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Design Criteria For Reinforced Concrete Columns Under Seismic Loading

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Abstract

After the devastating Bhuj earthquake, the seismic design of structures is becoming more important. Earthquake induced motion is one of the sources of dynamic loads, that must be considered in the design of structures. The revised code IS 1893-2002 (Part 1) has reclassified the zonal map of India into four zones, thus bringing more than 55% of the area under seismic zones. An attempt has been made in this paper to study the behaviour of interior columns of multistoried building frames in various seismic zones. In normal practice, the interior columns of a symmetric building are designed only for axial loads using IS 456:2000 with a minimum eccentricity. But during earthquakes, higher moments are generated in these interior columns and there is no provision in IS 1893-2002 for the eccentricity to be adopted in the design of columns. Several multistoried building frames were analysed using STAAD Pro and the eccentricities of loading in the interior columns were calculated. Based on the study, suitable equations were developed for each seismic zone to calculate the eccentricity of an interior column in symmetric buildings. This eccentricity can be adopted as the design criterion for the seismic design of interior columns.

1. Introduction

A column is generally a compression member supporting beams and slabs in a structural system and having an effective length exceeding three times the least lateral dimension. A column may be considered to be short when its effective length does not exceed 12 times the least lateral dimension. If the ratio of effective length to least lateral dimension exceeds 12, the column is considered as long or slender for design purposes.

1.1 Slenderness Limits for Columns

The unsupported length between the end restraints shall not exceed 60 times the least lateral dimension of a column. If in any given plane, one end of a column is unrestrained, its unsupported length L, shall not exceed ($100b^2/D$) [1] where, b = width of the cross section, D = depth of the cross section measured in the plane under consideration.

1.2 Minimum Eccentricity

If columns have axial loads and bending moment about either the x or y axes only, they are classified as uni-axially eccentrically loaded columns. The peripheral columns located on the sides of a building are of this category. On the other hand, the corner columns of a building are loaded vertically and in addition they have moments about the x and y axes. These columns are known as bi-axially eccentrically loaded columns. Due to initial crookedness, non-uniformity of concrete and possible eccentricity in loading, all columns may be conceived to be biaxially eccentrically loaded. All columns shall be designed for minimum eccentricity equal to the unsupported length of column / 500 plus lateral dimension / 30, subject to a minimum of 20 mm. The minimum eccentricity is incorporated in the design equation recommended in IS: 456 for axially loaded compression members.

$$P_{uz} = 0.4\, f_{ck}\, A_c + 0.67\, f_y\, A_{sc} \qquad (1)$$

Where, f_{ck} = Characteristic compressive strength of concrete. A_c = Gross sectional area of concrete excluding any finishing material and reinforcing steel. f_y = Characteristic strength of reinforcement. A_{sc} = Cross sectional area of longitudinal steel.

1.3 Permissible Loads in Short Columns

The permissible axial load P on a short column reinforced with longitudinal bars and lateral ties shall not exceed

$$P = \sigma_{cc}\, A_c + \sigma_{sc}\, A_{sc} \qquad (2)$$

Where, σ_{cc} = Permissible stress in concrete in direct compression. A_c = Gross sectional area of concrete excluding any finishing material and reinforcing steel. σ_{sc} = Permissible compressive stress for column bars. A_{sc} = Cross sectional area of longitudinal steel.

