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Seismic behaviour of Multistorey RC Frames with vertical mass irregularities

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Abstract

The buildings with mass irregularity behave differently as compared to regular buildings. In the present study, a parameter called mass irregularity index has been proposed to quantify the mass irregularity. The proposed factor depends mainly upon magnitude and location of mass irregularity. Further the present study aims to modify the expression of time period proposed by IS 1893:2002 and relation between mass irregularity coefficient and time period has been evaluated. For present study a family of 108 frames with mass irregularity have been modelled and analyzed by time history analysis. The proposed expression for time period has been validated for buildings with mass irregularity.

Keywords – *Mass irregularity, Vertical irregularity, Irregularity in buildings, Fundamental time period.*

1. Introduction

In recent years different floors of buildings are used for different purposes like car parking, storing heavy mechanical appliances, for observatory towers at top etc. this results in variation of mass, strength and stiffness at different storeys. Although limits of mass irregularity have been defined by different codes of practice but quantification of mass irregularity in terms of a parameter has yet not been reported. Further building codes specify the same expression of time periods for regular and irregular building frames. But in actual practice the time period for irregular structures will be different from that of their regular counterparts.

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In previous years large numbers of research works have been carried out in relation to mass irregularity. Valmundson and Nau (1997) concluded that ELF procedure prescribed by UBC 97 code predicts seismic response accurately up to mass ratio of five. Al-Ali and Krawinkler (1998) studied the seismic response of 10 storey building frames with different types of vertical irregularities and Presence of mass irregularity at top had maximum impact on drift as compared to the case when mass irregularity was present at bottom and at mid-height. Magulinno *et al.* (2002) found that mass irregularity had negligible impact on seismic response.

Das and Nau (2003) determined the seismic response of 5, 10 and 20 storey buildings with mass, stiffness and strength irregularities by equivalent lateral force procedure as prescribed by UBC 97 code and found that seismic response showed variation in vicinity of irregularities.

Choi (2004) concluded that the frames with mass irregularity especially at lower or upper floors had severe impact on seismic response which was evaluated in terms of plastic hinge distributions and rotations. Ayidin (2007) conducted analytical studies on a 5, 10 and 20 storey frames with mass irregularities using ELF procedure as prescribed by UBC 97 code, from analytical studies it was found that mass irregularity affects shear in storey below and ELF procedure overestimates the seismic response. Athanassiodu (2008) found that the setback frames designed as per EC8 provisions showed better seismic performance. Karavasilis *et al.* (2008) determined seismic response parameters of multi-storey steel frames, the expressions for parameters were developed on basis of regression analysis. Sehgal *et al.* (2011) based on their analytical studies observed combination of stiffness and setback irregularities to generate the maximum seismic response as compared to the case when they are singly present. Varadharajan *et al.* (2012a) has conducted a detailed review of different structural irregularities in the building. The review studies of different types of irregularities showed seismic response to vary drastically near vicinity of irregularities. These results were later confirmed by Vardaharajan *et al.* (2012 b).

Varadharajan 2013 (a) observed short period irregular structures to exhibit a strong response as compared to long period structures which were studied by Varadharajan *et al.* (2013 b). Varadharajan *et al.* (2014) determined the inelastic seismic response of setback frames designed as per EC8:2004 and IS 456 provisions. The results of analytical study EC 8 provisions to be over conservative in estimation of seismic demands. Varadharajan *et al.* (2015) observed the variation in fundamental time period due to presence of irregularity.

2. Design code perspective regarding mass irregularity

The limits of mass irregularity have been specified by different codes like Indian code IS1893:2002 as per which mass irregularity is said to exist in a storey if its mass exceeds 200 % of adjacent storey. However EC8:2004 and UBC 97 specify this limit as 150 %. These codes prescribe dynamic analysis for all types of irregular building. The code proposed expression for time period as

$$T = 0.075 h^{0.075} \tag{1}$$

In empirical equation proposed by IS 1893:2002, the fundamental time period is function of overall building height and this does not consider the variations in building mass along the building height. It can be seen from the analysis that irregular mass distributions change the fundamental time period irrespective of same building height. Therefore, the natural time period of the structure will be different for regular and for irregular structures. However, different codes of practice prescribe same expression for all types of buildings. Furthermore, natural time period of the structure will depend on extent and location of irregularity. So the expression proposed by the codes for estimation of fundamental time period needs to be modified for irregular structures and correspondingly with variation in natural time period of irregular structures, the spectral acceleration coefficient (S_a/g) will vary which will change the magnitude of base shear.

3. Proposed method for quantifying mass irregularity

The present study aims in quantification of mass irregularity and to evaluate its relationship with ratio of natural time period of irregular structures (T_i) with that of regular structures (T_r). The other main aim of present study is to specify a correction factor for expression of time period proposed by different codes of practice to make it valid for structures with mass irregularity. Most of the current seismic codes describe mass irregularity in terms of its magnitude only. But the effect of mass irregularity on seismic response depends not only on it's magnitude but also on it's location and building properties. The proposed parameter called as 'mass irregularity index 'expresses mass irregularity in a building frame with respect

a) Magnitude of irregularity
b) Location of irregularity
c) Building properties

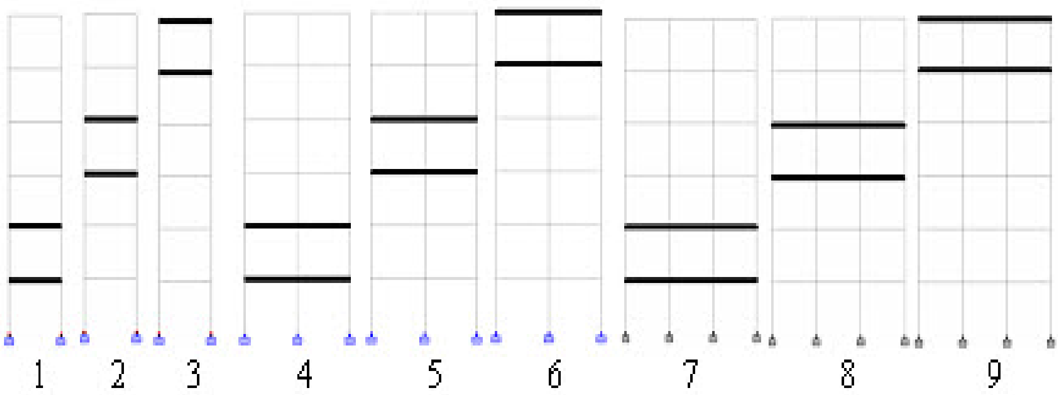
The proposed parameter of mass irregularity index is described as

$$\eta_m = \frac{b}{L} . b \frac{h_i}{h} \frac{M_i}{M} \tag{2}$$

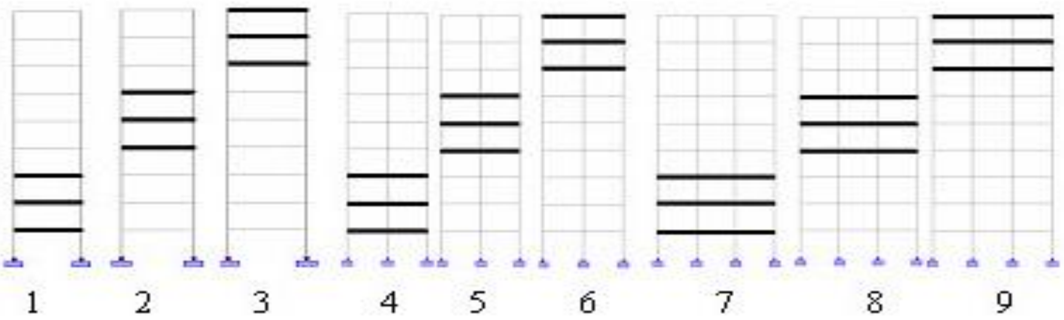
Where b is the plan width in direction of seismic excitation, L is the plan width transverse to the direction of seismic excitation, h_i is the height of mass irregular floor from base of the structure, h is the total height of the structure, M_i is the mass of floor containing irregularity, M is the total mass of the structure

