CHAPTER 10

THE CONCEPT AND ANALYSIS OF HYBRID FRAMES UNDER SEISMIC FORCES

10.1 GENERAL CONCEPT

The joint rigidity of RC frames under seismic loads is affecting the performance of th e building. This fact has been utilized to study the effect of introducing semi rigid joints in various combinations in an RC space frame. The effect of joint rigidity on bending moment diagram is shown in **Fig. 10.1**.

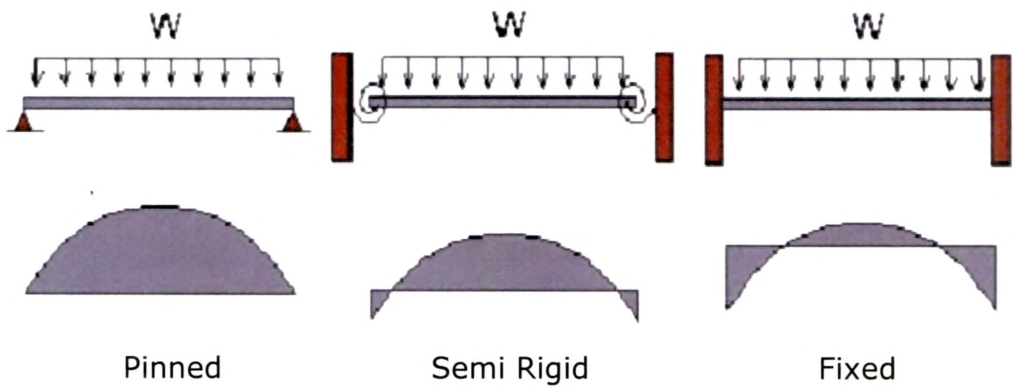


Fig. 10.1 Bending Moments for Beams with Varying Joint Rigidity

Although, this behaviour is well accepted, it should be borne in mind that the actual behavior of the beam column joint depends on the relative flexural rigidity of the beam and column under consideration. This is shown in **Fig. 10.2**.

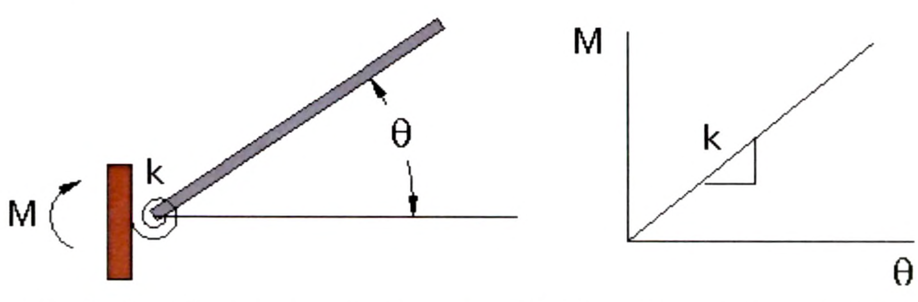


Fig. 10.2 Relation between Action M, Displacement θ and Stiffness K

Thus, if the rigidity of the column is very high relative to that of beam, the beam may behave as semi rigid with inclination towards fixed case shown in **Fig. 10.1**. As against this, if the flexural rigidity of the beam is very high as compared to that of column, the joint will behave as semi rigid with properties nearer to pinned case of **Fig. 10.1**. This fact is depicted in **Fig. 10.3** in terms of relative stiffness of a beam.

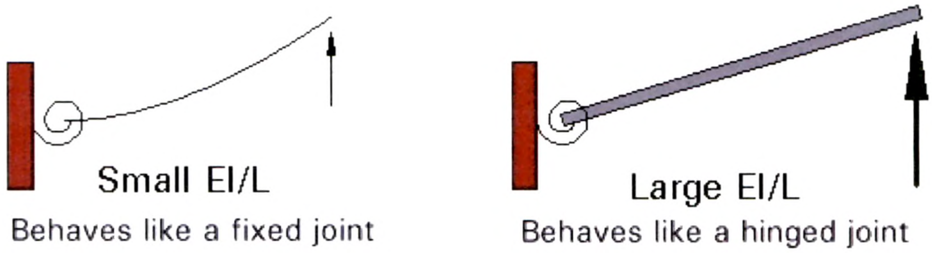


Fig. 10.3 Effect of Relative Stiffness of Beam on Joint Behavior

The effect of semi rigid joint is further extended to the fundamental natural frequency of the structure, which has direct relation to the dynamic loads. The variation in natural frequency for the pinned, semi rigid and fixed beam ends is given in **Fig. 10.4 [38]**.

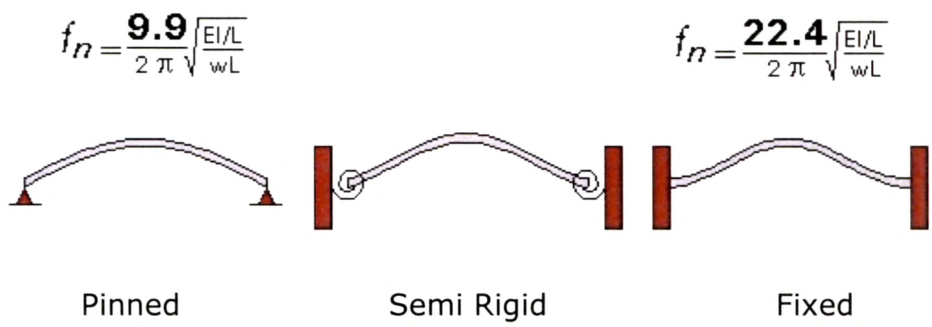


Fig. 10.4 Variation in Fundamental Natural Frequency with Rigidity

The realistic behavior of a frame is always between the ideally pinned and fully rigid state. This fact is obvious from the graph of rotation Φ versus the moment M shown in **Fig. 10.5**. The slope of this graph represents the stiffness of the joint. Thus, there are enough evidences from the literature survey that semi rigid joints should be considered in the analysis.

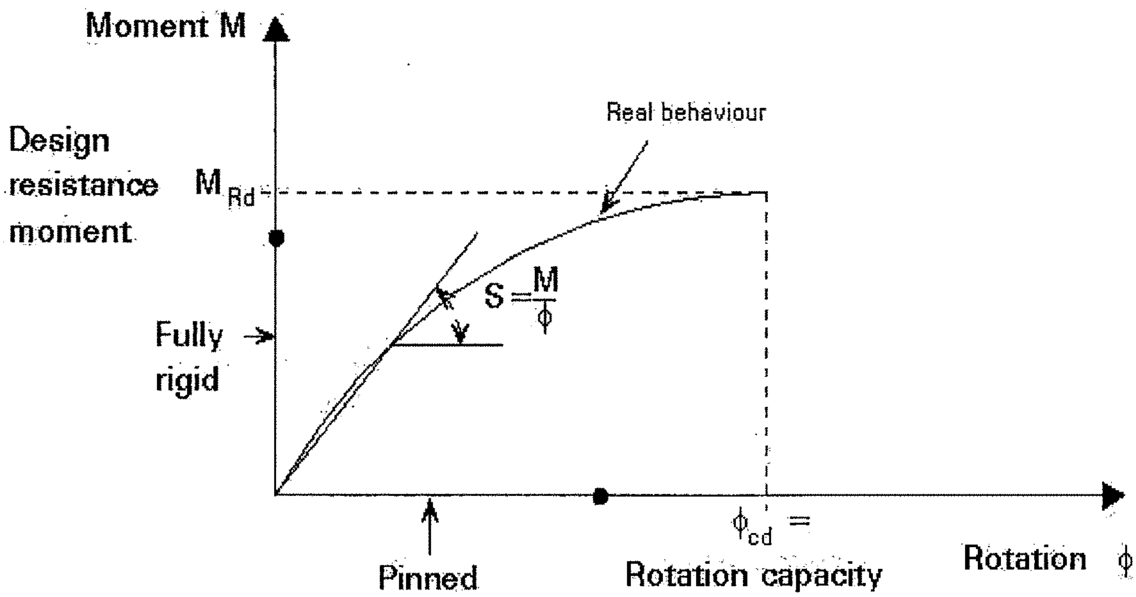


Fig. 10.5 Graph of Rotation vs Moment Representing Joint Stiffness

It is proposed to study the RC space frame models under the following three types of mathematical models developed on the concept of three types of variations.

1. Considering the frames as having all joints as fully rigid joints.
2. Considering the frames having all joints as semi rigid.
3. Considering the internal joints as semi rigid and external joints as fully rigid resulting in what is called here as hybrid frame.

In the case of semi rigid frames, the joint stiffness is taken as 0 kNm/rad representing pinned ends, 7500 kNm/rad representing very low stiffness, 100000 kNm/rad representing intermediate stiffness and 290000 kNm/rad representing a very high value of stiffness corresponding to fixed ends.

10.2 MATHEMATICAL MODELS CONSIDERED FOR ANALYSIS

The mathematical models which are considered for analysis are 2 x 2 bay RC space frames having 6m x 6m overall plan and 6m x 9m overall plan dimensions with G+3 to G+7 stories having two variations of column shapes. Each model is considered with three variations in the joint stiffness. The models considered for the analysis are based on a chart shown in **Fig. 10.6**.