1.4 Ultimate load of columns with Negligible Eccentricity (e = 0 to e min)

The ultimate strength of axially loaded columns is to be computed when $\epsilon_{cu} = 0.002$. From the stress-strain diagrams of concrete and steel it will be clearly seen that $f_c = 0.45$, $f_{ck} = (0.67 / 1.5\ f_{ck})$ and $f_s = 0.87\ f_y$ for mild steel. For high strength steels, f_s=0.75 f_y. In the case of biaxial bending, where P_{uz}, the axial load capacity becomes a parameter, the ultimate compressive load is given by

$$P_{uz} = 0.45\ f_{ck}\ A_c + 0.75\ f_y\ A_{sc} \qquad (3)$$

As a further modification to suit eccentricities that are not greater than 0.05 times the lateral dimension, the axial capacity has been reduced to (11% reduction)

$$P_{uz} = 0.4\ f_{ck}\ A_c + 0.67\ f_y\ A_{sc} \qquad (4)$$

1.5 Regular and Irregular Configuration

IS: 1893 – 2002[2] classifies buildings into two types namely, Regular and Irregular buildings. Buildings having simple and regular geometry and uniformly distributed mass in plan as well as in elevation, suffer much less damage than buildings with irregular configuration. A building can be considered as irregular if atleast one of the conditions given in Table 1 and Table 2 is applicable.

Table 1. Definitions of Irregular Buildings – Plan Irregularities

Sl. No.	Irregularity Type and Description
1.	**Torsion irregularity** To be considered when floor diaphragms are rigid in their own plan in relation to the vertical structural elements that resist the lateral forces. Torsion irregularity to be considered to exist when the maximum storey drift, computed with the design eccentricity, at one end of the structure transverse to an axis is more than 1.2 times the average of the storey drifts at the two ends of the structure.
2.	**Re-entrant Corners** Plan configurations of a structure and its lateral force resisting system contains re-entrant corners, where both the projections of the structure beyond the re-entrant corners are greater than the 15 percent of its plan dimension in the given direction.
3.	**Diaphragm Discontinuity** Diaphragm with abrupt discontinuities or variation in stiffness, including those having cut-out or open areas greater than 50% of the gross enclosed Diaphragm area, or change in effective diaphragm stiffness of more than 50% from one storey to the next.
4.	**Out-of-Plane Offsets** Discontinuities in a lateral forces resistance path, such as out-of-plane offsets of vertical elements.
5.	**Non-Parallel Systems** The vertical elements resisting the lateral forces are not parallel to or symmetric about the major orthogonal axes or the lateral force resisting elements.

Table 2. Definitions of Irregular Buildings – Vertical irregularities

Sl. No.	Irregularity type and Description
1.	**a) Stiffness Irregularity – Soft Storey** A soft storey is one in which the lateral stiffness is less than 70 percent of that in the storey above or less than 80 percent of the average lateral stiffness of the three storeys above. b) Stiffness Irregularity – Extreme Soft Storey A extreme soft storey is one in which the lateral stiffness is less than 60 percent of that in the storey above or less than 70 percent of the average stiffness of the three storeys above. For example, buildings on SILTS will fall under this category.
2.	**Mass Irregularity** Mass irregularity shall be considered to exist where the seismic weight of any storey is more than 200 percent of that of its adjacent storeys. The irregularity need not be considered in case of roofs.
3.	**Vertical Geometric Irregularity** Vertical Geometric irregularity shall be considered to exist where the horizontal dimensions of the lateral force resisting system in any storey is more than 150 percent of that in its adjacent storey.
4.	**In-Plane Discontinuity in Vertical Elements Resisting Lateral Forces** A in-plane offset of the lateral force resisting elements greater than the length of those elements.
5.	**Discontinuity in Capacity – Weak Storey** A weak storey is one in which the storey lateral strength is less than 80 percent of that in the storey above. The storey lateral strength is the total strength of all seismic force resisting elements sharing the storey shear in the considered direction

2. Modal Analysis

The failure of the column occurs at the plastic hinge in the eccentric compression side and significant failure starts to occur from the corners at the eccentric compression side [3]. Lower strength than calculated occurred for some high strength columns with close tie spacing, high percentage of longitudinal steel and larger cover [4]. For columns made of high strength concrete under eccentric loading no significant benefit were obtained than normal conventional concrete [5]. In this study, an attempt is made to arrive at a necessary design criterion for the interior columns under various seismic zones.

