CHAPTER 6

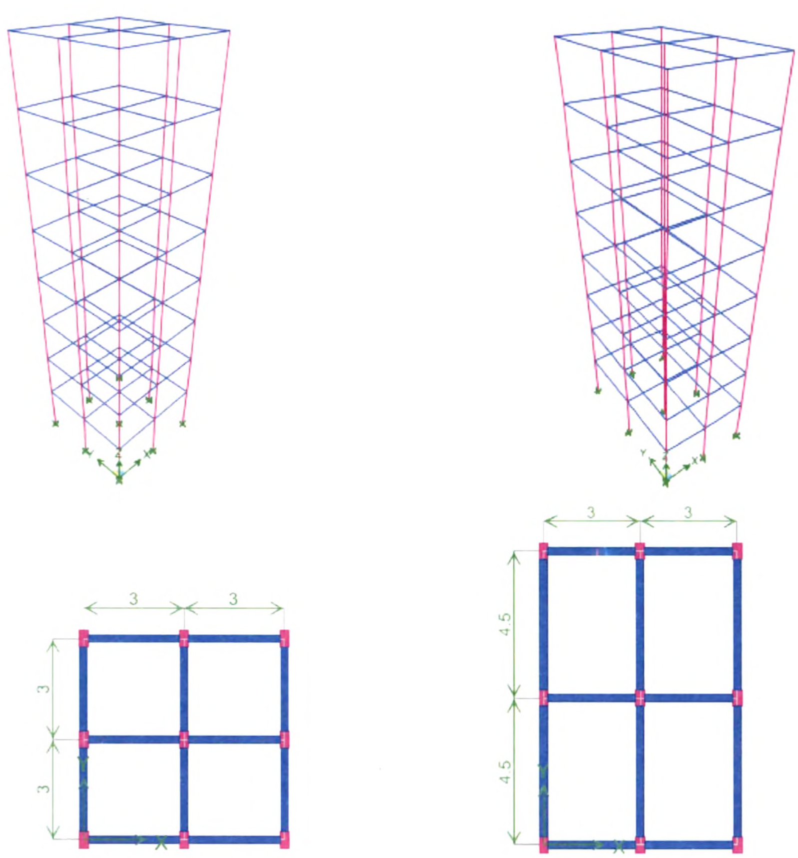
SEISMIC EVALUATION OF FRAMES WITH INFILL WALLS

6.1 MATHEMATICAL MODEL

In the present chapter, a 6m x 6m plan building with a 3m x 3m grid and having rectangular columns of size 230mm x 450mm at all panel points is studied. All the columns are oriented such that their longer side is parallel to the global Y direction and the shorter side is parallel to the global X direction of the building. The height of the columns in the global Z direction is considered as 3m for each floor level and the columns extend for 3m below plinth level up to the foundation. From practical point of view, the sizes of columns below plinth level are considered 50mm more in both the lateral directions. The slab is modeled as a shell element which accounts for a rigid diaphragm action in the analysis. The columns are considered to be fixed at the foundation level. All the beam members are considered rectangular in cross section of size 230mm x 450mm deep. Four basic types of plastic hinges are defined at 5% span length from either end of all beams and columns. The four basic type of default hinges defined are Axial (P), Flexural (M), Combined Axial and Flexural (PMM) and Shear (V). Over and above these, flexural hinges are also considered at mid-span of all beams to consider the effect of possible hinge formation due to gravity loads. Keeping all the above geometric features as same, another model is developed with columns having equivalent square cross section of size 322mm x 322mm. Another set of models with all the above features as same but with brick infill walls considered in the peripheral frames as shell elements is considered for analysis.

One more set of mathematical model is considered with an overall plan dimensions of 6m x 9m with two panels in each lateral direction of

3m x 4.5m. Keeping all the geometric parameters same, the model with rectangular column cross section is compared with equivalent square cross section. The ground and six storey building with overall plan dimensions of 6m x 9m described above is considered with brick infill walls modeled as 1) shell elements and 2) equivalent diagonal strut in the periphery. The seismic response under static push given in the lateral directions is studied and compared for rectangular columns and equivalent square columns. The schematic diagrams for models considered are shown in **Fig. 6.1.**



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

Fig. 6.1 G+6 Storeyed Buildings with Rectangular Columns

6.2 LOADS CONSIDERED FOR ANALYSIS

Each of the above eight structural models are subjected to gravity loads in the form of floor loads considered as dead load of intensity 5 kN/sq.m. on all typical floors and 6 kN/sq.m. on terrace floor. The live load is considered as 2 kN/sq.m. on all typical floors with 1.5 kN/sq.m. on terrace floor. All external peripheral beams are subjected to a uniformly distributed load of 13 kN/m on typical floors and 6 kN/m on the terrace floor to account for parapet walls. The wall loads for models having brick infill walls modeled as elements are considered as self weight generated by the software. The seismic loads in the two lateral directions are applied as per response spectrum method as per IS:1893 Part 1, 2002 [24]. Thus, in all, following four basic load cases are considered: 1. Dead load, 2. Live load, 3. Earthquake load in X direction, 4. Earthquake load in Y direction.

For carrying out design, the 13 load combinations based on the four basic load cases as defined in IS 1893, Part 1, 2002 are considered. SAP2000 is used to do the analysis as well as design of the 3D frame structures. There are in all eight different mathematical models which are defined based on the variation in parameters as stated above.

6.3 DEFINITION OF PUSHOVER CASES

For all the models, the first push PZ is considered in the gravity direction due to dead and live loads. The stresses developed in the defined hinges are monitored step wise till the full magnitude of gravity loads is applied. Thus, push PZ is the push in the gravity direction with load control.

Next, the second push PX is applied in the lateral X direction, which is the weaker direction for rectangular columns, and its initial condition is considered as the end of the gravity direction push PZ. Thus, the stresses in the hinges which developed due to gravity push are retained and are added to those developed due to the lateral push. The X displacement of the roof level node is monitored up to the target displacement of 4% of the total height of the building, when push is given as per mode 1 (the fundamental mode) profile of the space frame. Thus, the lateral push defined by PX is displacement controlled, monitored by the displacement of the selected roof level node of the model. This displacement is monitored and applied in a stepwise manner by the software till the structure collapses or the target displacement is achieved.

A third push PY is the push applied in the lateral Y direction and its initial condition is considered as the end of the gravity direction push PZ. The Y displacement of the roof level node is monitored when push is given as per corresponding mode shape in the Y direction. For the 3m x 3m panel models, the push PY is not compared as it is not critical for rectangular columns which are stronger in the Y direction. The non linear static push over analysis is carried out for all the models as per ATC 40 **[1]** guidelines considering Seismic Zone factor Z as 0.16 for stiff soil.

6.4 MODELING OF INFILL WALLS

In the current chapter, the infill walls are considered as four noded isoparametric elements with the nodes matching with the ends of the frame panels. The thickness of the elements considered is same as that of the brick wall thickness with all material properties defined for bricks. The shell elements are modeled as membrane combined with plate bending behavior. Thus, there are no compatibility issues in case of a space frame structure as each node of the shell element has 6 DOF. A variable, four-to-eight-point numerical integration formulation is used for the Shell stiffness. Stresses and internal forces and moments, in the element local coordinate system, are evaluated at the 2-by-2 Gauss integration points and extrapolated to the joints of the element.

The infill walls are also considered as equivalent struts as defined by Das and Murty **[23]**. The dimensions of the equivalent strut considered in the analysis for the particular wall panel of 3m x 3m is 230mm x 1710mm with the material defined as brick. The strut element has it's ends released for moments and hence only axial forces are transferred to the strut element.

