CHAPTER 5
SEISMIC EVALUATION OF RC FRAMES WITHOUT INFILL WALLS

5.1 GENERAL REMARKS

The 2001 Bhuj earthquake of India was an eye opener. It made thousands of people lose their lives and rendered millions to lose their houses. The effect was so wide spread that it not only affected the people in the vicinity of the epicenter but those living in a metro city Ahmedabad, about 250 km away from the epicenter were badly affected. One more time it revealed the inherent weakness lying in the concrete building which are not detailed as per ductile detailing. A major damage was observed in RC framed structures which were in the range of ground + three storey (G+3) to (G+7) storey. Further, these buildings were having a normal grid of 3m x 3m column spacing with a normal storey height of 3m.

Due to aesthetic considerations, the columns were generally 230mm wide in order to be flush with the 230 mm thick brick wall which is a standard building material used in India. Hence, keeping all these factors in mind, it is decided to study a typical RC building frame having these dimensions under pushover analysis and to report the findings in a systematic manner. It is also decided to study another structure having a panel size to be 3m x 4.5m to incorporate the effect of asymmetry. It is proposed to subject these two models to pushover analysis and compare their performance by using a commercial software SAP2000.

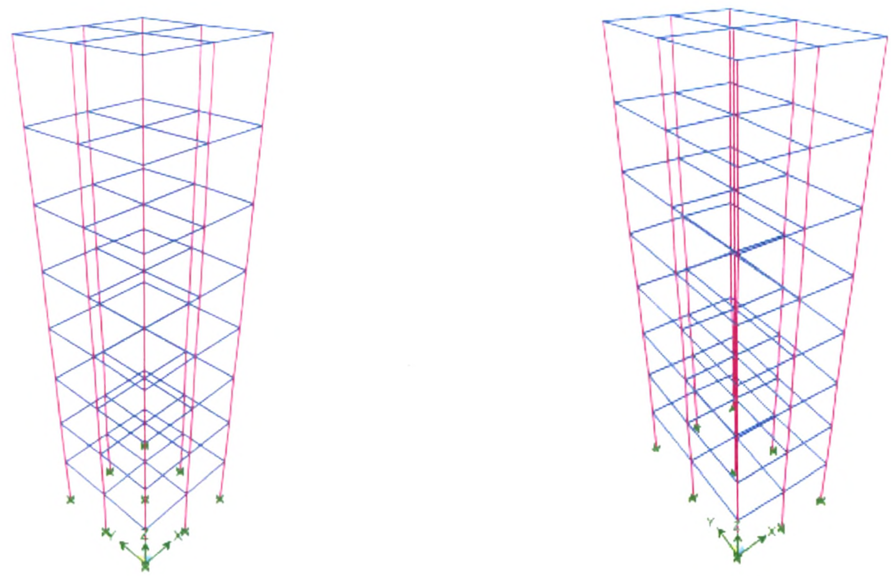
5.2 STEPS FOR ANALYSIS THROUGH SAP2000

The following general sequence of steps are followed in performing a nonlinear static pushover analysis using SAP2000 software:

1. Create a model Keeping in mind that material nonlinearity and pushover analysis results are restricted to frame elements, although other element types may be present in the model.
2. Define the static load cases, like dead, live, etc. that are needed for use in the pushover analysis (Define > Static Load Cases).
3. Define any other static and dynamic analysis cases, like quake, response spectrum, etc. that may be needed for steel or concrete design of frame elements.
4. Define the pushover load cases (Define > Static Pushover Cases).
5. Define hinge properties (Define > Hinge Properties).
6. Assign hinge properties to frame elements (Assign > Frame > Hinges (Pushover)).
7. Run the basic linear and dynamic analyses (Analyze > Run).
8. If any concrete hinge properties are based on default values to be computed by the program, one must perform concrete design so that reinforcing steel is determined (Design > Concrete Frame Design > Start Design/Check of Structure).
10. Run the pushover analysis (Analyze > Run Static Pushover).
11. Review the pushover results (Display > Show Static Pushover Curve), (Display > Show Deformed Shape), (Display > Show Element Forces/Stresses > Frames...), and (File > Print Output Tables... Frame forces in spreadsheet format).
12. Revise the model as necessary and repeat.

5.3 MATHEMATICAL MODELS DEVELOPED

There are two mathematical models developed for a Ground + 6 storey (G+6) RC space frame. **Figure 5.1** shows an isometric view of the two models considered: a) with an overall plan dimensions of 6m x 6m and b) with plan dimensions as 6m x 9m overall.



a) G+6 with 3m x 3m panels b) G+6 with 3m x 4.5m panels

Fig. 5.1 The Models Considered for Pushover Analysis

Typical plan views of the 6m x 6m and 6m x 9m overall dimension models are as shown in **Fig. 5.2**.

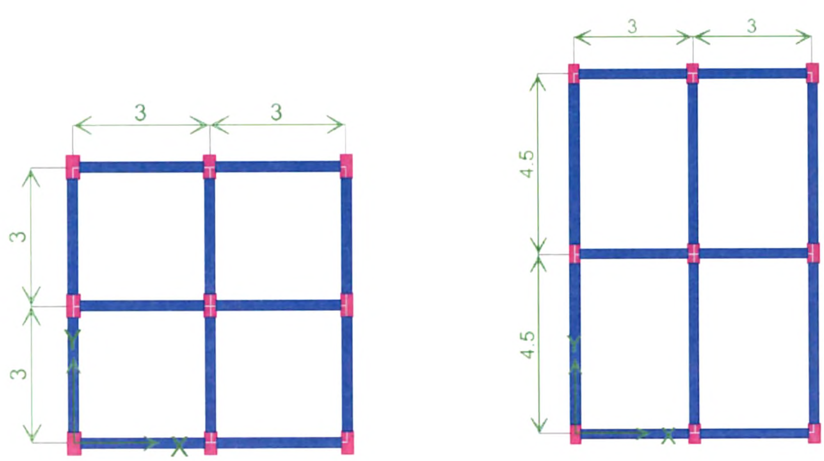


Fig. 5.2 Plan View Showing Orientation of Rectangular Columns

5.3.1 Geometry and Loads Considered

Panel size = 3m x 3m

Number of panels in each direction = 2

Overall plan dimension = 6m x 6m

Storey height = 3m

Column size = Rectangular columns - 230mm x 450mm

Equivalent square columns - 322mm x 322mm

Beam size = 230mm x 450mm

The loading is considered as follows:

Dead load : on typical floors 4 kN/sq.m., on terrace floor 6 kN/sq.m.

Live load : on typical floors 2 kN/sq.m., on terrace floor 1.5 kN/sq.m.