Two types of regular buildings were taken for the analysis. One has a square plan and the other has a rectangular plan as shown in Figure 1 and Figure 2. Preliminary design was done and the size of columns and beams were arrived. The height of each floor is restricted to 3m. The live load on the floor is assumed as 3kN/m2. The live load on the roof is taken as 0.75kN/m2. The number of stories was taken as 10. Analysis was done using STAAD Pro.

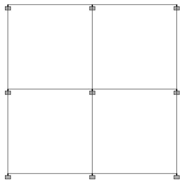

Figure. 1 Square Plan Building

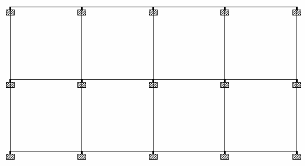

Figure. 2 Rectangular Plan Building

For buildings having square plan the seismic force was applied only in the X–direction as shown in Figure 3. For buildings having rectangular plan the seismic force was applied in the X-direction and also in the Z-direction as shown in Figure 4. The building is analysed in all the four zones with all the load combinations given in IS 1893 – 2002. The Axial load at a section and the maximum moment at any section were obtained using STAAD Pro. Five different span lengths were used in both square and rectangular plan buildings namely 3m, 3.5m, 4m, 4.5m and 5m.

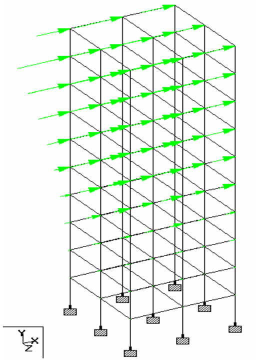

Figure 3. Load application for a Square Plan Building in X direction

The eccentricity at a section can be obtained using the equation

$$e = M/P \qquad (5)$$

Where, e = Eccentricity. M = Maximum Moment at the section. P = Axial Load at the section of the Column

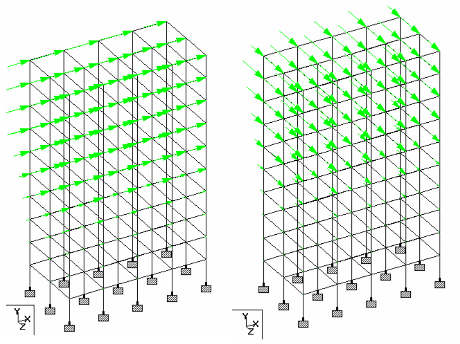

Figure 4. Load application for a Rectangular Plan in Building in X and Z direction

The following Load Combinations recommended in IS: 1893 – 2002 were used in the analysis:

a) 1.5(DL+LL)
b) 1.2(DL+LL+SL)
c) 1.2(DL+LL-SL)
d) 1.5(DL+SL)
e) 1.5(DL-SL)
f) 0.9DL + 1.5SL
g) 0.9DL – 1.5SL

Where, DL = Dead Load. LL = Live Load. SL = Seismic Load.

The Seismic analysis was done using STAAD Pro and the top and bottom moments were obtained for the interior columns at different floors. The eccentricity and eccentricity to depth of the section (e/D) ratios of all the floors were calculated. The Axial load and Moments on the top and bottom of the interior column can be obtained from STAAD Pro as shown in Figure 5 and Figure 6. All the multistoried building frames were analysed and from the Moment and the Load at the top and bottom of the column in each floor was obtained and the eccentricity can be calculated.