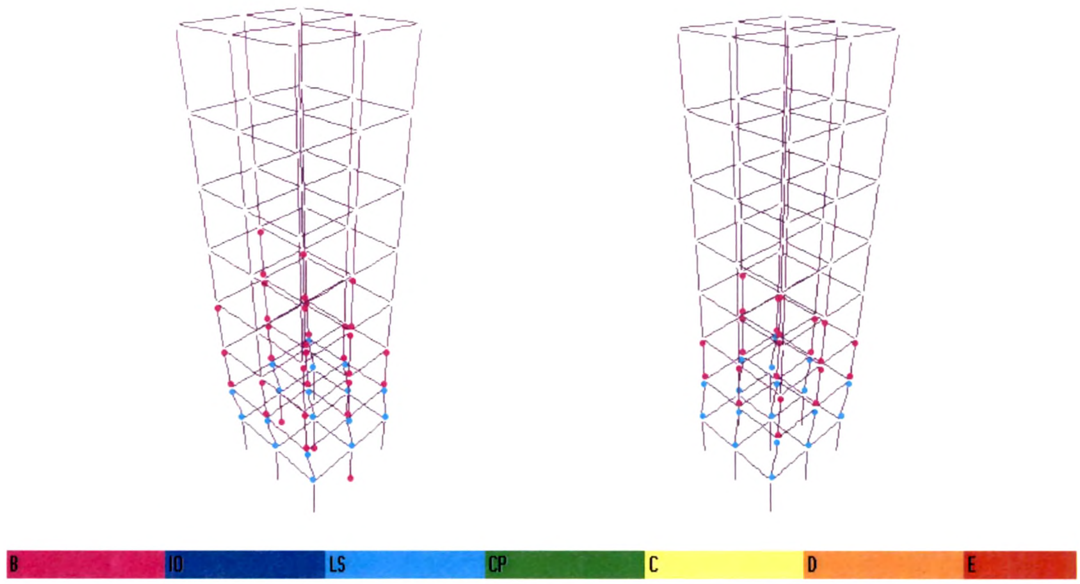
6.5 RESULTS OF THE ANALYSIS

The results obtained are extracted in a graphical form as a pushover curve for each of the above discussed cases and presented. In order to get the relevant data for all the models, the pushover analysis is carried out in two steps. Once, a performance point is obtained in a particular analysis, the target displacement for the next analysis is specified as that obtained from the performance point. Thus, in the second run, the analysis will stop just near the performance point. Each figure consists of the final deformed shape of the frame showing colour coded hinges developed at the performance point. **Figures 6.2, 6.4, and 6.6** show the final deformed shapes for 3m x 3m panel models without infill walls, with infill walls modeled as shells and with infill walls modeled as struts respectively. The final deformed shapes for models with 3m x 4.5m panels without infill walls under push in the X and Y directions are shown in **Fig. 6.8** and **6.10** respectively. **Figures 6.12** and **6.16** show the final deformed shapes for the 3m x 4.5m panel models under push in X direction with walls modeled as shells and walls modeled as struts respectively. The models with 3m x 4.5m panel size when pushed in the Y direction get deformed as shown in **Fig. 6.14** and **6.18** with walls modeled as shells and struts respectively. The colour legend for the hinge level is indicated below each of the figures.

The results also include the superimposed capacity and demand spectrum in the ADRS format along with a family of demand spectra for 5, 10, 15 and 20% damping. These are denoted by the red coloured lines. The push over plots for square and rectangular columns is shown in **Figs. 6.3, 6.5, and 6.7** for 3m x 3m panel size. While **Fig. 6.9, 6.11, 6.13, 6.15, 6.17** and **6.19** shows the push over plots for 3m x 4.5m panel size models. The graphs also include a single demand spectrum with variable damping on the same axis. These are shown by blue dash-dot lines in the figures. The capacity spectrum is shown in magenta colour as a broken line. The graph shows grey radial lines representing the constant period lines.

The results are also presented in a tabular format which lists the number of hinges developed at the performance point along with the stress level of the hinges representing the severity of the hinges. These are shown as **Tables 6.1, 6.2,** and **6.3** for 3m x 3m panel size models while **Tables 6.4, 6.5, 6.6, 6.7, 6.8** and **6.9** represent those for 3m x 4.5m panel size models. The tables also show the roof displacement and the base shear.

3m x 3m Panel Models without Infill Walls under Push X



Square columns | Rectangular columns

Fig. 6.2 Performance Point Deformed Shape with Developed Hinges

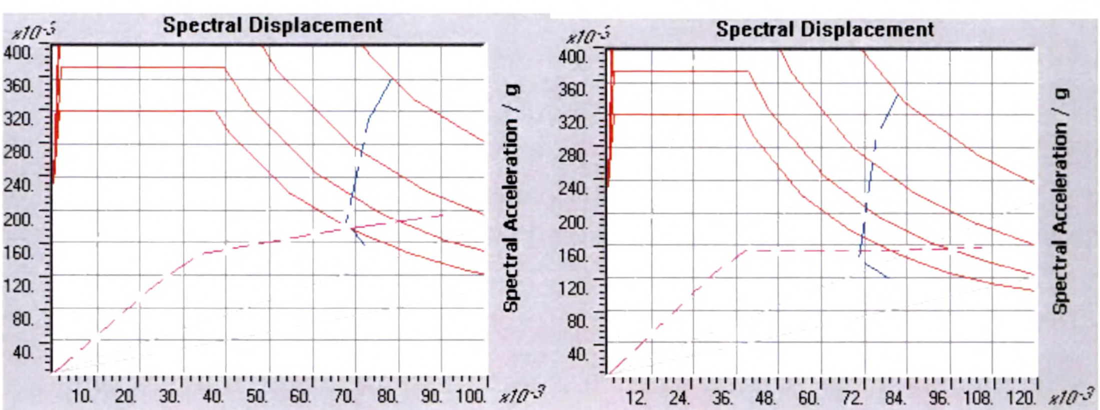
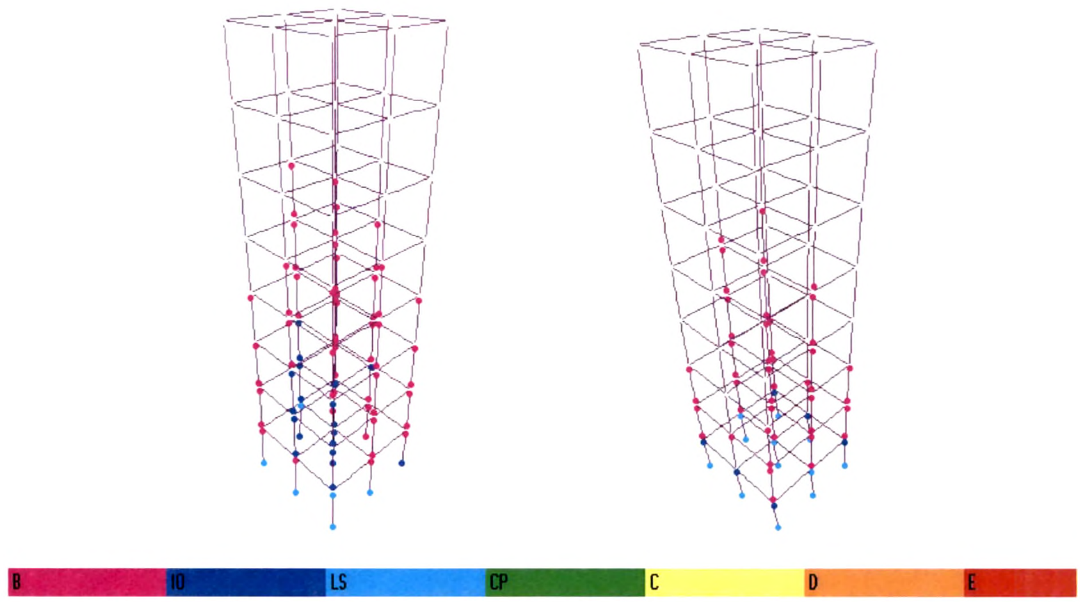


Fig. 6.3 Demand Capacity Spectra at Performance Point

Table 6.1 Number of Hinges with Roof Displacement and Base Shear

Column Type	Roof Disp. in m	Base Force in kN	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	> E
Square	0.096	504.35	1386	36	0	18	0	0	0	0
Rect.	0.082	285.18	1398	24	0	18	0	0	0	0