For the present study 108 building frames with no. of stories varying from 6-15, bay width is kept constant as 4m in both X and Z directions and extent of mass ratio varying from 200% - 400%. Each basic model i.e. 6, 9, 12 and 15 storey models. The detailed modelling scheme of the building models has been shown in Figure.1. For every model the bay width is kept as 4m and storey height is kept as 3.5m. 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 factor are taken as 1.5 and 5 (S.M.R.F) respectively. Regarding the loading, the dead load is taken as 6.0 KN/m^2 and live load at roof and other intermediate floors are taken as 1.5kN/m^2 and 4.0KN/m^2 respectively.

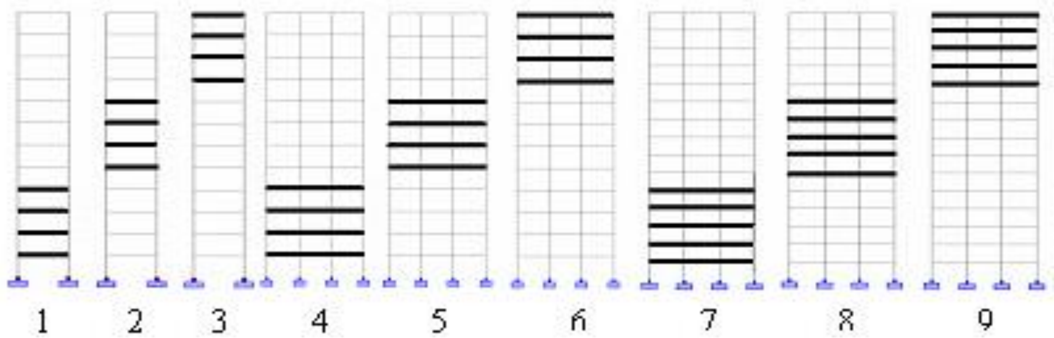
The beam dimensions were considered as 0.4m x 0.4m, while the column dimensions were assumed to be 0.4m x 0.6m.The soil condition was assumed as hard soil. The results of analytical study regarding the time period are presented in Table 1. These frames were subjected to EC8 spectrum and analyzed by time history method of analysis. The fundamental period versus total height of selected frames were kept in accordance with empirical relationships proposed by Goel and Chopra (1997) as shown in Figure 2. The results presented are for 108 different building frames considered. The mass irregularity index for above frames were calculated and plotted against ratio of T_i/T_r obtained from dynamic analysis and the relation between both these parameters was obtained in form of a polynomial equation. The models considered have been named depending on building properties, magnitude and location of mass irregularity by suffix M_{sbml} . Here 's' stands for no. of stories, 'b' stands for no. of bays, 'm' stands for magnitude of mass irregularity and 'L' describes the location of irregularity. For example the model denoted by suffix 'M_{6121}' has 6 stories 1 bay with mass irregularity of 2M (M is the storey mass) and mass irregularity located at the bottom one third height of the building. The variation of mass irregularity index with different building properties are studied as described in Table 1. The analytical studies have been conducted on the building models using E-Tabs Version 9 software.



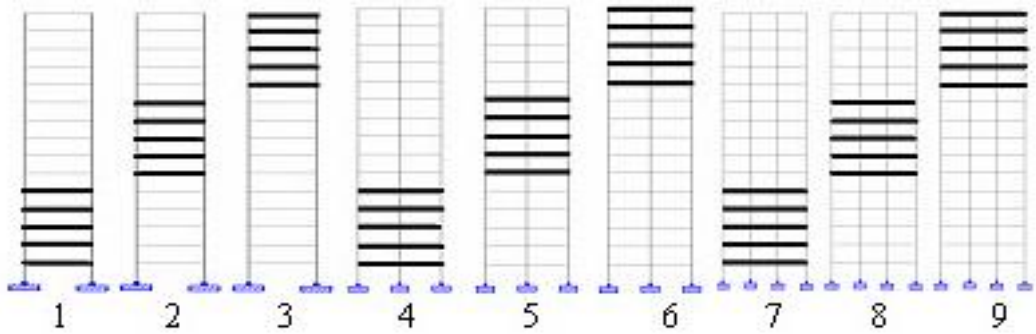
a): 6 Storey building models



b): 9 Storey building models



c): 12 Storey building models



d) 15 Storey building models

Figure 1: Side Elevations of 9 different building configurations and mass irregularity locations for 6, 9, 12, 15 storey building models considered for analytical study

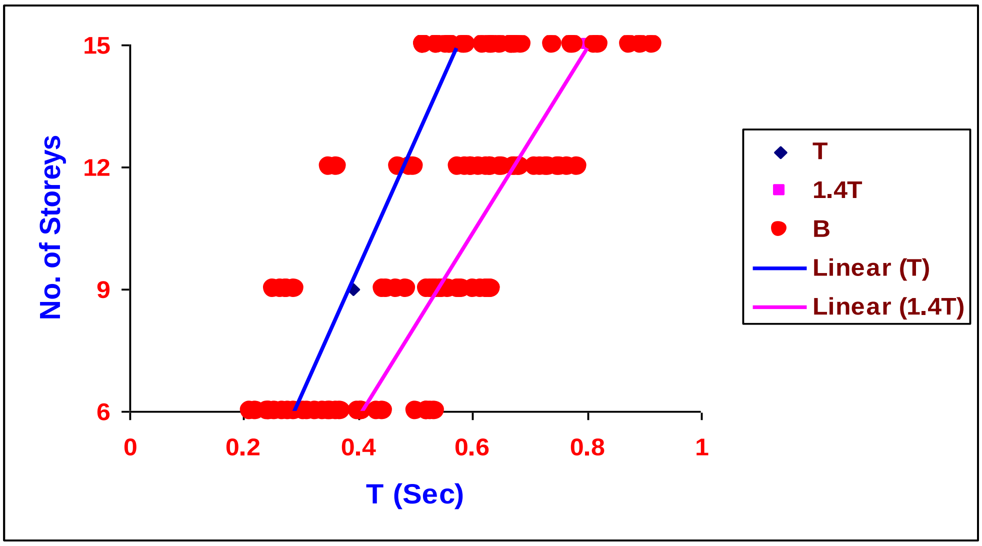


Figure 2: Variation of fundamental period with frame height of frames considered superimposed by boundary limits specified by Goel and Chopra (1997)

4. Variation of mass irregularity index (η_m) with different building properties, extent and location of mass irregularity