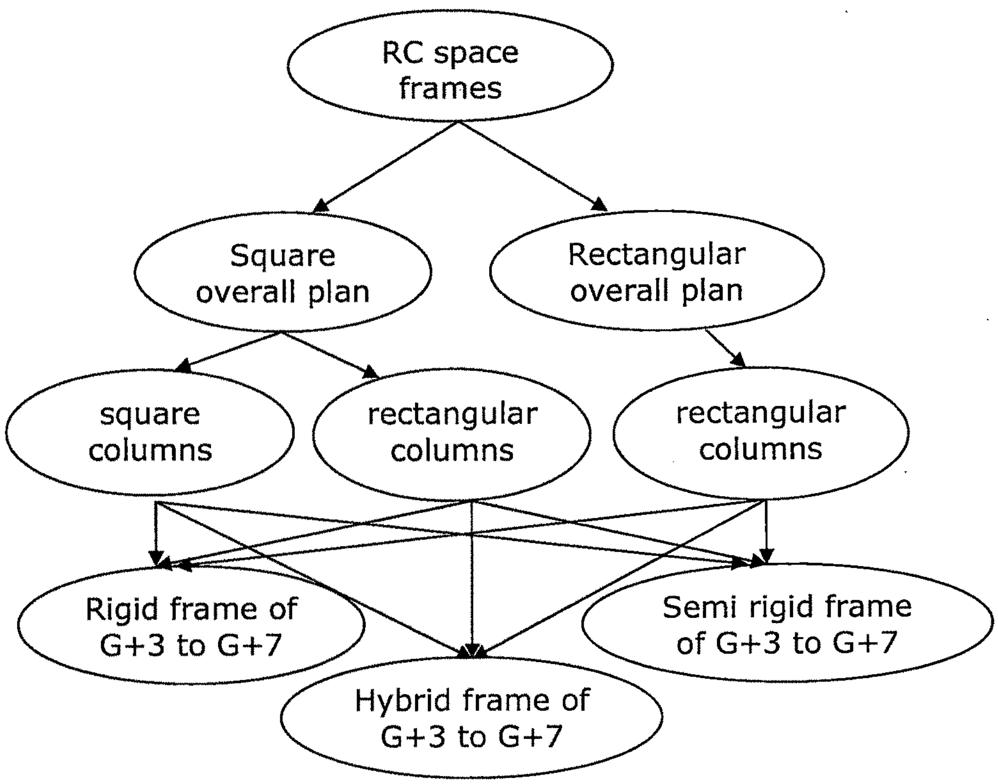


Fig. 10.6 Various Mathematical Models considered for Analysis

10.3 TYPES OF FRAMES CONSIDERED

10.3.1 Rigid Frame

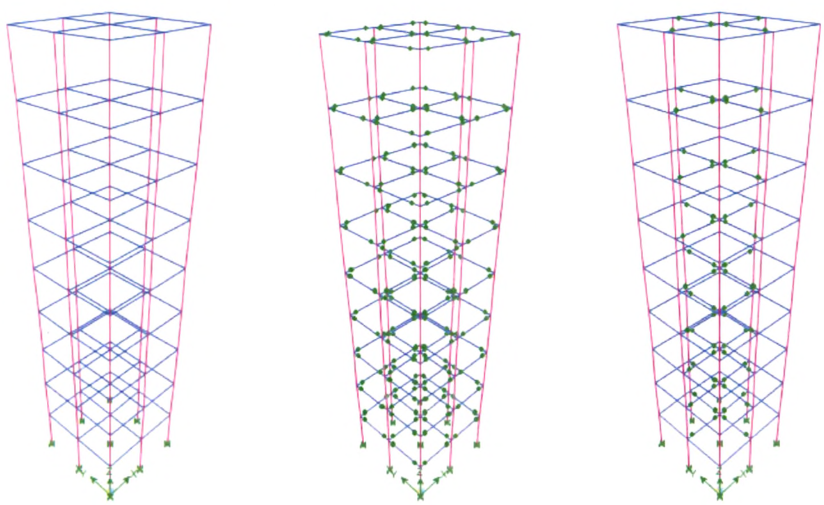
Rigid frame is a moment resisting frame of having all the joints as rigid and resists the external load by frame action. A typical G+7 storey rigid frame is shown in **Fig. 10.7 (a).**

10.3.2 Semi Rigid Frame

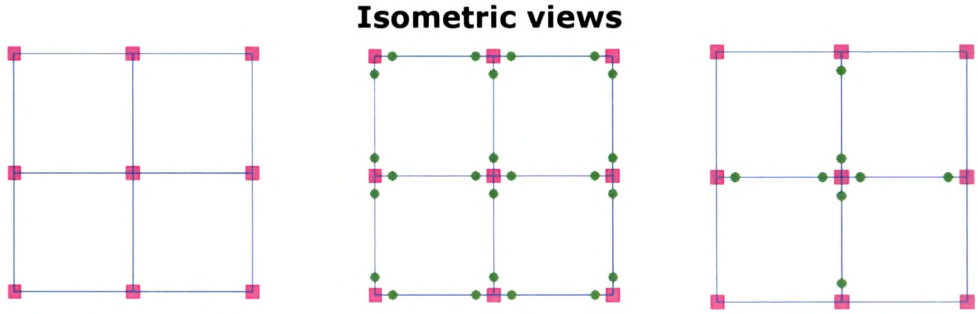
A semi rigid frame is a type of frame having all the joints as semi rigid and resists the external load by truss or combined (truss and frame) action. A typical G+7 storey semi rigid frame is shown in **Fig.10.7 (b).**

10.3.3 Hybrid Frame

Hybrid frames has presence of both rigid and semi rigid joints. In hybrid frame, all the joints other than external are being considered as semi rigid which contributes to the better post earthquake performance and external joints being considered rigid which fulfills the need for higher initial stiffness and better pre earthquake performance. A typical G+7 storey hybrid frame is shown in **Fig. 10.7 (c)**.



Isometric views



Plan Views

(a) Rigid **(b) Semi Rigid** **(c) Hybrid**

Fig. 10.7 Views Defining the Types of Frames considered

The semi rigid joints are indicated by a dot near the joint in the models of typical frames. Thus, it can be seen that in a hybrid frame, the combination of a rigid and a semi rigid frame is considered. It may be noted from the figures of the typical frames that rigidity of only beam elements are varied in all models whereas the column to column connection is considered as rigid.

10.4 GEOMETRIC PROPERTIES AND LOADS CONSIDERED

A 3m x 3m panel model giving an overall plan dimensions as 6m x 6m is considered. The storey height is considered as 3m and the columns are extended up to foundation level assumed to be 3m below ground level. Five different models comprising of G+3 to G+7 storey buildings are considered for the analysis. The beam sizes considered are 230 x 450 mm for all floors. The cross sectional dimensions for all columns are considered as 230 x 450 mm when considering rectangular columns and it is taken as 322 x 322 mm for equivalent square sections. The column sizes between ground level and foundation level are increased by 50mm in columns in both lateral directions. Thus, for a typical rigid frame, five models with G+3 to G+7 storey are considered with rectangular columns and five models with equivalent square columns are considered.

Similarly, ten models for semi rigid frames and ten models with hybrid frames are considered. Again, within each category of semi rigid and hybrid frames, the models are considered having four different variations in joint stiffnesses as 0, 7500, 100000 and 290000 kNm/rad. Thus, in all there are 90 models which are analyzed, 40 for hybrid frames, 40 for semi rigid frames and 10 for rigid frames.

Another set of models is comprising of rectangular panels of 3m x 4.5m arranged such that a 2 x 2 bay frame gives an overall plan dimensions of

6m x 9m. Considering all other dimensions as same, these models are considered with rectangular columns only. Thus, totally 45 models are considered for analysis of rectangular plan. The typical plans for the models considered for analysis showing the orientations of the columns is shown in **Fig. 10.8**.

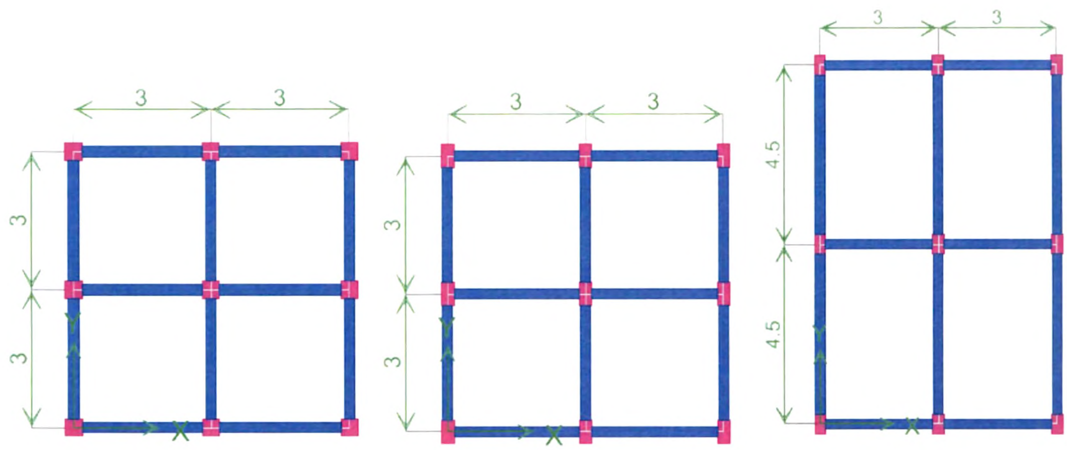


Fig. 10.8 Typical Plan Views showing Column Orientations in Models

The materials considered in all the models are concrete of grade M25 with a characteristic strength of 25 N/mm^2 and reinforcing steel of grade Fe 415 with a strength of 415 N/mm^2.