3m x 3m Panel Models with Infill Walls as Shells under Push X



Square columns Rectangular columns

Fig. 6.4 Performance Point Deformed Shape with Developed Hinges

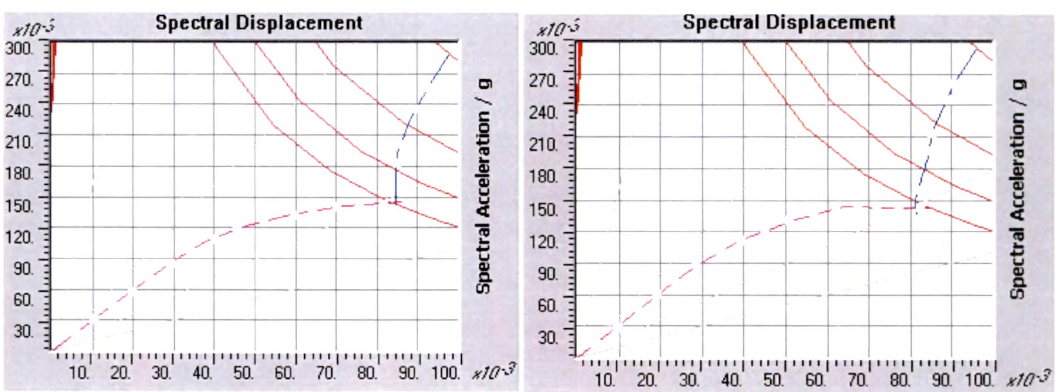
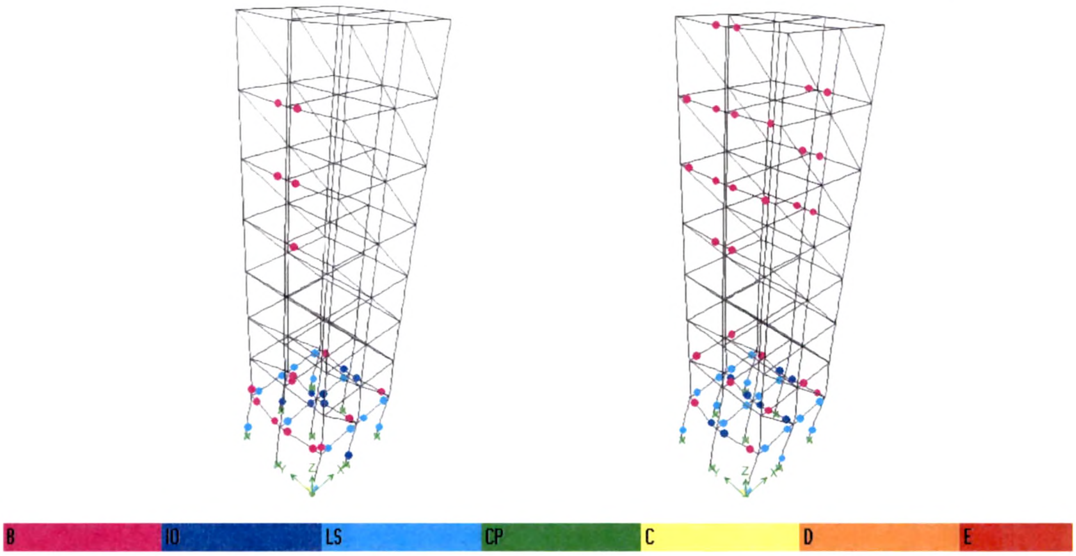


Fig. 6.5 Demand Capacity Spectra at Performance Point

Table 6.2 Number of Hinges with Roof Displacement and Base Shear

Column Type	Roof Disp. in m	Base Force in kN	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	> E
Square	0.091	902.60	1321	83	29	7	0	0	0	0
Rect.	0.100	463.04	1376	46	6	12	0	0	0	0

3m x 3m Panel Models with Infill Walls as Struts under Push X



Square columns Rectangular columns

Fig. 6.6 Performance Point Deformed Shape with Developed Hinges

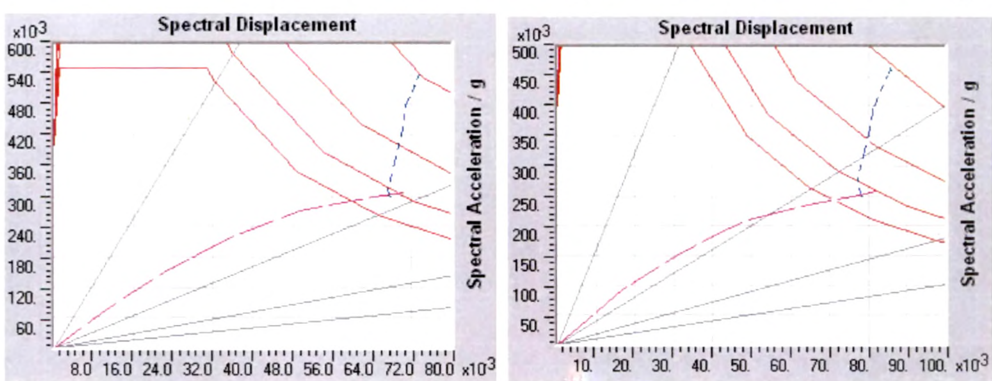
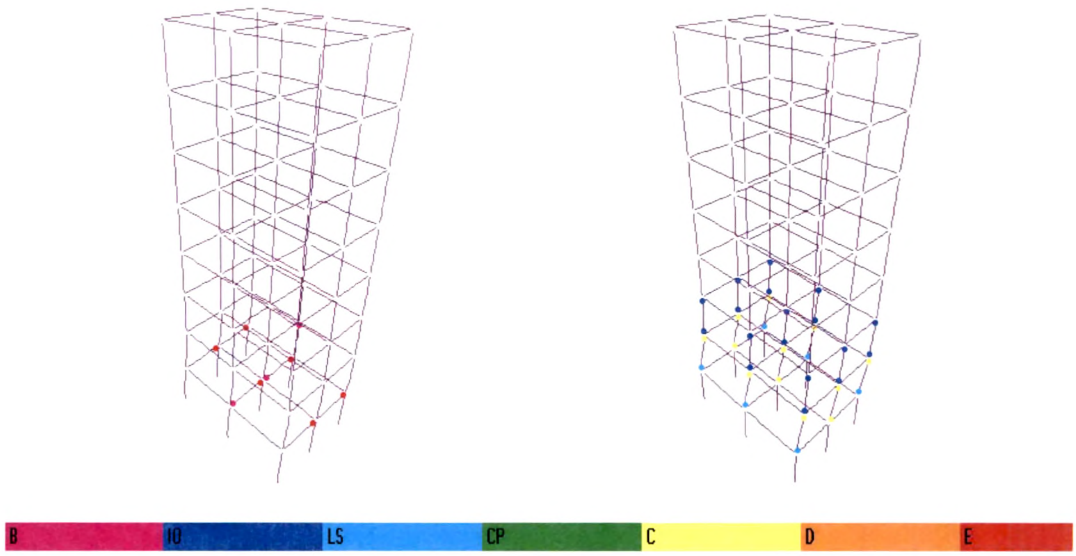


Fig. 6.7 Demand Capacity Spectra at Performance Point

Table 6.3 Number of Hinges with Roof Displacement and Base Shear

Column Type	Roof Disp. in m	Base Force in kN	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	> E
Square	0.088	1796.8	394	16	8	14	0	0	0	0
Rect.	0.097	1588.9	401	5	8	18	0	0	0	0