The mass irregularity index varies from 0 to 3 for building models considered in the analytical study**.** The mass irregularity index (η_m) will depend on building properties, magnitude and location of mass irregularity. The relationship of mass η_m with ratio of T_i/T_r is plotted in Figure 3 to Figure 5 from which it can be observed that

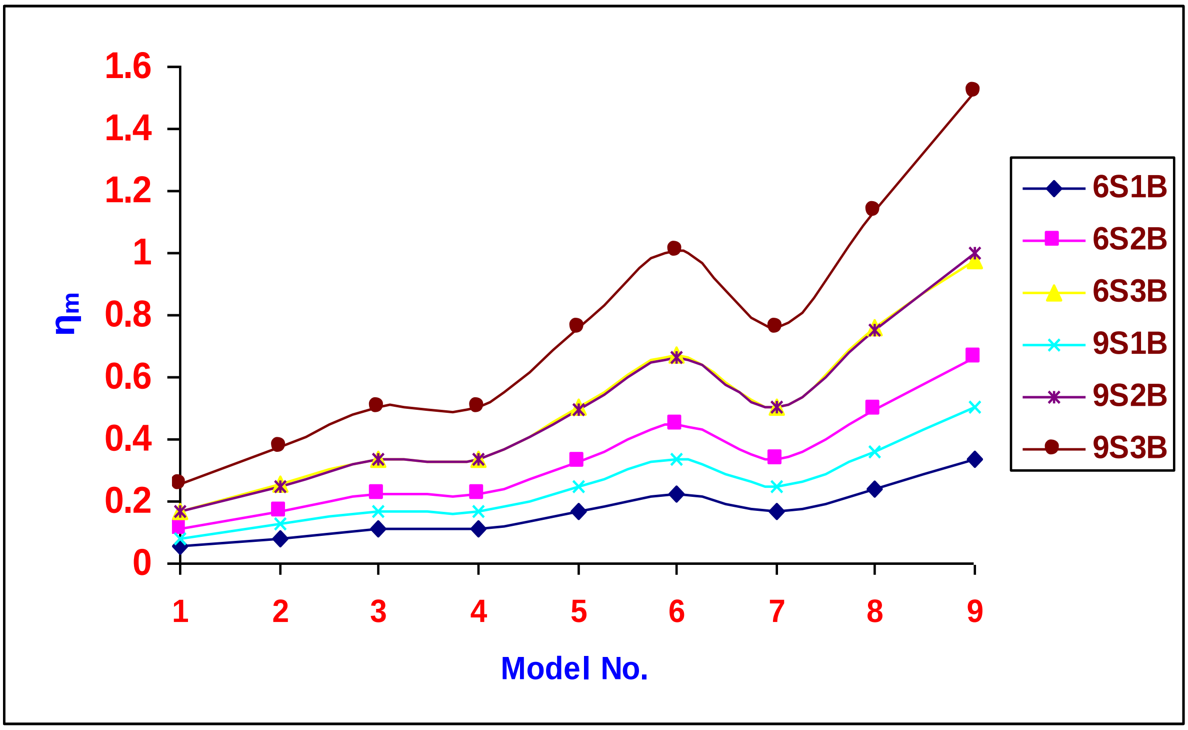
a) Mass irregularity index increases with increase in position of mass irregularity along storey height i.e. Mass irregularity index is least for the building models in which irregularity is present in bottom storey.
b) The magnitude of increase of mass irregularity index is found to be same for 6,9,12 and 15 storey building models.
c) The mass irregularity index increases with bay width and with number of bays.

In nutshell, mass irregularity index increases with magnitude of mass irregularity.

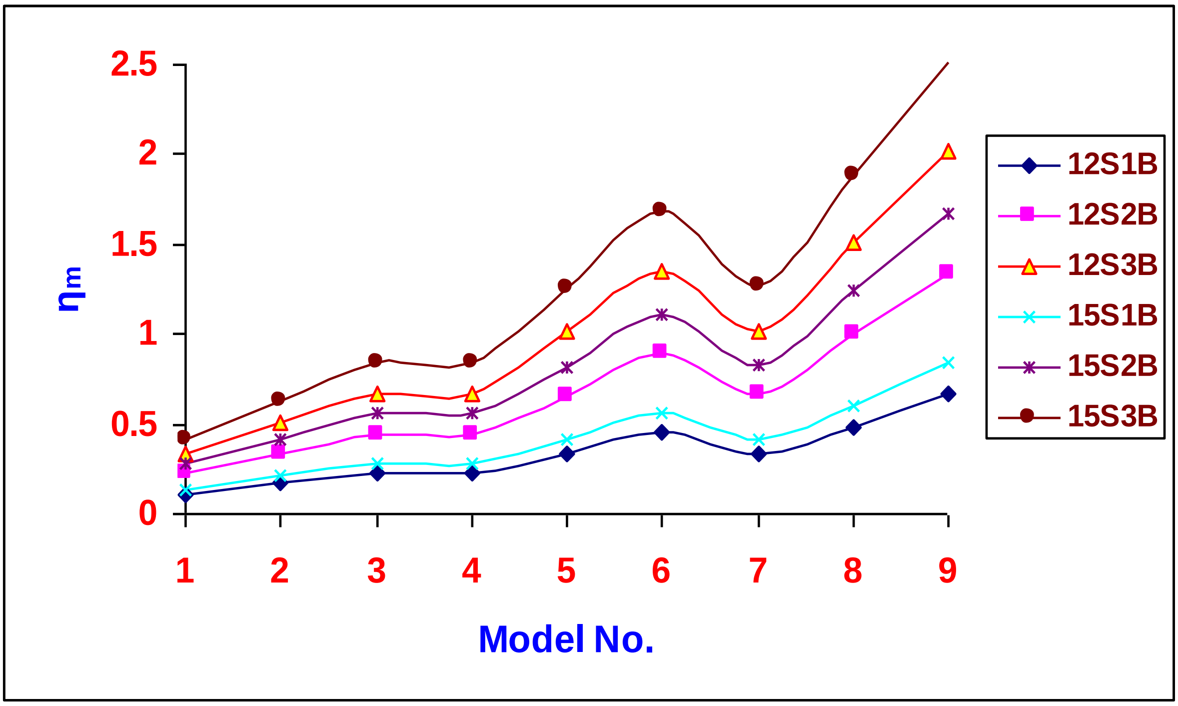
Furthermore, Figure 4 to Figure 6 show that the T_i/T_r ratio increases with increase in number of bays and with increase in location of building irregularity measured from the base. However, this percentage increase is different for different type of building models. Therefore, it can be concluded that T_i/T_r ratio is not only influenced by mass irregularity index but by other factors also. The increase of storey height does not have any substantial effect of T_i/T_r ratio it increases for 12 storey building models but decreases slightly for 9 and 15 storey building models.