A uniformly distributed load of 5 kN/m^2 is considered as dead load on all typical floors with a live load of 2 kN/m^2. On the terrace floor, the dead load of 6 kN/m^2 and a live load of 2 kN/m^2 is considered. A uniform load of 13 kN/m is considered on all perimeter beams of typical floors to account for 230 thick brick wall and the same is considered as 6 kN/m on terrace floor for parapet wall. The earthquake loads are generated as per IS 1893, Part 1, 2002 **[24]** considering the mass contribution as 100% from dead load and 25% from live load.

10.5 PARAMETERS FOR PUSHOVER ANALYSIS

The mathematical models developed are subjected to push over analysis using commercial software ETABS with the parameters defined for the same. Default plastic hinges of four types are available in the software. Out of them, P-M-M type of hinges are defined at 5% and 95% of the span for all beam and column elements. Moreover, flexural plastic hinges M3 are defined at the midspan of all beams to capture the possible development of stresses beyond yield point due to gravity loads. The static analysis is carried out for the frame models under dead, live and earthquake load cases. Wind load is not considered as the structures are only up to G+7 storey and for RC structures, earthquake loads will govern due to heavy mass. The members of the frame are designed for standard load combinations as specified in IS 456, 2000 **[28]** and IS 1893, Part 1, 2002.

There are three push over cases specified for each model. The first case is PUSH1 which is the push given in the gravity direction up to the full magnitude of dead load and 50% of live load, applied in an incremental manner. Next, the two lateral pushes, PUSH2 in the lateral X direction and PUSH3 in the lateral Y direction are applied to the structure in a step wise manner. The two lateral push are displacement controlled in which a designated roof level node is monitored up to the target displacement of 0.04 times the height of the building. The plastic hinges developed stage wise are noted along with the performance point which gives an indication of the seismic performance of a building.

10.5.1 Seismic Coefficients C_V and C_A

The seismic coefficients Cv and Ca, given in **Tables 10.1** and **10.3**, are site-dependent ground motion coefficients that define the seismic response throughout the spectral range. They are measures of expected ground acceleration at a site. The coefficients, and hence the expected ground accelerations, are dependent on the seismic zone and soil profile type. They therefore reflect regional seismicity and soil conditions at the site. Additionally, in seismic zone 4, they also depend on the seismic source type and near-source factors Na and Nv.

For a given earthquake, a building on soft soil types such as C or D experiences a greater force than if the same building were located on rock, type A or B. This is addressed in the UBC through the Ca and Cv coefficients, which are calibrated to soil type B with a value of unity. Instead of a single coefficient, two coefficients, Ca and Cv, are used to distinguish the response characteristics of short-period and long-period buildings. Long period buildings are more affected by soft soils than short-period buildings. For present study, there is a need to modify the seismic coefficients Ca and Cv of UBC 1997 **[86]** to IS 1893 **[24]**. One can compare the soil types and interpolate the zone factors of UBC 1997 with IS 1893 to obtain the values of seismic coefficients as per IS 1893. **Table 10.1** shows seismic coefficient Ca as per UBC 1997 and **Table 10.2** shows modified seismic coefficient Ca for IS 1893: 2002. **Table 10.3** shows seismic coefficient Cv as per UBC 1997 and **Table 10.4** shows modified seismic coefficient Cv for IS 1893: 2002. Thus, for the present study, considering **zone III** and a building on **medium** soil, from **Tables 10.2** and **10.4** the values of Ca = 0.232 and Cv = 0.336 are considered for the analysis. The building type considered in the software is type B as per the UBC code. The other important parameters used in the software are presented in the next section.

Table 10.1 Seismic Coefficient Ca as per UBC 1997 (Table 16-Q)

Seismic source type = B			Na = 1.0		
Soil Type	**Seismic zone factor Z**				
	0.075	**0.15**	**0.2**	**0.3**	**0.4**
A	0.06	0.12	0.16	0.24	.32*Na= 0.32
B	0.08	0.15	0.20	0.30	.40*Na= 0.40
C	0.09	0.18	0.24	0.33	.40*Na= 0.40
D	0.12	0.22	0.28	0.36	.44*Na= 0.44
E	0.19	0.30	0.34	0.36	.36*Na= 0.36
F	Site specific investigation is required				

Table 10.2 Modified Seismic Coefficient Ca for IS 1893: 2002

Strata Type	**Soil Type**	**Seismic zone factor Z**			
IS 1893	**UBC 1997**	**0.10**	**0.16**	**0.24**	**0.36**
Hard	**C**	0.120	0.192	0.276	0.372
Medium	**D**	0.153	0.232	0.312	0.408
Soft	**E**	0.227	0.308	0.348	0.360
Seismic Zone		**II**	**III**	**IV**	**V**

Table 10.3 Seismic Coefficient Cv as per UBC 1997 (Table 16-R)

Seismic source type = B			Nv = 1.0		
Soil Type	**Seismic zone factor Z**				
	0.075	**0.15**	**0.2**	**0.3**	**0.4**
A	0.06	0.12	0.16	0.24	.32*Nv= 0.32
B	0.08	0.15	0.20	0.30	.40*Nv= 0.40
C	0.13	0.25	0.32	0.45	.56*Nv= 0.56
D	0.18	0.32	0.40	0.54	.64*Nv= 0.64
E	0.26	0.50	0.64	0.84	.96*Nv= 0.96
F	Site specific investigation is required				

Table 10.4 Modified Seismic Coefficient Cv for IS 1893: 2002

Strata Type	**Soil Type**	**Seismic zone factor Z**			
IS 1893	**UBC 1997**	**0.10**	**0.16**	**0.24**	**0.36**
Hard	**C**	0.170	0.264	0.372	0.516
Medium	**D**	0.227	0.336	0.456	0.600
Soft	**E**	0.340	0.528	0.720	0.912
Seismic Zone		**II**	**III**	**IV**	**V**

10.5.2 The Other Parameters for Push Over Analysis

Apart from the values of Ca and Cv, the other parameters considered for push over analysis by ETABS are the consideration of P-delta effects for incorporating geometric non linearity. These effects start governing especially when a few plastic hinges are fully developed and they deform the structure considerably.

When a plastic hinge is fully developed, it is not able to sustain any further moment. Under such situations, the hinges drop load and thus it is required to redistribute the load. Such situations can be handled by the software in three ways, viz. either the entire structure is unloaded and the loads are applied in the reverse direction, a local redistribution of forces can be applied for the yielding element or a secant stiffness is calculated. In the current work, local redistribution of the forces is selected when a hinge drops load.

10.6 RESULTS OBTAINED FROM THE PUSHOVER ANALYSIS

The results obtained from the push over analysis for all the above mathematical models are presented in the form of tables and graphs. In all the tables, base shear is represented as V and roof displacement is shown as D. The type of model considered is represented by R for rigid frame, H for hybrid frame and SR for semi rigid frame. The results for various semi rigid joint conditions are tabulated. **Table 10.5** shows the results for a set of 45 models of 6m x 6m overall plan dimension frames with square columns and pushed in the lateral X-direction. Due to symmetry of the structure, the push in lateral Y-direction yields the same results. The same results are graphically presented in **Fig. 10.9**. Another set of 45 models are analyzed and the performance point results are presented in **Table 10.6.** The table presents the value of base shear and roof displacement at performance point for 6m x 6m overall plan buildings but having rectangular columns with push given in the lateral X (weak) direction of the frame. These results are again graphically presented in **Fig. 10.10**. **Table 10.7** shows the values for the same 45 set of building frames but with rectangular columns pushed in the lateral Y direction. The same are presented graphically in **Fig. 10.11**.

To study the effect of unsymmetrical framing, a set of 45 mathematical models with rigid, semi rigid and hybrid frames with four variations in the joint rigidity are analyzed using push over analysis with push given in the two lateral directions. All the models are having rectangular columns and the results obtained for performance point are presented in **Table 10.8** for push in X (weak) direction and **Table 10.9** for push given in the lateral Y direction. The corresponding results are plotted and graphically presented in **Figs. 10.12** and **10.13**.

Figure 10.14 a) depicts a graph of roof displacement versus the base shear for the G+7 frame for varying joint rigidity considering hybrid and semi rigid type of framing. The performance points representing various joint rigidities for hybrid type of framing are joined by a line and another line is drawn connecting the results obtained for semi rigid type of framing. It may be clarified here that at a rigidity of 290000 kNm/rad, all frames behave as fully rigid frame. The difference in performance between square shaped columns and equivalent rectangular shaped columns is evident in this figure. Similarly, **Figs. 10.14 b)** thru **10.14 e)** represents the performance point values for G+6, G+5, G+4 and G+3 frames respectively.

Table 10.5 Performance Point Results: 6m x 6m Frames- Sq. Col.