3m x 4.5m Panel Models without Infill Walls under Push X



Square columns   Rectangular columns

Fig. 6.8 Performance Point Deformed Shape with Developed Hinges

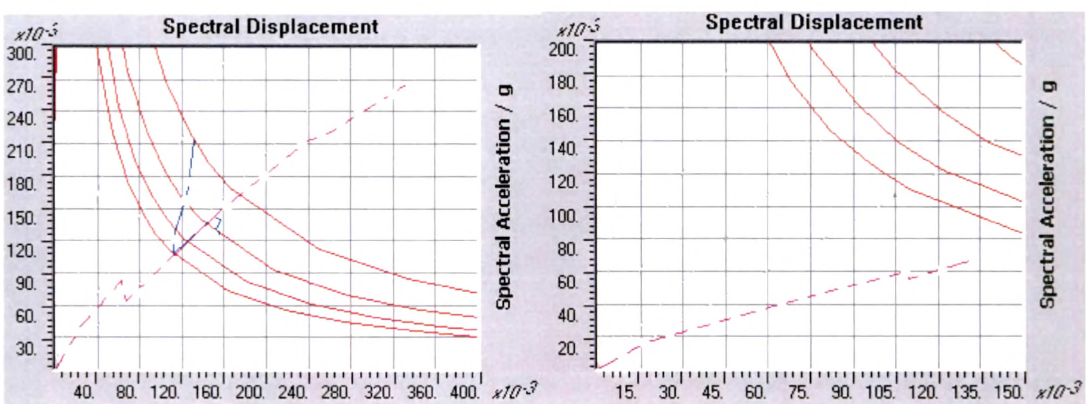
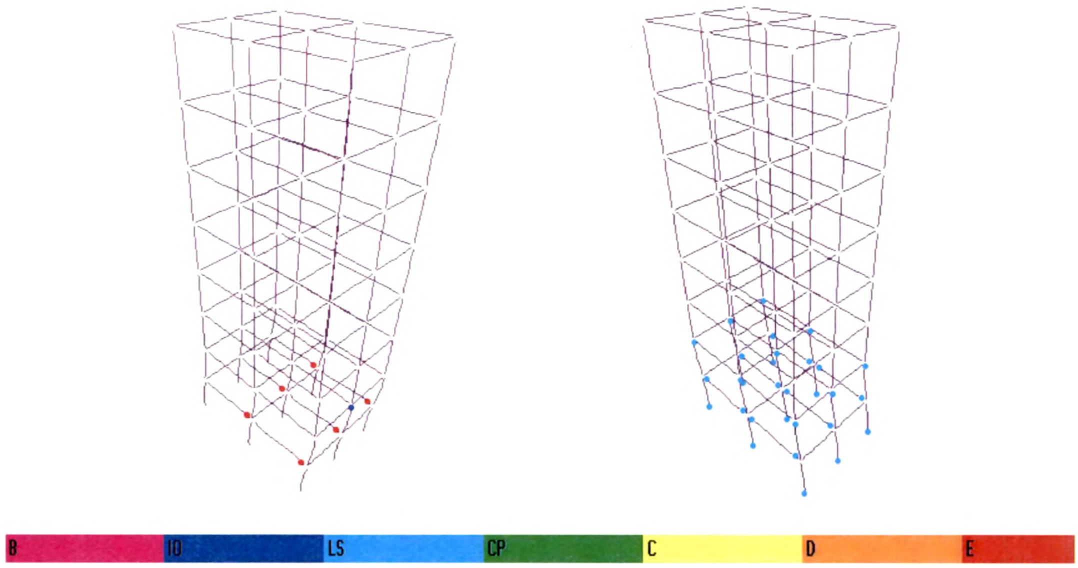


Fig. 6.9 Demand Capacity Spectra at Performance Point

Table 6.4 Number of Hinges with Roof Displacement and Base Shear

Column Type	Roof Disp. in m	Base Force in kN	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	> E
Square	0.175	1346.0	1431	3	0	0	0	0	0	6
Rect.	-	-	1404	0	18	6	0	12	0	0

3m x 4.5m Panel Models without Infill Walls under Push Y



Square columns Rectangular columns

Fig. 6.10 Performance Point Deformed Shape with Developed Hinges

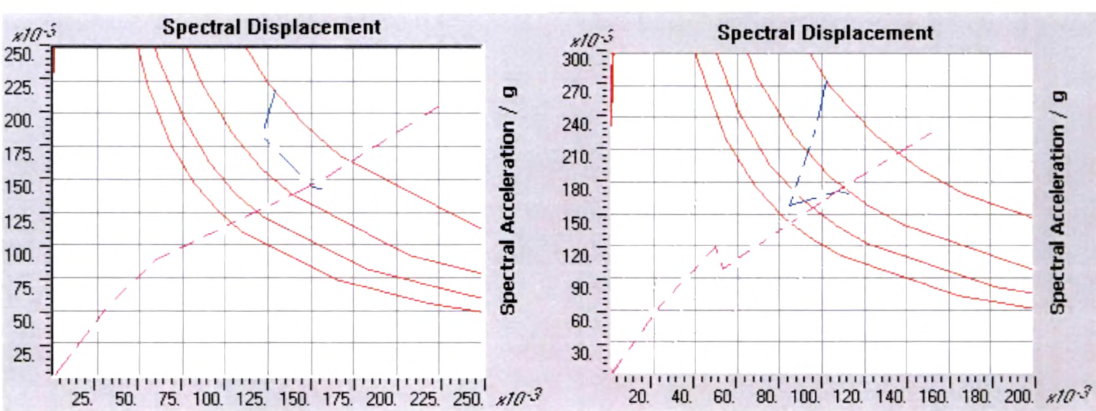
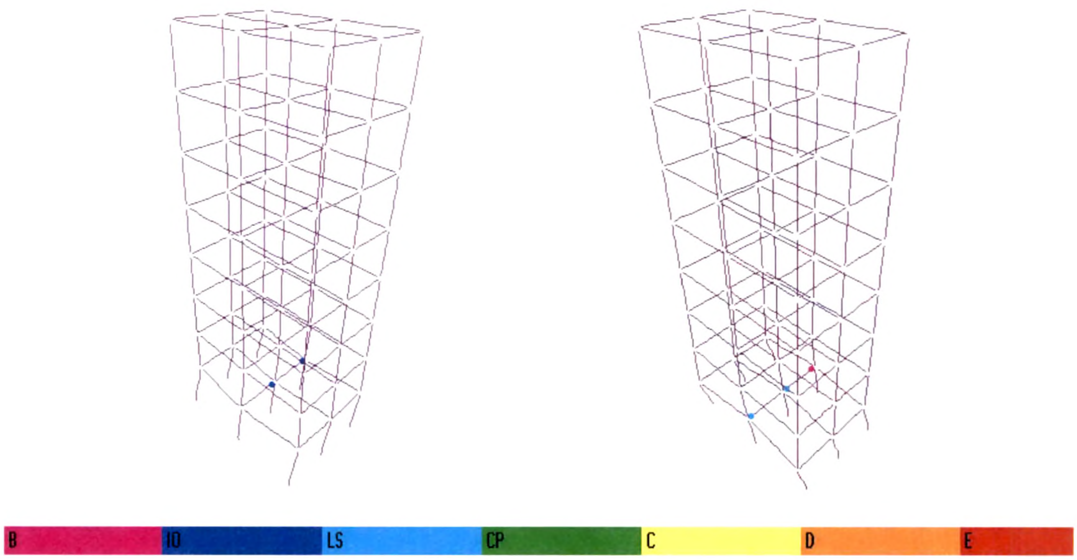


Fig. 6.11 Demand Capacity Spectra at Performance Point

Table 6.5 Number of Hinges with Roof Displacement and Base Shear

Column Type	Roof Disp. in m	Base Force in kN	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	> E
Square	0.17	1367.9	1433	0	1	0	0	0	0	6
Rect.	0.12	886.0	1410	0	0	30	0	0	0	0

