Seismic Behavior of Moment Resisting Frame (MRF) Buildings

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Moment resisting frames (MRFs) are highly regarded for their simplicity, convenience in construction, flexibility in floor planning and, seismic performance. But, behaviors of moment frames are different under gravity and lateral loading. Results obtained from linear and non-linear static analyses of a midrise 20-storey building and a low-rise 4-storey building are compared to understand flow of forces, deformation profile, and pattern of hinge formation in MRF buildings. The results obtained show the importance of having relatively large exterior columns for better building performance against combined gravity and lateral loading. Also, relative column-to-beam stiffness ratio plays a major role in controlling the behavior of moment frames, in addition to column-to-beam strength ratio. In particular, seismic behavior of steel MRF buildings changes significantly with building height.

Key Words : *pushover analysis, plastic hinge, strength ratio, stiffness ratio*

1. INTRODUCTION

A large percentage of buildings constructed today use MRFs as their primary gravity and lateral load resisting systems. Today, backed by extensive research worldwide, MRFs are highly regarded for their seismic performance based on their relatively good performance in past earthquakes. Moment frames are believed to be efficient as well as economical structural systems for up to 20-30 storey buildings[1)].

In conventional force based design procedures for gravity loads, similar design methodologies are used for both relatively short as well as tall buildings. However, other critical factors govern the behavior of buildings expected in resisting lateral forces, particularly earthquake induced effects[2)]. For instance, relative beam-column stiffness ratio governs moment and deflections patterns in frames as well as the pattern of hinge formation in short buildings (of up to about 6 storey). But, axial stiffness of the column and aspect ratio of the building also govern the overall response of taller buildings (of say, 15-20 storey tall). This work aims at understanding the behavior of a 20-storey steel MRF building subjected to seismic actions in comparison to the behavior of a 4-storey steel MRF building. The effects are observed of variation in, relative column-to-beam flexural stiffness, relative column-to-beam strength ratio, and, axial stiffness of columns on the overall behavior of steel MRFs. Linear and nonlinear static analyses of various building cases are carried out to understand load path in these buildings, overall deformations, and hinge formation patterns.

2. DESCRIPTION OF STRUCTURE AND LOADING

The study building is a predesigned 20-storey steel MRF building reported in literature and is a 3-bay by 4-bay rectangular office building[3)]. The building is modeled in SAP 2000 Advanced v14.2.2[4)]. For the 4-storey building case, the first 4 storeys of the building are considered. The gravity load acting on the building is assumed to be the total of, a dead load of 100 pounds per square foot (psf), live load of 80psf and 20psf acting on the floor and roof respectively, and, exterior wall weight of 35psf. The seismic loading on the building is as per the equivalent force method as described in IS 1893[5)].