Models with square columns under push-X	Frame type		Joint flexural rigidity in kNm/rad							
			0		7500		100000		290000	
			V in kN	D in m	V in kN	D in m	V in kN	D in m	V in kN	D in m
	G+7	R							827	0.169
		H	779	0.187	798	0.182	816	0.169	821	0.167
		SR	626	0.315	724	0.251	815	0.174	820	0.167
	G+6	R							818	0.145
		H	770	0.163	797	0.158	814	0.147	818	0.144
		SR	629	0.276	724	0.218	806	0.152	818	0.144
	G+5	R							812	0.123
		H	765	0.139	793	0.135	808	0.125	812	0.123
		SR	631	0.239	726	0.188	798	0.129	812	0.123
	G+4	R							799	0.102
		H	755	0.116	784	0.113	796	0.104	799	0.102
		SR	631	0.201	723	0.157	787	0.108	799	0.102
	G+3	R							780	0.082
		H	738	0.094	770	0.091	776	0.084	780	0.082
		SR	629	0.164	718	0.127	768	0.087	780	0.082

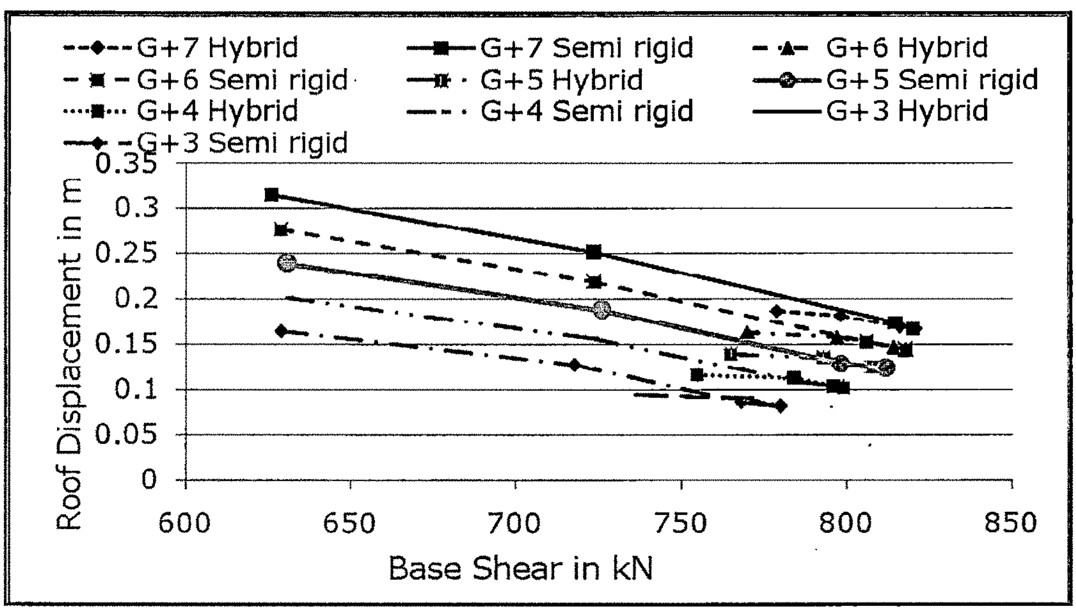


Fig. 10.9 6mx6m Frames with Square Columns under Push X

Table 10.6 Performance Point Results: 6m x 6m Frames- Rect. Col.

Models with rectangular columns - Push-X	Frame type		Joint flexural rigidity in kNm/rad							
			0		7500		100000		290000	
			V in kN	D in m	V in kN	D in m	V in kN	D in m	V in kN	D in m
	G+7	R							708	0.192
		H	687	0.215	704	0.21	701	0.201	711	0.205
		SR	562	0.355	630	0.282	700	0.21	708	0.193
	G+6	R							685	0.161
		H	645	0.192	681	0.188	683	0.171	684	0.169
		SR	561	0.314	666	0.255	679	0.176	684	0.169
	G+5	R							664	0.145
		H	642	0.161	662	0.157	663	0.147	664	0.146
		SR	558	0.273	615	0.211	658	0.153	664	0.146
	G+4	R							643	0.124
		H	620	0.137	641	0.133	640	0.126	642	0.124
		SR	553	0.232	607	0.177	634	0.13	642	0.124
	G+3	R							616	0.103
		H	600	0.116	617	0.11	615	0.104	616	0.103
		SR	544	0.192	596	0.144	613	0.108	615	0.103

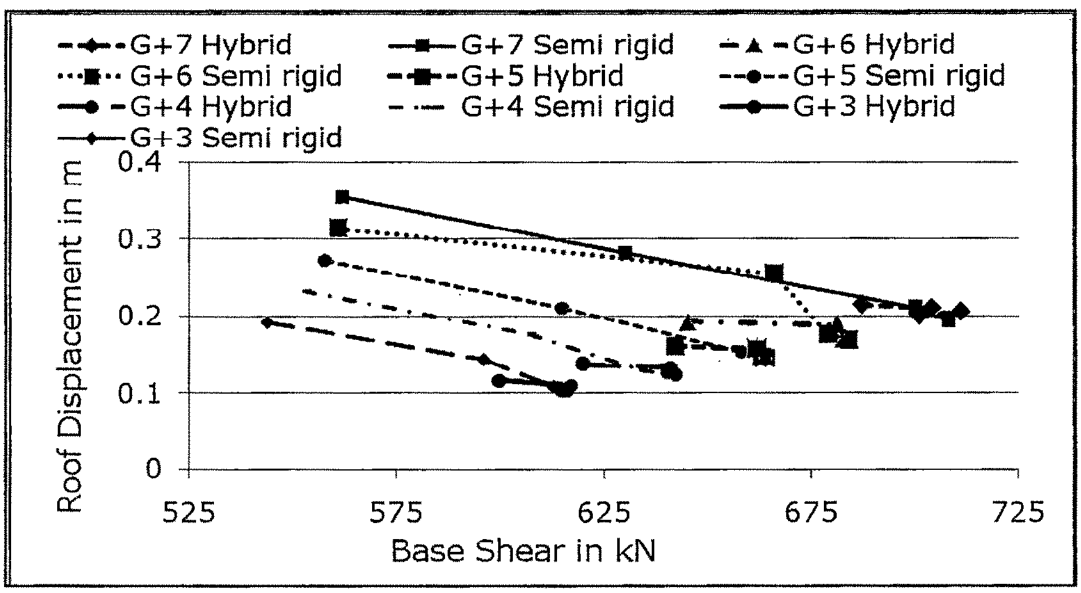


Fig. 10.10 6m x 6m Frames with Rectangular Columns under Push X

Table 10.7 Performance Point Results: 6m x 6m Frames- Rect. Col.

Models with rectangular columns - push-Y	Frame type		Joint flexural rigidity in kNm/rad. 0		7500		100000		290000	
			V in kN	D in m	V in kN	D in m	V in kN	D in m	V in kN	D in m
	G+7	R							958	0.145
		H	893	0.162	925	0.159	954	0.147	956	0.157
		SR	674	0.287	812	0.229	945	0.150	955	0.158
	G+6	R							973	0.125
		H	896	0.143	934	0.140	971	0.126	973	0.125
		SR	682	0.251	845	0.202	962	0.128	980	0.121
	G+5	R							962	0.110
		H	892	0.123	928	0.120	959	0.111	965	0.109
		SR	690	0.215	826	0.170	951	0.114	970	0.107
	G+4	R							960	0.093
		H	892	0.105	928	0.102	957	0.094	963	0.092
		SR	699	0.180	834	0.142	950	0.096	969	0.090
	G+3	R							949	0.075
		H	894	0.087	924	0.083	946	0.076	951	0.075
		SR	708	0.145	840	0.114	939	0.077	957	0.074

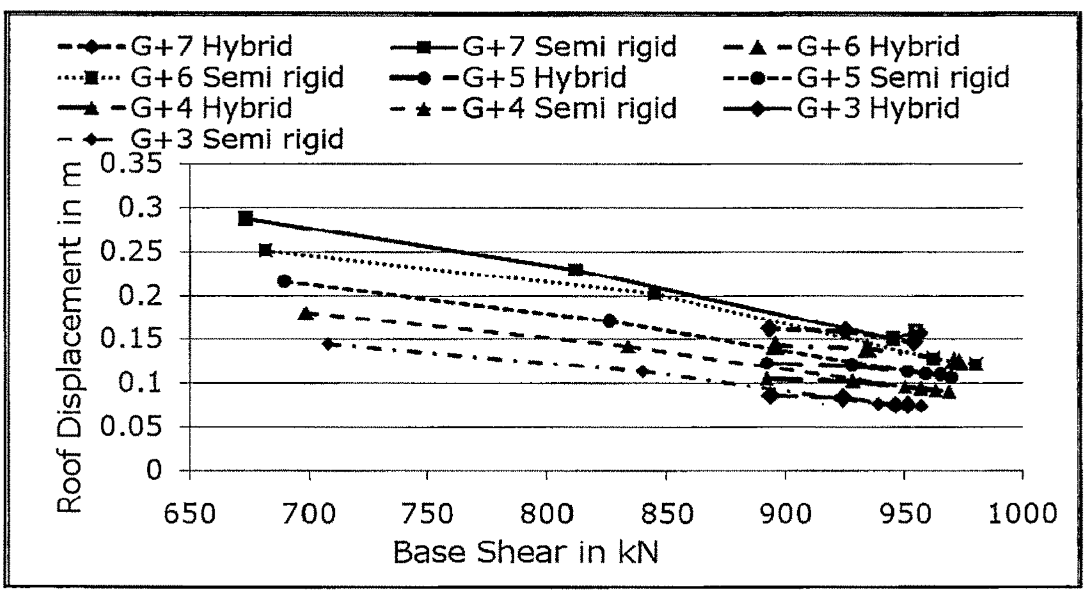


Fig. 10.11 6m x 6m Frames with Rectangular Columns under Push Y

Table 10.8 Performance Point Results: 6m x 9m Frames-Rect. Col.