3m x 4.5m Panel Models with Infill Walls as Shells under Push X



Square columns Rectangular columns

Fig. 6.12 Performance Point Deformed Shape with Developed Hinges

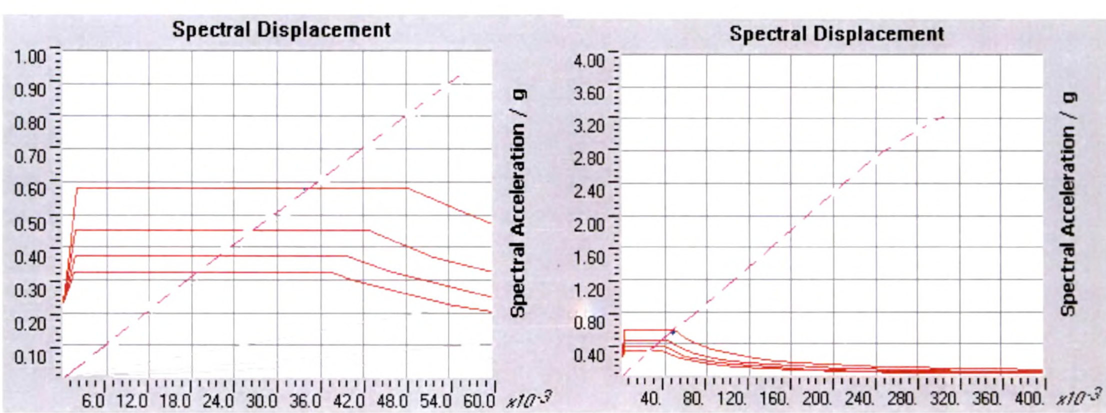
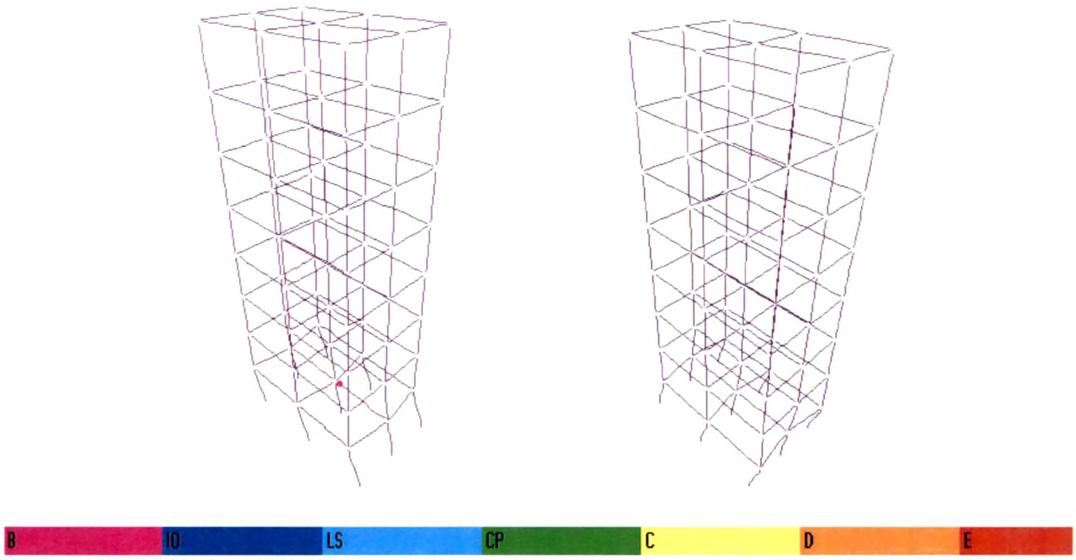


Fig. 6.13 Demand Capacity Spectra at Performance Point

Table 6.6 Number of Hinges with Roof Displacement and Base Shear

Column Type	Roof Disp. in m	Base Force in kN	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	> E
Square	0.042	2463.5	1438	0	2	0	0	0	0	0
Rect.	0.055	2454.1	1437	1	0	2	0	0	0	0

3m x 4.5m Panel Models with Infill Walls as Shells under Push Y



Square columns Rectangular columns

Fig. 6.14 Performance Point Deformed Shape with Developed Hinges

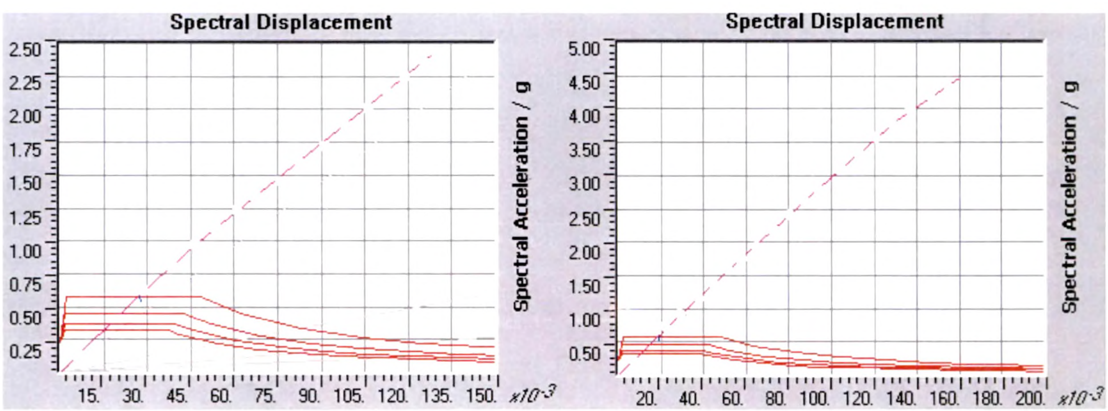
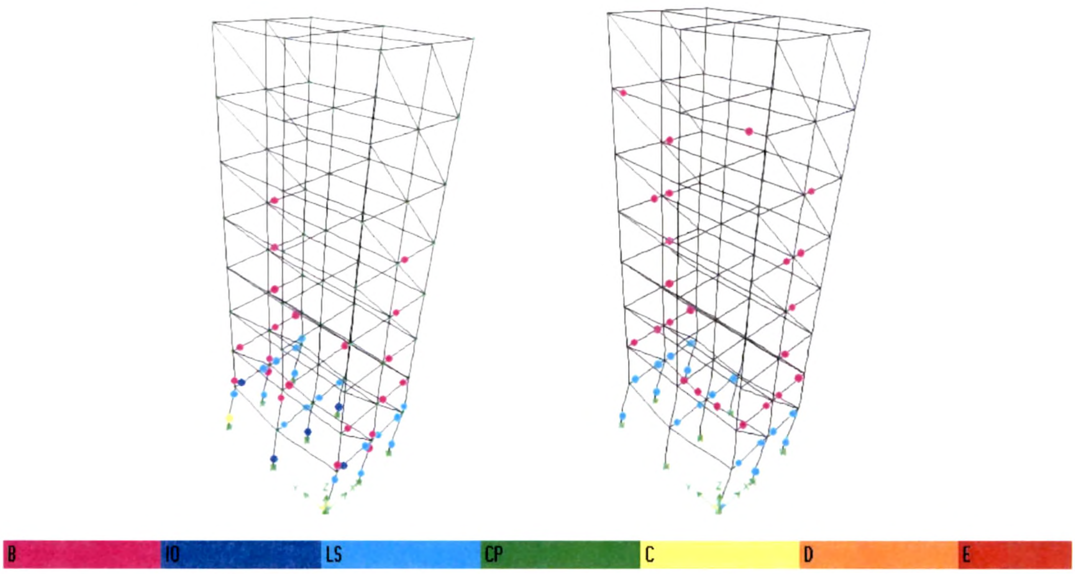


Fig. 6.15 Demand Capacity Spectra at Performance Point

Table 6.7 Number of Hinges with Roof Displacement and Base Shear

Column Type	Roof Disp. in m	Base Force in kN	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	>E
Square	0.032	2570.7	1439	1	0	0	0	0	0	0
Rect.	0.023	2533.2	1440	0	0	0	0	0	0	0