Wall load of 20 kN/m is considered on all peripheral beams of typical floors and it is considered as 6 kN/m on the terrace floor peripheral beams to account for parapet wall. The columns are extended for 3m below plinth level and are considered as fixed at the foundation level. The lateral loads due to earthquake are considered in the two lateral directions X and Y as per the method given in IS 1893 (Part 1) : 2002 **[24]**. The building is considered to be located in zone III as per the code with an importance factor of 1 and a response reduction factor of 3.

The static analysis is carried out with following four basic load cases :

1. Dead Load (DL) 2. Live load (LL) 3. Earthquake load X (EX) and
4. Earthquake load Y (EY).

5.3.2 Defining the Pushover Load Parameters

There are four categories of default plastic hinges defined in the software. They are: i) The axial hinge (P), ii) The flexural hinge corresponding to M3 moment (M), iii) The shear hinge (V) and iv) The combined axial (P) and flexural hinges (M2 & M3) designated as PMM hinge. To understand the behavior of the considered 3D RC frame, all the four types of hinges are defined at the ends of all beams and columns. A separate account is kept for the development of each of these hinges when a push is given. There are two lateral push defined in the X and Y direction. First, a push is given in the gravity direction up to the full magnitude of dead and live load. Later, a lateral push is given in each of the plan directions, i.e. X and Y defined as PUSH1 and PUSH2 which are displacement controlled. The target displacement is defined as 4% of the building height.

The values of S_A and S_D are noted at each step of the lateral push and a capacity spectrum in ADRS format is plotted. This spectrum is converted into a bilinear curve as per the procedure mentioned in ATC-40 **[1]**. The demand spectrum based on the design response spectrum given in IS 1893 Part 1 : 2002 **[24]**, is also constructed in the ADRS format and it is plotted as a reduced demand spectrum on the same plot as the capacity spectrum. The intersection point of the reduced demand spectrum with the capacity spectrum, known as the performance point is evaluated and reported. The mathematical steps are given in the next section.

5.4 RESULTS OF THE PUSHOVER ANALYSIS

The static analysis is carried out in SAP2000 for the four basic load cases. In all 13 load combinations as prescribed in IS-1893 Part 1, 2002 are defined. Design of all the beams and columns of the frame is carried out. Next, pushover analysis is carried out as per the three pushover cases defined in 5.3.2 above. Thé results for rectangular columns are noted down from the software in a tabular form as given in **Table 5.1** and the same is represented in the bilenear form in **Fig. 5.3**.

Table 5.1 Capacity Curve values for Rectangular Columns

Displacement D_{roof} in mm	Base Shear V kN	Sa (g)	Sd mm
0.00	0.00	0.00	0.00
10.00	703.92	0.09	7.87
20.00	1402.73	0.17	15.83
30.00	2096.46	0.26	23.70
40.00	2437.17	0.30	27.56
50.00	2976.56	0.36	35.75
60.00	3357.83	0.41	45.75
60.00	3396.05	0.41	47.32
60.00	3399.23	0.42	47.48
60.00	3400.49	0.42	47.64
70.00	3276.90	0.40	55.51
80.00	3164.93	0.39	63.39
90.00	3059.42	0.37	71.18
100.00	2964.44	0.36	78.66

In **Table 5.1**, $Sa=(V/W*\dot{\alpha})$, $Sd=D_{roof}/P_F\phi$, $P_F=9.53$ (Modal Participation factor), $\dot{\alpha}=0.75$ (Modal Mass coefficient for the 1st natural mode), $\Phi=0.134$ (Amplitude of mode 1 at roof) and W=10920 kN (Weight of the building).

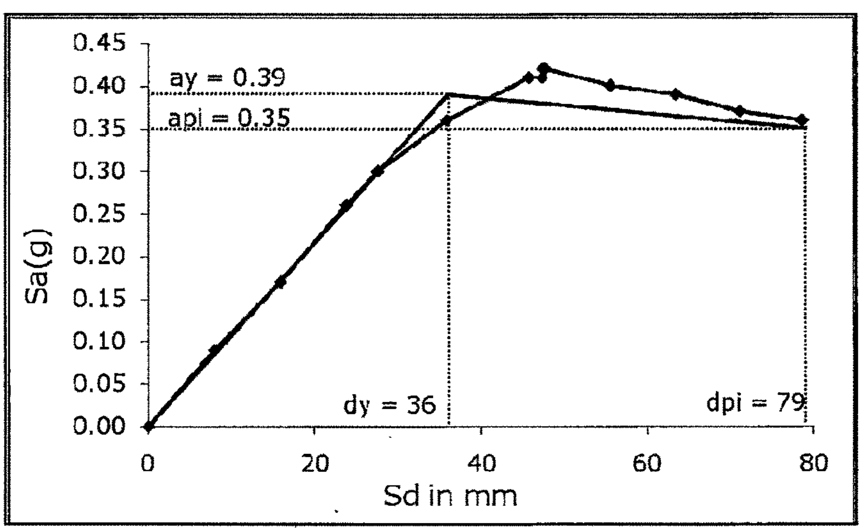


Fig. 5.3 Capacity Curve for Rectangular Columns

The values of ay, api, dy and dpi extracted from **Fig. 5.3** are used to reduce the initial demand spectrum given in IS 1893 for 5% damping and the values are presented in **Table 5.2**.

Table 5.2 Demand Curve Values for Rectangular Columns

Original Demand		Reduced Demand	
Sa in g	**Sd in mm**	**Sa in g**	**Sd in mm**
1.15	0.03	1.00	0.00
1.30	0.13	1.15	0.03
1.45	0.33	1.30	0.13
1.60	0.64	1.45	0.33
1.75	1.09	1.60	0.64
1.90	1.71	1.75	1.09
2.05	2.51	1.90	1.71
2.20	3.52	2.05	2.51
2.35	4.76	2.20	3.52
2.50	6.25	2.35	4.76
2.50	25.00	0.83	8.25
2.50	56.25	0.83	18.56
2.50	100.00	0.83	33.00
2.50	156.25	0.83	51.56
2.50	189.06	0.83	62.39
2.26	203.40	0.83	101.70
1.94	237.65	0.83	118.83
1.70	272.00	0.83	136.00
1.51	305.78	0.76	152.89
1.36	340.00	0.68	170.00
0.68	680.00	0.34	340.00
0.45	1012.50	0.23	506.25
0.34	1360.00	0.17	680.00

Thus, it is seen that as the pushover proceeds into inelastic zone, and as the plastic hinges get developed in the members of the structure, the inherent damping increases from 5% to higher values, thus reducing the demand on the structure. The plot of capacity spectrum in ADRS format as in **Fig. 5.3** is superimposed on the demand spectrum in **Fig. 5.4**. The intersecting point of capacity spectrum and the demand spectrum is known as the performance point. The damping is evaluated using the relations given by **Eq. 4.5** and **Eq. 4.7**. This will yield the performance point for the model of G+6 frame having rectangular shaped columns. It is seen from the plot of **Fig. 5.4** that the capacity spectrum does not intersect demand spectrum and hence the performance point does not exist for this mathematical model.