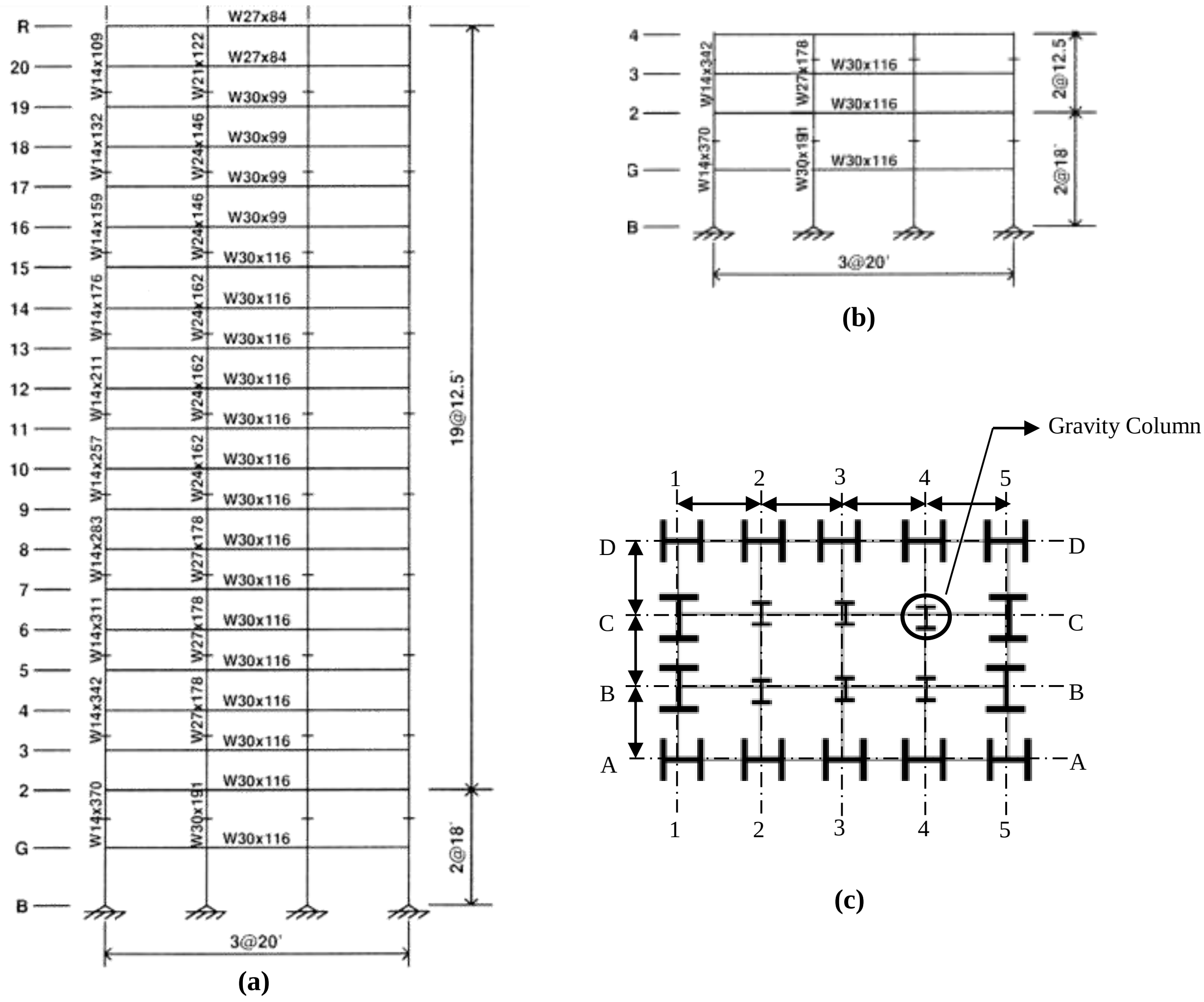

Fig.1 Elevation of (a) 20-storey building, and (b) 4-storey building, with sectional details of beams and columns, and (c) Plan of the buildings

The building is assumed to be in Indian seismic zone V and founded over a layer of soft soil with a damping percentage of 5%. The joints are assumed to be rigid in the analysis. The locations of the hinges provided in beams (M3) and columns (P-M3), their elasto-plastic force-deformation relations, and, their performance levels are based on the recommendation given in FEMA 356[6].

3. LINEAR STATIC ANALYSIS

In order to express and compare the force flow between the 4- and 20- storey buildings, normalized graphs are presented. The graphs contain the normalized height of building on the vertical axis, i.e. the ratio of the storey height to the overall building height. The horizontal axis contains the normalized axial force, shear force and bending moments, normalized with the overall vertical load acting on the building, the overall base shear acting on the building, overall overturning moment caused by the base shear respectively. The graphs are plotted for the Bay A-A of the 4 – and 20-storey building for the left (1-1), middle (3-3) and right (5-5) (Fig. 1) set of columns for gravity only, lateral only and combined gravity and lateral loading effects.

(1) Observations

Generally, it is expected that the axial force, shear force and bending moment demands in the columns keep increasing towards the base of the building, with the maximum force demand values at the bottommost columns. This is due to the accumulation of applied shear and overturning moment at each storey level till the base.