3m x 4.5m Panel Models with Infill Walls as Struts under Push X



Square columns　　　　　　　　Rectangular columns

Fig. 6.16 Performance Point Deformed Shape with Developed Hinges

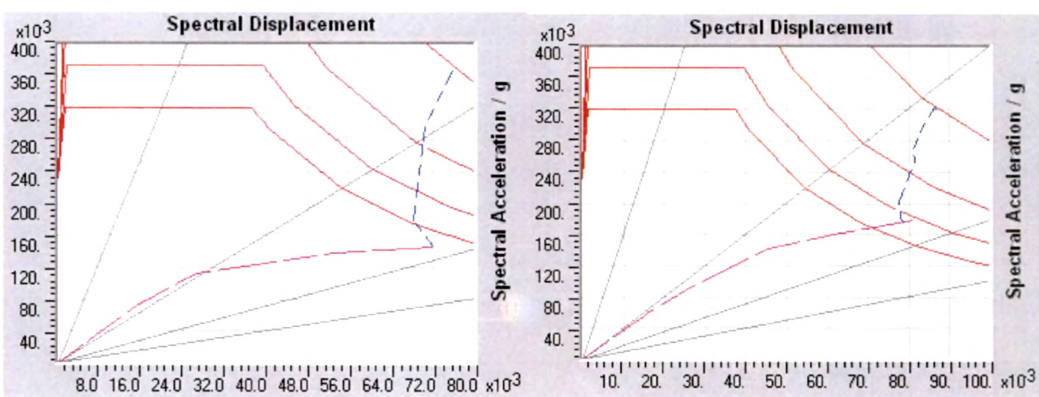
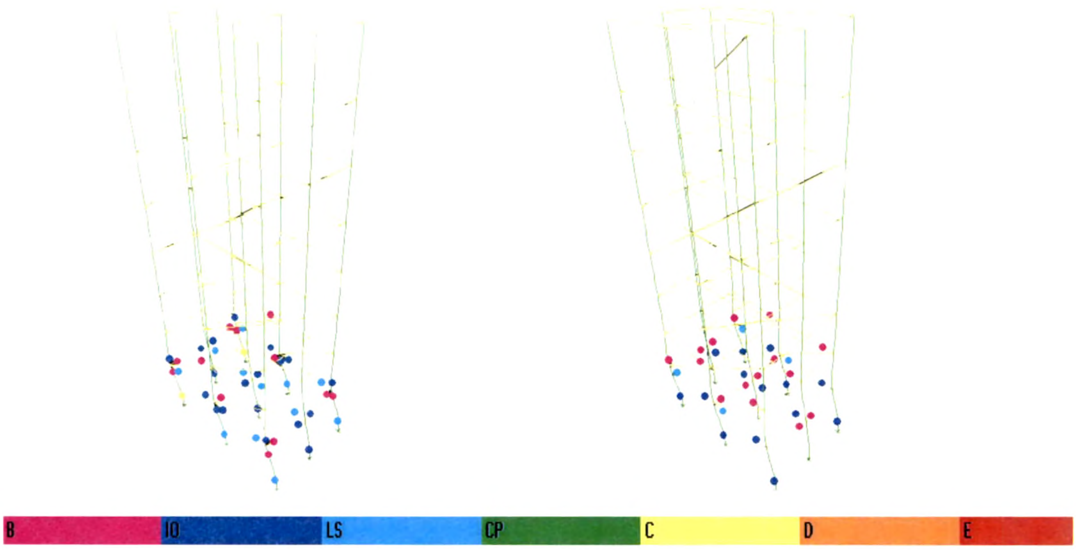


Fig. 6.17 Demand Capacity Spectra at Performance Point

Table 6.8 Number of Hinges with Roof Displacement and Base Shear

Column Type	Roof Disp. in m	Base Force in kN	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	>E
Square	0.091	1199.32	401	6	13	10	0	2	0	0
Rect.	0.097	1468.40	404	10	0	18	0	0	0	0

3m x 4.5m Panel Models with Infill Walls as Struts under Push Y



Square columns Rectangular columns

Fig. 6.18 Performance Point Deformed Shape with Developed Hinges

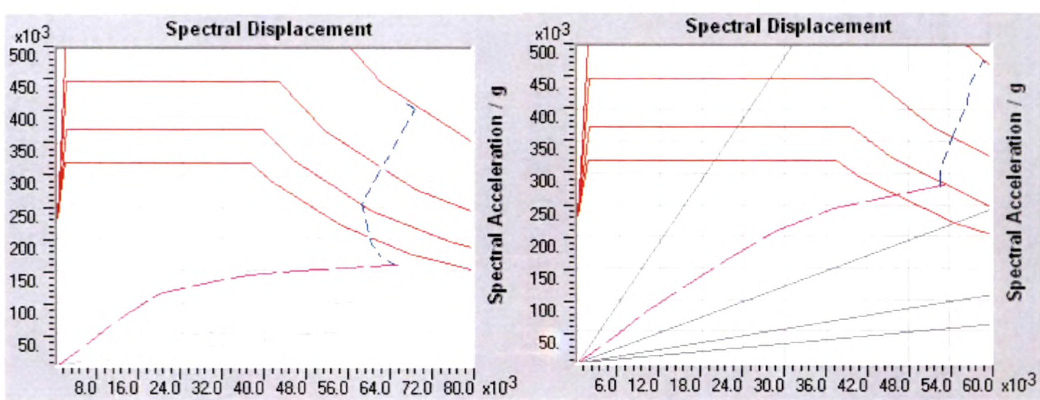


Fig. 6.19 Demand Capacity Spectra at Performance Point

Table 6.9 Number of Hinges with Roof Displacement and Base Shear

Column Type	Roof Disp. in m	Base Force in kN	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	> E
Square	0.075	1396.46	387	12	19	12	0	2	0	0
Rect.	0.066	2374.62	399	15	14	4	0	0	0	0

The results presented here are used to plot number of important charts which gives a clear idea about the relative performance of frames modeled with and without infill walls for the various mathematical models under study. They also compare the performance for the same model with square and rectangular columns. The number and severity of plastic hinges developed at performance point for the for 3m x 3m panel size model with walls modeled as shell elements is presented in **Fig. 6.20** and with walls modeled as struts in **Fig. 6.22.** For the 3m x 4.5m panel size the number and stress level in plastic hinges developed at performance point are shown in **Fig. 6.21** with walls modeled as shells and **Fig. 6.23** with walls modeled as struts.

Figure 6.24 and **Fig. 6.26** depicts the effective damping and base shear at performance point for models with 3m x 3m panel size. The comparison of the effective damping and base shear obtained for the mathematical models under push over analysis are shown in **Fig. 6.25** and **Fig. 6.27** for panel size of 3m x 4.5m. The effective damping at performance point is one of the important parameters which indicate the level of damage induced in the models when subjected to a monotonously increasing push in the lateral direction. The initial damping considered in the un stressed condition for all models is 5% which keeps on increasing as the plastic hinges keep on developing under the lateral push.