Models with rectangular columns - Push-X	Frame type		Joint flexural rigidity in kNm/rad							
			0		7500		100000		290000	
			V in kN	D in m	V in kN	D in m	V in kN	D in m	V in kN	D in m
	G+7	R							857	0.228
		H	854	0.243	871	0.24	863	0.229	858	0.228
		SR	673	0.299	809	0.282	858	0.235	859	0.229
	G+6	R							834	0.198
		H	830	0.211	840	0.208	834	0.2	833	0.198
		SR	667	0.266	792	0.247	831	0.205	833	0.198
	G+5	R							804	0.172
		H	799	0.183	814	0.18	804	0.174	805	0.172
		SR	659	0.233	778	0.215	802	0.178	804	0.172
	G+4	R							775	0.147
		H	774	0.157	786	0.153	776	0.148	775	0.147
		SR	783	0.224	793	0.187	775	0.151	775	0.147
	G+3	R							728	0.123
		H	720	0.132	742	0.128	732	0.124	732	0.124
		SR	630	0.169	743	0.151	728	0.126	729	0.123

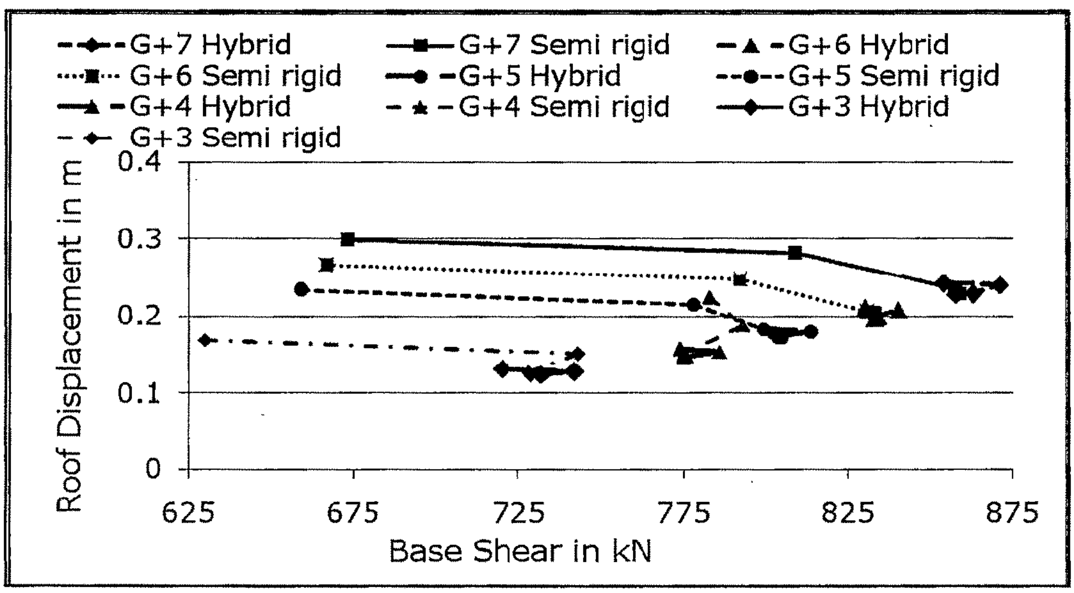


Fig. 10.12 6m x 9m Frames with Rectangular Columns under Push X

Table 10.9 Performance Point Results: 6m x 9m Frames- Rect. Col.

	Frame type		Joint flexural rigidity in kNm/rad							
			0		7500		100000		290000	
			V in kN	D in m	V in kN	D in m	V in kN	D in m	V in kN	D in m
Models with rectangular columns - Push-Y	**G+7**	**R**							1091	0.172
		H	1047	0.19	1076	0.186	1089	0.173	1090	0.178
		SR	915	0.297	1016	0.251	1085	0.178	1091	0.176
	G+6	**R**							1077	0.153
		H	1033	0.168	1063	0.165	1076	0.154	1078	0.151
		SR	918	0.262	1018	0.221	1073	0.158	1078	0.153
	G+5	**R**							1066	0.134
		H	1021	0.148	1052	0.144	1065	0.135	1067	0.133
		SR	918	0.226	1017	0.191	1062	0.138	1068	0.131
	G+4	**R**							1055	0.114
		H	1010	0.126	1041	0.123	1054	0.115	1055	0.114
		SR	918	0.191	1014	0.161	1051	0.121	1054	0.114
	G+3	**R**							1036	0.095
		H	995	0.106	1026	0.103	1035	0.096	1036	0.095
		SR	913	0.156	1007	0.131	1033	0.098	1036	0.094

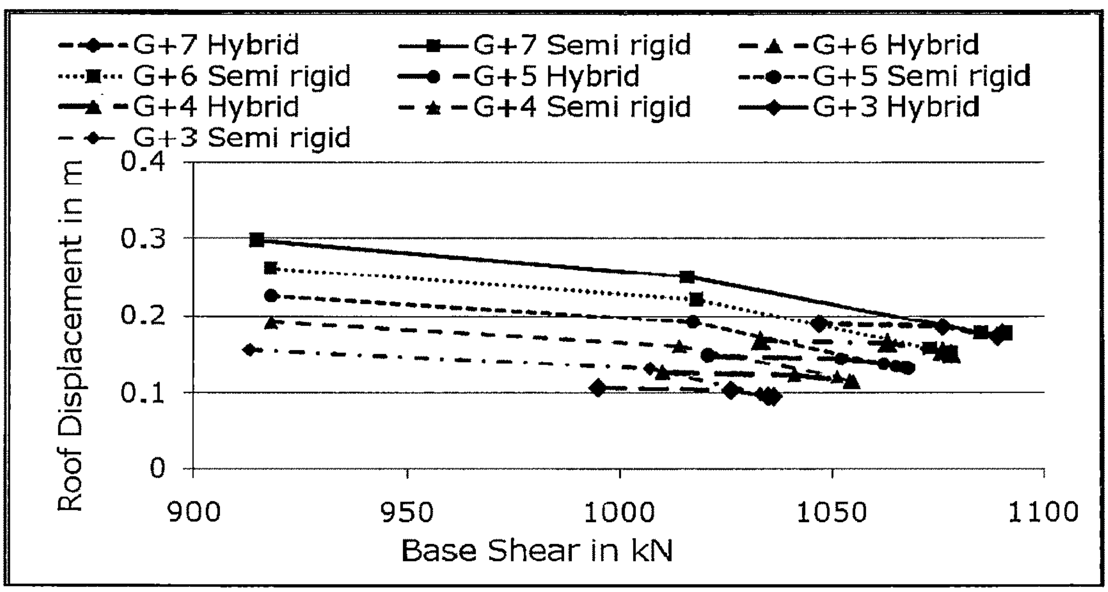
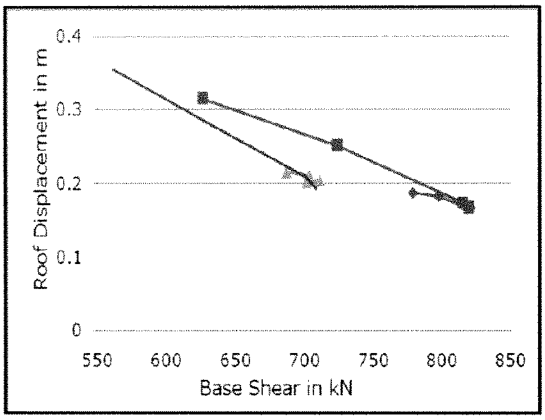
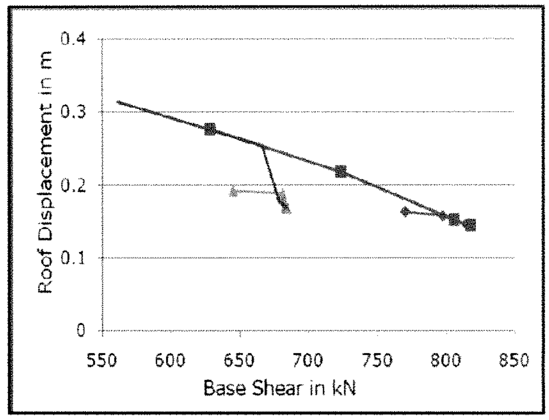


