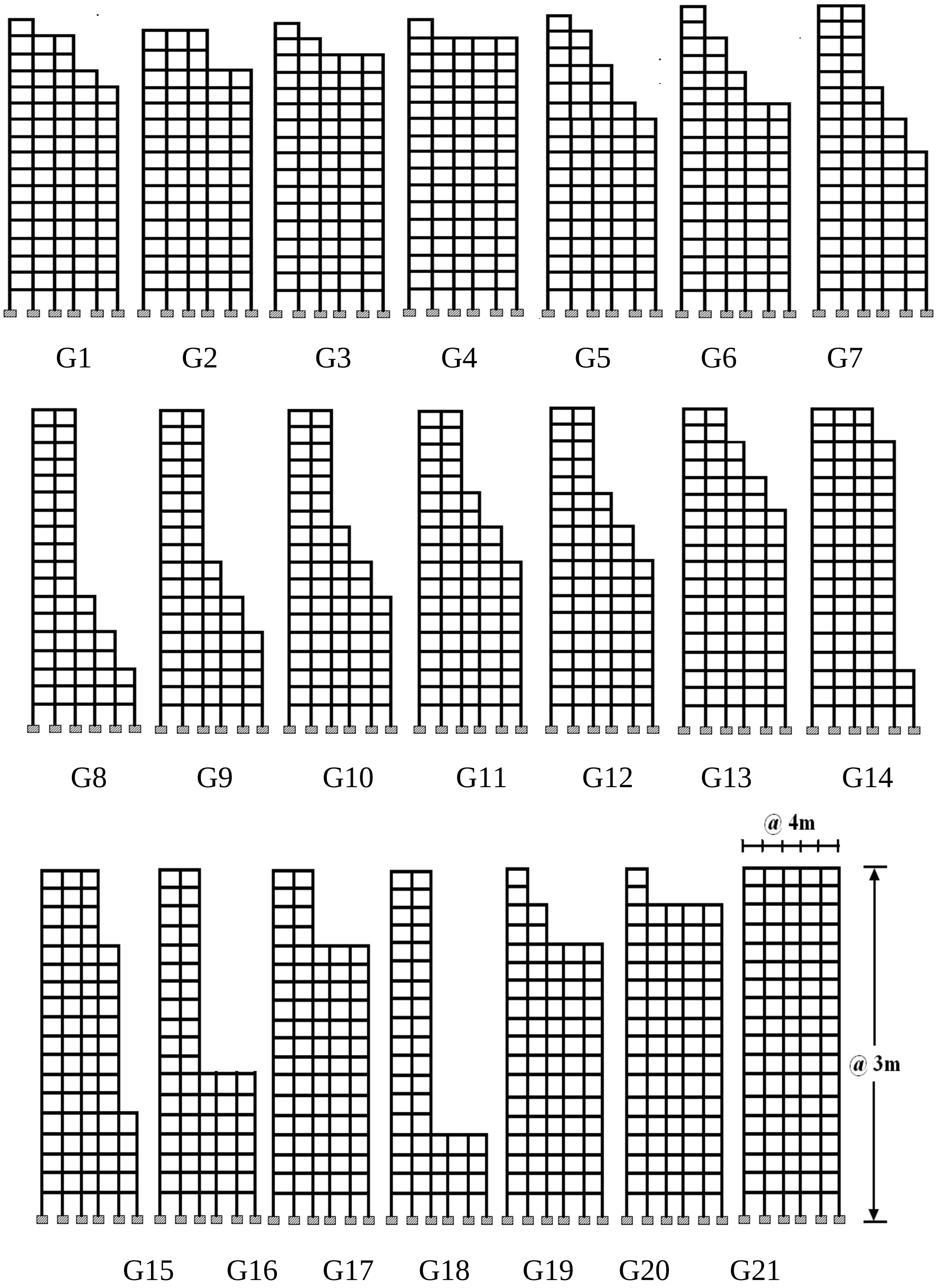


Figure. 4a: Some of the building geometries considered for the analytical study

The selected building models are subjected to an ensemble of 11 ground motions as presented in Table 3. The ground motions data for the present study have been selected from the PEER database.

4.1 Sensitivity Analysis

In quantifying the vertical the dynamic response parameters like natural frequency of the vibration and mass participation factor can be considered, as these parameters effectively represent the change of mass and stiffness due to presence of setback irregularity. Furthermore, these parameters have a dominant effect on the fundamental period of vibration. To determine the parameter that has the most significant impact on the fundamental period of vibration, the sensitivity analysis was carried out. In general, the sensitivity represents the impact of an input parameter on an output parameter. Using sensitivity analysis, the parameter with the most significant effect on the fundamental period of vibration can be determined. To obtain sensitivity, the standard deviation of an input parameter is divided by the standard deviation of the output parameter. The input parameter with the highest sensitivity has the greatest influence on the output parameter. In the present study, the dynamic response parameters like natural frequency of the vibration and participation factor are treated as the input parameters, and the fundamental time period is treated as the output parameter. The results of sensitivity analysis, for all the building frames considered are presented in Figure 4b.

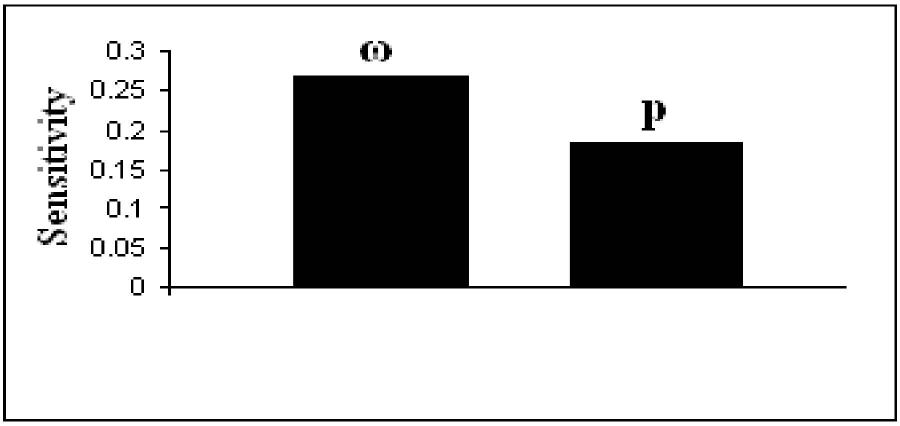


Figure 4b: Results of Sensitivity analysis

It can be seen from Fig. 4b that the fundamental frequency of vibration (ω) has the larger impact on the fundamental period of vibration as compared to the mass participation factor (p). Therefore, based on these results, an irregularity index (η_{ir}) has been proposed to quantify the vertical setback irregularity by authors in their previous research work (Varadharajan *et al.* 2013b) as shown below in Eq. (6).

$$\eta_{ir} = \frac{\omega_i}{\omega_r} \tag{6}$$

where, ω_i and ω_r are the modal combinations of frequency of vibration of the irregular and regular building frames. The approximate values of these two factors can be obtained by eigenvalue analysis using Eq.7 as mentioned below

$$\left[K - \omega^2 M\right] = 0 \tag{7}$$

Where K, M, ω are the Stiffness matrix, Mass matrix and Natural frequency of vibration of the building .The matrix operations to determine the natural frequency of vibration are performed using MatLab v 8.2 software. The higher value of the proposed parameter represents larger floor area reductions and setbacks of greater width and height resembling the tower like shape. The comparison of approaches for quantifying the setback irregularity is presented in Table 4.

From Table 4, it can be seen that the code defined approaches are found to be ineffective in capturing the variation of setback irregularity. For example, B312 and C409 models are completely different in height, number of bays and in geometry still, code defined approaches specify the same value of setback irregularity for these frames. Nevertheless, the seismic responses of the frames with different type of setbacks are dissimilar, due to variation in torsion generated. Furthermore, Figure 6 shows the torsional response in the form of lateral displacement, inter storey drift and torsional moment profiles for building models B309 and B312 respectively. From Figure 5, the difference in torsional response of these models can be clearly seen. However, as earlier stated, the code specifies the same value of setback irregularity index for both these building models. Therefore, the code provisions are inadequate in capturing the setback irregularity.