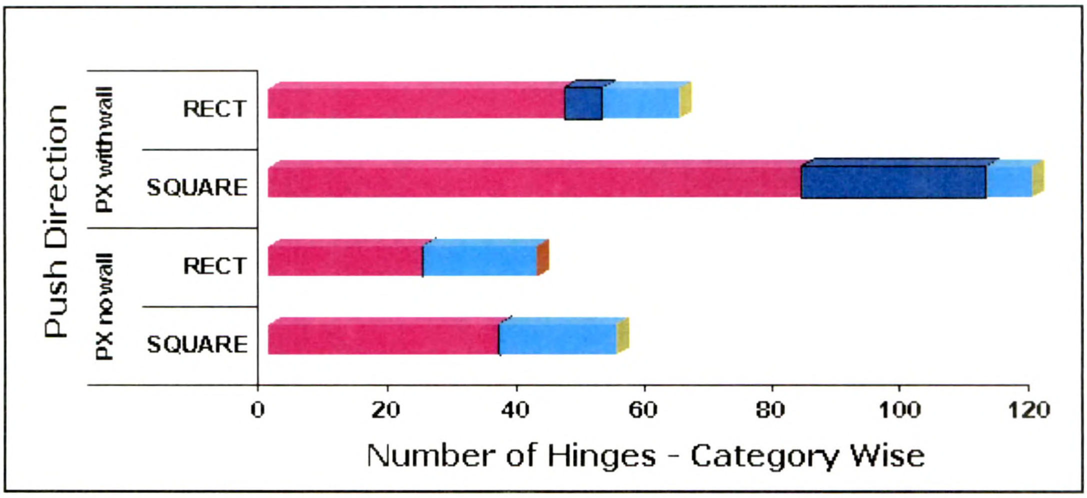


Fig. 6.20 Hinges in 3m x 3m Panel Model with Walls as Shell

Legend for hinge colours

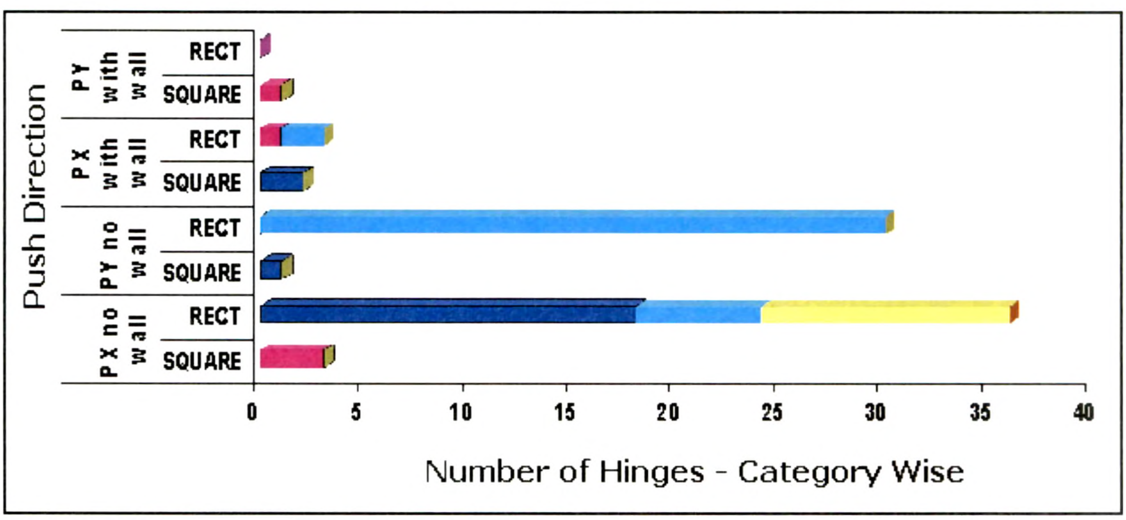


Fig. 6.21 Hinges for 3m x 4.5m Panel Model with Walls as Shells

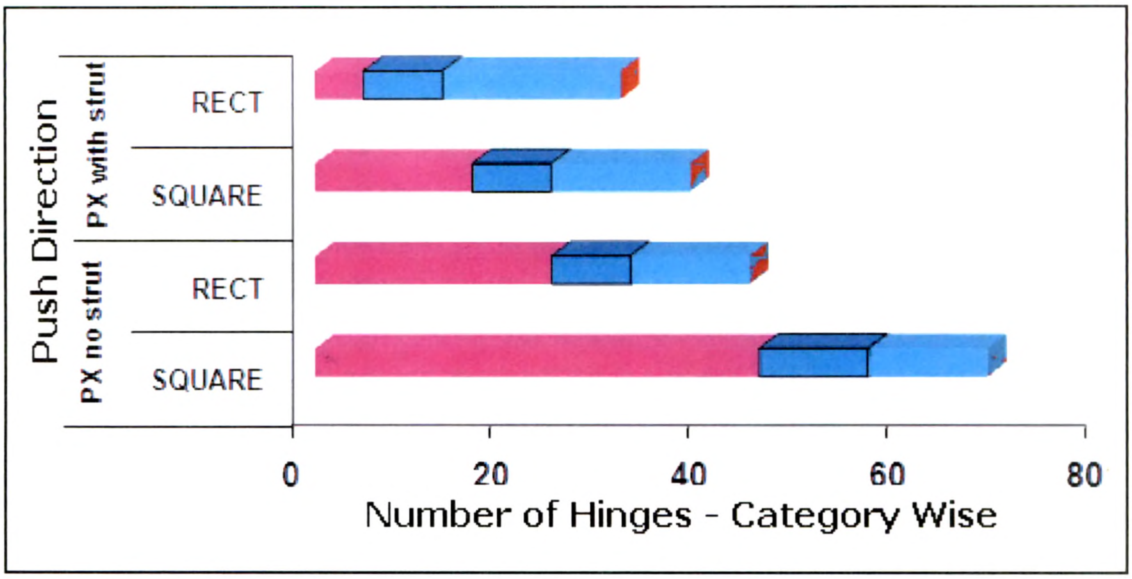


Fig. 6.22 Hinges for 3m x 3m Panel Model with Walls as Struts

Legend for hinge colours

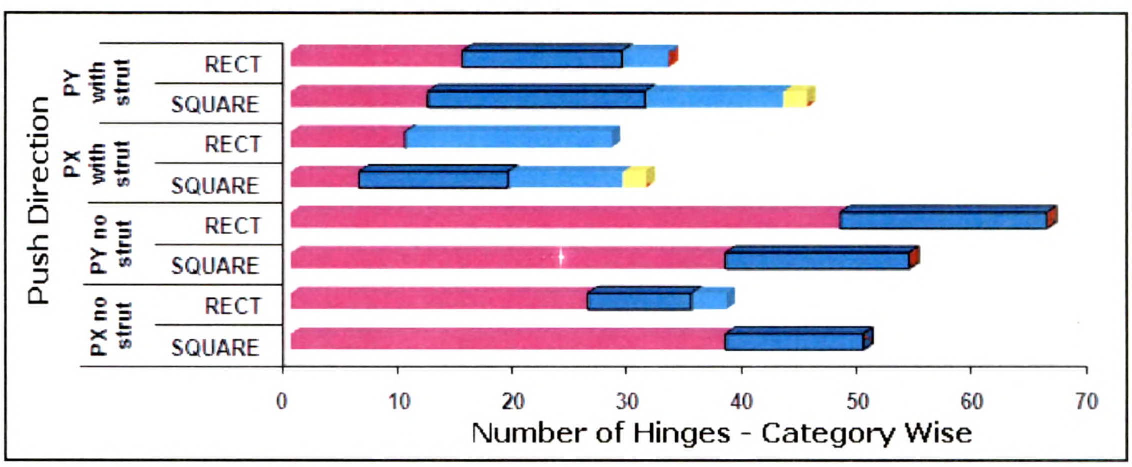


Fig. 6.23 Hinges for 3m x 4.5m Panel Model with Walls as Struts

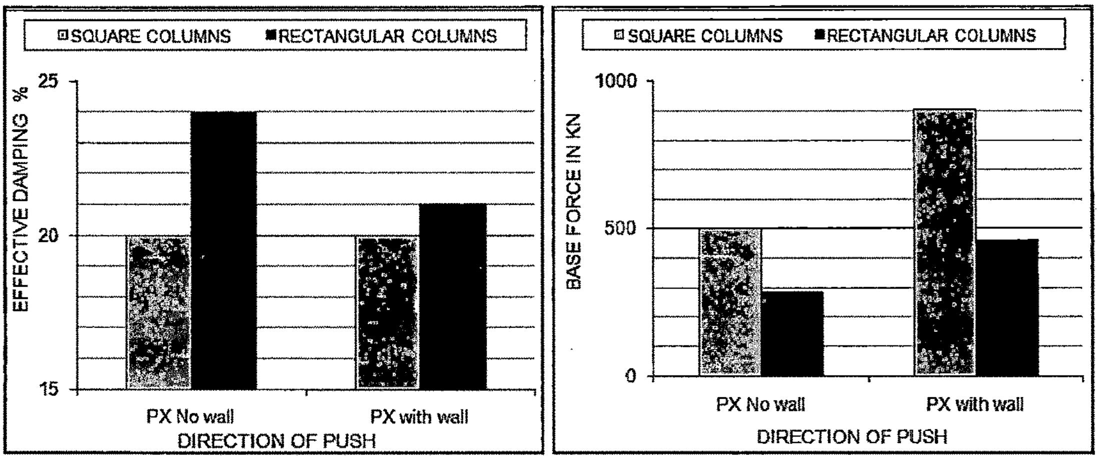


Fig. 6.24 Effective Damping and Base Shear - 3m x 3m Panel Model

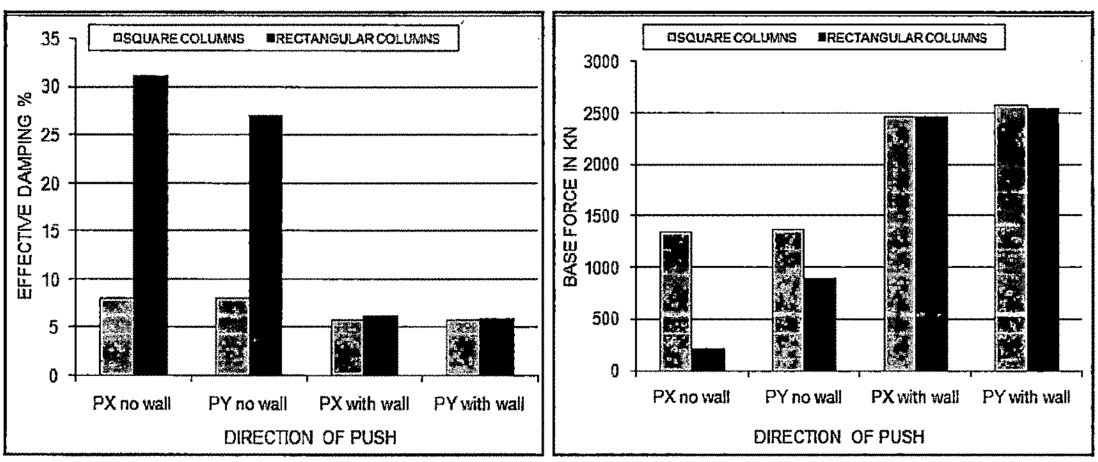


Fig. 6.25 Effective Damping and Base Shear - 3m x 4.5m Panel Model

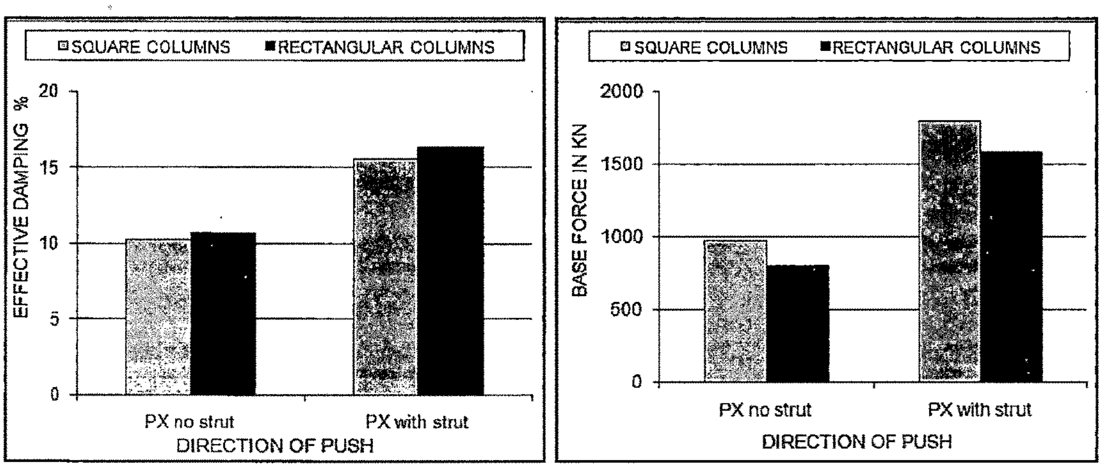


Fig. 6.26 Effective Damping and Base Shear - 3m x 3m Panel Model

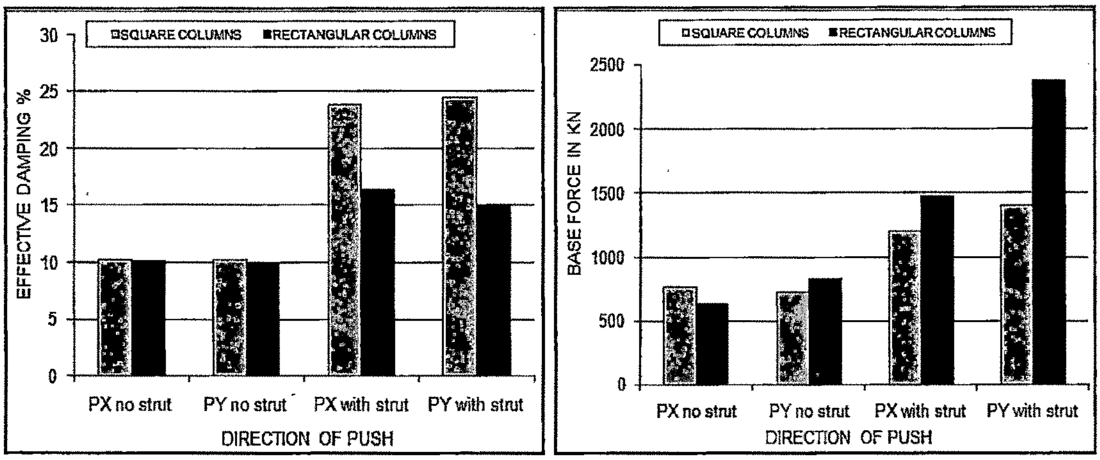


Fig. 6.27 Effective Damping and Base Shear - 3m x 4.5m Panel Model

6.6 OBSERVATIONS AND DISCUSSIONS

- It is seen from **Figs. 6.2, 6.4** and **6.6** that G+6 storey RC frames with square shaped columns perform better than those with rectangular shaped columns, with or without considering the infill walls, for a 3m x 3m size panel.
- **Figures 6.20 and 6.22** show that for 3m x 3m panel size, the number of plastic hinges developed in case of square columns is more in number when infill walls are considered either as shell or struts but the number of hinges with severity of stress under lateral push is more for rectangular columns. The number as well as severity of hinges for both square and rectangular columns reduces when infill walls are considered as struts.
- One more indicator for the seismic performance obtained from pushover analysis is the effective damping and base shear at performance point. These are presented in **Fig. 6.24** and **Fig. 6.26** for 3m x 3m panel models showing less damping and more base shear for square columns indicating a better performance.

- Looking at the deformed shape of 3m x 4.5m panel models at performance point, when pushed in the X as well as Y directions, it can be stated that the square shaped columns perform better as compared to rectangular columns for models without infill walls. The number as well as severity of hinges in square columns is less as compared to rectangular columns as seen in **Fig. 6.21** and **Fig. 6.23**. However, it is observed that when infill walls are considered as struts, models with square columns show more severe hinges as compared to those with rectangular columns.