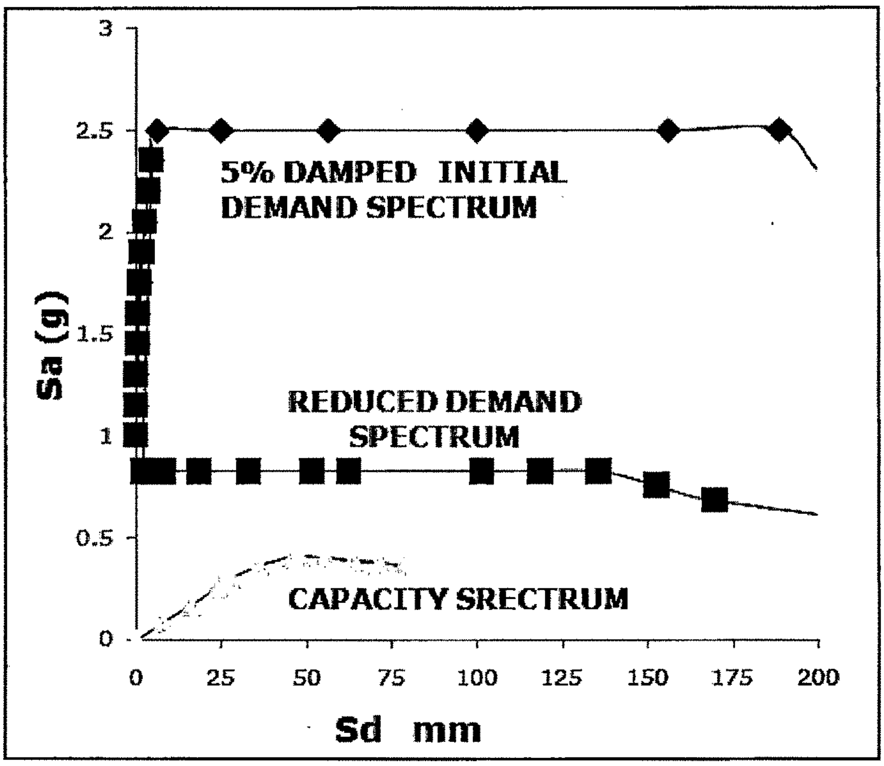


Fig. 5.4 Performance Point for Rectangular Columns

A similar procedure is carried out for equivalent square columns, where the size of the square columns is evaluated by keeping the same cross sectional area as that of rectangular columns. Thus, an equivalent square column for a rectangular column of 230 mm x 450 mm works out to be sqrt (230 x 450) = 322 mm. The capacity curve for square columns is based on the values evaluated from the SAP2000 software which is presented in **Table 5.3**. Based on these values, a capacity spectrum in a bilinear form is drawn as depicted in **Fig. 5.5**.

Table 5.3 Capacity Curve values for Square Columns

Displacement D_{roof} in mm	Base Shear V kN	Sa (g)	Sd mm
0.00	0.00	0.00	0.00
12.31	869.91	0.20	8.80
24.63	1735.37	0.40	17.59
36.94	2596.39	0.59	26.39
49.26	3452.99	0.79	35.19
61.57	4305.18	0.99	43.98
73.89	5152.98	1.18	52.78
83.84	5838.21	1.34	59.89
98.46	6805.90	1.56	70.33
110.87	7511.15	1.72	79.19
123.11	8062.15	1.85	87.94

In **Table 5.3**, P_F = 9.87, ά = 0.79, Φ = 0.132 and W = 10920 kN

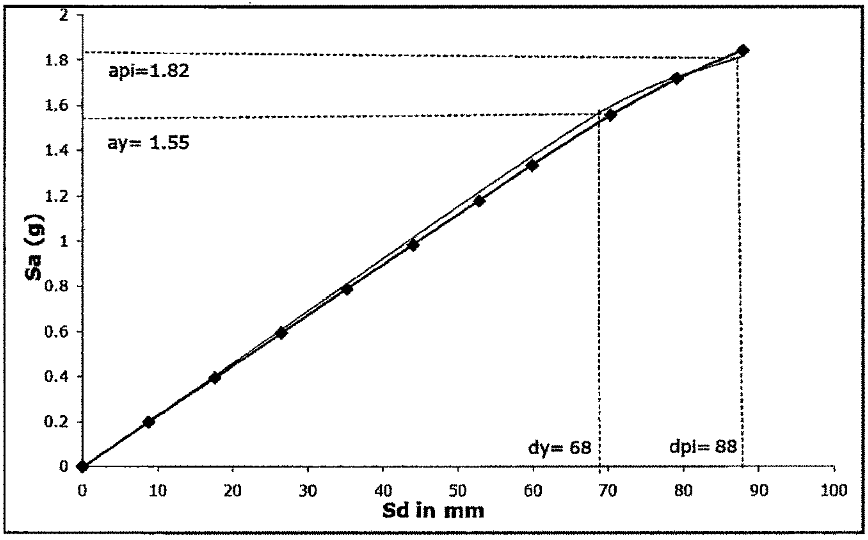


Fig. 5.5 Capacity Curve for Square Columns

The values of ay, api, dy and dpi which are noted from **Fig. 5.5** are used to develop the reduced demand spectrum whose values are given in **Table 5.4**.

Table 5.4 Demand Curve values for Square Columns

Original Demand		Reduced Demand	
Sa in g	Sd in mm	Sa in g	Sd in mm
1.15	0.03	1.00	0.00
1.30	0.13	1.15	0.03
1.45	0.33	1.30	0.13
1.60	0.64	1.45	0.33
1.75	1.09	1.60	0.64
1.90	1.71	1.75	1.09
2.05	2.51	1.90	1.71
2.20	3.52	2.05	2.51
2.35	4.76	2.20	3.52
2.50	6.25	2.35	4.76
2.50	25.00	0.83	8.25
2.50	56.25	0.83	18.56
2.50	100.00	0.83	33.00
2.50	156.25	0.83	51.56
2.50	189.06	0.83	62.39
2.26	203.40	0.83	101.70
1.94	237.65	0.83	118.83
1.70	272.00	0.83	136.00
1.51	305.78	0.76	152.89
1.36	340.00	0.68	170.00
0.68	680.00	0.34	340.00
0.45	1012.50	0.23	506.25
0.34	1360.00	0.17	680.00

The superimposed plot of capacity spectrum on the original 5% damped and reduced demand spectrum calculated using **Eq. 4.5** is presented in **Fig. 5.6**. It is seen from this plot that the reduced demand spectrum intersects the capacity spectrum at a point which is the performance point. Thus, the performance point in the ADRS format is represented as (35, 0.8g).