Karavallis *et al.* (2008) approach performs better than the code defined approach, but it has a major disadvantage of requiring two indices to quantify the setback irregularity. However, the present approach is found to me more effective as compared to other approaches. The building models presented in Table 4, cover a broad range fundamental time periods from 0.76s to 2.65s. The parameters $¢_s$ and $¢_b$, as proposed by Karavasilis *et al.* (2008) vary from 1 to1.4, and from 1 to 2.39 respectively. Furthermore, it can be said that, unlike the proposed index, the other approaches does not consider the non - uniform distribution of mass and the stiffness irregularity.

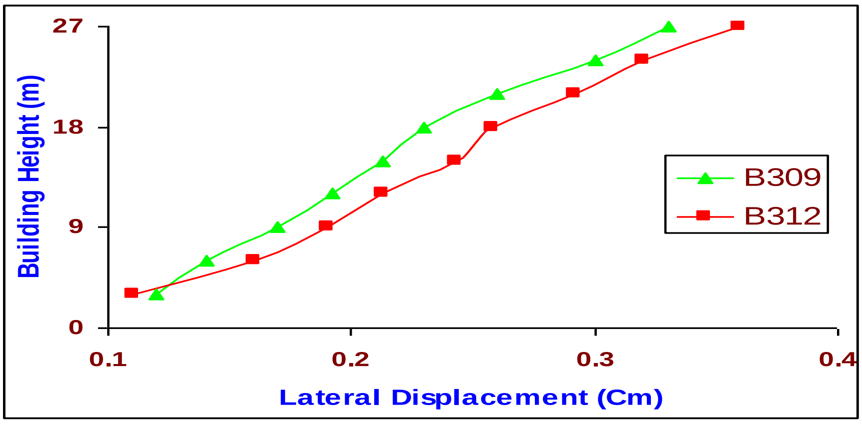
TABLE 4: DIFFERENT IRREGULARITY INDICES FOR DIFFERENT BUILDING MODELS CONSIDERED

Frame ID	**T (Sec)**	**IS 1893:**	**ASCE 7-05**	**¢s**	**¢b**	**Varadharajan *et al.* 2013**
A121	0.976	1	2	1.2	0	1.068925
A214	0.984	0.8	1.33	1.316	6	1.065938
A310	0.967	0.8	1.5	1.390	3	1.06619
A305	0.995	0.8	2.0	1.396	3	1.087688
B303	0.998	0.4	2.0	1.437	6	1.072782
B221	1.03	1	2	1.125	12	1.067747
B312	1.17	0.8	1.5	1.260	6	1.063117
C409	1.21	0.8	1.5	1.189	5	1.065062
C307	1.32	1	2	1.189	7.5	1.085907
C416	1.06	0.4	2.5	1.227	5	1.085685
D309	1.32	1	2	1.148	7.5	1.056788
D401	1.37	0.80	2	1.255	5	1.075403

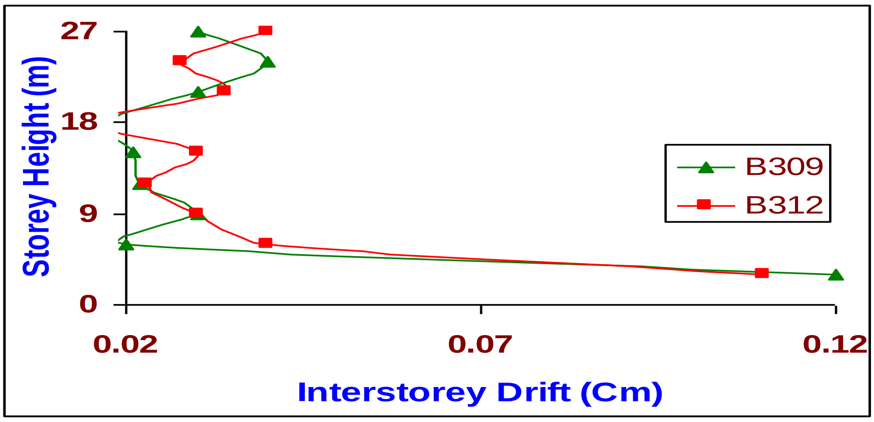
5. Variation of the irregularity index with building properties

The variation of building properties with irregularity index is shown in Figures 6 and 7. From Figure 7, it can be observed that the irregularity index tends to increase gradually with the storey height. The proposed irregularity index assumes a minimum value of 1.21 for the six storey building model (Geometry 7) and assumes the maximum value of 1.43 for eighteen storey building model (Geometry 6). Therefore, it can be said that the value of the irregularity index depends collectively on storey height and the geometry. The variation of irregularity index with the number of bays is presented in Figure 6.

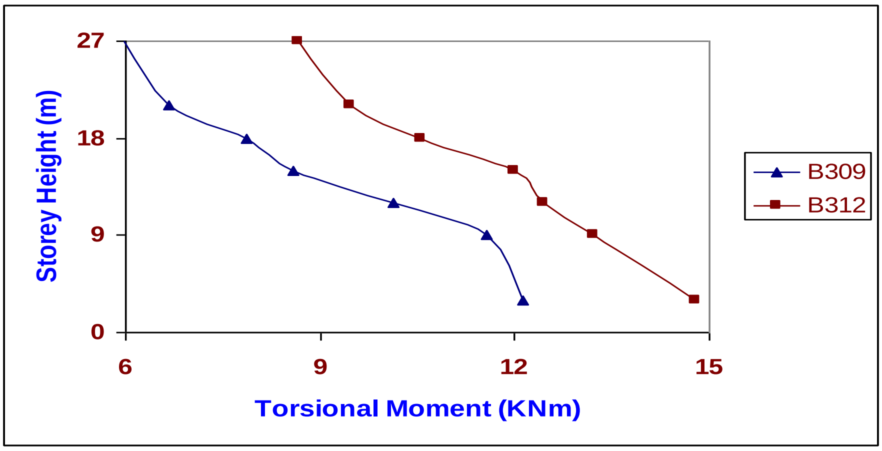
Figure 7 shows that the irregularity index increases with the number of bays but this increase is very marginal. Hence, it can be said that the affect of the setback irregularity is least effected by variation in the number of bays. Moreover, it can be said that the variation of proposed irregularity index with the setback geometry is non-uniform and does not follow any pattern indicating that the setback geometry has the major influence on the irregularity index. Thus, it can be said that the proposed irregularity index effectively captures the variations in the setback geometry.



a) Lateral displacement profile



b) Interstorey Drift profile



c) Torsional Moment profile

Figure. 5: Torsional response of a 9 storey Setback frame

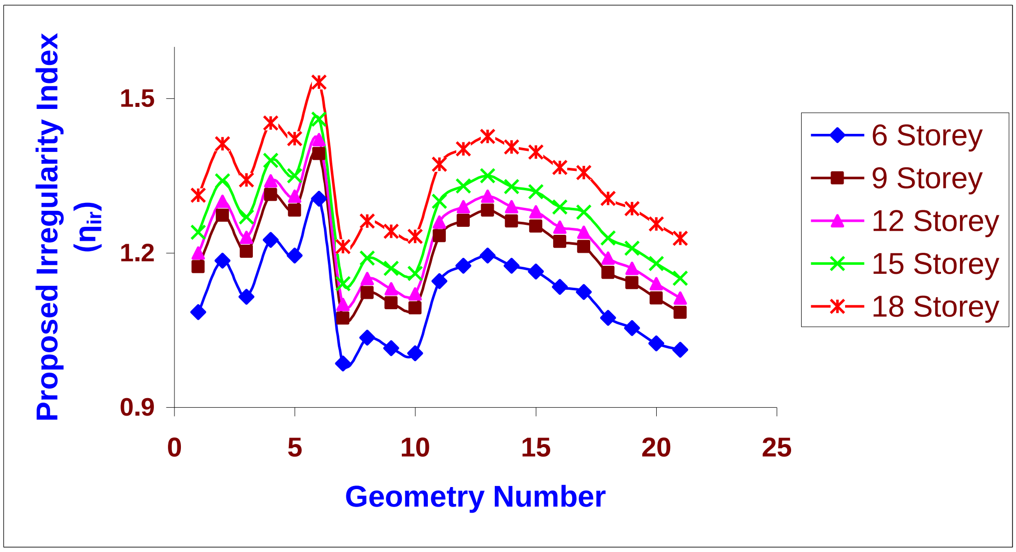


Figure. 6: Variation of irregularity index (η_{ir}) with different geometries and Storey height for an 18 storey irregular building

