PREDICTION OF SEISMIC TORSIONAL EFFECTS IN TALL SYMMETRIC BUILDINGS

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ABSTRACT

The investigations conducted in this study of earthquake response of tall symmetric buildings are based on the observation that these structures share many important dynamic properties. Earlier these types of studies were not reported much due to the lack of computational facilities. Introduction of reliable and widely recognised computer tools changed the situation to a great extend. The present work begins by quantifying the similarities and differences in equivalent static method and response spectrum method of tall regular building analysis under fundamental period and torsional period based on Indian seismic code provisions. Design moments of columns and roof displacements are taken as the parameters of the study. From the present investigation of three dimensional static and dynamic analyses, it is observed that torsional period excitations are significant than the fundamental period and those effects started from low raised buildings even for regular structures. Shortfall of the Indian seismic code provisions in this area is observed. Guidelines and design tools are prepared based on the study which helps to a better understanding of the torsional behaviour of tall symmetric structures.

Keywords: *Indian seismic codes, Seismic linear analysis, Tall symmetric buildings, Torsional effects.*

1. INTRODUCTION

Tall regular structures have uniformity in height, cross-sectional area and mass per storey which yield a general similarity in mode shape of vibration [1]. Instability of tall buildings during seismic response is recognised by some of the previous researchers [2]. Detailed investigations of static and dynamic analysis for symmetric tall buildings are not reported much due to lack of computational facilities in the past. Symmetric structures are considered as regular structures and special provisions are available in all seismic codes including Indian standards. But most of the tall buildings are asymmetric in one way or other, when it responds the seismic forces which are also random in nature [3]. Seismic torsional response has always been a principal cause of structural failure in most of the major earthquakes [4]. Designs for seismic torsional effect, the simplified assumptions provided by the codes are inadequate for tall structures [5].

The torsional provisions in Indian codes are introduced in all buildings for increase in shear forces on the lateral force resisting elements resulting from the horizontal torsional moment arising due to eccentricity between the centre of mass and centre of rigidity [6]. This is based on the static eccentricity and floor plan dimension which is effective for irregular structures. For symmetric structures, the dynamic amplification part will be vanished due to zero static eccentricity and only the effect of accidental eccentricity will exist. A three dimensional static and dynamic analysis under linear range is conducted for different floor area building to study the behaviour. Linear seismic analysis for tall buildings is reported the literature based on the application of endurance time method [7]. Equivalent linear methods are widely adopting for the evaluation of existing structures using the maximum displacement demand of an equivalent linear system [8]. Buildings with symmetric configurations are designed as per the provisions of IS 1893 (Part 1) : 2002. Design column moments and roof displacements are considered as the parameters. A comparative study of Equivalent Static Method (ESM) and Response Spectrum Method (RSM) is conducted using SAP 2000 [9]. As per the provisions, ESM can be used up to 40m height for regular buildings and above 40m height, RSM is recommended for severe seismic zones. Performance of buildings under Fundamental Period (FP) and Torsional Period (TP) is examined. The significance of torsional mode in the seismic analysis of tall structures is studied. Observations have revealed the deficiency of ESM even for symmetric buildings within the limited heights and guide lines are prepared for the general behaviour of tall symmetric structures.

2. NUMERICAL MODELLING

In the present work, a conventional 3dimensional rigid frame modelling with linear elastic material behaviour is employed for the analysis of the building system. Thus the beams and columns are modelled as two noded space frame element. The floor loads are transferred to the frame by pure membrane behaviour. Computer models are generated and analyzed in SAP 2000. The buildings considered in the present study are three dimensional reinforced column beam structures with rigid diaphragms having 'm x m' bays ('m' bays in each plan direction) and 'n' stories designated as mBnS. The studies span over 1B9S, 1B9S and 3B9S as shown in Fig.1. Floor heights and column spacing are taken as 3m and 5m respectively. All building models have been taken as perfectly symmetric in plan with square columns and uniform rigid diaphragms so that the centre of mass and centre of rigidity coincide. Columns are considered fixed at their base. For the seismic weight calculation, self weight of the structure and 50% of the imposed load (4kN/m^2) is considered.