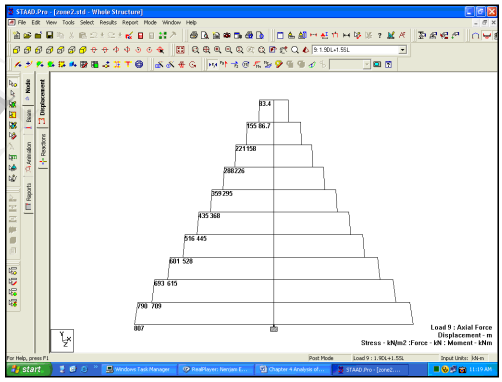

Figure 5. Axial Load Diagram for a 3m span Zone 2 Square Plan Building

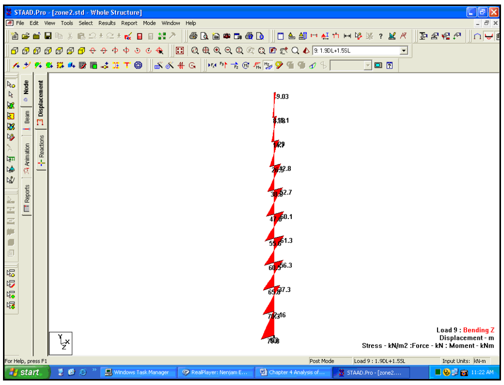

Figure 6. Column Moment Diagram for a 3m span Zone 2 Square Plan Building

3. Results and Discussion

The results obtained from different problems were consolidated. The values of all the top and bottom moments for the interior columns were tabulated with respect to e/D ratio for various spans of buildings and Floor Numbers. Graph was plotted between the e/D ratio and the Floor Number for various spans. Equations were developed for different zones with span of the building and depth of column as variables. The equations were developed for the ground storey and the top storey of the square and rectangular plan buildings. The minimum eccentricity can be calculated from these equations. For other floors the equations can be interpolated and the values of minimum eccentricities can be obtained. The e/D ratio calculation for a 3m span square plan building in zone 2 was given in Table 3 and Table 4.

Table 3. e/D ratio at the top of the column for a 3m span square plan building in zone 2

Floor Number	Moment (kN m)	Load (kN)	Depth (mm)	Eccentricity (mm)	e/D
10	7.32	60.1	230	121.79	0.53
9	17.71	150	230	118.06	0.51
8	21.84	237	230	92.15	0.40
7	25.43	321	240	79.22	0.33
6	35.36	407	275	86.87	0.32
5	38.32	498	300	76.94	0.26
4	42.21	595	330	70.94	0.25
3	38.58	698	350	55.27	0.16
2	29.79	809	375	36.82	0.09
1	3.77	927	400	4.06	0.01

Table 4. e/D ratio at the bottom of the column for a 3m span square plan building in zone 2

Floor Number	Moment (kN m)	Load (kN)	Depth (mm)	Eccentricity (mm)	e/D
10	8.77	68	450	128.97	0.28
9	15.07	165	450	91.33	0.20
8	24.89	263	450	94.63	0.21
7	33.35	362	450	92.12	0.20
6	40.25	463	450	86.93	0.19
5	45.43	566	450	80.26	0.17
4	49.14	673	450	73.01	0.16
3	51.59	783	450	65.88	0.14
2	53.63	897	450	59.78	0.13
1	52.28	1016	450	51.45	0.11

From the results obtained graphs were plotted between e/D ratio and Floor number for all the spans and zones for square and rectangular plan buildings. It is clear that the moment at the top of the column is giving the critical moment. For further discussion only the top moments and the e/D ratios at the top were considered. The e/D ratio of all the zones for a 3m span square building was shown in Figure 7. The e/D ratio profile is slightly different for a rectangular plan building and is shown in Figure 8 for 3m span.