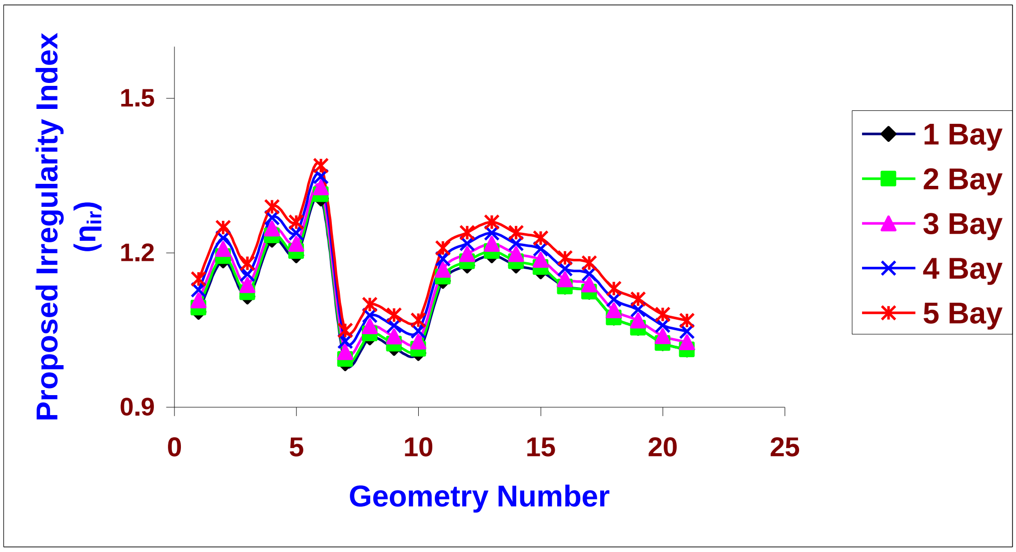


Figure. 7: Variation of irregularity index (η_{ir}) with different geometries and different number of bays for an 18 storey irregular building

6. Estimation of fundamental period of vibration for building frames with vertical setback irregularity

As explained earlier, the design codes prescribe the dynamic analysis for the irregular building. The base shear is obtained corresponding to the value of the fundamental period of vibration as per code specified empirical formulae. Moreover, these formulae are developed considering the buildings to be regular. In these expressions, the fundamental period is a function of the building height only, and the presence of structural irregularity is ignored. In general, the height of the models with vertical setback irregularity shows the variation on both sides of the frame, and the periods obtained will be less at a side with low height, which will result in a higher base shear.

Nevertheless, if the total height of the structure is considered in computing the fundamental period of vibration, an un-conservative value of base shear will be obtained. The fundamental periods of vibration for the majority of the existing building frames with vertical setback irregularity come in the constant velocity region of the response spectrum presented in IS1893:2002 and EC8:2004. This region is very sensitive to variation of spectral acceleration and a minor variation of the fundamental period of vibration will have a huge impact on the base shear obtained. The presence of vertical setback irregularity induces, both mass and stiffness variations in a building frame. These variations in the mass and stiffness will have the substantial effect on the fundamental period of vibration.

The reduction in the mass reduces the fundamental period of vibration, and the stiffness reduction increases it. This variation in the fundamental period of vibration affects the base shear. To obtain the modified time period, the correction factor λ', which is the ratio of T_i / T_r has been obtained for 305 building frames with different geometries, different bays and with different storey height by time history analysis. The correction factor λ' obtained is plotted against the proposed irregularity index in the form of a graph. The relations between these parameters were obtained by using a polynomial fit as shown in Figure 8.

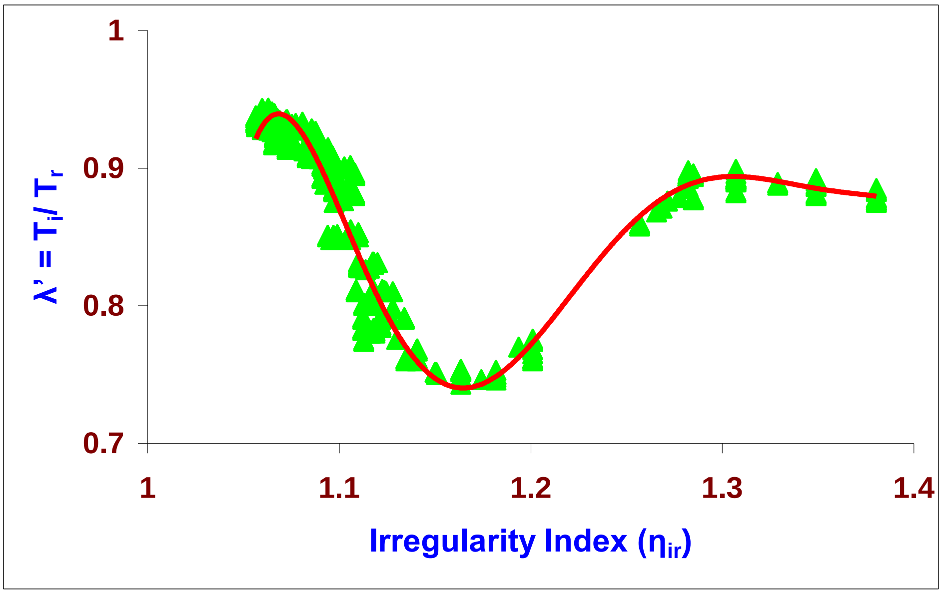


Figure 8: Relationship between irregularity index and $\lambda' = T_i/T_r$

Based on the polynomial fit, the correction factor is proposed as

$$\lambda' = \frac{T_i}{T_r} = 4.4032\eta_{ir}^2 - 10.582\eta_{ir} + 7.2936 \tag{8}$$

And the modified time period can be expressed as

$$T = \lambda' 0.075h^{0.75} \tag{9}$$

Figure 9, shows that the correction, at first decreases with increasing irregularity index, and reaches its minimum value of 0.746, at this point η_{ir} = 1.17, after this point the correction factor increases with increasing irregularity index (η_{ir}) up to a point at which η_{ir} = 1.28, after this point, it finally decreases up to the final point, at which η_{ir} = 1.39. The correction factor varies between 0.746 – 0.94, which generally covers the majority of the setback buildings encountered in practice. Also, the mean of ratio of T_i/T_r for some of the selected geometries from 1 to 5 bays is shown in Table 5. This is done due to difficulty in presenting such a large number of data. Moreover, the variation of correction factor and proposed irregularity index are least effected by number of bays. However, the equations of corrected fundamental period are proposed on basis of all the results (of 305 building models) for better accuracy.

Although, the corrected equation of the fundamental time period is based on results of the large number of setback building models, it is very necessary to check its accuracy. For checking the proposed equation, the correction factors for all the building models considered are computed by both, proposed equation and by dynamic analysis. The comparison is plotted in a form of a graph as shown in Figure 9.

From Figure 9, it can be seen that the results obtained by both methods are in close agreement, and the correlation coefficient between the results of both methods was found to be 0.9866, which validates the accuracy of the proposed equation.

7. Applications of the proposed irregularity index

The presence of setback irregularity induces changes in mass and stiffness, thereby resulting in change of seismic demands of the structure. It is very important to study the effect of setbacks on seismic demands, to formulate the improved design philosophies. Deformation demands are one of the principle forms of seismic demands on basis of which, the performance of the structure is assessed. The seismic demands may be categorized into three types namely global demand, local demand and storey level demand. The global demand is evaluated by computing the displacement pattern with respect to the base shear at the roof of the building. The local demands refer to the inelastic rotations at ends of the structural elements, and the storey demands refer to the inter storey drift value at that particular storey. It is very important to study the effect of setbacks on thee demands. For this purpose, building models shown in Figure 4a are analysed to determine the effect of introduction of the setback on the deformation demands.