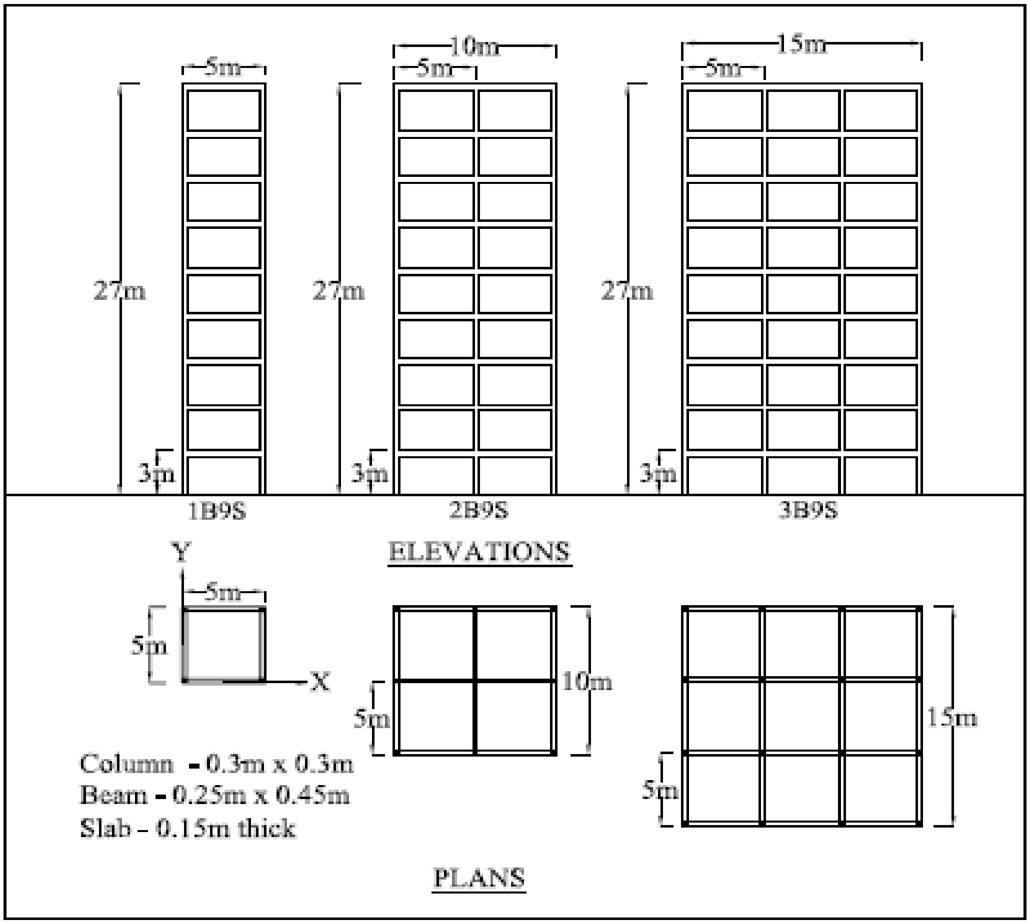

Figure 1. Nine storey regular buildings of different floor area.

From the initial analysis on single bay building frames starting with a single storey continued up to 25 stories with one storey interval revealed that the characteristics of frames with more than 7 stories are identical to frame with 7 stories and hence detailed studies have been limited to frames up to 9 stories only.

3. ANALYSIS METHODOLOGY

Seismic analysis is carried out for the building systems discussed using the static approach - ESM and dynamic approach - RSM as proposed in IS 1893 (Part 1) : 2002 with an Importance factor I=1, Response reduction factor R=5, and Zone factor Z=0.36. The buildings are considered to be founded on medium soil (type 2). SAP 2000 version 14 is used as the computational tool in the present work. To compare the behaviour of the building frames, column moments and drift were chosen as typical parameters.

4. RESULTS AND DISCUSSIONS

4.1. Design Column Moments

Under seismic behaviour, columns become critical and assume greater importance for design in accordance with the recent design philosophy of strong column weak beam concept. In the present work, detailed analysis is carried out to study the variation of design column moments at different floor levels under earthquake characteristics as discussed in section 3.