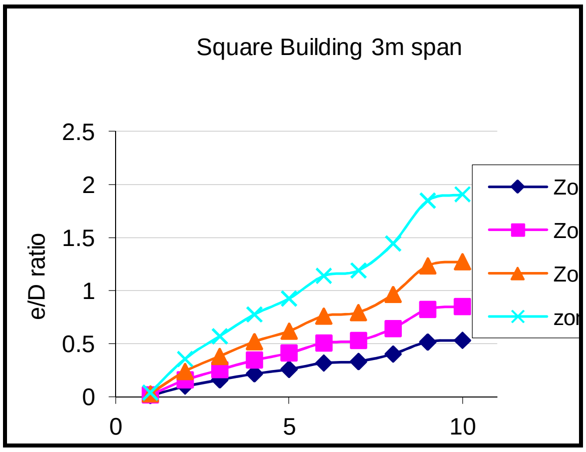

Figure 7. Comparison of e/D ratio of all 4 zones for a 3m Square Plan Building

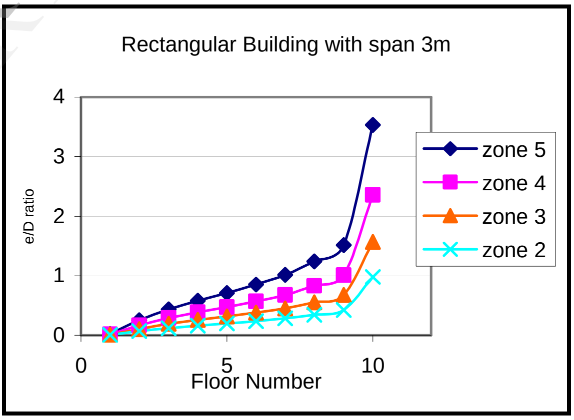

Figure 8. Comparison of e/D ratio of all 4 zones for a 3m Rectangular Plan Building

The details of e/D ratios for different spans for a square plan building in zone 2 were given in Table 5. Figure 9 shows the details of e/D ratio of various floors with respect to the length of the span.

Table 5. e/D ratio for all spans in square plan building in zone 2

	e/D ratio				
Floor	3m	3.5m	4m	4.5m	5m
10	0.53	0.35	0.26	0.20	0.18
9	0.51	0.31	0.19	0.14	0.12
8	0.40	0.25	0.21	0.17	0.14
7	0.33	0.25	0.20	0.16	0.13
6	0.31	0.22	0.17	0.14	0.11
5	0.25	0.18	0.14	0.11	0.09
4	0.21	0.15	0.11	0.09	0.07
3	0.15	0.10	0.08	0.06	0.04
2	0.09	0.06	0.04	0.03	0.02
1	0.01	0.0007	0.002	0.003	0.005

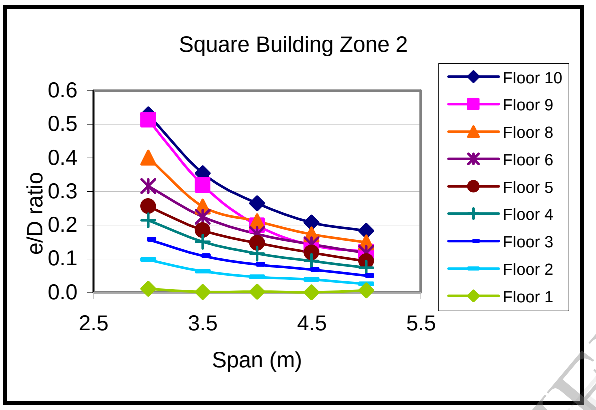

Figure 9. e/D ratio in different span length for various floors in zone 2

The details of e/D ratio for a square plan building having different spans were compared from Figure 10 to Figure 12.