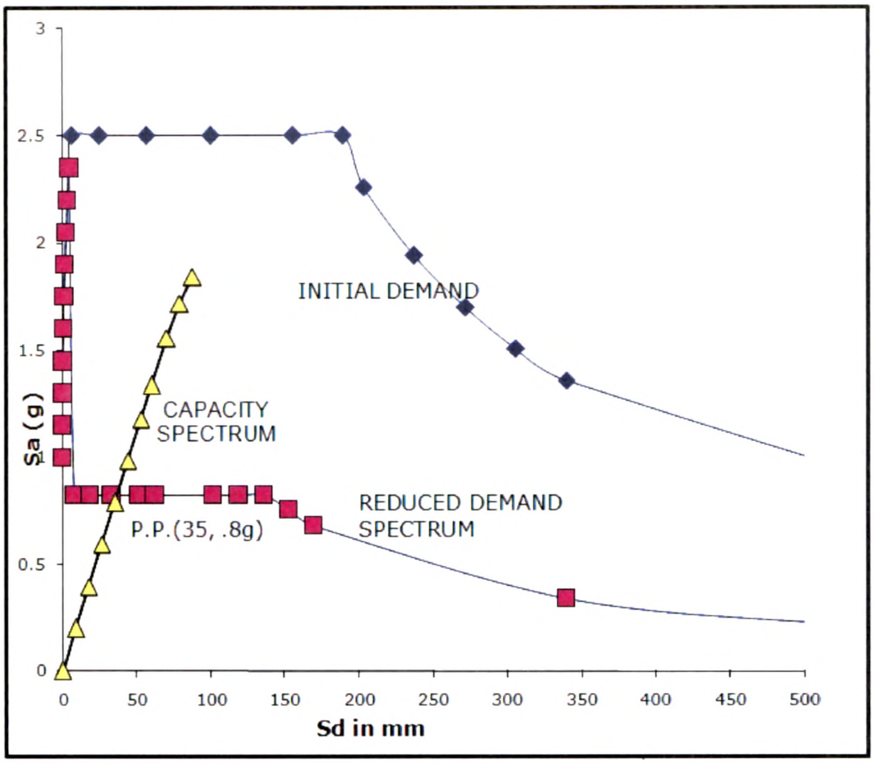


Fig. 5.6 Performance Point for Square Columns

Moreover, another comparison between the performance of rectangular (R) and square (S) columns is made by noting down the data for the plastic hinges developed in column elements and beam elements. The number as well as stress level of the hinges is an indication of the performance of the building. Under these circumstances, a detailed account of number of hinges developed and it's corresponding stress level is presented for square and rectangular columns.

This comparison is presented in **Tables 5.5** and **5.6** for hinges developed in beams and columns in both the models and it is also represented graphically with colour coded hinges in **Figs. 5.7** and **5.8**. The final deformed shapes of both the models having rectangular and square columns with colour coded hinges is shown in **Fig. 5.9.**

Table 5.5 Beam Hinges Developed in R and S Column Models

Hinge Type	Push Dir.	Category of hinges															
		B-IO		IO-LS		LS-CP		CP-C		C-D		D-E		TOTAL		Disp. in mm	
		R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S
M	x	9	4	0	1	2	0	0	0	1	1	0	0	12	6	0.24	7
M	Y	9	6	1	0	0	0	0	0	0	0	0	0	10	6	40	9
PMM	x	4	4	1	3	1	3	0	0	0	0	0	0	6	10	0.25	28
PMM	Y	4	14	0	3	2	1	0	0	0	3	0	0	6	21	48	31
V	x	1	1	0	0	0	0	0	0	1	1	0	0	2	2	0.29	29
V	Y	3	32	1	18	0	2	0	1	0	0	0	0	4	53	60	60
P	x	0	0	36	0	12	0	12	0	8	0	0	0	68	0	3.6	60
P	Y	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	60

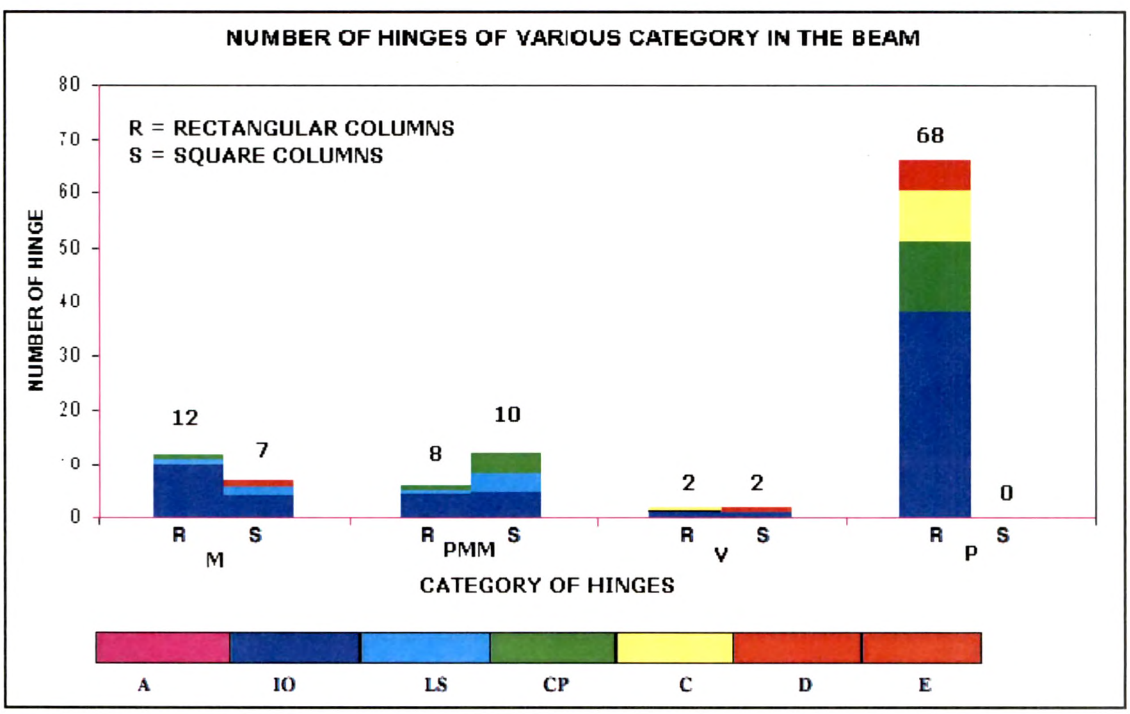


Fig. 5.7 Hinges Developed in Beams for Push in X-Direction

Table 5.6 Column Hinges Developed in R and S Column Models

Hinge Type	Push Dir.	Category of hinges														Displ. in mm	
		B-IO		IO-LS		LS-CP		CP-C		C-D		D-E		TOTAL			
		R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S
M	x	88	4	0	1	0	0	0	0	0	2	0	0	88	7	3.05	7
M	Y	0	6	0	0	0	0	0	0	0	0	0	0	0	6	60	6
PMM	x	26	1	4	1	15	1	0	0	0	0	0	0	45	3	1.31	33
PMM	Y	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	28
V	x	4	1	16	0	0	0	4	0	4	1	0	0	28	2	31	29
V	Y	0	1	0	0	0	0	0	0	0	1	0	0	0	2	60	30
P	x	0	0	2	0	0	0	0	0	2	0	0	0	4	0	1.6	60
P	Y	0	0	0	0	0	0	0	0	0	0	0	0	88	0	60	60