From Table 1, it is observed that the percentage variation of ESM and RSM column moments are varied from 1st to 9th storey in a particular fashion. The maximum variation is found in the intermediate floors which are above the middle floors. However, the variation between the RSM design column moment under FP and TP was almost constant for all floors. This constant value is different for different height or floor buildings.

Table 1 Comparison of design column moments of a one bay nine storey symmetric building

Story Level	Design column moments (kNm)				% Vari. RSM & ESM under TP	% Vari. FP & TP under RSM
	FP		TP			
	RSM	ESM	RSM	ESM		
1	41.42	41.4	44.24	46.71	5.58	6.37
2	33.36	35.29	35.63	39.82	11.76	6.37
3	30.51	34.13	32.59	38.5	18.13	6.38
4	27.9	32.8	29.8	37	24.16	6.38
5	25.46	31.08	27.2	35.06	28.90	6.40
6	23.2	28.28	24.78	31.9	28.73	6.38
7	20.42	24.14	21.81	27.24	24.90	6.37
8	16.47	18.4	17.59	20.77	18.08	6.37
9	10.06	10.6	10.74	11.95	11.27	6.33

Numerical experiments are carried out on 1B1S of TP = 0.227s to 1B40S of TP = 7.68s. RSM column moments under FP and TP of the first floor column moments are plotted as shown in Fig.2. The approximate time period of regular buildings can be calculated by the empirical expression of $T=0.09h/\sqrt{d}$ as mentioned in IS [6]. For one bay symmetric structure, if this time period is less than 0.55s, the structure will not suffer any torsional mode effects. This assumption can be used to fix the height and width of symmetric tall structures in the design offices as a design tool

The structure will be highly rigid when the time period T<0.55s, and there will not be much torsional effects. Similarly when the time period T>4s, the structure will be highly flexible and roof displacement will be beyond the limit. This will lead a non linear deformation of the members which is beyond the scope of this study.

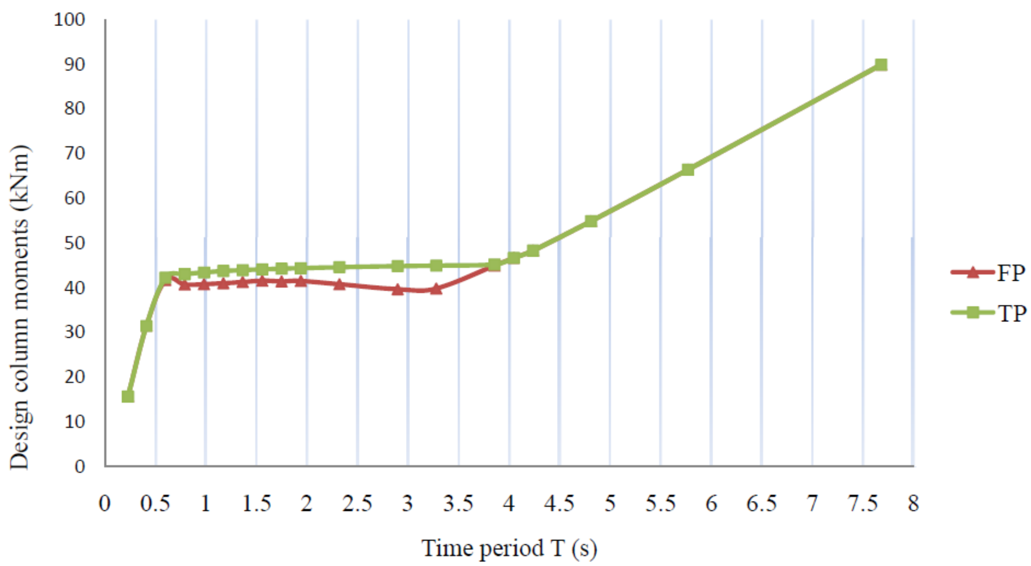

Figure 2. RSM column moments under TP and FP of one bay symmetric buildings

For a particular intermediate floor of any of the considered buildings, the RSM column moments are found identical. This value will be reduced in upper floors as shown in Fig.3. However, column moments at roof floors are not identical because of discontinues end. The behaviour is same in the case of ESM column moments, but the magnitudes are different.