Table 1: T_i/T_r ratio and mass irregularity index (η_m) for building models considered

Model No.	η_m	T_i/T_r	**Model No.**	η_m	T_i/T_r	**Model No.**	η_m	T_i/T_r
M6121	0.056	1.030	M9221	0.168	1.010	M12321	0.336	1.15
M6122	0.114	1.210	M9222	0.334	1.033	M12322	0.668	1.269
M6123	0.169	1.330	M9223	0.506	1.100	M12323	1.012	1.365
M6131	0.084	1.090	M9231	0.252	1.150	M12331	0.477	1.301
M6132	0.165	1.360	M9232	0.50	1.266	M12332	1.000	1.365
M6133	0.252	1.600	M9233	0.758	1.310	M12333	1.516	1.460
M6141	0.112	1.180	M9241	0.336	1.280	M12341	0.672	1.350
M6142	0.225	1.510	M9242	0.668	1.480	M12342	1.336	1.470
M6143	0.337	1.780	M9243	1.012	1.680	M12343	2.023	1.510
M6221	0.112	1.050	M9321	0.252	1.074	M15121	0.140	1.030
M6222	0.228	1.200	M9322	0.501	1.208	M15122	0.277	1.170
M6223	0.337	1.340	M9323	0.759	1.253	M15123	0.421	1.303
M6231	0.168	1.100	M9331	0.358	1.164	M15131	0.210	1.030
M6232	0.330	1.170	M9332	0.750	1.230	M15132	0.416	1.265
M6233	0.505	1.320	M9333	1.137	1.552	M15133	0.631	1.556
M6241	0.224	1.150	M9341	0.504	1.253	M15141	0.280	1.113
M6242	0.445	1.220	M9342	1.002	1.402	M15142	0.556	1.350
M6243	0.674	1.360	M9343	1.518	1.761	M15143	0.840	1.835
M6321	0.168	1.048	M12121	0.112	1.150	M15221	0.280	1.080
M6322	0.334	1.193	M12122	0.222	1.500	M15222	0.557	1.236
M6323	0.506	1.274	M12123	0.337	1.680	M15223	0.840	1.372
M6331	0.238	1.096	M12131	0.168	1.263	M15231	0.420	1.127
M6332	0.500	1.370	M12132	0.333	1.710	M15232	0.820	1.272
M6333	0.758	1.500	M12133	0.505	1.894	M15233	1.260	1.550
M6341	0.336	1.140	M12141	0.224	1.421	M15241	0.560	1.354
M6342	0.668	1.530	M12142	0.445	1.763	M15242	1.110	1.627
M6343	1.011	1.690	M12143	0.674	2.070	M15243	1.680	1.754
M9121	0.084	1.070	M12221	0.224	1.100	M15321	0.420	1.030
M9122	0.167	1.315	M12222	0.445	1.235	M15322	0.835	1.180
M9123	0.253	1.368	M12223	0.674	1.264	M15323	1.265	1.340
M9131	0.126	1.157	M12231	0.336	1.205	M15331	0.596	1.076
M9132	0.250	1.369	M12232	0.660	1.352	M15332	1.250	1.340
M9133	0.379	1.447	M12233	1.010	1.441	M15333	1.890	1.122
M9141	0.168	1.263	M12241	0.448	1.308	M15341	0.840	1.480
M9142	0.334	1.473	M12242	0.890	1.617	M15342	1.670	1.640
M9143	0.506	1.552	M12243	1.349	1.970	M15343	2.520	1.790

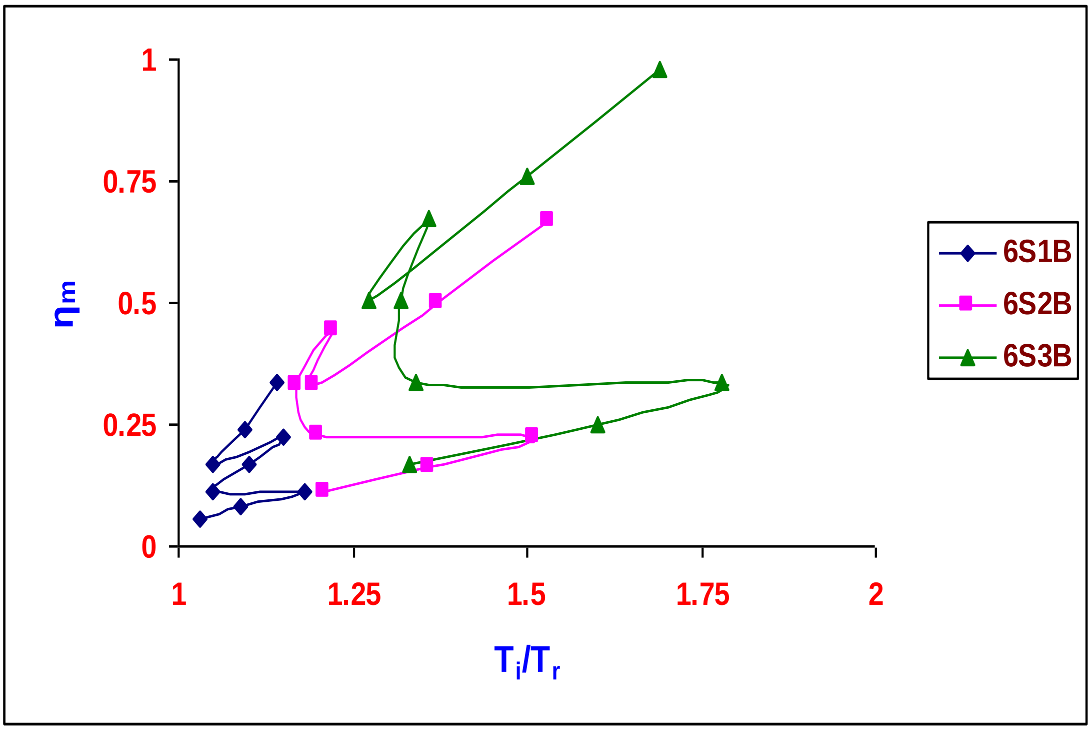


a) 6 and 9 storey building models



b) 12 and 15 storey building models

Figure 3: Variation of mass irregularity index with building properties and mass irregularity