TABLE 5 VARIATION OF IRREGULARITY INDEX WITH T_I/T_R MEAN FOR SOME SELECTED GEOMETRIES

G.No	**6 STOREY**		**9 STOREY**		**12 STOREY**		**15 STOREY**		**18 STOREY**	
	η_{ir}	**T_i/T_r Mean**	η_{ir}	**T_i/T_r Mean**	η_{ir}	**T_i/T_r Mean**	η_{ir}	**T_i/T_r Mean**	η_{ir}	**T_i/T_r Mean**
1	1.0817	1.233	1.0947	1.246	1.109	1.146	1.1243	0.96	1.1399	0.896
5	1.0659	1.143	1.246	0.892	1.2603	0.931	1.2756	0.92	1.2912	0.864
9	1.0661	1.16	1.156	0.892	1.1703	0.882	1.1856	0.914	1.2012	0.882
13	1.0876	1.233	1.12	0.995	1.1223	1.04	1.1302	0.942	1.1458	0.889
17	1.0727	1.226	1.246	0.907	1.2603	0.894	1.2756	0.887	1.2912	0.903
21	1.0856	1.221	1.239	0.875	1.2533	0.894	1.2686	0.885	1.2842	0.91
25	1.0895	1.216	1.2225	0.898	1.2368	0.896	1.2521	0.861	1.2677	0.903
29	1.091	1.247	1.2175	0.902	1.2318	0.891	1.2471	0.882	1.2627	0.909
33	1.0973	1.233	1.2485	0.883	1.2628	0.858	1.2777	0.89	1.2933	0.908
37	1.1082	1.157	1.2345	0.92	1.236	0.876	1.2509	0.863	1.2658	0.933
41	1.108	1.15	1.2394	0.886	1.2408	0.886	1.2557	0.88	1.2706	0.933
45	1.095	1.267	1.2134	0.917	1.2148	0.913	1.2299	0.902	1.2452	0.937
49	1.0833	1.209	1.2684	0.885	1.2698	0.93	1.2849	0.9	1.3002	0.919
53	1.0949	1.21	1.2104	0.894	1.2118	0.93	1.2269	0.91	1.2422	0.933
57	1.0918	1.226	1.135	0.967	1.142	0.909	1.1147	1.051	1.125	0.97
61	1.0945	1.226	1.2274	0.913	1.2288	0.909	1.2439	0.907	1.2592	0.901

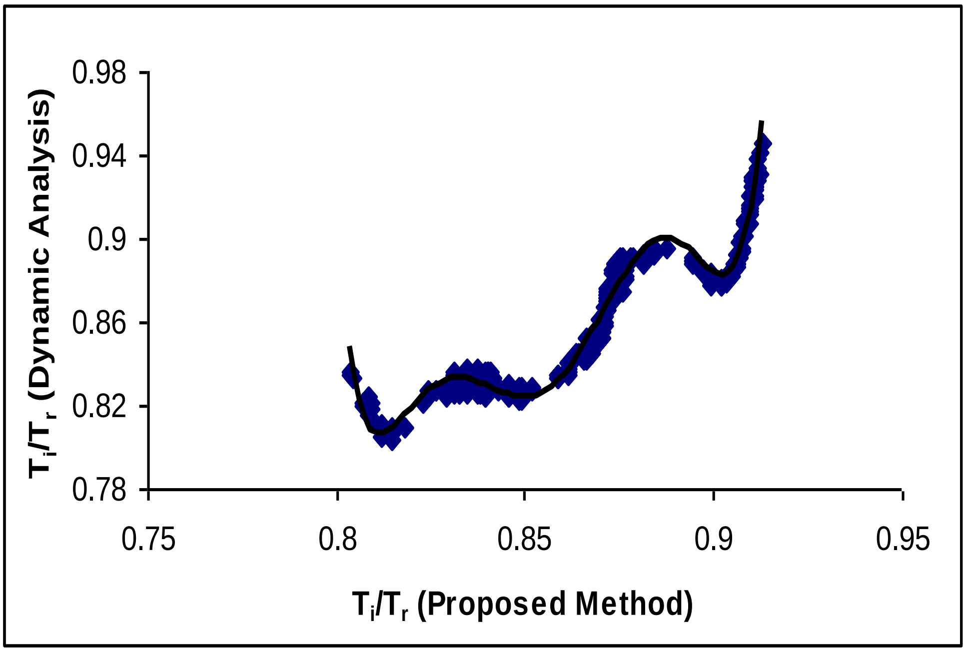
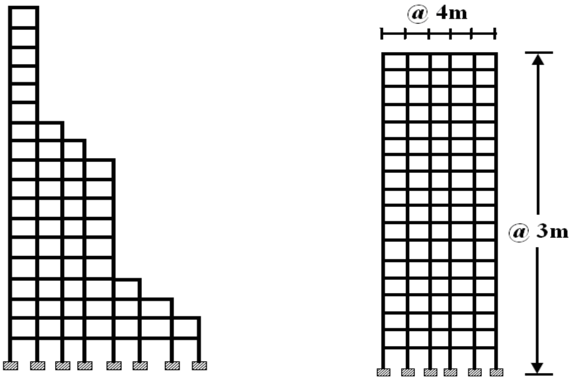


Figure. 9: Correlation between fundamental time periods obtained by proposed method and dynamic analysis

7.1 Global and Storey deformation demands

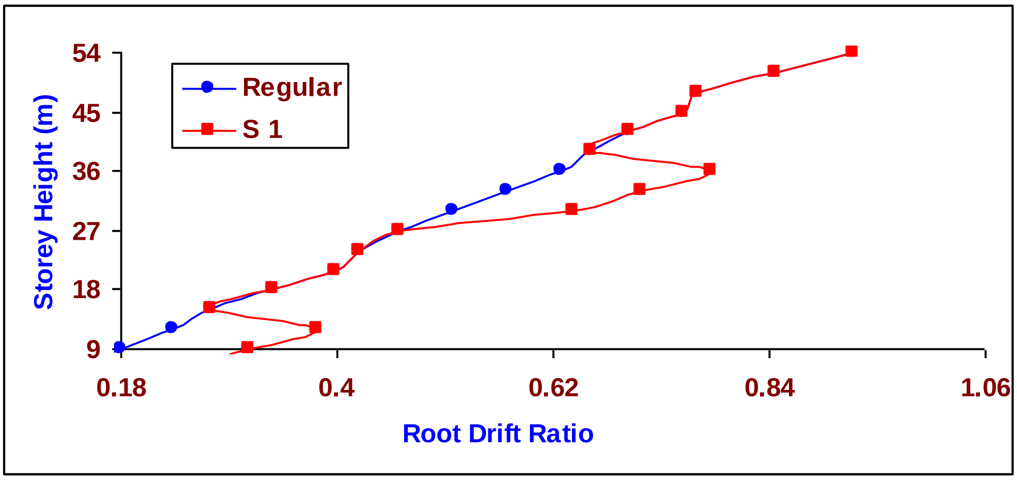
The global demand can be estimated from non-linear time history analysis, and these demands correspond to the maximum deformation demands for regular and irregular structure (Figure 10).

The global demand for the selected setback structure and corresponding regular structure are plotted on Figure 11. Figure 11 shows that the deformation demands increases in storeys with setbacks i.e. 2, 3, 4,10,11,12. In the first storey, the drift ratio is 0.09 and, with the introduction of setbacks in the second storey it creases abruptly by 20 %. The drift ratio shows a progressive increase up to 30 % at the fourth storey, then it returns to its normal trend up to the ninth storey. From tenth storey onwards, the drift ratio shows an abrupt increase of 27 %, due to introduction of the setback and this trend continues up to the twelfth storey (till which the setbacks are present), after which it returns to its normal pattern for the rest of the storey height. The similar pattern is observed in case of the inter-storey drift ratio (IDR) profile, except the difference in percentage of the increase. However, the regular structure does not show any abrupt increase in both drift and IDR profiles. This may be due to the absence of the setback irregularity. Therefore, it can be said that presence of setbacks increase the global and storey deformation demands.