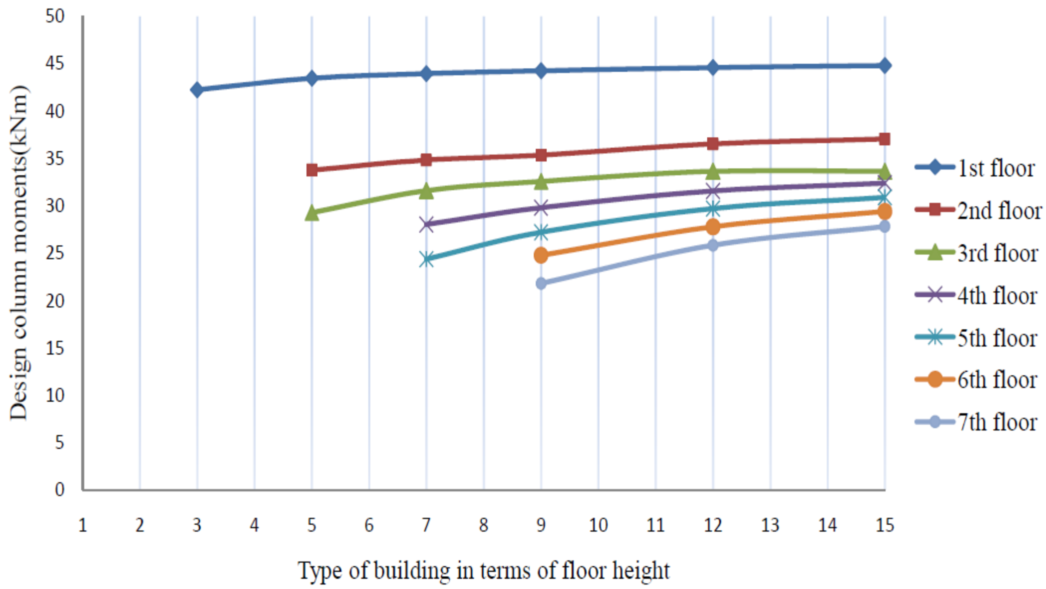

Figure 3. RSM design column moments of intermediate floors of one bay buildings.

The variation between RSM and ESM design column moments of a regular tall building is almost constant. This value is increased for higher floors as constants without depending the total height or number of floors of such building. This is expressed in Fig.4 which can be a useful tool for the designers in this area.

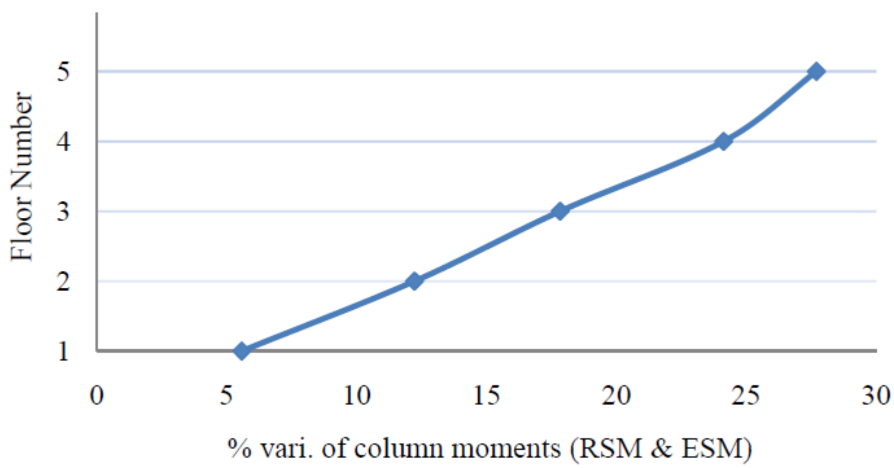

Figure 4. Percentage variation in RSM and ESM column moments of regular tall buildings

The variation was found as linear for initial floors. This figure can be used to predict the dynamic properties of column moments of tall symmetric buildings. This will lead an economic analysis of symmetric tall building using static analysis only

The irregular variation between RSM and ESM column moments of the roof floors are depicted in Fig.5. This is predominant up to 1B7S buildings and after that the column moments has identical values.