It is observed that the in the exterior columns, axial force, shear and moment demand increase till the base. Whereas, in the interior column, the shear and moment demand keeps increasing up till a point (around 0.3 times the height of the building) beyond which there is a reduction in the demand (Fig. 2). But, there is an increase in axial force demand in the exterior column as the base approaches (Fig. 3). This effect is predominant in the taller 20-storey building.

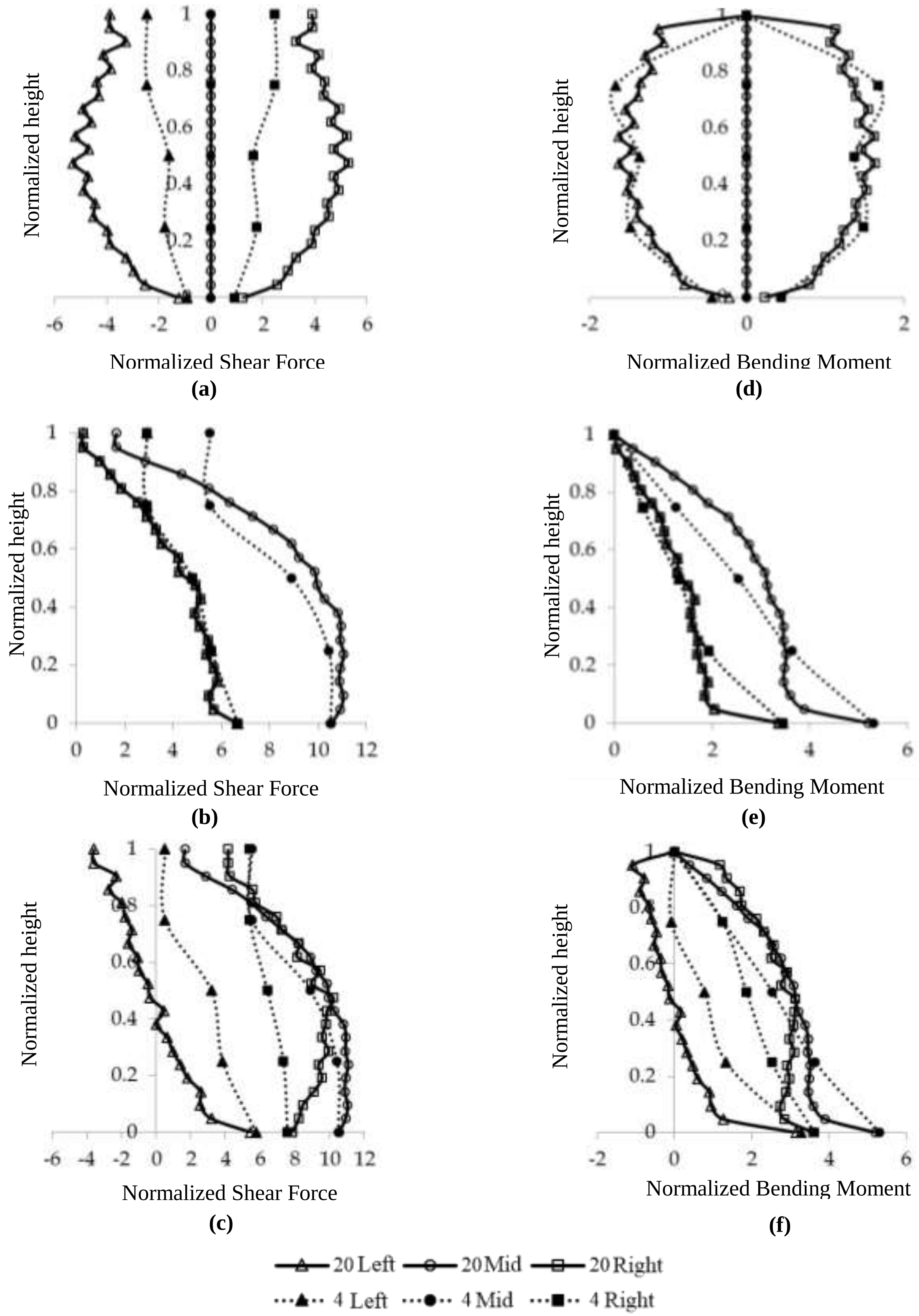

Fig.2 Comparison of column demand variation along height for 4- and 20- storey buildings: Bending Moment variation for (a) Gravity load (GL) only, (b) Lateral load (LL) only, nd (c) GL+LL; Shear Force variation for (d) GL only, (e) LL only, and (f) GL +LL