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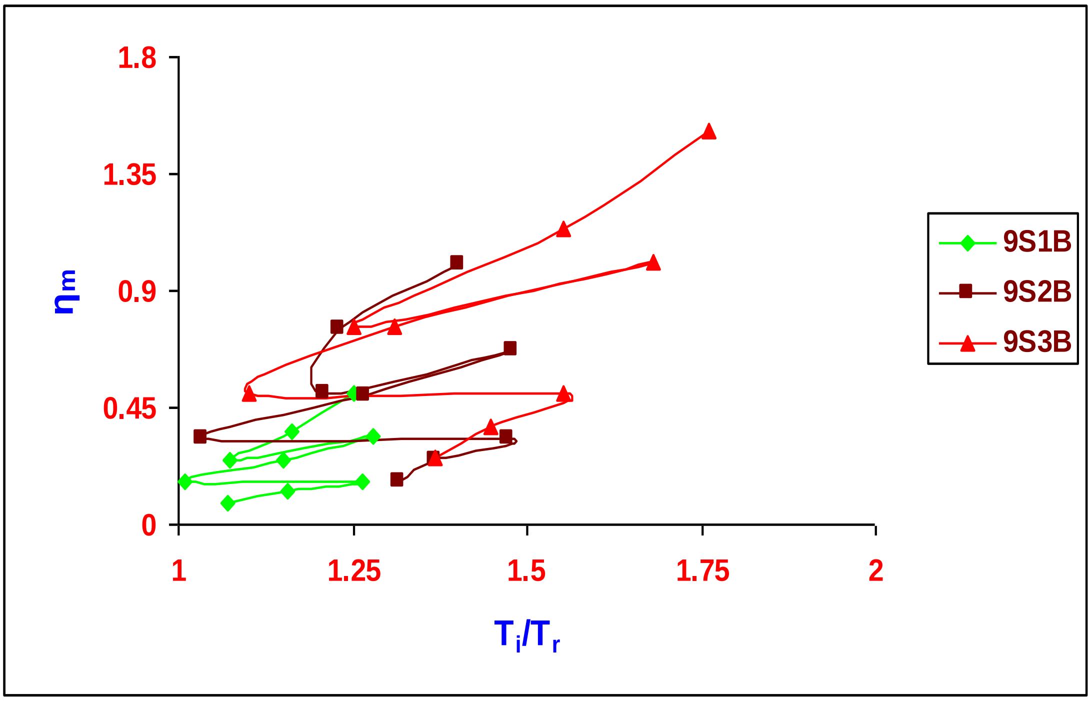
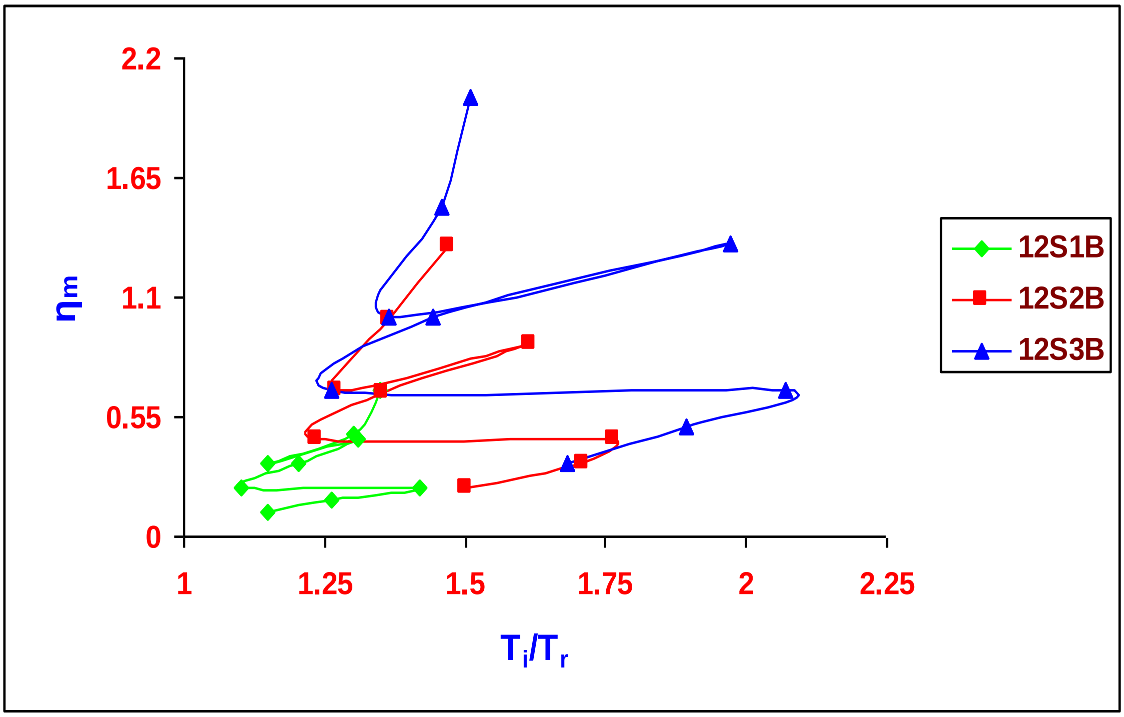


b)

Figure 4: Variation of mass irregularity index with T_i/T_r ratio for storey and 9 storey building models



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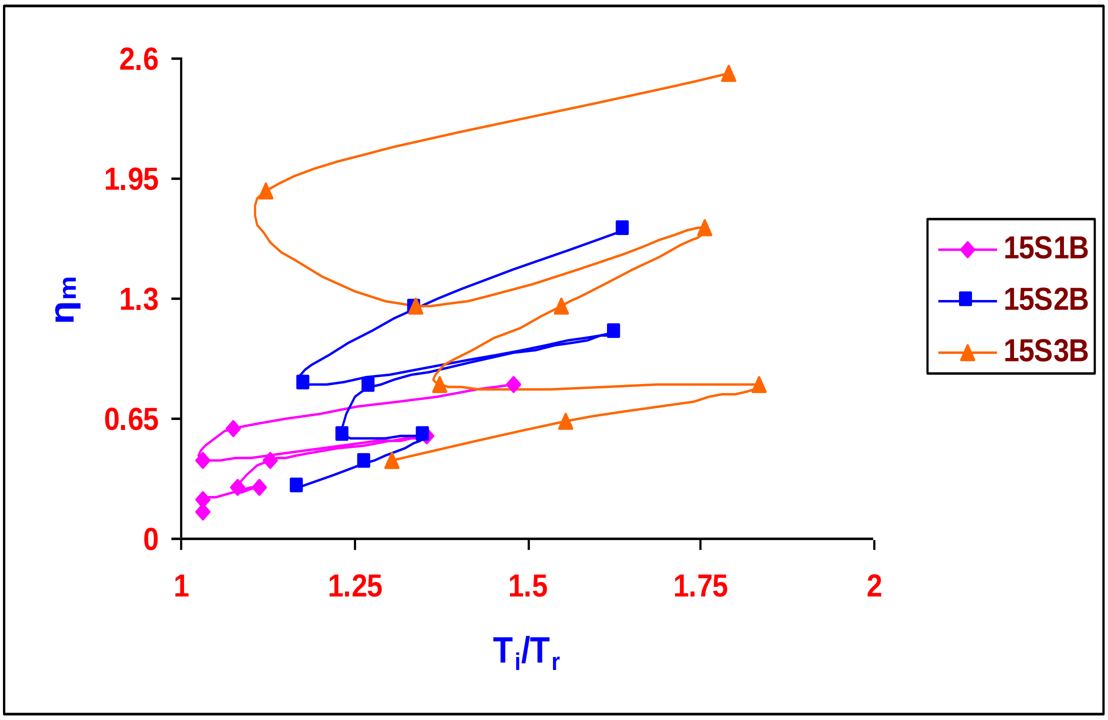


b)

Figure 5: Variation of mass irregularity index with T_i/T_r ratio for different types of building models

5. Variation of mass irregularity index with T_i/T_r ratio for different building models considered

Based on regression analysis carried out on seismic response databank the correction factor for time period equation has been proposed as

$$\lambda_m = \frac{T_i}{T_r} = 1.8449\eta_m^6 - 9.066\eta_m^5 + 17.84\eta_m^4 + 18.34\eta_m^3 - 10.35\eta_m^2 + 3.127\eta_m + 0.9682 \quad (3)$$

and the modified equation to estimate fundamental time period has been proposed as

$$T_i = \lambda_m 0.075 h^{0.075} \quad (4)$$

Figure 3 to Figure 5 show that proposed correction factor first decreases with increase in mass irregularity index and then it follows a reverse trend and starts increasing with increase in the magnitude of mass irregularity. The minimum value of correction factor is obtained when mass irregularity index reaches the value of 0.124. The correction factor (λ_m) in equation 3 is valid when the value of irregularity index lies between 0 and 0.9 which generally covers the mass irregular buildings in practice. The correction factor calculated using equation 3 exhibits a good correlation with the value obtained from dynamic analysis with average ratio of predicted to actual correction factor being 0.923 for 108 building models. Moreover, the correlation coefficient between actual and predicted correction factor being 0.965 (Figures 6 and 7).