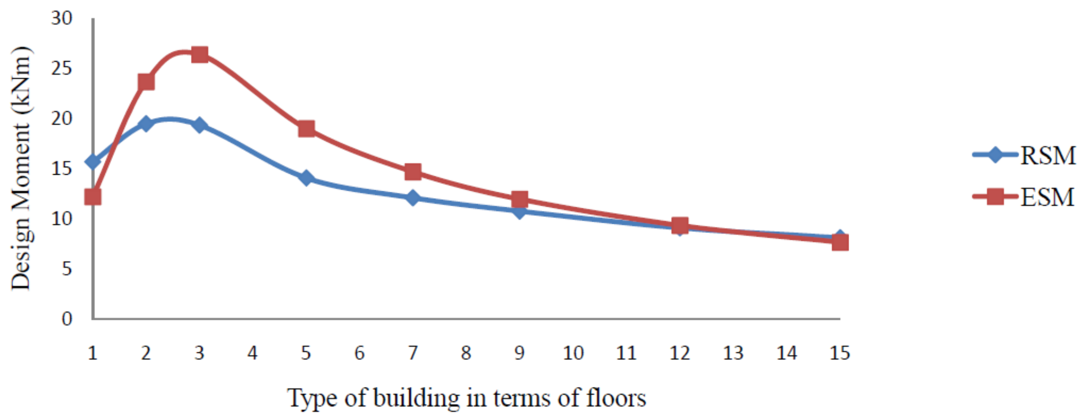

Figure 5. Variation of roof floor RSM design column moments in tall building.

From the initial analysis on single bay buildings, the frames with more than 7 stories has identical behaviour to frame with 7 stories and hence detailed analysis of 2 and 3 bay structures with 9 stories are employed for further investigation. The same behaviour and trend are exhibited by 2B9S and 3B9S buildings. Table 2 & 3 are exhibited similar trends of Table 1 which represents 1B9S.

Table 2 Comparisons of design column moments of a two bay nine storey symmetric building

Story Level	Design column moments (kNm)				% Vari. of RSM & ESM under TP	% Vari. of FP & TP under RSM
	FP		TP			
	RSM	ESM	RSM	ESM		
1	58.84	57.21	61.47	66.41	8.04	4.28
2	59.62	60.96	62.28	70.76	13.62	4.27
3	54.37	58.95	56.8	68.42	20.46	4.28
4	50.03	57.12	52.26	66.29	26.85	4.27
5	45.51	53.81	47.54	62.46	31.38	4.27
6	40.82	48.6	42.64	56.41	32.29	4.27
7	35.17	41.07	36.74	47.67	29.75	4.27
8	27.67	30.65	28.9	35.57	23.08	4.26
9	16.99	17.72	17.75	20.56	15.83	4.28

Table 3 Comparison of design column moments of a three bay nine storey symmetric building

Story Level	Design column moments (kNm)				% Vari.of RSM & ESM under TP	% Vari.of FP & TP under RSM
	FP		TP			
	RSM	ESM	RSM	ESM		
1	63.01	61.23	64.18	70.34	9.60	1.82
2	60.39	61.98	61.52	71.19	15.72	1.84
3	55.91	60.59	56.95	69.59	22.19	1.83
4	51.78	59.02	52.75	67.79	28.51	1.84
5	47.26	55.84	48.14	64.14	33.24	1.83
6	42.39	50.69	43.18	58.22	34.83	1.83
7	36.58	43.15	37.27	49.57	33.00	1.85
8	29.11	32.66	29.66	37.52	26.50	1.85
9	18.46	19.78	18.81	22.72	20.79	1.86

The magnitudes in design column moments are different for 2B9S and 3B9S buildings. The variation between TP and FP design column moments is reduced from 4.27% to 1.84% for 2B9S to 3B9S buildings due to more stability and reduced slenderness ratio. This observation is helped to predict the behaviour of higher bay and higher storey symmetric buildings. Fig.6 gives a comparative illustration if one bay, two bay and three bay tall structures.