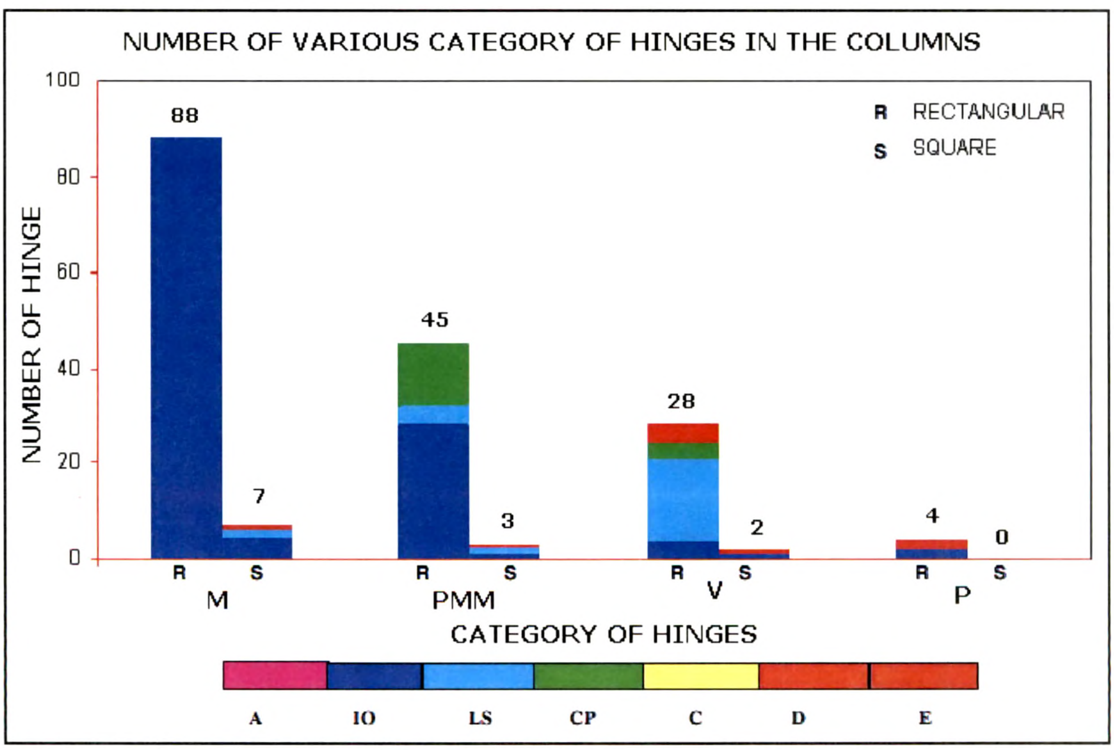
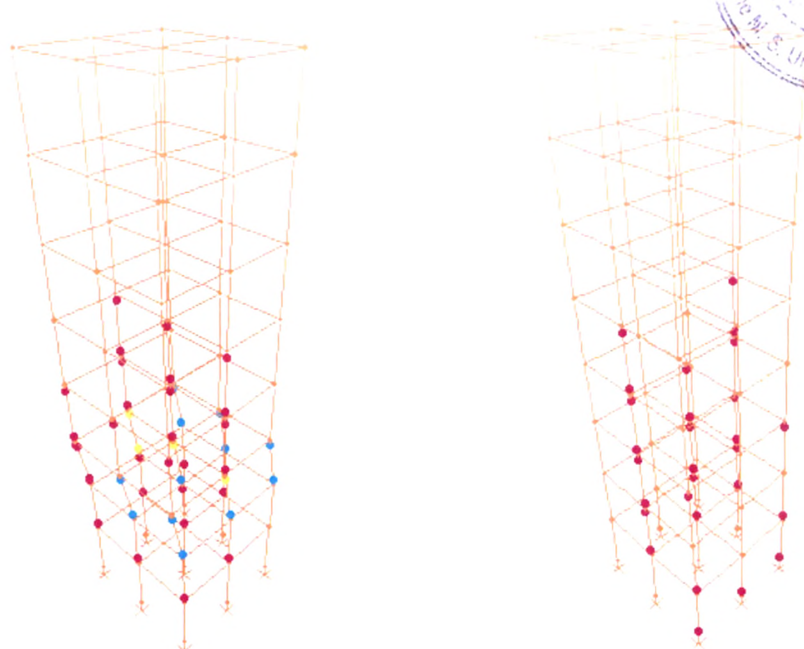


Fig. 5.8 Hinges Developed in Columns for Push in X-Direction



a)Rectangular Columns b)Square Columns

IO= Immediate Occupancy, LS = Life Safety, CP = Collapse Prevention

Fig. 5.9 Hinges Developed in R & S Models under Push in X-Direction

One more important factor under lateral loads which is directly related to the performance of a structure is the storey drift. The drift values for the square and rectangular columns for the 3m x 3m panel size are presented in **Table 5.7** and the corresponding plot is presented in **Fig. 5.10**.