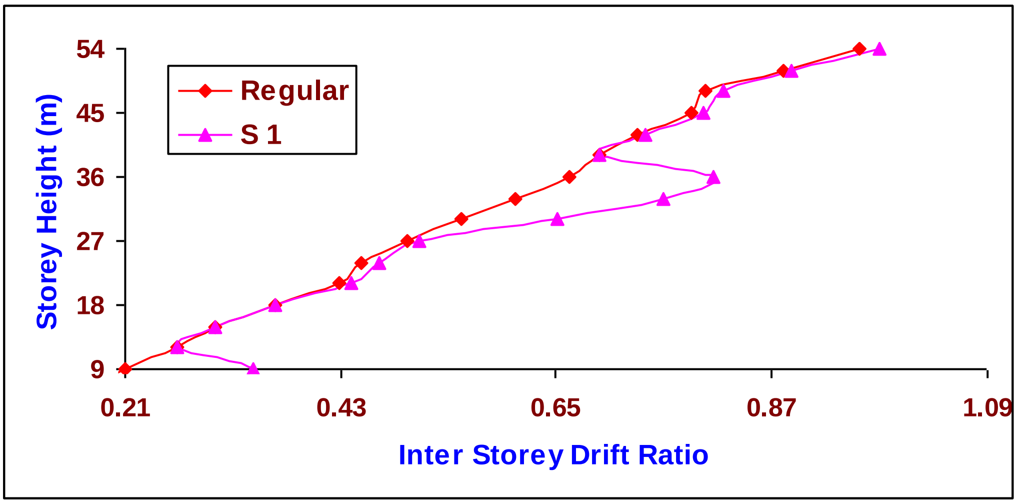


a) Irregular building b) Regular building

Figure 10: Building model considered for the analytical study



a)



b)

Figure 11: Variation of global and storey deformation demands for regular and setback structure a) Root Drift ratio vs storey height b) Interstorey drift ratio Vs Storey height

7.2 Ductility Demand and behaviour factor

In general, ductility is defined as the ability of the structure to resist deformations beyond the yield point without fracture. In earthquake engineering, the ductility is often expressed in terms of demand and supply. The ductility demand may be defined as the maximum ductility that a structure undergoes during an occurrence of an earthquake. The ductility demand depends upon both types of structure and seismic excitation. The ductility supply may be defined as the ductility that a structure can withstand without any fracture. The displacement ductility can be represented as the as the ratio of maximum displacement to the displacement at first yield of the structure.

$$\mu = \frac{d_m}{d_y} \tag{10}$$

Where μ = displacement ductility, d_m = Maximum displacement and d_y = displacement at first yield

It is very interesting to study the variation of the ductility factor with different parameters like number of storey, number of bays and setback irregularity, etc. Figure 12 shows the variation of the ductility factor for a regular and a setback frame. From Figure 12, it can be seen that the ductility factor increases with the number of storeys, with maximum value at the top storey for both the frames. The ductility factor for both the frames are almost similar except at the stories where the setback is present, i.e., 2, 3, 4, 10, 11, 12. In these stories, the ductility factor shows an abrupt increase. Therefore, it can be concluded that the presence of a setback magnifies the ductility demand.

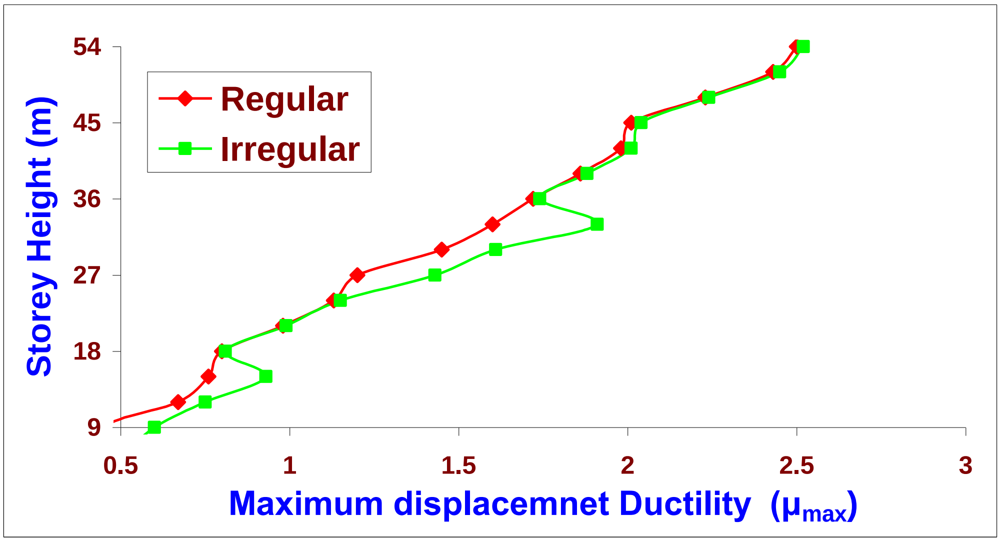


Figure 12: Variation of ductility demand with storey height for regular and a setback structure

7.3 Behaviour factor

The behavior factor is a factor by which the forces and moments obtained from elastic analysis need to be multiplied to apply them for seismic design process. EC8 has specified, different values of behavior factor for different types of structures. In the present paper, the behaviour factor is evaluated as the ratio of the scale factors of the earthquake at which maximum displacement is obtained to the scale factor at which the first plastic hinge occurs.

7.4 Estimation of maximum interstorey drift along the frame height (H)

The inter storey drift can also be computed for the setback frames using correlation studies between the inter storey drift and the proposed irregularity index obtained for 305 building models used for the analytical study. The maximum inter storey drift ratio (I_r) can be obtained from the following equation.

$$I_r = 2.89\eta_{ir} + 0.001757H - 2.403 \tag{11}$$

The above equation is proposed based on regression analysis and is valid for RC buildings ranging from 6 -18 m, with the irregularity index ranging between 1.17 – 1.39. It is very necessary to check the equation proposed. Figure 13 presents the comparison of inter storey drift obtained by the proposed equation and by dynamic analysis. From comparison, it is found that the results of both methods were found to be in close agreement with a correlation coefficient of 0.9912. Table 6 shows the mean of interstorey drift ratio and ductility factor for some of the selected geometries. However, the equations are formulated based on the total results of all the building models for better accuracy.

7.5 Estimation of maximum displacement ductility

As per EC8:2004, the maximum displacement ductility is calculated by equal displacement rule which assumes the displacement ductility and behaviour factor as equal but, in actual case it is not so. Therefore, based on the regression analysis, following equation is proposed to compute the displacement ductility for the setback frames. The proposed equation is given as under

$$\mu_{\max} = 0.930 - 0.000369H + 0.189\eta_{ir} + 0.0249q \tag{12}$$

The proposed equation needs to be checked for its accuracy. Figure 14 presents the comparison between the maximum displacement ductility evaluated by both dynamic analysis and by the proposed equation .On comparison, results of both methods are found to be in a close agreement with a correlation coefficient of 0.9845.

Furthermore, the comparison between the maximum displacement ductility obtained by the dynamic analysis, equal displacement rule and the proposed equation is presented in Figure 14. From Figure 15, it can be clearly seen that the results of dynamic analysis and the proposed equation are comparable whereas, the equal displacement rule overestimates the behaviour maximum displacement ductility (Table 6).

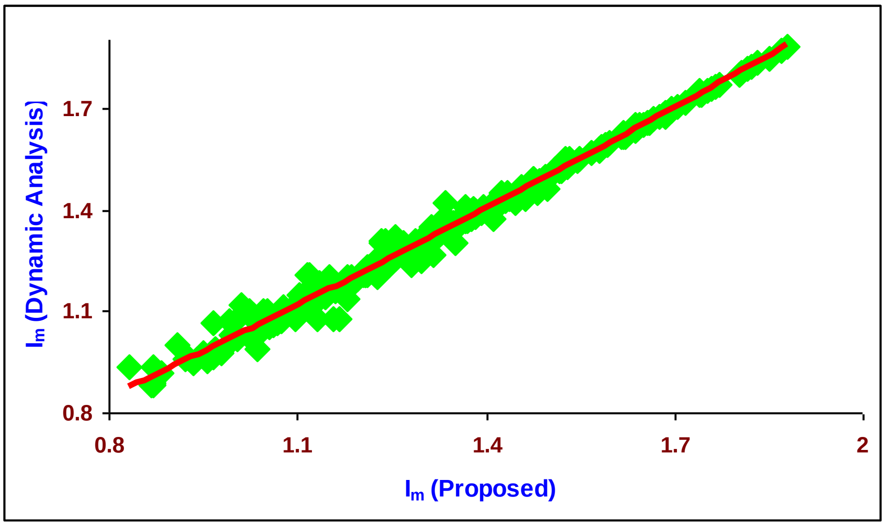


Figure 13: Comparison between maximum interstorey drift (I_m) computed by the proposed method and dynamic analysis