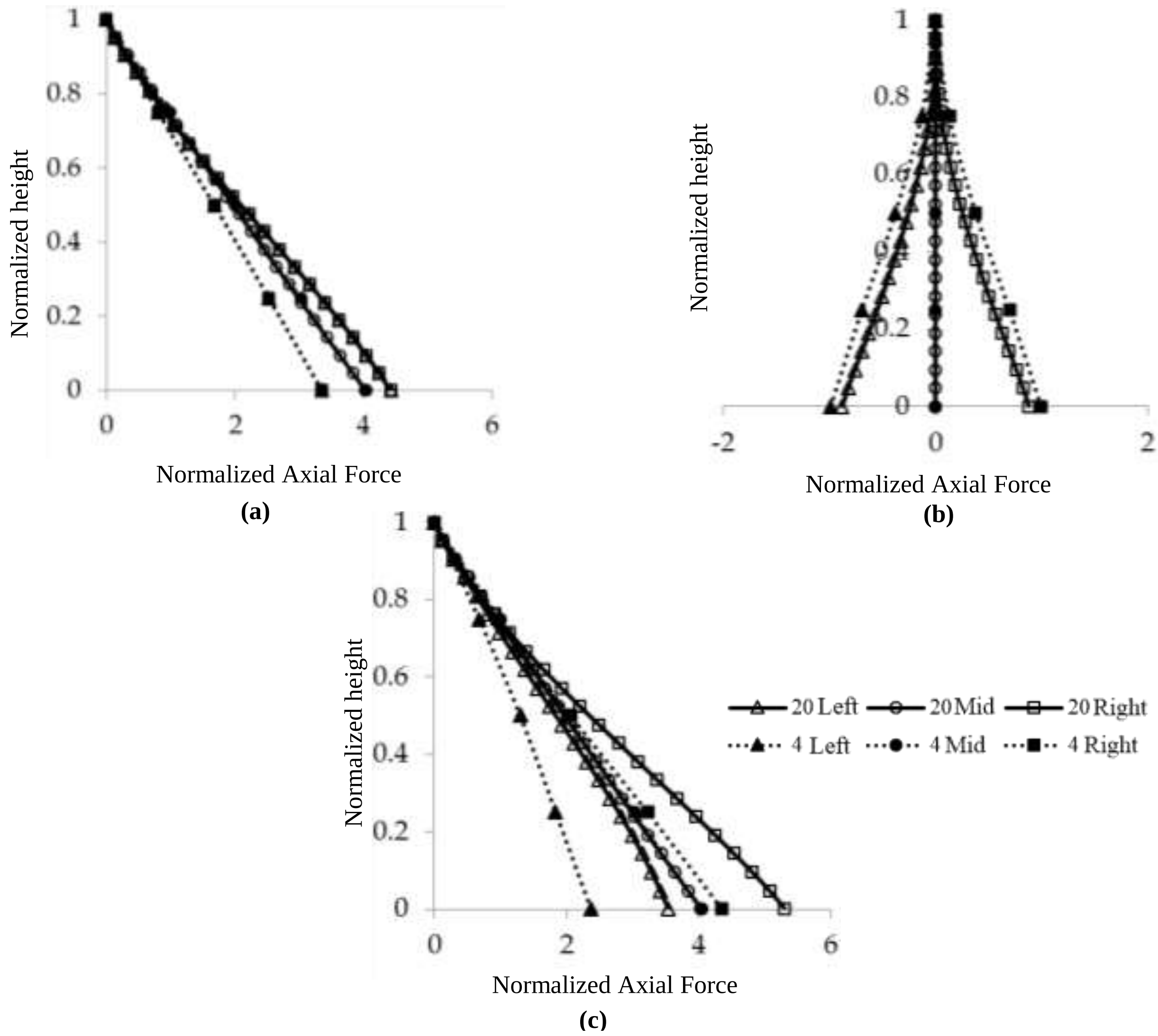

Fig.3 Comparison of axial force variation in column along height for 4- and 20- storey buildings: for (a) Gravity load (GL) only, (b) Lateral load (LL) only, and (c) GL+LL.