Table 5.7 Storey Drift for R & S Models under Push in X-Direction

Storey Level	Drift in mm	
	Square Columns	Rectangular Columns
7	6.09	2.02
6	9.92	3.74
5	13.67	5.47
4	17.04	7.88
3	20.33	11.46
2	23.15	59.36
1	21.71	9.44
0	11.21	2.11

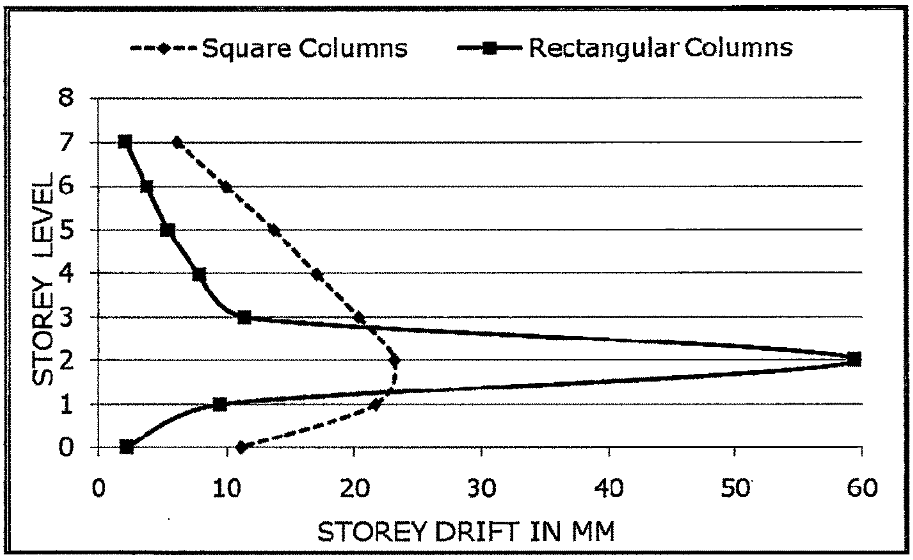


Fig. 5.10 Storey Drift for R & S Models under Push in X-Direction

Similar observations are made for a panel size of 3m x 4.5m with a G+6 storey space frame. The mathematical model developed for the same is shown in **Fig. 5.1 b)**. The results obtained in terms of capacity spectra along with bilinear representations are presented. The capacity values to construct the capacity curve for bilinear representation for rectangular columns, noted from the output of SAP2000 software, are presented in **Table 5.8**. The bilinear curve is drawn in **Fig. 5.11** and all relevant values are calculated from the same.

Table 5.8 Capacity for Rectangular Columns with 3 m x 4.5 m panel

Displacement D_{roof} in mm	Base Shear V kN	Sa (g)	Sd mm
0	0	0	0
3.38	11533.44	1.1	2.68
4.38	14527.97	1.38	3.47
5.48	16166.25	1.54	4.35
22.01	25292.6	2.4	17.47

P_F = 0.34, ά = 0.76, Φ = 3.71 and W = 13854 kN

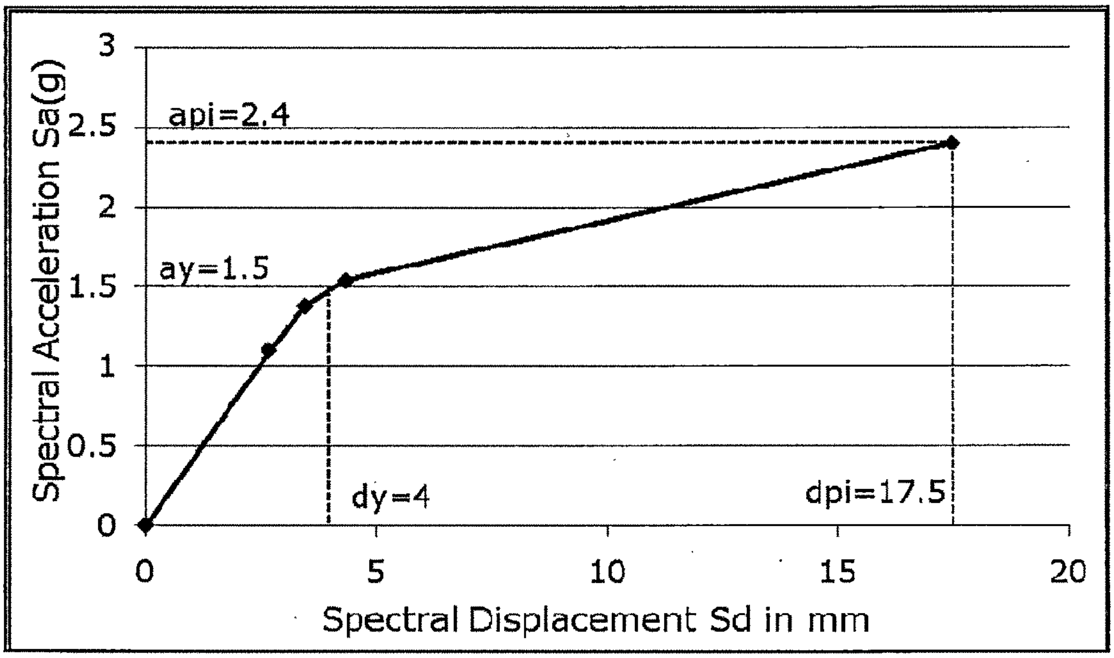


Fig. 5.11 Bilinear Curve for Rectangular Columns

From bilinear curve, api = 2.4, ay = 1.5, dy = 4, dpi = 17.46

Beq = βo+5 = 0.637{(ay*dpi-dy*api)}/api*dpi+5 = 25.21 + 5 = 30.21

From ATC 40, S_{RA} = 0.4 and S_{RV} = 0.55

The relevant values of effective damping are evaluated and are used to reduce the demand spectrum for rectangular columns. The values for constructing the reduced demand spectrum are presented in **Table 5.9** and the plot of capacity spectrum superimposed on reduced demand spectrum to get the performance point is shown in **Fig. 5.12**.

The performance point obtained from **Fig. 5.12** for a 3m x 4.5m panel size with rectangular columns in ADRS format is (2.5, 1g).

Table 5.9 Reduced Demand Values for Rectangular Columns

Original Demand		Reduced Demand	
Sa in g	Sd in mm	Sa in g	Sd in mm
1.15	0.03	0.46	0.01
1.30	0.13	0.52	0.05
1.45	0.33	0.58	0.13
1.60	0.64	0.64	0.26
1.75	1.09	0.70	0.44
1.90	1.71	0.76	0.68
2.05	2.51	0.82	1.00
2.20	3.52	0.88	1.41
2.35	4.76	0.94	1.90
2.50	6.25	1.00	2.50
2.50	25.00	1.00	10.00
2.50	56.25	1.00	22.50
2.50	100.00	1.00	40.00
2.50	156.25	1.00	62.50
2.50	189.06	1.00	75.63
2.26	203.40	0.90	81.36
1.94	237.65	1.07	130.71
1.70	272.00	0.94	149.60
1.51	305.78	0.83	168.18
1.36	340.00	0.75	187.00
0.68	680.00	0.37	374.00
0.45	1012.50	0.25	556.88
0.34	1360.00	0.19	748.00