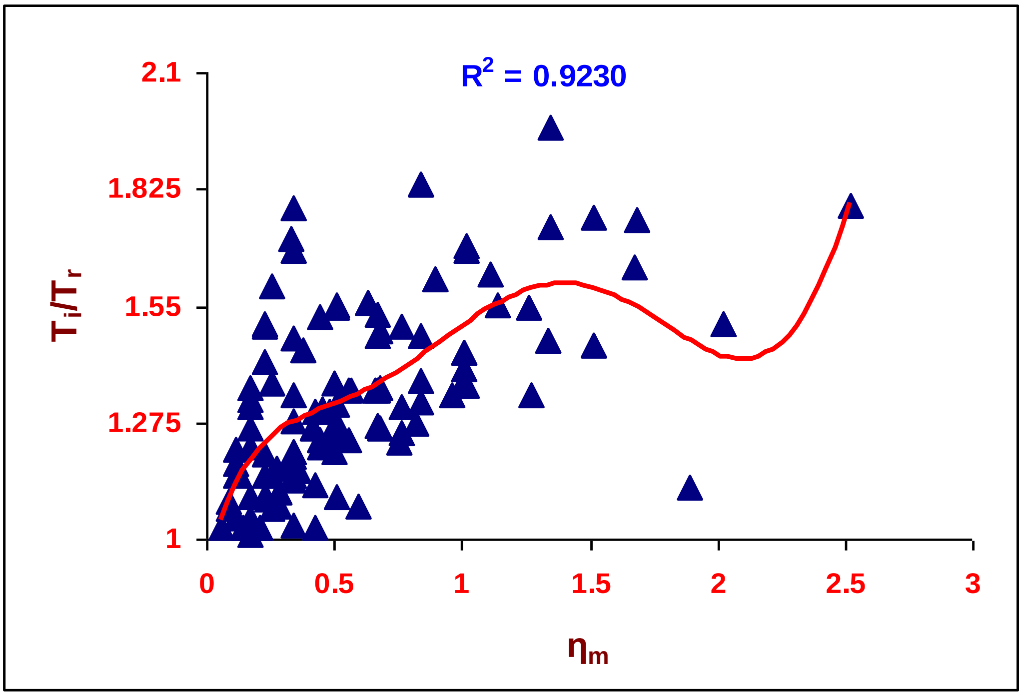


Figure 6: Variation of T_i/T_r with mass irregularity index

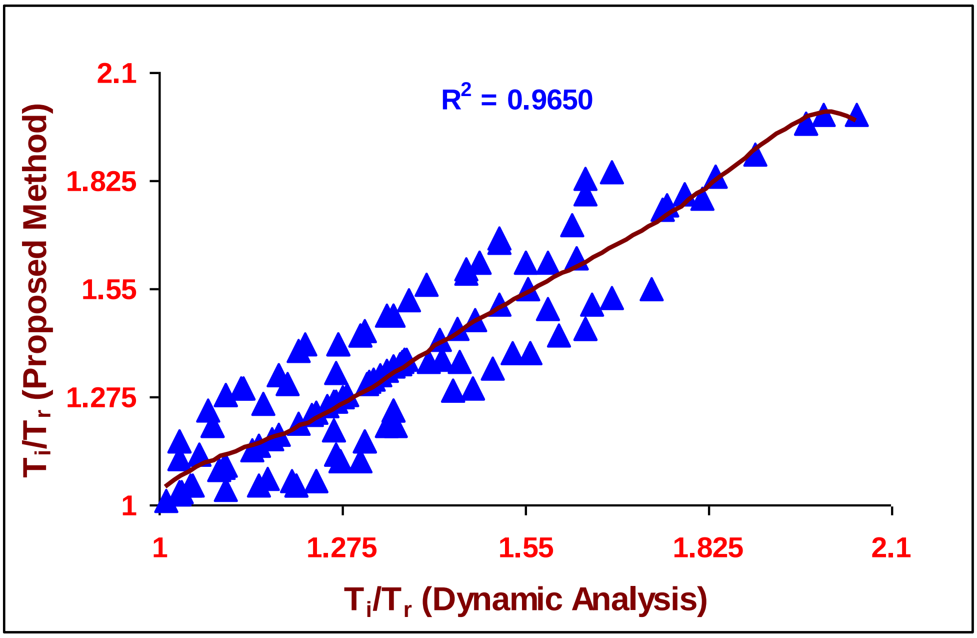
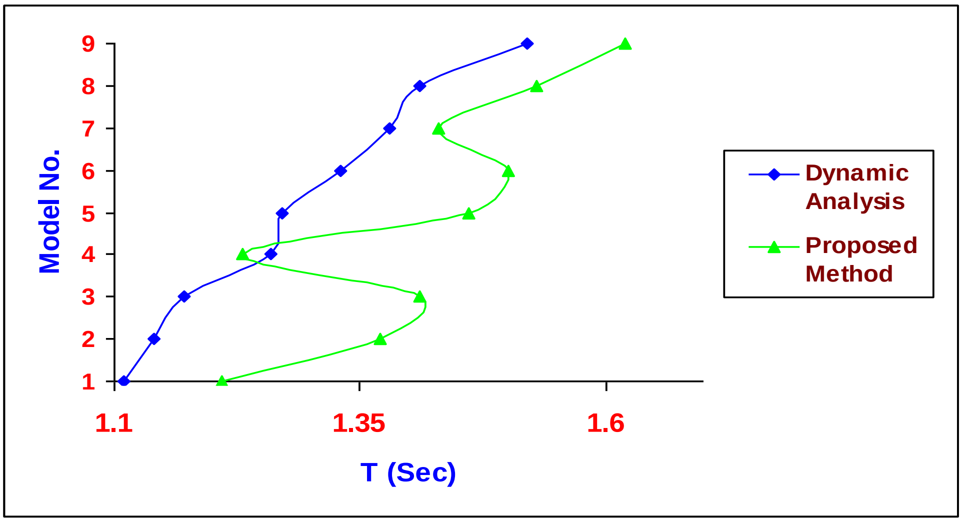


Figure 7: Comparison of T_i/T_r values using proposed method and dynamic analysis

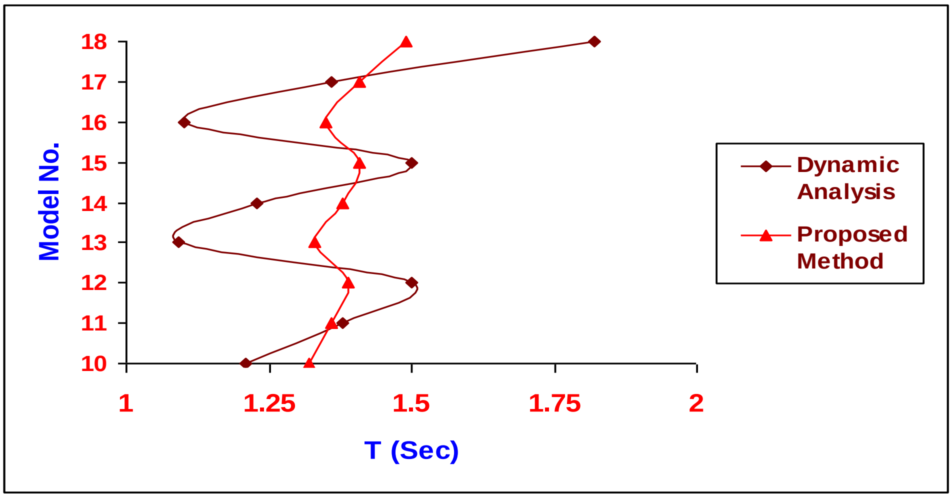
6. Determination of fundamental time period using proposed equations