- The roof displacement at performance point is less and the base shear resisted is more for models with 3m x 4.5m panel size and square columns as seen in **Fig. 6.25** which considers shells elements for modeling the infill walls. These two factors are indicative of the better performance of square columns for models without infill walls and with shell elements used for infill walls. But, **Fig. 6.27** indicates that when infill walls are modeled by struts, the model with square column is proving to be inferior in performance as compared to rectangular columns.
- It may be noted that the difference in performance is very less between models with square and rectangular columns when the effect of infill walls is considered. This is true for both 3m x 3m and 3m x 4.5m panel sizes as indicated by **Figs. 6.20, 6.21, 6.22** and **6.23**.
- It may also be noted from **Fig. 6.20** that the number and severity of hinges increases in both models with square as well as rectangular columns when infill walls are modeled as shells in 3m x 3m size panel.
- It is also observed that for a 3m x 3m panel size, the number and severity of hinges increases when infill walls are modeled as shell elements, whereas when the walls are modeled as equivalent struts,

the number of hinges decreases whereas severity increases as compared to models without walls. When one compares the effective damping, it decreases when shells are considered to model infills whereas it increases when struts are considered. This fact points out that struts induce more damage in frames as compared to shell elements. This is due to the fact that in case of struts, the compression member induces lot of stiffness reducing the ductility of the system.

- For a 3m x 4.5m panel size, the severity of hinges is more in case of models with infill walls modeled as struts as compared to the same modeled as shells. The effective damping at performance point decreases when infills are modeled as shell elements whereas it increases when struts are considered in the same model. This observation is valid for both type of models with square as well as rectangular columns.
- It should be kept in mind that there is a discrepancy between the behavior of walls modeled as shell element as against those modeled as struts. This is particularly so because of the fact that in case of shell elements, out of plane failure of masonry infills is not represented. Thus, the infill walls must be modeled as equivalent struts which are connected by hinge joint at both the ends of a diagonal.