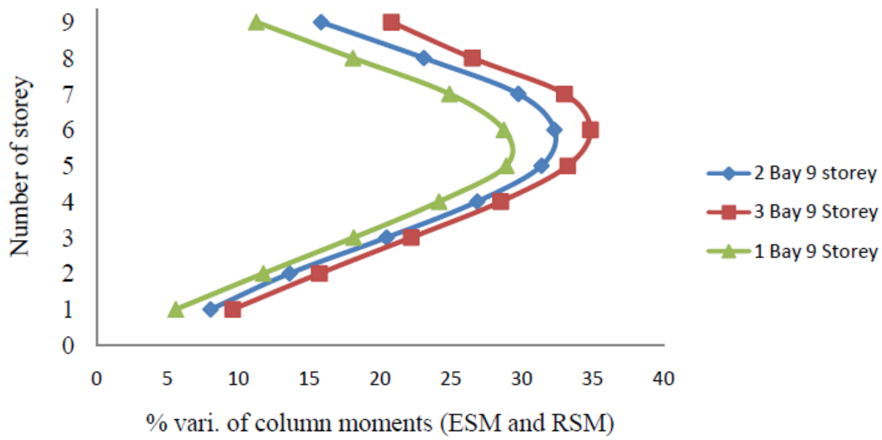

Figure 6. Percentage variation in RSM and ESM column moments of 1B9S, 2B9S and 3B9S buildings.

4.2. Roof Displacements.

Roof displacements are another important parameter to study the behaviour of tall structure under earthquake. Since the buildings considered in this study are symmetric, torsional effects are not much influenced. The roof displacements of extreme columns in ESM have some torsional effect due to the provision of accidental eccentricity in that method. The total drift of the buildings considered in this study are within the limits of the provision of IS code [6] which lead to the assumption of elastic analysis.
Roof displacements are calculated from all the simulation analysis conducted for the design column moments. It is observed that, the roof displacements are more in ESM even for symmetric structures when compared with the RSM (Table 4). The comparison of ESM and RSM roof displacements for one bay symmetric buildings are depicted in Fig.7 which has almost a linear behaviour up to 1B15S.

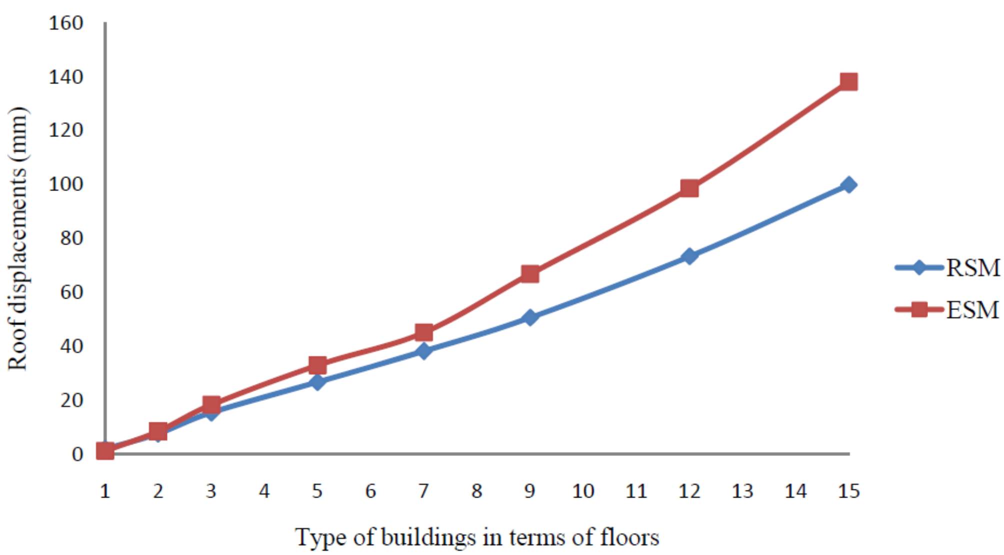

Figure 7. Variation of roof displacement in different one bay building.

The ESM and RSM roof displacements are different from 2nd floor buildings onwards and the difference increased for higher floor buildings as shown in Fig.7. Table 4 represents the ESM and RSM roof displacements of one bay one storey buildings under FP and TP.