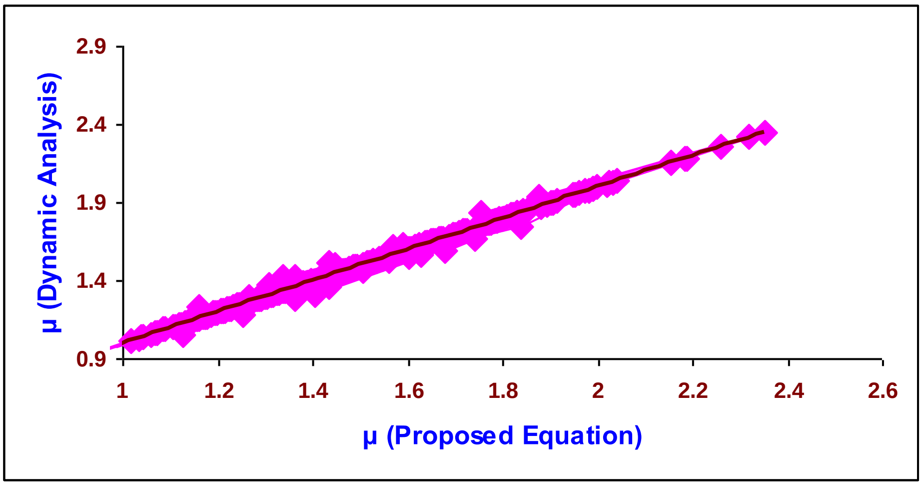


Figure 14: Comparison between maximum displacement ductility (μ_{max}) computed by the proposed method and dynamic analysis

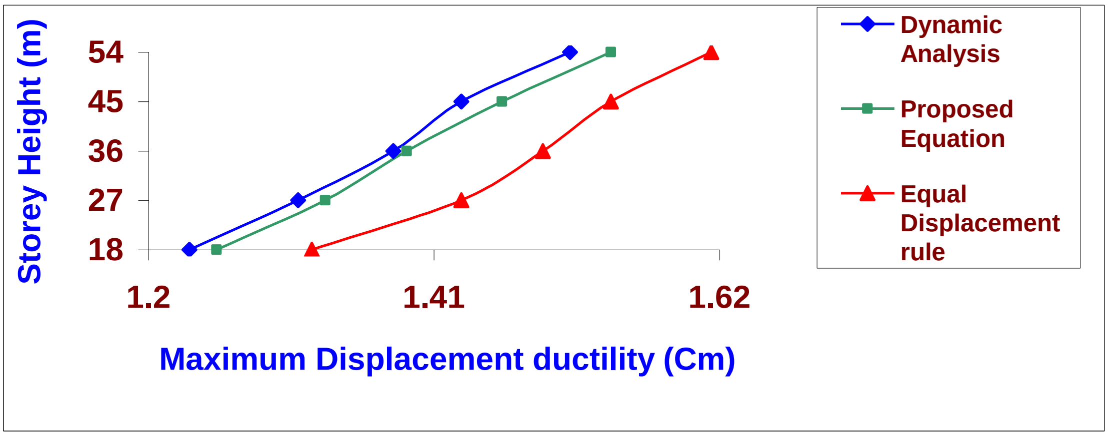


Figure. 15: Comparison of maximum displacement ductility by three methods

TABLE 6 VARIATION OF MEAN OF MAXIMUM DISPLACEMENT DUCTILITY (M_{MAX}) AND MAXIMUM INTERSTOREY DRIFT RATIO (I_M) FOR SOME OF THE BUILDING GEOMETRIES CONSIDERED

G. No	**6 STOREY**		**9 STOREY**		**12 STOREY**		**15 STOREY**		**18 STOREY**	
	I_m	**μ_{max}**	**I_m**	**μ_{max}**	**I_m**	**μ_{max}**	**I_m**	**μ_{max}**	**I_m**	**μ_{max}**
1	0.867	1.351	0.871	1.372	0.882	1.352	0.784	1.412	0.909	1.304
5	0.98	1.212	0.993	1.211	1.005	1.207	1.102	1.223	1.121	1.219
9	1.23	1.233	1.214	1.265	1.225	1.273	1.232	1.265	1.243	1.253
13	1.13	1.233	1.156	1.247	1.165	1.233	1.186	1.24	1.023	1.189
17	0.87	1.374	0.927	1.273	0.935	1.24	0.94	1.251	0.956	1.233
21	1.34	1.311	1.368	1.36	1.375	1.37	1.332	1.337	1.376	1.377
25	0.97	1.216	1.029	1.205	1.035	1.213	1.045	1.221	1.213	1.269
29	1.21	1.247	1.282	1.311	1.295	1.297	1.234	1.267	1.312	1.32
33	0.95	1.233	0.921	1.269	1.005	1.218	1.034	1.207	1.123	1.229
37	1.18	1.238	1.245	1.267	1.256	1.253	1.232	1.26	1.432	1.325
41	0.99	1.212	1.076	1.213	1.086	1.229	1.12	1.229	1.213	1.256
45	1.24	1.267	1.274	1.267	1.286	1.293	1.203	1.238	1.312	1.304
49	1.32	1.308	1.352	1.357	1.366	1.363	1.33	1.352	1.412	1.36
53	1.09	1.21	1.132	1.255	1.118	1.219	1.121	1.24	1.143	1.256
57	1.05	1.226	1.096	1.227	1.108	1.226	1.213	1.24	1.412	1.357
61	1.03	1.226	1.317	1.32	1.328	1.311	1.312	1.315	1.334	1.332

8. Verification studies on 2D building models

Although, the applicability of the proposed equation has been verified for building geometries considered, it is very important to check the accuracy for some other building geometries different from those considered for the analytical study. So, for the verification studies, the five eighteen storey-building frames as shown in Figure 16, with bay width varying from 4 m to 12 m.

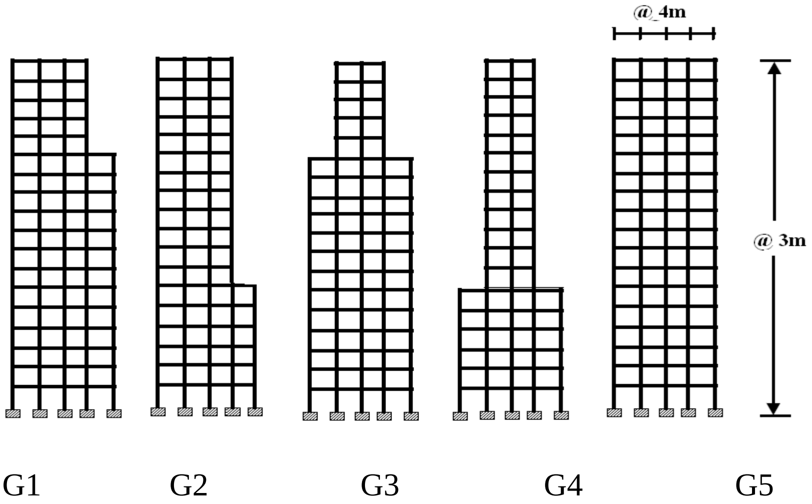


Figure 16: Elevation of different geometries of 18 storey test structures

The storey height is kept as 3.5 m. Modulus of elasticity of concrete is assumed as 2.55 x 10^7 KN/m and Poisson's ratio is taken as 0.2. The building is assumed to be located in Zone-v as per IS 1893:2002. The importance and response reduction factors are assumed as 1.5 and 5 (S.M.R.F) respectively. The loading is same as in case of previous building models. The beam dimensions are considered as 0.4 m x 0. 5 m, while the column dimensions are assumed to be 0.4 m x 0.55 m. The soil condition is assumed as hard soil. The results of study regarding the fundamental period of the vibration were presented in Table 7. From the results of analytical study as presented in Table 7, it can be seen that the values of the fundamental period of vibration obtained by the proposed method depends upon the geometry of the building model whereas, the expression proposed by IS 1893:2002 and UBC 97 suggest same values for all the building models irrespective of building geometry. Hence, the proposed equation effectively captures the variation of setback irregularity in the building frames. The results of the fundamental time period obtained by the proposed method were found to be comparable with results of results obtained from the dynamic analysis.