(2) Conclusions from Linear Elastic Behavior

Under combined gravity and lateral loading, the maximum column shear and moment demand is not at the base of the building, but at a higher storey level. There is a reduction of moment and shear demands in the central columns present in the lower storey levels. There is a higher moment and shear demand on the exterior columns, especially in the lower storey level. Therefore under lateral loading, the reduction in shear force and bending moment in the central lowers columns is compensated by an increase in forces in the lowers exterior columns. This means, in a three dimensional space, the lateral loading acting on the building due to seismic forces tends to flow towards the corner columns, as it flows towards the supporting ground.

Therefore for better seismic performance, it is imperative that larger exterior columns are provided to facilitate this flow of forces efficiently. Providing a cluster of columns at the corners would be beneficial.

4. NONLINEAR STATIC ANALYSISS

In order to see the influence of exterior columns on the nonlinear behavior of the steel MRF, a parametric study is performed by varying the stiffness and strength of the exterior columns. The relative axial stiffness, flexural stiffness, and moment capacity of the exterior columns benchmark building (B; Fig. 1) are varied (by 50% and 200%) as shown in Table 1 to create 9 load cases. Pushover analyses of the 9 building cases is performed. Fig. 4 shows the variation of the plastic hinge formation with the variation of strength and stiffness of the exterior columns.