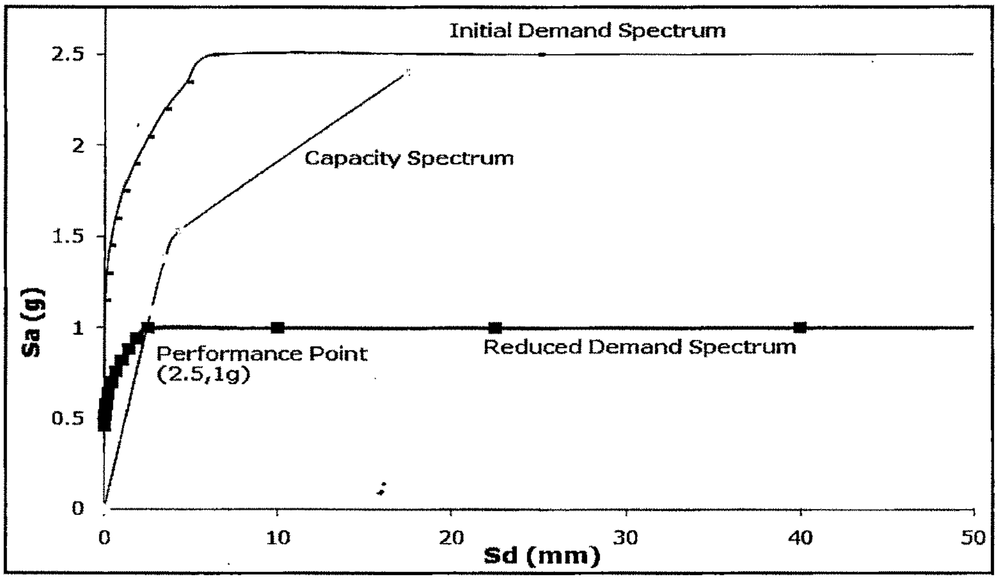


Fig. 5.12 Performance Point for Rectangular Columns

The same mathematical model with square columns is subjected to push over analysis in SAP2000 and the values for constructing the capacity curve is noted down in **Table 5.10.** Based on this, a bilinear curve is drawn in **Fig. 5.13.**

Table 5.10 Capacity for Square Columns for 3m x 4.5m panel

Displacement D_{roof} in mm	Base Shear V kN	Sa (g)	Sd mm
0.00	0.00	0.00	0.00
4.04	13998.07	1.28	3.16
6.04	20219.59	1.85	4.72
7.82	22990.30	2.10	6.11
14.03	26288.12	2.40	10.96

In **Table 5.10**, PF=0.35, ά = 0.79, Φ = 3.66 , W = 13854 kN

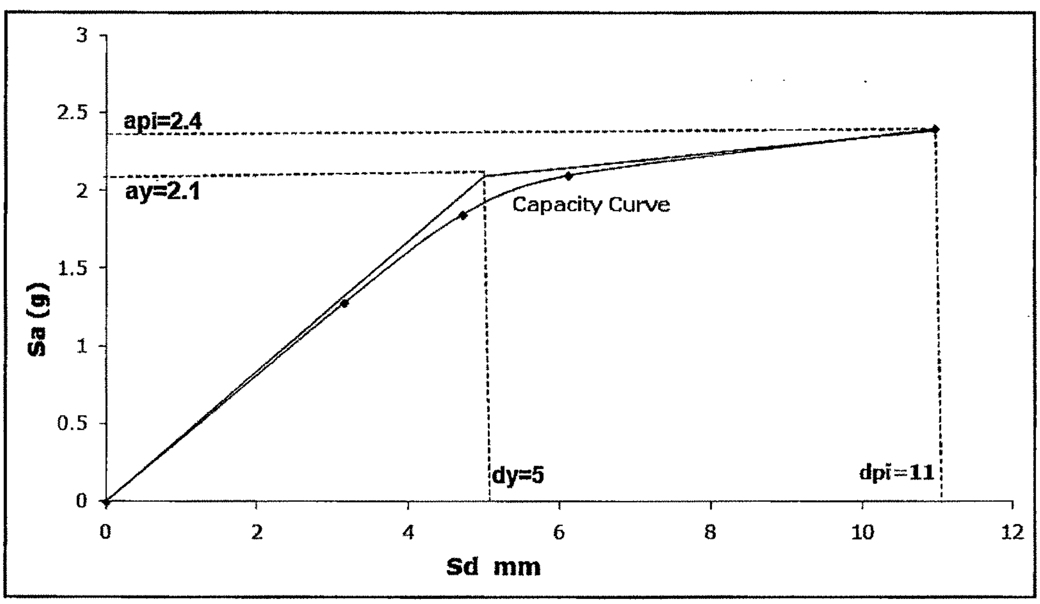


Fig. 5.13 Bilinear Curve for Square Columns

From the bilinear curve, the value of api = 2.4, ay = 2.1, dy = 5, dpi = 11

Beq = βo+5 = 0.637{(ay*dpi-dy*api)}/api*dpi+5 = 12.5 + 5 = 17.5

From ATC 40, $S_{RA} = 0.55$ and $S_{RV} = 0.65$

The above values are used to reduce the demand spectrum specified by the code as per ATC 40 provisions. The values for the initial demand spectrum and the reduced demand spectrum for this particular model are presented in **Table 5.11**, whereas **Fig. 5.14** shows the superimposed plot of capacity and reduced demand spectrum for the model with square columns. The intersection of the reduced demand with the capacity spectrum in the ADRS format represents the performance point which comes out to be (3.35, 1.35g) in the ADRS format.

Table 5.11 Reduced Demand Values for Square Columns

Original Demand		Reduced Demand	
Sa in g	Sd in mm	Sa in g	Sd in mm
1.15	0.03	0.46	0.01
1.30	0.13	0.52	0.05
1.45	0.33	0.58	0.13
1.60	0.64	0.64	0.26
1.75	1.09	0.70	0.44
1.90	1.71	0.76	0.68
2.05	2.51	0.82	1.00
2.20	3.52	0.88	1.41
2.35	4.76	1.29	2.62
2.50	6.25	1.38	3.44
2.50	25.00	1.38	13.75
2.50	56.25	1.38	30.94
2.50	100.00	1.38	55.00
2.50	156.25	1.38	85.94
2.50	189.06	1.38	103.98
2.26	203.40	1.24	111.87
1.94	237.65	1.26	154.47
1.70	272.00	1.11	176.80
1.51	305.78	0.98	198.75
1.36	340.00	0.88	221.00
0.68	680.00	0.44	442.00
0.45	1012.50	0.29	658.13
0.34	1360.00	0.22	884.00