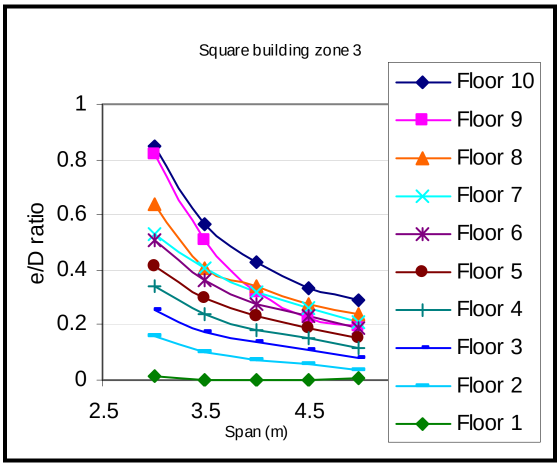

Figure 10. e/D ratio in different span length for various floors in zone 3

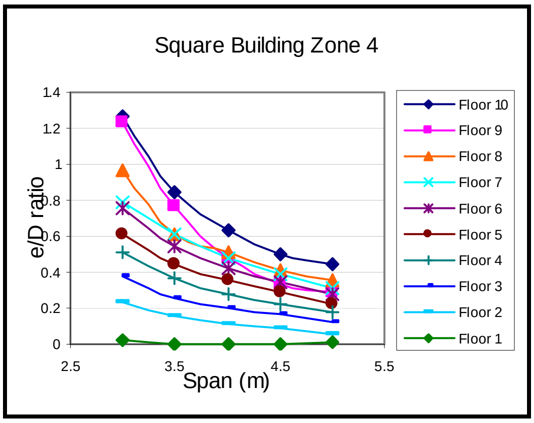

Figure11. e/D ratio in different span length for various floors in zone 4

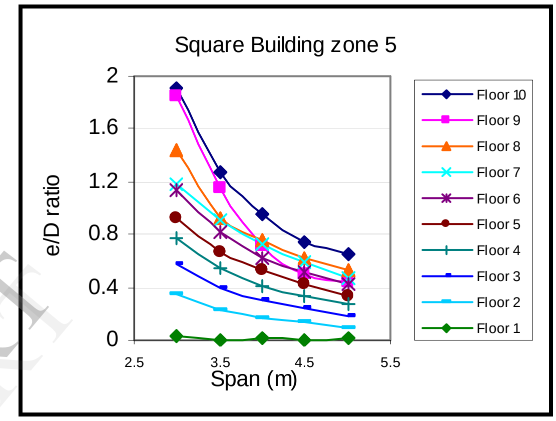

Fig. 12 e/D ratio in different span length for various floors in zone 5

The same analysis methods was used for the rectangular plan building and the e/D ratios of various spans and in various zones were given from Table 6 to Table 9.

Table 6. e/D ratio for all spans in rectangular plan building in zone 2

Floor No	e/D ratio				
	3m	3.5m	4m	4.5m	5m
10	0.98	0.76	0.84	0.66	0.50
9	0.42	0.32	0.30	0.26	0.18
8	0.34	0.26	0.22	0.211	0.13
7	0.28	0.22	0.16	0.17	0.10
6	0.23	0.18	0.12	0.13	0.07
5	0.19	0.15	0.08	0.11	0.04
4	0.16	0.12	0.04	0.08	0.02
3	0.12	0.09	0.011	0.06	0.002
2	0.07	0.05	0.02	0.02	0.021
1	0.006	0.008	0.06	0.01	0.04

Table 7. e/D ratio for all spans in rectangular plan building in zone 3

Floor No	e/D ratio				
	3m	3.5m	4m	4.5m	5m
10	1.57	1.209	1.35	1.05	0.803
9	0.67	0.51	0.48	0.42	0.30
8	0.55	0.42	0.36	0.33	0.22
7	0.45	0.343	0.26	0.27	0.16
6	0.37	0.28	0.19	0.22	0.11
5	0.31	0.23	0.13	0.18	0.07
4	0.25	0.19	0.07	0.14	0.03
3	0.19	0.14	0.01	0.09	0.003
2	0.10	0.078	0.047	0.04	0.03
1	0.0099	0.012	0.10	0.02	0.07