Table 4 roof displacements of one bay symmetric multi-storey buildings.

Type of Bldg.	Roof displacement (mm)							
	FP				TP			
	RSM		ESM		RSM		ESM	
	U1	U2	U1	U2	U1	U2	U1	U2
1	1.86	-	1.81	0.08	1.86	-	1.81	0.08
2	7.56	-	8.4	0.36	7.56	-	8.4	0.36
3	15.21	-	17.14	0.71	15.39	-	18.28	0.76
5	25.06	-	30.32	1.21	26.7	-	32.92	1.32
7	35.87	-	40.84	1.69	38.18	-	45.13	1.87
9	47.41	-	59.19	2.14	50.64	-	66.78	2.42
12	67.07	-	84.25	2.77	73.36	-	98.61	3.24
15	88.46	-	113.06	3.33	99.94	-	138.1	4.06

In RSM, the Y directional displacement (U_2) is negligibly small for both FP and TP analysis and in ESM, there are values for U_2 due to the accidental eccentricity provision in the codes. The magnitude of roof displacement is always more in TP both in ESM and RSM. This again reveals the importance of torsional mode in the analysis. However, the variation is not critical in the case of symmetric buildings considered in this study.

From the initial studies it was observed that the character of "tall buildings" starts from 7 storied buildings onwards. The same behaviour is exhibited by the curve which is plotted for the variation between roof displacement under TP and FP as shown in Fig. 8.

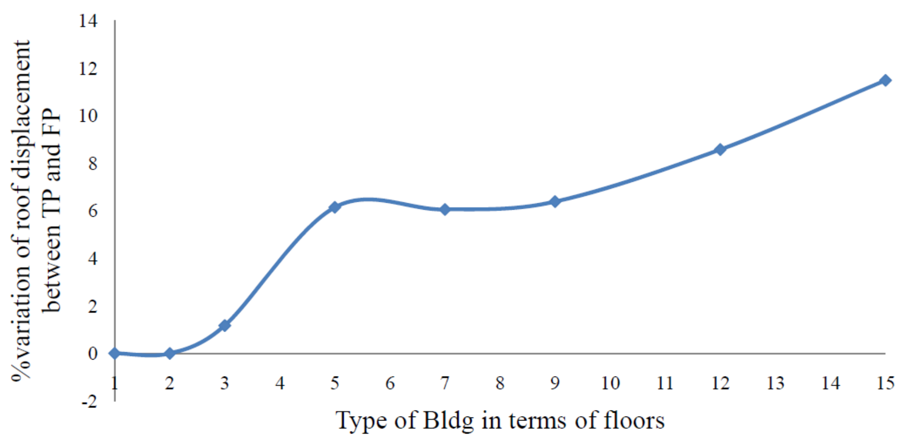

Figure 8. Variation of roof displacement between TP and FP of one bay building.

5. CONCLUSIONS

From the present study, it is observed that the torsional mode has significant effect from law raised buildings onwards even for symmetric structures. Provisions in IS 1893 regarding the ESM for seismic analysis of regular structures are inadequate to provide an effective and economic design for tall symmetric structures. The behaviour of the different floor area symmetric tall structures is same in both ESM and RSM. The maximum percentage variation between these two methods observed in the middle floors, in which ESM is overestimated. The symmetric buildings exhibited torsional effects only when the torsional time period T has a value between 0.55s and 4s. Empirically the height and width of tall symmetrical structures can be fixed based on this time period to eliminate the effect of torsion. Irrespective of the height of the building, column moments of a particular intermediate floor of a tall symmetric structure has the same value. This will help to predict the column moments of tall buildings at any level. The percentage variation of ESM and RSM column moments of a tall symmetric structure is linear. The percentage variation between FP and TP column moments of all floors of a tall symmetric buildings are found constant and this constant value depends on the number of floors of the building. This can be used as a conversion tool in the seismic analysis to accommodate the torsional effects. The bahaviour of two bay and three bay tall symmetric structures with different floor areas are same as one bay tall symmetric structure. ESM has higher values for roof displacement than RSM due to the accidental eccentricity in the provisions.

6. ACKNOWLEDGEMENTS

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