Three ten-storey building models with one, two and three bays respectively are considered with arrangement of mass irregularity as shown in Figure.1. The input data for these building models are same as for previous models. The results of analytical study regarding the time period are presented in Tables 2 - 3 and in Figures 7 - 8. The time period of building systems increases with no. of bays, no. of stories and with increase in location of irregularity along the building height. From the previous section, it could be observed that location and magnitude of irregularity have the least effect on time period as compared to no. of bays and no. of stories (Figures 3 – 5).

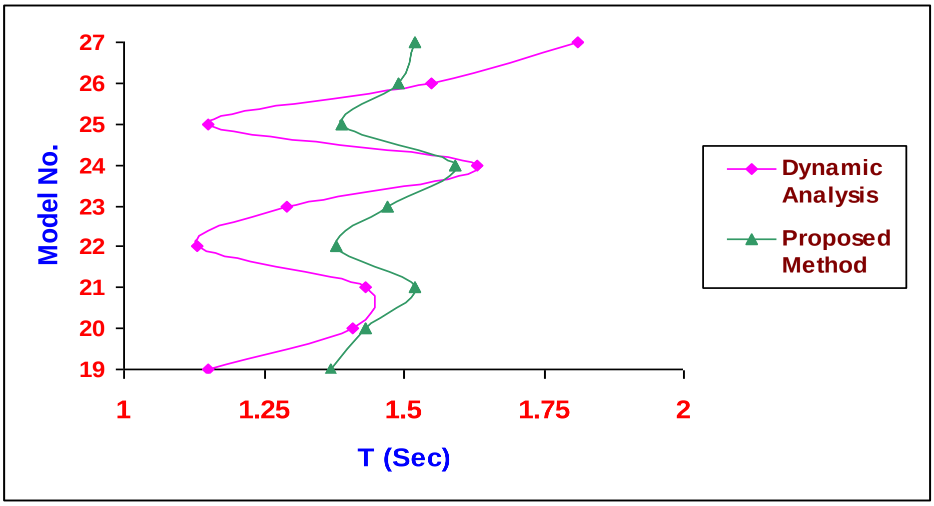
So, the latter parameters were found to have larger impact on natural time period of building systems. The results obtained by proposed method were found to be in close agreement with dynamic analysis results but were slightly higher as compared to IS 1893:2002, but very high as compared to UBC 97 code. The base shear is found to increase with number of stories, number of bays and with increase in the magnitude of mass irregularity, but extent and location of mass irregularity had least impact on base shear. Time period computed using UBC 9 code results maximum base shear. The results of base shear obtained from proposed method were found to be closer to dynamic analysis, with proposed method results on lower side. The base shear and fundamental time period are computed using IS 1893 and EC 8 wee identical as expression for time period is same (Figures 8 and 9, Tables 2 and 3).



a) 10 Storey 1 bay

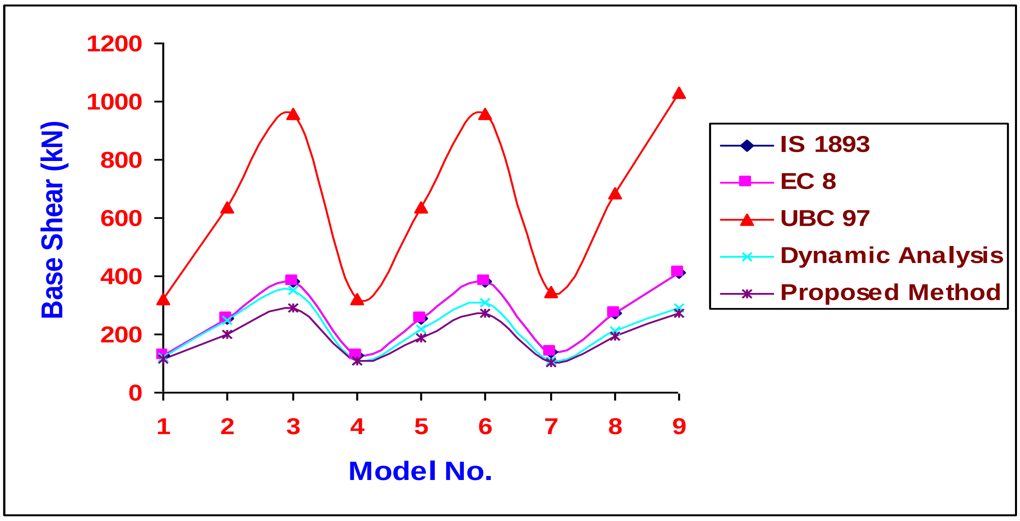


b) 10 Storey 2 bay



b) 10 Storey 3 bay

Figure 8: Variation of fundamental time period for 10 Storey building model



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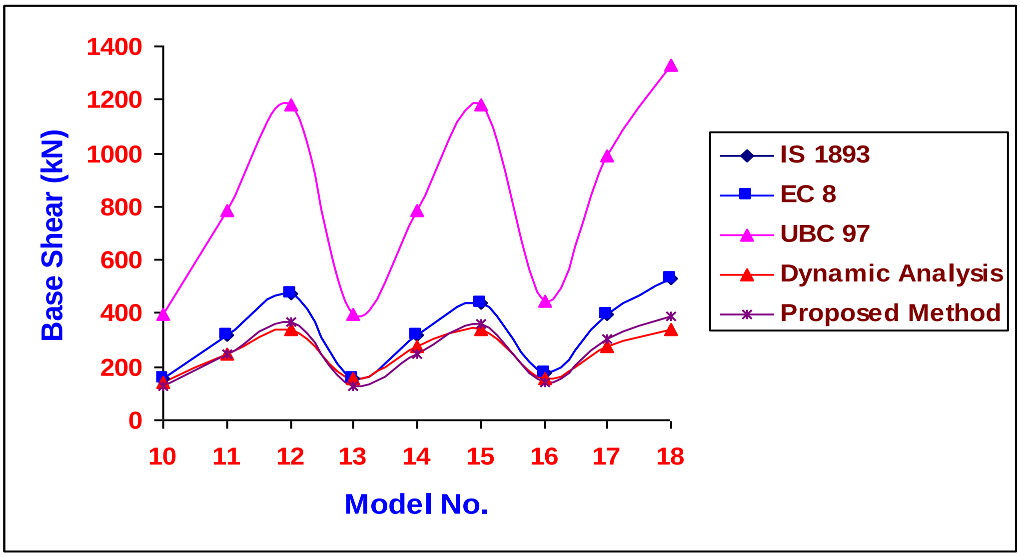