TABLE 7: EVALUATION RESULTS FOR STRUCTURES FOR TIME PERIOD AND BASE SHEAR

Geometry	**Time Period (Sec)**				**Base Shear (KN)**			
	IS 1893	**UBC 97**	**Dynamic analysis**	**Proposed Equation**	**IS 1893**	**UBC 97**	**Dynamic analysis**	**Proposed Equation**
G1	0.074	0.029	0.0720	0.0722	4742.09	3225.07	4674.66	4681.41
G2	0.074	0.029	0.0712	0.0713s	3372.06	2211.24	3206.93	3209.49
G3	0.074	0.029	0.0673	0.0680	4725.77	3193.65	4500.68	4524.20
G4	0.074	0.029	0.0650	0.0655	3649.95	2466.61	3416.42	3429.39

The base shear obtained using computed fundamental period of vibration for different building geometries were presented in Table 7. From Table 7, it can be seen that the base shear evaluated by consideration of UBC 97 calculated fundamental period of vibration yielded the maximum values of base shear. The results of base shear obtained by proposed method and dynamic analysis are found to be comparable to all the four building geometries considered. Table 8 shows the comparison of Interstorey drift ratio and ductility factor for different building models considered. The results obtained for these factors by dynamic analysis and proposed equation are found to be in close agreement.

TABLE 8: EVALUATION RESULTS FOR STRUCTURES FOR INTERSTOREY DRIFT RATIO AND MAXIMUM DISPLACEMENT DUCTILITY

Geometry	**Interstorey Drift Ratio(I_m)**		**Maximum displacement Ductility**	
	Dynamic analysis	**Proposed Equation**	**Dynamic analysis**	**Proposed Equation**
G1	1.232	1.245	1.341	1.394
G2	1.343	1.349	1.453	1.495
G3	1.126	1.143	1.234	1.278
G4	1.459	1.478	1.537	1.543

9. Verification studies on 3D building models

The 3D building model used for verification study is presented in Figure 17.

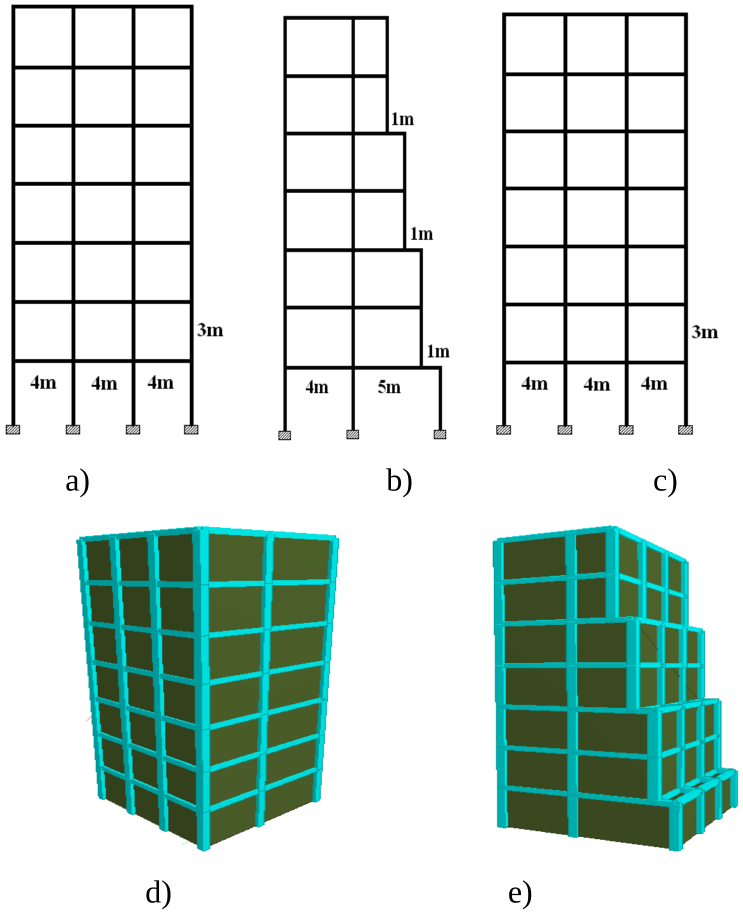


Figure 17: Views of 3D regular and irregular building model considered. a) Front and side elevation of regular building model b) Front elevation of irregular building model c) Side elevation of irregular building model d) Typical 3D View of regular building e) Typical 3D View of irregular building

The proposed correction for the fundamental time period for building models with the setback irregularity are based on databank results obtained from the analysis results of 2D building frames. So, it is very necessary to check the applicability of proposed equations for 3D building models with setbacks. To achieve the above purpose, a 12 storey, 3D RC building model with a setback along Z direction, which is the direction of the earthquake is modelled. The building is designed as a 12 storied office building located in Chandigarh city (Seismic Zone –v with PGA = 0.

36g as per IS 1893:2002). The selected building with setback irregularity, and a similar regular building without steps was analysed for input data, same as for 2D building models. The selected properties of the 3D model are presented in Table 9.

TABLE 9: SELECTED PROPERTIES OF THE 3D BUILDING MODEL

S.No.	**STIFFNESS (K) (KN/m)**		**MASS (M) (KN)**		**Mode**	**FREQUENCY(ω) (Hz)**			
	(K_{irr})	**(K_{reg})**	**M_{irr}**	**M_{reg}**		**ω_i (Eq.8)**	**ω_r (Eq.8)**	**ω_i Dynamic analysis**	**ω_r Dynamic analysis**
1	149697	149697	1149.1	1149.1	1	11.61	11.42	11.63	11.56
2	140243	149697	1149.1	1149.1	2	13.03	12.94	13.07	13.01
3	140243	149697	1054.1	1149.1	3	15.13	15.03	15.19	15.06
4	139721	149697	1054.1	1149.1	4	17.69	17.6	17.81	17.62
5	139721	149697	959.04	1149.1	5	17.72	17.65	17.84	17.71
6	138657	149697	959.04	1149.1	6	18.95	18.6	19.01	18.67
7	138657	149697	959.04	1149.1	7	20.58	20.23	20.71	20.27

The approximate value of the natural frequency of vibration for the building was determined from Eq. 7 by eigenvalue analysis. The beams and columns are modelled as the frame elements with two nodes, with each node having two degrees of freedom. Slabs and Infill walls are modelled as the four nodded surface elements. All exterior walls are assumed to be 0.23 m thick, and the partition walls were assumed to be 0. 115m thick, and the density of concrete and brick is taken as 25 KN/m^3 and 19.8 KN/m^3 respectively.

The front and side elevation of regular and irregular 3D models are shown in Fig 12. The results of both the analysis are presented in Table 7. The different parameters for the selected building are presented in Table 9. The matrix operations to determine the natural frequency of vibration as per Eq. 7 have been performed using MatLab software.

9.1 Calculations for computing the fundamental period of vibration

The values for calculation are taken from Table 9 and the detailed results of these calculations are presented in Table 10. The calculations for fundamental period of vibration are given below

(i) For building model with setback irregularity

The proposed irregularity as per Eq.6 is given by

Case a) Proposed equation

$$\eta_{\mathrm{ir}} = \frac{\omega_i}{\omega_r} = \frac{11.60}{11.42} = 1.015$$

$$\lambda^{'}(Eq.8) = \frac{T_i}{T_r} = 4.4032(1.015) - 10.582(1.015) + 7.2936 = 1.022$$

So, corrected fundamental period of vibration is given by

$$\mathrm{T(Eq.8)} = \lambda^{'}\,0.075\mathrm{h}^{0.75} = 1.077\,(0.075 \times 21^{0.75}) = 0.751\mathrm{sec}$$

Case b) Dynamic analysis

As per analysis results of E-Tabs software, the irregularity index is given by

$$\eta_{\mathrm{ir}}\,(\mathrm{D}) = \frac{\omega_i}{\omega_r} = \frac{11.63}{11.56} = 1.006$$

Putting the values from Eq. 6 in eq. 2 we get the correction factor λ’ as

$$\lambda^{'}(D) = \frac{T_i}{T_r} = 4.4032(1.006) - 10.582(1.006) + 7.2936 = 1.077$$

So, corrected fundamental period of vibration is given by

$$\mathrm{T\,(D)} = \lambda^{'}\,0.075\mathrm{h}^{0.75} = 1.077\,(0.075 \times 21^{0.75}) = 0.803\ \mathrm{sec}$$

(ii) For Regular building model

Case a) Proposed equation 2

$$\eta_{\text{ir}}\,(\text{Eq.8}) = \frac{\omega_i}{\omega_r} = \frac{11.42}{11.42} = 1.00$$

$$\lambda^{'}\,(\text{Eq.5})) = \frac{T_i}{T_r} = 4.4032(1) - 10.582(1) + 7.2936 = 1.11$$

Case b) Dynamic Analysis

$$\eta_{\text{ir}}\,(\text{D}) = \frac{\omega_i}{\omega_r} = \frac{11.56}{11.56} = 1.00$$

$$\lambda^{'}\,(D) = \frac{T_i}{T_r} = 4.4032(1) - 10.582(1) + 7.2936 = 1.11$$

$$\text{T (D)} = \lambda^{'}\,0.075\text{h}^{0.75} = 1.077\ (0.075 \times 21^{0.75}) = 0.792 \text{ sec}$$

Table 10 results are pictorially presented in Figures 18 and 19.