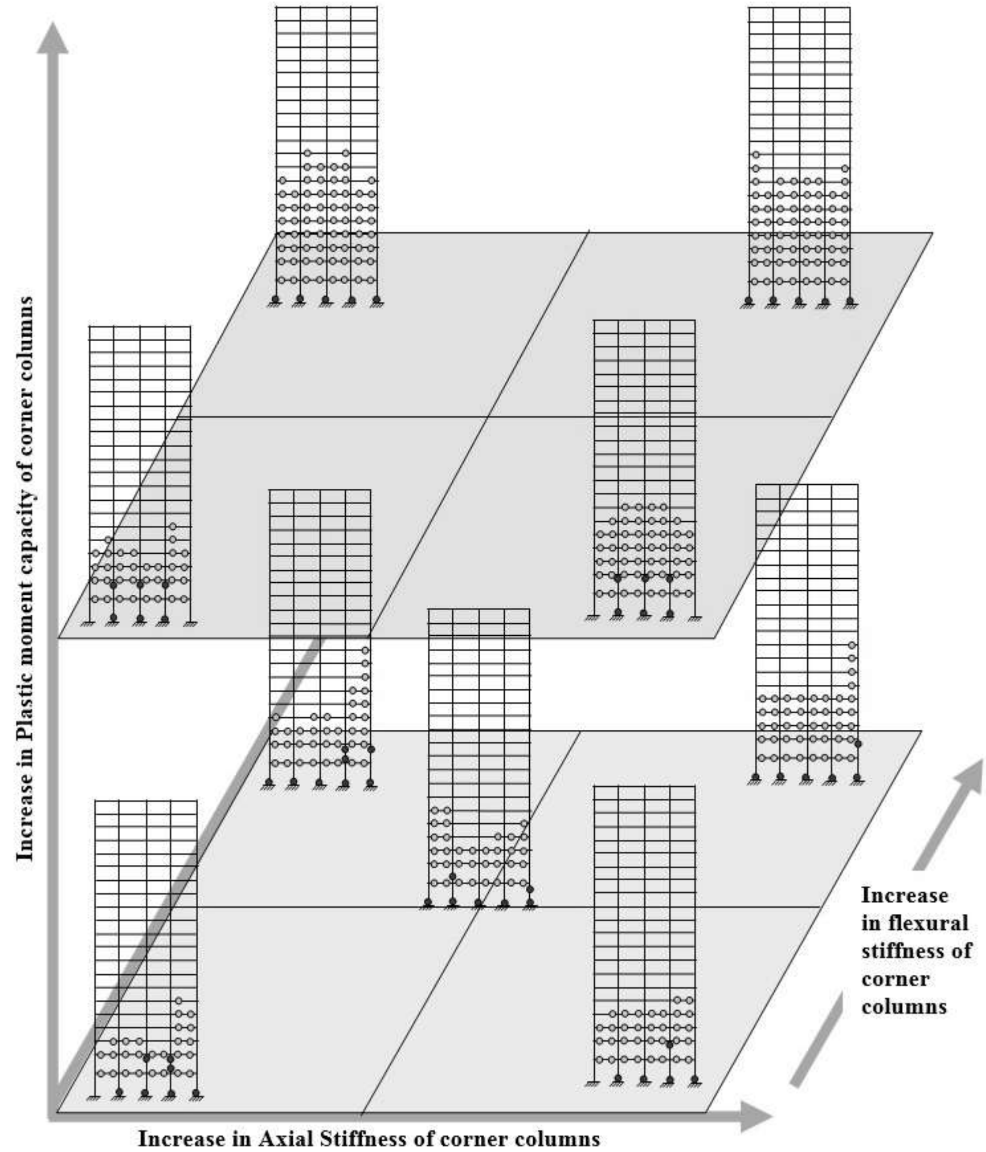

Fig.4 Plastic hinge formation pattern due to variations in strength and stiffness parameters in the exterior column of the building

Table 1 Various cases studied: Values of property modifiers applied to each parameters (B: Benchmark building)

Case	Axial Stiffness $\frac{E_C A_C}{E_b A_{\boldsymbol{b}}}$	Flexural Stiffness $\frac{E_c I_c / L_c}{E_b I_b / L_b}$	Moment Capacity $\frac{M_{p,c}}{M_{\boldsymbol{p,b}}}$
1	B	B	B
2	0.5	0.5	B
3	0.5	2	B
4	2	0.5	B
5	2	2	B
6	0.5	0.5	2
7	0.5	2	2
8	2	0.5	2
9	2	2	2

where,
E_c and E_b is the elastic modulus of column and beam, respectively
A_c and A_b is the cross sectional area of column and beam, respectively
I_c and I_b is the moment of inertia of column and beam, respectively
$M_{p,c}$ and $M_{p,b}$ is the moment of inertia of column and beam, respectively

It is desirable that more number of beam hinges is formed, and that they are well distributed along the height of the building, for better seismic performance.

(1) Observations

The increase in moment capacity of the exterior columns improves the overall nonlinear performance of the building as there are more well spread beam hinges. An increase in the flexural stiffness also causes more beam hinges to be formed in higher storey levels. The axial stiffness does not influence much the nonlinear behavior of the building.

(2) Conclusions from non-linear behavior

The results obtained from the inelastic analysis comply with conclusion obtained from the linear elastic analysis in that, providing larger exterior columns results in better seismic performance of the building. By increasing the stiffness and strength parameters of the exterior/corner columns alone, more favorable global inelastic behavior of the building is achieved in terms of (i) more number of plastic hinges being formed at beam ends, (ii) better propagation of plastic hinges along the building height, and (iii) higher base shear capacity.

5. CONCLUSION

The objective of the paper was to understand the flow of forces in moment resisting frames when subject to seismic loading. By understanding the "force flow" through the building, it is seen why it is better to provide large columns on the corners of a building and how it improves the non-linear behavior of building as well. When a seismic performance evaluation of buildings with ancient Chinese traditional architecture in seismically active regions was done[7], it was observed that the buildings with very large exterior columns performed extremely well. Thus, these large columns that were provided intuitively few thousand years back effectively facilitated the flow of forces through the building; modern construction should take a cue from the traditional art.

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