Fig. 10.13 6m x 9m Frames with Rectangular Columns under Push Y

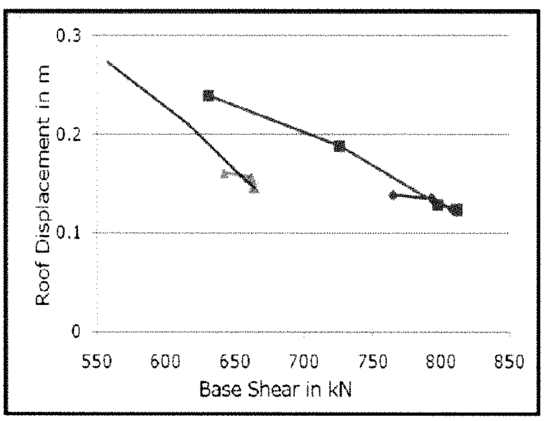
Performance Point Plots



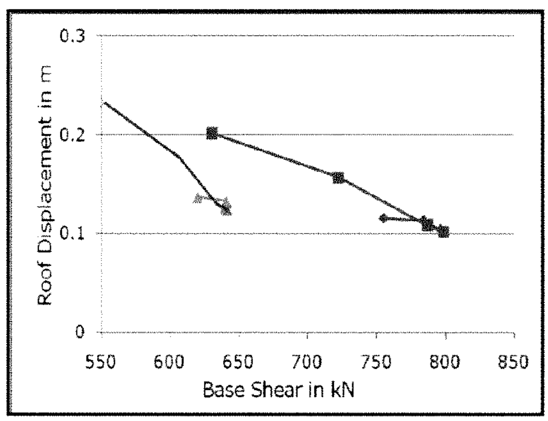
a) G+7 Frame



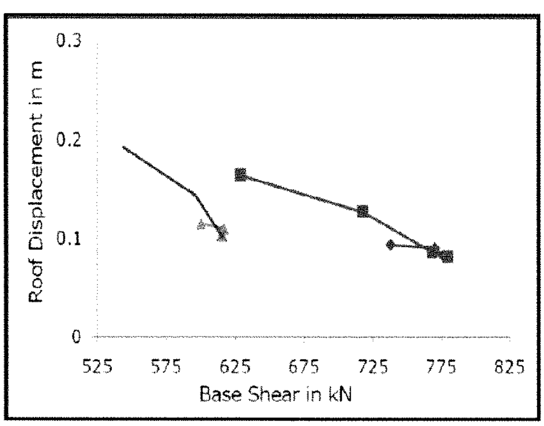
b) G+6 Frame

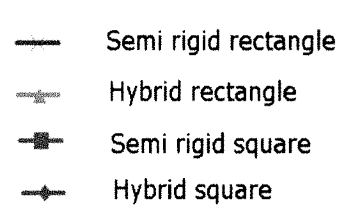


c) G+5 Frame



d) G+4 Frame





e) G+3 Frame

Fig. 10.14 6m x 6m Frame with Square and Rectangular Columns

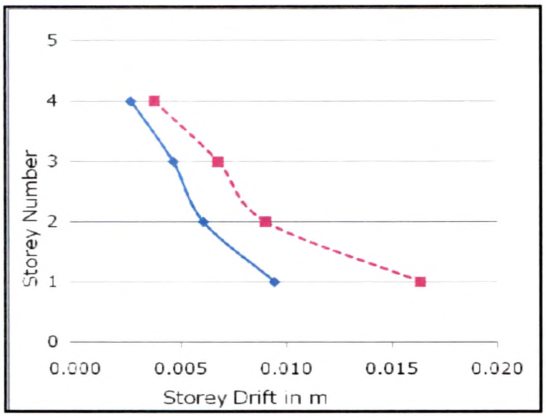
Storey drift is one of the important parameters which is useful in judging the performance of a structure under lateral loads. Thus, the storey drifs obtained at performance point for various frames studied above are presented in a tabular format representing the seismic performance. The storey drifts are presented in **Table 10.10** for frames with square and rectangular shaped columns for G+3 to G+7 structures having all joints as rigid. The comparison is presented for push given in the X direction only which is the weak direction for rectangular columns. The plots of storey drift for G+3 to G+7 storey frames for square and rectangular columns with fully rigid joints are presented in **Fig. 10.15**. The percentage difference between drift value for square and rectangular columns at each storey level is presented in **Table 10.11** and a corresponding graph representing the same is shown in **Fig. 10.16**. The smaller value of storey drift at performance point represents a better performing structure.

Table 10.10 Storey Drift at Performance Point for Frames – PUSH X

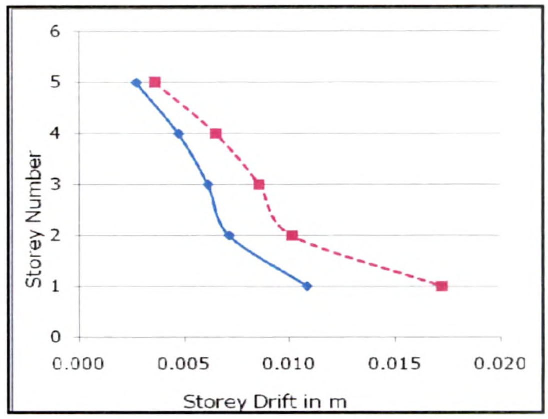
Storey	G+3		G+4		G+5		G+6		G+7	
	Square	Rect	Square	Rect	Square	Rect	Square	Rect	Square	Rect
8									0.0027	0.0040
7							0.0026	0.0034	0.0043	0.0066
6					0.0025	0.0028	0.0043	0.0059	0.0056	0.0089
5			0.0027	0.0036	0.0043	0.0049	0.0056	0.0079	0.0066	0.0104
4	0.0026	0.0037	0.0047	0.0065	0.0057	0.0065	0.0065	0.0092	0.0071	0.0115
3	0.0046	0.0067	0.0061	0.0085	0.0065	0.0075	0.0071	0.0100	0.0075	0.0122
2	0.0061	0.0090	0.0071	0.0101	0.0072	0.0084	0.0076	0.0108	0.0078	0.0130
1	0.0094	0.0163	0.0108	0.0172	0.0108	0.0133	0.0110	0.0182	0.0102	0.0198

All drift values are in m with fully rigid frames

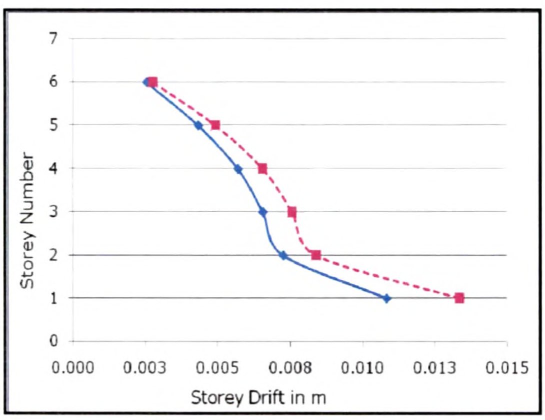
6m x 6m Frames with Fully Rigid Joints



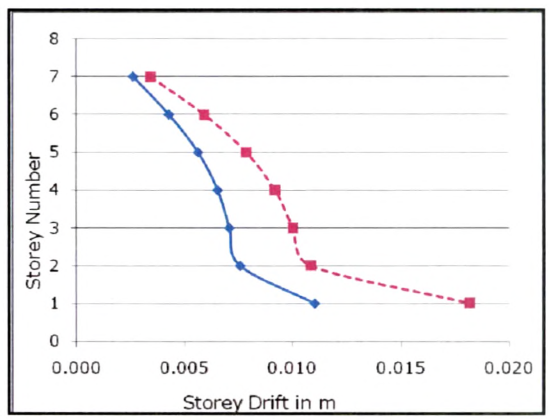
a) G+3 Frame



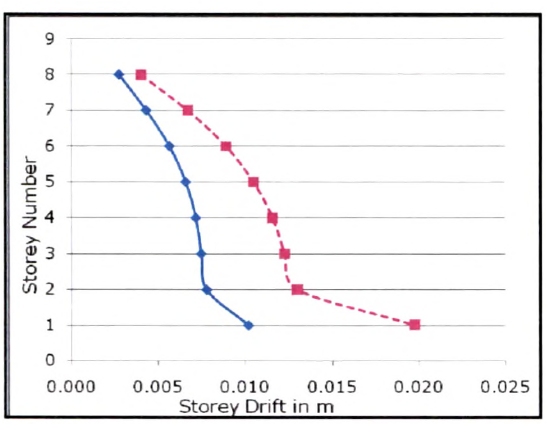
b) G+4 Frame



c) G+5 Frame



d) G+6 Frame



e) G+7 Frame

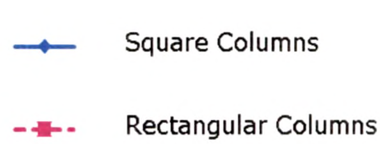


Fig. 10.15 Drift in Frames with Square and Rectangular Columns

Table 10.11 Storey Drift Percentage Difference between Square and Rectangular Columns at Performance Point - Fully Rigid

Storey	G+3	G+4	G+5	G+6	G+7
8					30.9
7				23.1	35.3
6			7.9	27.7	36.4
5		24.5	12.2	28.4	37.2
4	29.3	27.3	13.0	28.8	38.1
3	31.3	28.5	13.3	29.4	39.0
2	32.8	29.5	13.4	30.2	40.1
1	42.2	37.0	18.9	39.4	48.5

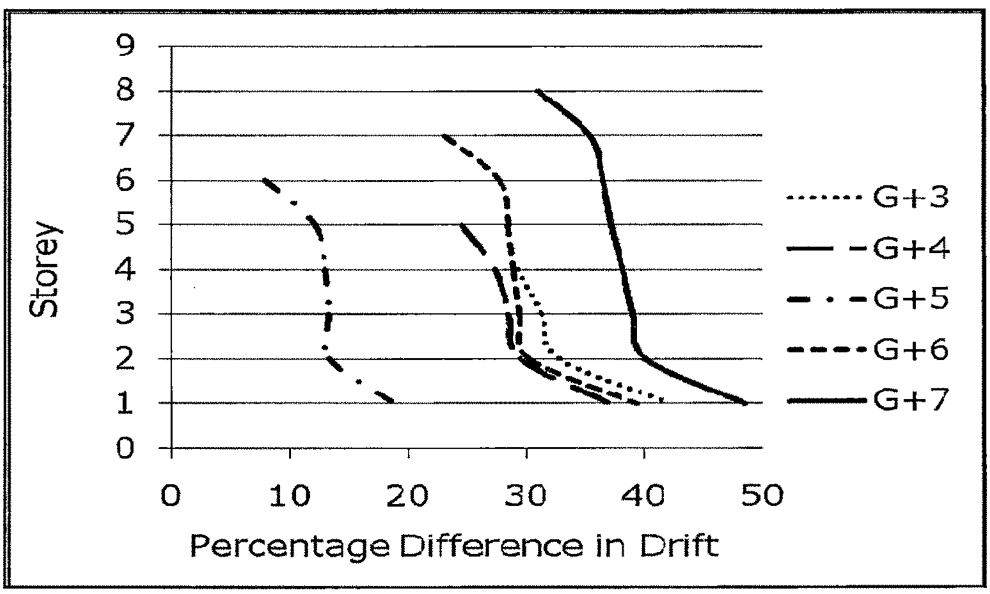


Fig. 10.16 Storey Drift %Difference Between Square and Rectangular Columns for 6m x 6m Plan Buildings - Fully Rigid