TABLE 10: RESULTS OF THE SEISMIC RESPONSE PARAMETERS

S.No	**Parameters**	**IS 1893 Irregular**	**IS 1893 Regular**	**Proposed Eq.5 Irregular**	**Dynamic analysis Irregular**	**Proposed Eq. 5 Regular**	**Dynamic analysis regular**
1	T (Sec)	0.73	0.73	0.751	0.792	0.820	0.820
2	S_a/g	1.369	1.369	1.329	1.262	1.219	1.219
3	A_h	0.0739	0.0739	0.0718	0.0681	0.0658	0.0658
4	W(KN)	7283.80	8044.19	7283.80	7283.80	8044.19	8044.19
5	V_b(KN)	538.27	594.46	523.08	496.02	529.30	529.30
6	I_m	-	-	0.986	0.978	0.976	0.964
7	μ_{max}	-	-	1.356	1.345	1.256	1.234

From Figure 18, it can be clearly seen that code equation overestimates the fundamental period of vibration as compared to the dynamic analysis and proposed equation. However, the results obtained from both methods were found to be in close agreement for setback structures. Also, from Table 10 it is clearly evident that the ductility factor and interstorey drift ratio for the 3D building model computed by proposed equation and dynamic analysis were found to be comparable.

Figure 19 shows a comparison of the fundamental period of vibration for both regular and setback irregular structure by code and the proposed equation. It can be observed from Figure 18, that the code equation does not consider the irregularity aspect in computing the fundamental period of vibration, and yields same results for both regular and irregular structure but the proposed equation makes a clear distinction between the periods of both types of structures. Furthermore, it can be observed that the introduction of setback irregularity results in shifting of spectrum outwards, i.e. it results in an increase in the fundamental period of vibration thereby reducing the base shear.

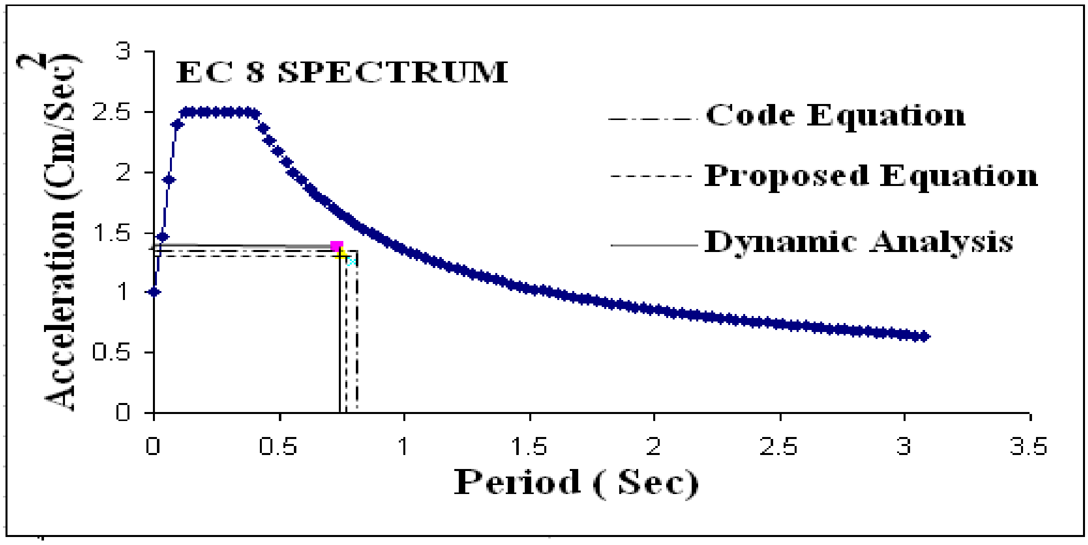


Figure 18: Spectrum of Irregular building by code equation, proposed equation and dynamic analysis superimposed on EC 8 spectrum

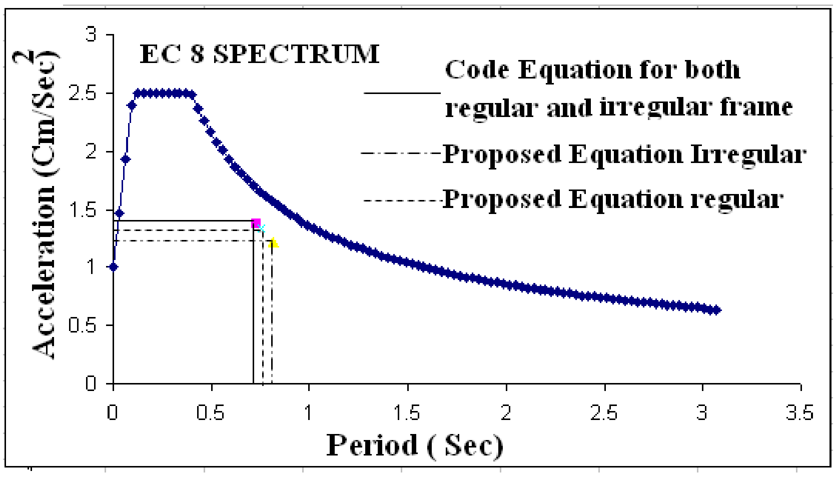


Figure 19: Spectrum of both regular and irregular buildings by code and the proposed equation superimposed on EC 8 spectrum

10. Conclusions

Buildings with the setback irregularity have not received much attention in previous researches, and in the formulation of seismic design methodologies. In the present study, a detailed analytical study has been carried out to overcome these shortcomings. The main conclusions were as follows:

- To quantify the setback irregularity a parameter called 'irregularity index', is proposed. The proposed irregularity index accounts for mass and stiffness changes due to the presence of setbacks along the building height. The proposed parameter is based on dynamic response of the building, and is found to be quite simple. The proposed irregularity index yielded better results as compared to the existing measures adopted by codes and other research works [Karavallis *et al.*] proposed, to quantify the setback irregularity.

- Based on the analytical studies, an empirical formula for modification of expression of the time period proposed by existing code is proposed. The proposed formula is a function of irregularity index. The results obtained from the proposed equation of the fundamental period of vibration is compared with the results of dynamic analysis for four building models with different location of setbacks. From analytical studies, it is found that the fundamental period of vibration evaluated by the proposed method yielded the accurate estimates of fundamental period and base shear, when compared with the results of dynamic analysis. Furthermore, the proposed equation is checked for its applicability in case of 3D building models. Results of study on a 3D building model obtained using proposed equation and dynamic analysis are found to be in close agreement.

- The interstorey drift and displacement ductility are the important seismic response parameters. The equations proposed for estimation of these quantities are based on results of regression analysis conducted on the seismic response databank obtained from results of analytical study conducted on a family of selected frames. The results of these proposed equations are found to be in close agreement with the results of the dynamic analysis. The proposed relation for estimating displacement ductility was comparable to results of dynamic analysis, and yields better results as compared to the equal displacement rule proposed by the EC 8.

- Finally, it can be said from the seismic design aspect that code equations yield lower base shear than actual, hence result in unsafe design of irregular structure. Nevertheless, some codes like EC8:2004, have made allowance for this aspect by introducing factors like behaviour factor, by which seismic response parameters like shear and moment are multiplied. The resulting values are then used for seismic design process, but still these factors are only an approximation and a more precise method like the proposed method need to be developed for safe and economical design of irregular structures.

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