Table 8. e/D ratio for all spans in rectangular plan building in zone 4

Floor No	e/D ratio				
	3m	3.5m	4m	4.5m	5m
10	2.3	1.81	2.02	1.58	1.20
9	1.01	0.77	0.72	0.63	0.45
8	0.82	0.63	0.54	0.50	0.33
7	0.67	0.51	0.40	0.40	0.24
6	0.56	0.43	0.29	0.33	0.17
5	0.47	0.35	0.19	0.27	0.11
4	0.38	0.28	0.11	0.21	0.05
3	0.28	0.21	0.02	0.14	0.005
2	0.16	0.11	0.06	0.06	0.05
1	0.01	0.018	0.16	0.03	0.11

Table 9. e/D ratio for all spans in rectangular plan building in zone 5

Floor No	e/D ratio				
	3m	3.5m	4m	4.5m	5m
10	3.53	2.72	3.04	2.38	1.80
9	1.51	1.16	1.09	0.95	0.68
8	1.24	0.95	0.82	0.75	0.49
7	1.01	0.77	0.60	0.61	0.36
6	0.85	0.64	0.43	0.50	0.25
5	0.70	0.53	0.29	0.40	0.16
4	0.57	0.43	0.16	0.31	0.08
3	0.43	0.31	0.03	0.21	0.007
2	0.24	0.17	0.094	0.10	0.076
1	0.022	0.027	0.24	0.053	0.16

4. Equations

Equations were developed for the e/D ratios of top and the bottom storey interior columns for each zone with length of the span and depth of column as the variables. For the intermediate stories the minimum eccentricity can be calculated by interpolation. Table 10 shows the equations for calculating the e/D ratio for various zones for a square plan building and Table 11 is for a rectangular Plan building.

Table 10. Equations for top and bottom storey eccentricity in various zones for a square plan building

Sl. No.	Zone	Top Storey	Bottom Storey
1	II	$0.095S^2 - 0.93S + 2.46$	$0.008S^2 - 0.06S + 0.13$
2	III	$0.152S^2 - 1.48S + 2.93$	$0.012S^2 - 0.10S + 0.21$
3	IV	$0.229S^2 - 2.23S + 5.89$	$0.018S^2 - 0.15S + 0.31$
4	V	$0.343S^2 - 3.34S + 8.83$	$0.028S^2 - 0.23S + 0.47$

Where, S = Span Length.

Table 11. Equations for top and bottom storey eccentricity in various zones for a rectangular plan building

Sl. No.	Zone	Top Storey	Bottom Storey
1	II	$0.59S^4 - 9.64S^3 + 58.34S^2 - 155.02S + 153.55$	$0.25S^4 - 3.97S^3 + 23.40S^2 - 60.57S + 58.02$
2	III	$0.95S^4 - 15.43S^3 + 93.34S^2 - 248.01S + 245.65$	$0.40S^4 - 6.34S^3 + 37.44S^2 - 96.91S + 92.83$
3	IV	$1.42S^4 - 23.16S^3 + 140.06S^2 - 372.15S + 368.61$	$0.60S^4 - 9.52S^3 + 56.16S^2 - 145.36S + 139.24$
4	V	$2.13S^4 - 34.74S^3 + 210.11S^2 - 558.27S + 552.96$	$0.89S^4 - 14.28S^3 + 84.25S^2 - 218.06S + 208.88$

Where, S = Span Length.

The above equations are for minimum eccentricity in respect of top and bottom storey interior columns for each zone with length of the span and depth of the column as variables. For the intermediate stories, the minimum eccentricity can be calculated by interpolation.

5. Conclusion

It is observed from the e/D ratios that even in mild earthquake Zone (i.e. Zone 2), the minimum eccentricity given in IS 456 – 2000 is exceeded. The e/D ratio is found to decrease when the span is increased. In addition, the e/D ratio is found to increase from bottom storey towards the top storey. It is also found out that e/D ratio increases with the Zone Number. Equations have been developed for finding the minimum eccentricity of interior columns of multistoried building frames. This minimum eccentricity can be used as the design criterion for the seismic design of interior columns of multistoried building frames.

6. References

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