From the plotted graphs of percentage difference in drift values at different storey level between square shaped columns and equivalent rectangular shaped columns, it is seen from **Fig. 10.16** that this ratio is the minimum for G+5 structure. Hence, further detailed investigations on the variation in storey drift at performance point due to push over analysis is carried out on G+5 structure. It may be noted here that for hybrid and semi rigid frames with joint stiffness as 290000 kNm/rad, the frames behave just like a fully rigid frame. Hence, the drift results are tabulated only for joint rigidity of 100000, 7500 and 0 kNm/rad for hybrid and semi rigid frames with square and rectangular columns. These values of drift under lateral push in X direction at performance point are presented in **Table 10.12**. All the results obtained from 7 mathematical models for G+5 storey with square columns and 7 models for rectangular columns are presented in **Fig. 10.17**. To study the effect of column shape (square and rectangular), joint stiffness (100000, 7500 and 0 kNm/rad) and type of frame (rigid, hybrid and semirigid) on the storey drift values, three more plots are included based on the available data. Thus, **Fig. 10.18** plots the storey drift for G+5 building with square columns with all variations in rigidities for hybrid and semi rigid cases.

Table 10.12 Storey Drift at Performance Point for G+5 Frame PUSH X

	Storey	Fully Rigid	Hybrid rigidity			Semi rigid rigidity		
			100000	7500	0	100000	7500	0
Square Column	6	0.0025	0.0026	0.0026	0.0025	0.0025	0.0041	0.0056
	5	0.0043	0.0044	0.0044	0.0045	0.0042	0.0066	0.0088
	4	0.0057	0.0057	0.0058	0.0059	0.0055	0.0087	0.0117
	3	0.0065	0.0066	0.0068	0.0069	0.0064	0.0103	0.0142
	2	0.0072	0.0073	0.0085	0.0087	0.0072	0.0118	0.0168
	1	0.0108	0.0109	0.0130	0.0135	0.0120	0.0160	0.0223
Rectangular Column	6	0.0028	0.0028	0.0030	0.0031	0.0030	0.0043	0.0056
	5	0.0049	0.0049	0.0054	0.0057	0.0053	0.0074	0.0095
	4	0.0065	0.0066	0.0072	0.0075	0.0070	0.0099	0.0129
	3	0.0075	0.0076	0.0084	0.0087	0.0081	0.0117	0.0154
	2	0.0084	0.0084	0.0093	0.0097	0.0090	0.0132	0.0181
	1	0.0133	0.0133	0.0135	0.0147	0.0141	0.0175	0.0244

All drift values are in m

1^{st} storey - Maximum drift = 0.0244m and Minimum drift = 0.0108m under push in the lateral X direction at performance point.

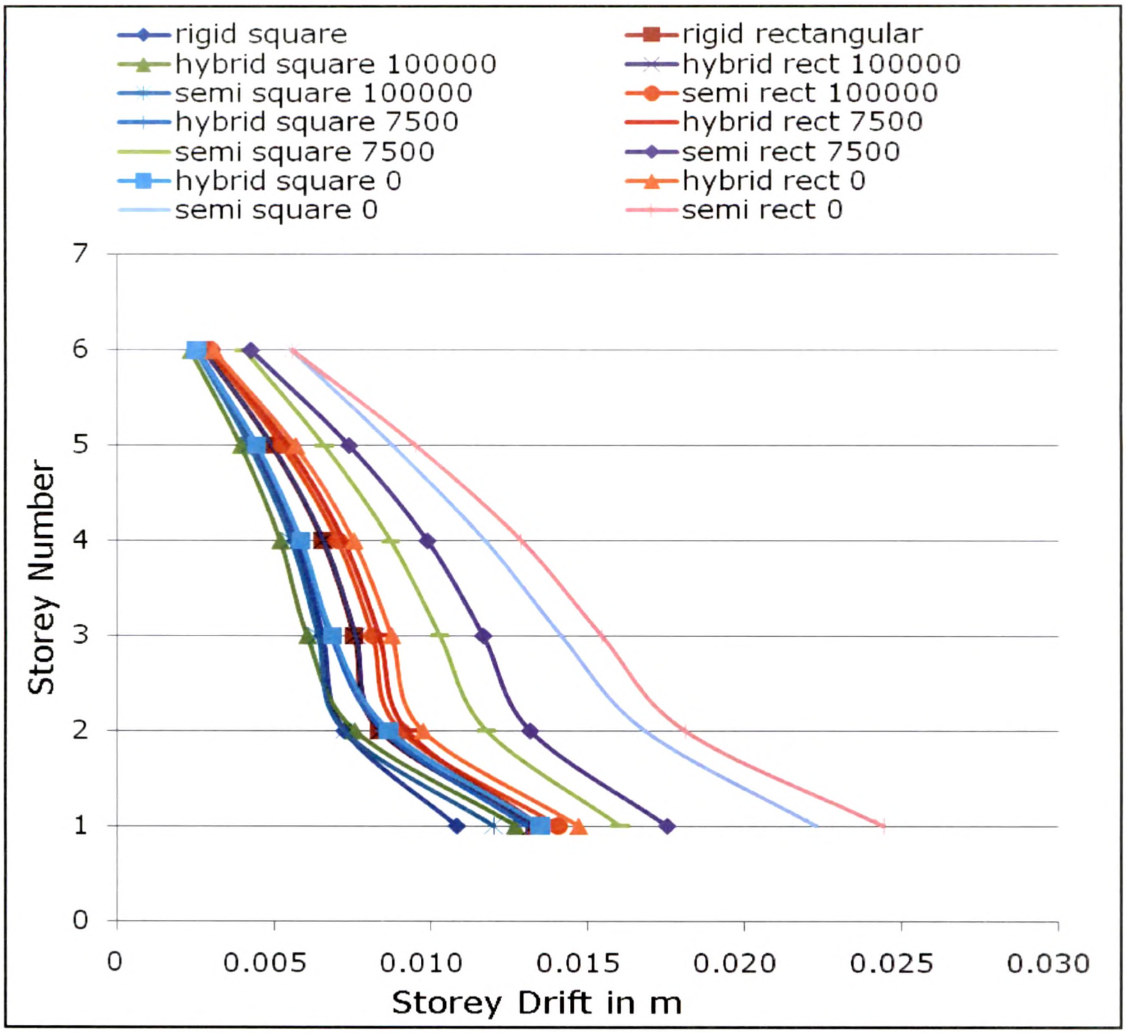


Fig. 10.17 6m x 6m G+5 Frame with Square and Rectangular Cols.

Fig. 10.19 presents the drift values for G+5 frame with rectangular columns with all cases of joint rigidities for hybrid and semi rigid type. To study the effect of type of frame along with the shape of columns on the storey drift, the cases of fully rigid joints as one extreme is plotted against a joint rigidity of 0 kNm/rad (representing a hinge end) as the other extreme. These parameters are shown in **Fig. 10.20** for rigid, hybrid and semi rigid type of frames. The percentage difference in the drift value at each storey is presented in **Table 10.13** for G+5 storey frame.