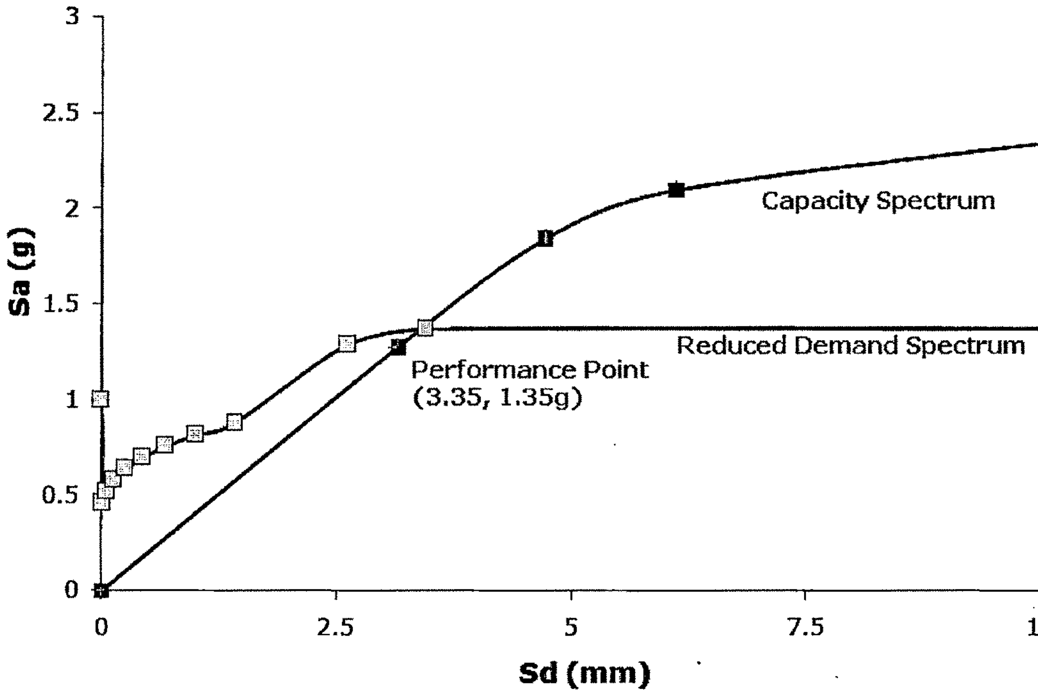


Fig. 5.14 Performance Point for Square Columns

The drift values for both square and rectangular column models are reported in **Table 5.12** and the corresponding plot is presented in **Fig. 5.15**. **Figure 5.16** shows the hinges developed at performance point for both the models.

Table 5.12 Drift Values for R and S Columns

Column Storey Level	RECTANGULAR Drift (X)	SQUARE Drift (X)
7	0.97	0.97
6	2.12	1.54
5	3.33	2.00
4	4.15	2.33
3	4.41	2.35
2	4.22	2.24
1	2.42	2.06
0	0.00	0.00

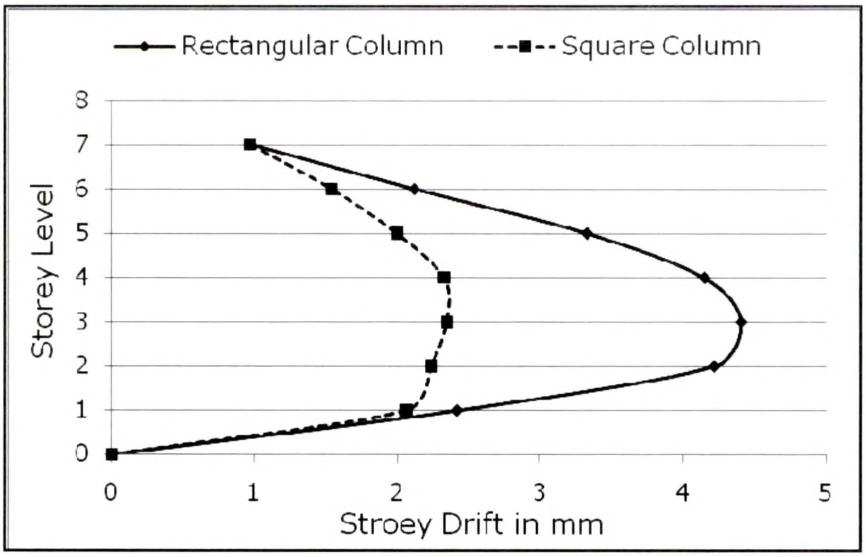
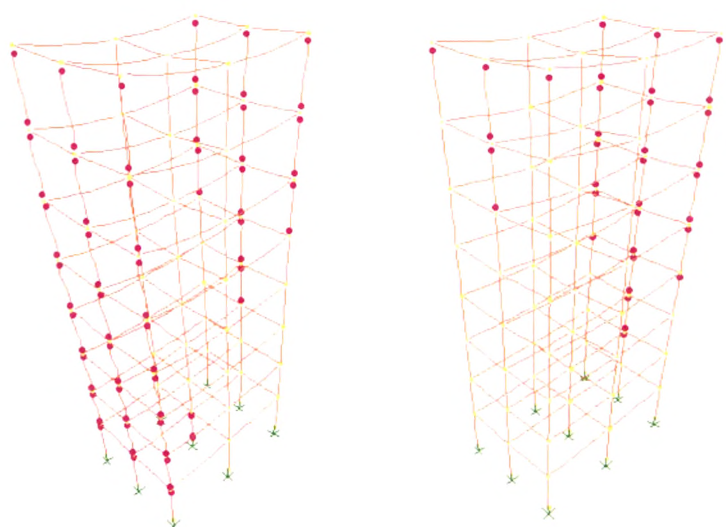


Fig. 5.15 Storey Drift for R and S Models under Push in X-Direction



a) Rectangular columns b) Square columns

Fig. 5.16 Hinges Developed in R & S Models - Push in X-Direction

5.5 DISCUSSION OF RESULTS

1. For the panel size of 3m x 3m, it can be seen that there is no distinct performance point observed for rectangular columns whereas the square columns show a distinct performance point.

2. The hinges developed in the rectangular column model for the 3m x 3m panel size are more in number as well as severe in nature. This is evident from **Fig. 5.7** and **Fig. 5.8**.
3. The deformed shape of both the models under a lateral push as shown in **Fig. 5.9** clearly indicates that there is an alarming lateral deformation in the model with rectangular columns. This is an indication that under similar seismic situations, a building with square columns will perform better.
4. **Figure 5.10** indicates that for the model with rectangular columns, there is an excessive drift at the first storey level which indicates a poor performance. The model with square columns shows a uniform variation in drift which signifies a better seismic performance.
5. For the 3m x 4.5m model, it can be seen that a performance point is achieved in both the models. Although the square shaped columns shows a slightly better performance, the performance of both the models are comparable.
6. The plot of storey drift in **Fig. 5.15** for 3m x 4.5m panel shows that square shaped columns exhibit a less storey drift as compared to rectangular columns. This is a clear indication of a better seismic performance by square shaped columns.
7. The final deformed shape with colour coded hinges shown in **Fig. 5.16** for square column depicts fewer hinges and with lower stress value as compared to the rectangular columns.