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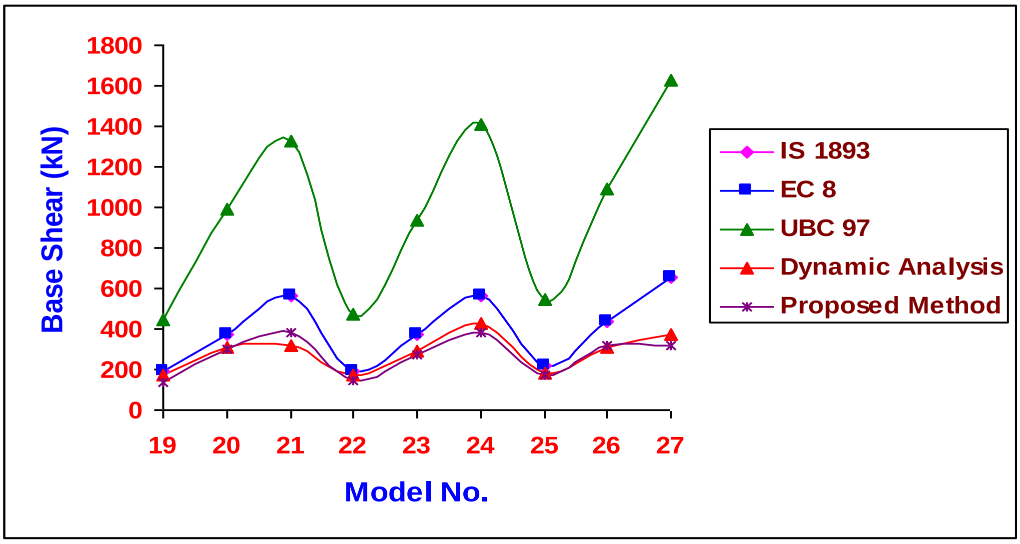

c)

Figure 9: Variation of base shear for 10 storey building model

Table 2: Comparison of fundamental time period calculated by different methods

S. No.	**Details of model**	**IS 1893**	**EC8**	**UBC 97**	**Dynamic analysis**	**Proposed Method**
1	M_1	1.079	1.079	0.431	1.11	1.21
2	M_2	1.079	1.079	0.431	1.14	1.37
3	M_3	1.079	1.079	0.431	1.17	1.41
4	M_4	1.079	1.079	0.431	1.26	1.23
5	M_5	1.079	1.079	0.431	1.27	1.46
6	M_6	1.079	1.079	0.431	1.33	1.50
7	M_7	1.079	1.079	0.431	1.38	1.43
8	M_8	1.079	1.079	0.431	1.41	1.53
9	M_9	1.079	1.079	0.431	1.52	1.62
10	M_{10}	1.079	1.079	0.431	1.21	1.32
11	M_{11}	1.079	1.079	0.431	1.38	1.36
12	M_{12}	1.079	1.079	0.431	1.50	1.39
13	M_{13}	1.079	1.079	0.431	1.092	1.33
14	M_{14}	1.079	1.079	0.431	1.23	1.38
15	M_{15}	1.079	1.079	0.431	1.50	1.41
16	M_{16}	1.079	1.079	0.431	1.10	1.35
17	M_{17}	1.079	1.079	0.431	1.36	1.41
18	M_{18}	1.079	1.079	0.431	1.82	1.49
19	M_{19}	1.079	1.079	0.431	1.15	1.37
20	M_{20}	1.079	1.079	0.431	1.41	1.43
21	M_{21}	1.079	1.079	0.431	1.43	1.52
22	M_{22}	1.079	1.079	0.431	1.13	1.38
23	M_{23}	1.079	1.079	0.431	1.29	1.47
24	M_{24}	1.079	1.079	0.431	1.63	1.59
25	M_{25}	1.079	1.079	0.431	1.15	1.39
26	M_{26}	1.079	1.079	0.431	1.55	1.49
27	M_{27}	1.079	1.079	0.431	1.81	1.521

Table 3: Comparison of base shear (kN) calculated by different methods

S. No.	Details of model	Mass irregularity index	IS 1893	EC8	UBC 97	Dynamic analysis	Proposed Method
1	M_1	0.0285	127.4	127.4	318.5	123.95	113.91
2	M_2	0.077	254.8	254.8	637	247.58	200.86
3	M_3	0.128	382.2	382.2	955.5	352.8	292.74
4	M_4	0.057`	127.4	127.4	318.5	109.2	111.86
5	M_5	0.154	254.8	254.8	637	216.68	188.48
6	M_6	0.253	382.2	382.2	955.5	310.35	275.18
7	M_7	0.1155	137.4	137.4	343.5	107.83	103.77
8	M_8	0.228	274.8	274.8	687	210.48	193.97
9	M_9	0.384	412.2	412.2	1030.5	292.87	274.8
10	M_{10}	0.077	157.4	157.4	393.5	140.48	128.78
11	M_{11}	0.154	314.8	314.8	787	246.36	249.98
12	M_{12}	0.258	472.2	472.2	1180.5	339.98	366.68
13	M_{13}	0.154	157.4	157.4	393.5	155.67	127.81
14	M_{14}	0.328	314.8	314.8	787	276.40	246.36
15	M_{15}	0.506	437.3	437.32	1180.5	339.98	361.48
16	M_{16}	0.231	177.4	177.4	443.5	155.67	141.92
17	M_{17}	0.462	394.8	394.8	987	276.40	302.40
18	M_{18}	0.769	532.2	532.2	1330.5	339.98	385.75
19	M_{19}	0.086	187.14	187.14	443.5	174.17	139.84
20	M_{20}	0.172	374.2	374.2	987	313.51	298.17
21	M_{21}	0.288	562.2	562.2	1330.5	315.811	378.14
22	M_{22}	0.272	187.4	187.4	468.5	175.99	146.66
23	M_{23}	0.344	374.8	374.8	937	287.08	275.35
24	M_{24}	0.576	567.2	567.2	1405.5	424.59	381.87
25	M_{25}	0.258	217.4	217.4	543.5	179.90	168.95
26	M_{26}	0.516	434.8	434.8	1087	313.38	315.15
27	M_{27}	0.864	652.2	652.2	1630.5	372.50	315.15

7. Conclusions

Buildings frames with mass irregularity comes under the category of vertical irregularity. In previous research works and in formulation of seismic codes, the concept of mass irregularity has not received much attention. In the present work a detailed analytical study on mass irregular buildings have been carried out to address the shortcoming. The main conclusions are as follows:

(1) A factor called ‘Mass irregularity index’ is proposed which accounts for changes in mass along the height of the building. As compared to code approaches which classify mass irregularity only based on its magnitude, the proposed index represents mass irregularity in terms of its magnitude and location. The proposed index was found to effective in representing mass irregularity.

(2) To account for effects of mass irregularity on fundamental period of the structure an empirical formula is proposed to calculate the fundamental time period of building structures with mass irregularity as a function of proposed parameter called ‘ Mass irregularity index’. The proposed formula is validated by comparison with free vibration analysis performed on 27 building frames.

(3) The time period evaluated from the proposed expression is applied to calculate the base shear for mass irregular buildings and the results were compared with the base shear obtained from time period evaluated using different codes of practice and dynamic analysis. On comparison of results it was found that proposed procedure yields comparable results of free vibration analysis.

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