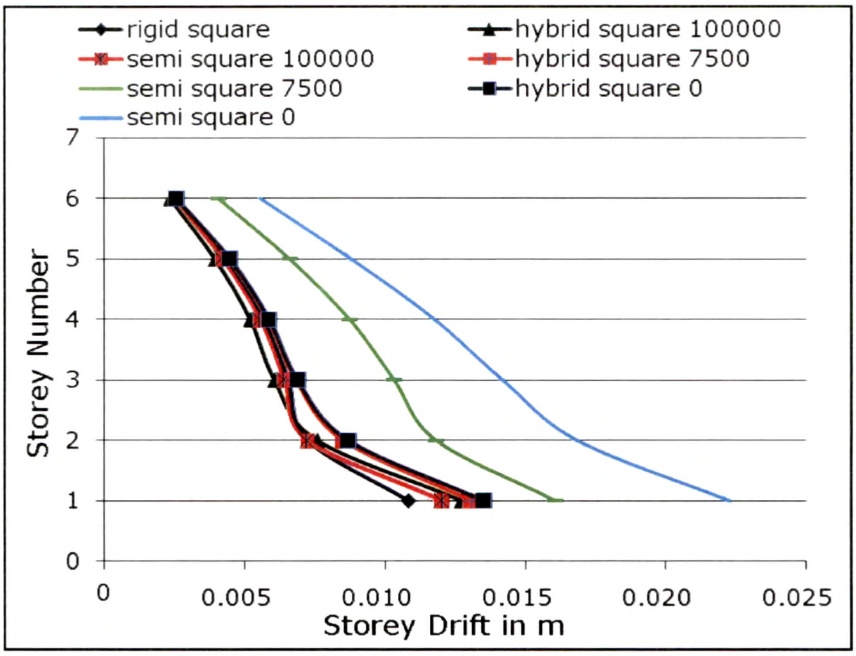


Fig. 10.18 6m x 6m G+5 Frame with Square Columns

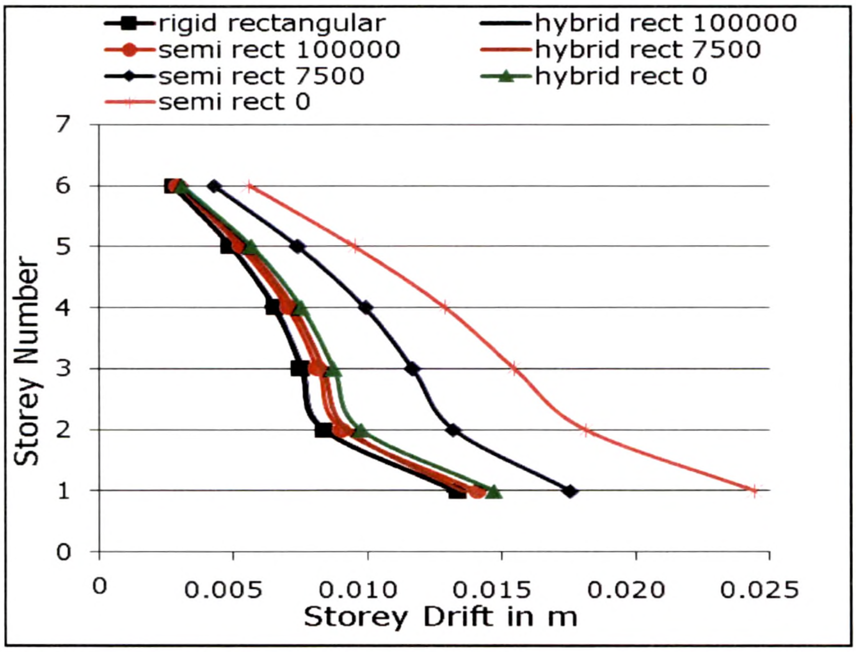


Fig. 10.19 6m x 6m G+5 Frame with Rectangular Columns

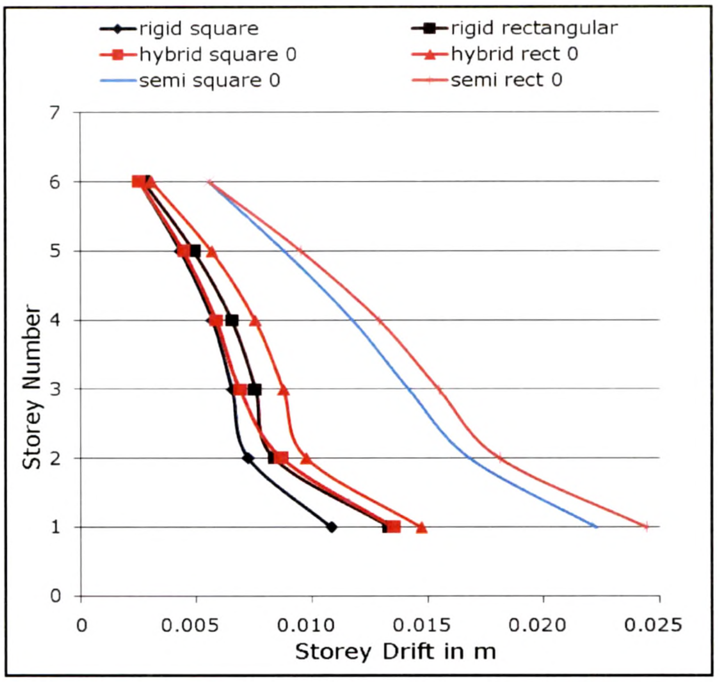


Fig. 10.20 6m x 6m G+5 Frame with Square and Rectangular Cols.

Table 10.13 Drift Diff. in % for G+5 Frames Compared to Fully Rigid

	Storey	Fully Rigid	Hybrid rigidity			Semi rigidity		
			100000	7500	0	100000	7500	0
Square Column	**6**	NA	0.4	0.8	0.0	-0.7	37.4	54.2
	5	NA	0.9	2.8	3.3	-2.6	34.6	50.9
	4	NA	1.0	2.3	3.1	-2.7	34.8	51.6
	3	NA	1.3	3.7	4.8	-2.3	36.4	53.8
	2	NA	1.3	14.6	16.6	-0.3	38.5	56.9
	1	NA	0.3	17.0	19.9	9.8	32.5	51.4
Rectangular Column	**6**	NA	-0.1	7.4	10.2	6.6	35.4	50.5
	5	NA	0.3	9.7	13.4	6.5	33.6	48.4
	4	NA	0.4	9.5	13.3	7.0	34.0	49.3
	3	NA	0.6	9.8	13.7	7.4	35.4	51.1
	2	NA	0.6	9.7	14.2	7.6	36.6	53.8
	1	NA	-0.6	1.3	9.2	5.1	23.9	45.4

10.7 OBSERVATIONS AND DISCUSSION

1. Regardless of the size and shape of the columns, the performance point values for frames with fully rigid joints is same as that observed for hybrid and semi rigid frames with joint rigidity as 290000 kNm/rad. This can be observed from **Tables 10.5** to **10.9** and the corresponding **Figs. 10.9** to **10.13**.
2. It is also observed from the same tables and graphs that the variation in the performance point value is very less for all joint rigidities in case of hybrid frames as compared to semi rigid frames. This is observed irrespective of number of storey.
3. The performance of hybrid frames is very near to the performance of fully rigid frames for joint rigidity greater than 100000 kNm/rad, which is almost 33% of the full rigidity value. This observation is valid for all frames regardless of number of storey or shape of the column.
4. From **Fig. 10.14**, it can be seen that the base shear at performance point for RC frames with square shaped columns with semi rigid frames with joint rigidity as 100000 kNm/rad is more than that resisted by rectangular shaped column with fully rigid joints. This shows that the square shaped columns perform better than the rectangular columns even when they lose their rigidity to 33% of that for fully rigid case.
5. For rectangular overall plan dimension of 6m x 9m with rectangular columns pushed in the weaker direction, it is observed from **Fig. 10.12** that there is hardly any effect of variation in joint rigidity on value of roof displacement at performance point. This is indicated by the almost horizontal lines for semi rigid frames for G+3 to G+7 storey structures. The same figure indicates that the base shear at performance point increases with the increase in the joint rigidity.
6. From comparison of **Fig. 10.10** with **Fig. 10.11** and **Fig. 10.12** with **Fig. 10.13**, it is clear that for frames with rectangular columns, the

performance point values for base shear are more for push in the stronger direction as compared to that in the weaker direction regardless of the number of storey in the frame. It is also seen from **Fig. 10.9** that the base shear values for all types of frames with square columns is between the values observed for a given frame with rectangular columns pushed in the two lateral directions.

7. It is clear from **Fig. 10.15** that the storey drift is maximum at the first storey level in all the 6m x 6m frames for both square and rectangular columns for G+3 to G+7 storey space frames. Thus, from seismic performance point of view, first storey is the most critical one.
8. **Figure 10.15** indicate that the drift is less for models with square shaped columns as compared to rectangular shaped columns for G+3 storey frame to G+7 storey frames. Further, the difference in drift between the two shape of cross sections decrease with the increase in number of storey.
9. **Figure 10.16** and **Table 10.11** shows that the percentage difference in the drift value observed between square and rectangular columns is as high as 48.5% for first storey level for G+7 storey frame and it is as low as 7.9% for the terrace storey of G+5 storey frame.
10. It is also observed that the percentage difference in the drift is minimum for G+5 storey frames when subjected to a lateral push as seen in **Fig. 10.16**. The percentage difference in drift between square and rectangular columns for 6m x 6m frames increases as number of storey increases or decreases from G+5 storey.
11. **Figure 10.17** and **Table 10.12** indicates that the drift values at performance point for G+5 frame under push in the lateral X direction is the maximum for rectangular columns with all beam to column joints released and it is minimum for frame with square columns with full rigidity.

12. It is also observed from **Fig. 10.17** that the performance of hybrid frame with square columns having all internal beam to column connections as released is better than the same frame with rectangular columns with fully rigid joints as far as the storey drift is concerned. From the same graph it is also seen that the storey drift for square as well as rectangular columns is relatively high for semi rigid frames with low rigidity. This fact is also supported by the high values of percentage difference in drift with reference to fully rigid frames shown in the last two columns of **Table 10.13**.
13. Comparison of plots given in **Fig. 10.18** shows that the drift values for G+5 storey frame with square columns with all joint rigidities, the drift values for joint rigidity below 100000 kNm/rad for semi rigid frames is quite high and should be avoided. The drift performance of square columns is almost unaffected by the joint rigidity in hybrid frames.
14. **Figure 10.19** shows identical behavior in case of rectangular columns for G+5 storey frame. This leads to the fact that the column shape does not help in reducing the storey drift for low joint rigidity. It can also be concluded that hybrid frames with any joint rigidity are showing almost similar drift.
15. The storey drift for square columns with hybrid frames having 0 kNm/rad joint rigidity is less than that for rectangular columns with fully rigid joints. This fact is evident from **Fig. 10.20** which shows the superiority of hybrid frames. At the same time it is also observed that semi rigid frames with low rigidity shows excessive drifts regardless of their cross sectional shape.