

Study on Influence of Floor Characteristics on the Seismic Performance of Soft Storey RC Frames from Pushover Analysis

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Abstract—Earthquakes are most devastating natural hazards among all the forces that structures are likely to be subjected to and it is very important to design the structure to resist both moderate and severe earthquakes. In multi storeyed buildings, damage from earthquake excitation are generally due to locations of structural weakness like irregularities, where large concentration of stresses leads to failure and also tall structures with such irregularities. Soft storey structure is one such irregularity, leading to their failure during an earthquake event. In such buildings, the stiffness of the lateral load resisting systems in a storey will be quite less compared to that of other storeys (Stiffness Ratio). This effect can be overcome with infills or bracings or increasing the flexural rigidity (EI) in the storey with low stiffness. Pushover analysis is a nonlinear static approach for the seismic analysis of structures subjected to permanent vertical load and gradually increasing lateral load at very large strains up to failure.

The present work focuses on the seismic performance of soft storey Reinforced Concrete (RC) 2D frames using pushover analysis. For this purpose, ETABS, a finite element software has been used. Typical 2D RC frames are considered for the analysis in which the effect of number of floors and the effect of height of floor have been studied. Base shear carried, roof displacements experienced, status of performance point, ductility characteristics and vulnerability index are the parameters used to quantify the performance of RC frames. It is inferred that structures with soft storey has low seismic capacity. Tall structures and structures with higher floor height are most vulnerable to seismic excitation.

Key words: Pushover analysis, soft storey, performance point, pushover curve, stiffness ratio, ductility demand, vulnerability index.

I. INTRODUCTION

Many urban multi-storey buildings in India today have open first storey as an unavoidable feature. This is primarily being adopted to accommodate parking or reception lobbies in the first stories. Also for offices or for any other purpose such as communication hall etc. soft storeys at different levels of structure are constructed. Provision for commercial and parking areas with higher storey heights and less infill walls reduce the stiffness of the lateral load resisting system at that storey and progressive collapse becomes unavoidable during a severe earthquake for such buildings. There has been collapse of many buildings in past earthquakes due to the

collapse of soft storey with higher floor heights and tall structures with soft storey compared to low height structures with soft storey where only damage has occurred not the complete collapse.



Figure 1: Collapse of soft middle storey in building at Bhuj during Bhuj Earthquake, 2001 [8]



Figure 2: Collapse of 9 storey apartment buildings due to soft storey at Ahmedabad during Bhuj Earthquake, 2001 [8]

The damage incurred by the some of the buildings in Bhuj earthquake, 2001 of magnitude 7.2 are due to the collapse of soft storey one such failure has shown in the figure 1, where the soft storey was at middle of the building. Then there is complete collapse of multi-storey (9 storeys) apartment buildings due to the failure and collapse of columns in the soft storey as shown in figure 2. There was collapse of many buildings in Wenchuan earthquake, 2008 China of magnitude 8.0, where there was collapse of school buildings with higher floor heights (figure 3) and complete collapse of soft storey high raised buildings (8 storeys) as shown in the figure 4.



Figure 3: Collapse of school building due to effect of soft storey at Yingxiu Town of Wenchuan County during Wenchuan Earthquake, 2008 [2]



Figure 4: Complete collapse of soft storey building at Yingxiu Town of Wenchuan County during Wenchuan Earthquake, 2008 [2]

II. SOFT STOREY COLLAPSE

The most prominent of the problems caused by severe stress concentration is that of the “soft” storey. The term has commonly been applied to buildings whose ground-level storey is less stiff than those above. The building code distinguishes between “soft” and “weak” storeys. Soft storeys are less stiff, or more flexible, than the storey above; weak storeys have less strength. A soft or weak storey at any height creates a problem, but since the cumulative loads are greatest towards the base of the building, a discontinuity between the first and second floor tends to result in the most serious

condition. The way in which severe stress concentration is caused at the top of the first floor is shown in the diagram sequence in Figure 5. Normal drift under earthquake forces that is distributed equally among the upper floors is shown in Figure 5A. With a soft story, almost all the drift occurs in the first floor, and stress concentrates at the second-floor connections (Figure 5B). This concentration overstresses the joints along the second floor line, leading to distortion or collapse (Figure 5C).

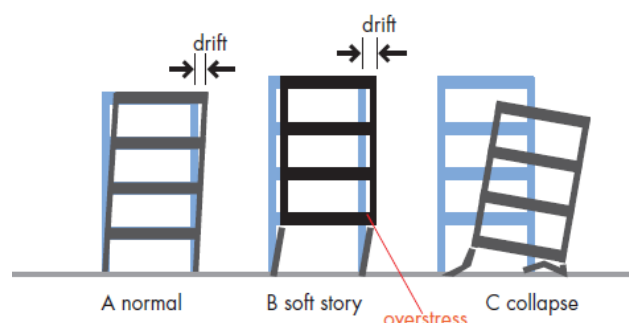


Figure 5: The Soft First Story Failure Mechanism [5]

In addition, if the local ductility demands are not met in the design of such a structure for that storey and the inter-storey drifts are not limited, a local failure mechanism or, even worse, a story failure mechanism, which may lead to the collapse of the system, may be formed due to the high level of load- deformation ($P-\Delta$) effects. As per Indian standard IS 1893 (Part 1) : 2002, soft storey is the one in which the lateral stiffness is less than 70% of the storey above/below or less than 80% of the average lateral stiffness of the three storeys above/below. The soft storey can be considered in many ways say by columns with lesser flexural rigidity (EI) and by higher floor height at that storey and also by not considering the infill at that storey.

III. PUSHOVER ANALYSIS

Pushover analysis is basically a nonlinear static procedure in which the magnitude of lateral loads is incrementally increased, maintaining a predefined load pattern along the height of the building. With the increase in magnitude of loads, weak links and failure modes of the building are found. At each step, the base shear and the roof displacement can be plotted to generate pushover curve (Figure 6). Pushover analysis may be classified as displacement controlled pushover analysis when lateral displacement is imposed on the structure and its equilibrium determines the forces. Similarly, when lateral forces are imposed, the analysis is termed as force-controlled pushover analysis. The target displacement or target force is intended to represent the maximum displacement or maximum force likely to be experienced by the structure during the design earthquake. In the present study, displacement-controlled pushover method is used for analysis of RC bare frames. A finite element software package ETABS 9.6.0 has been used for the purpose. The point of intersection of capacity and demand spectrums is known as performance point which will be in

Acceleration Displacement Response Spectrum (ADRS) format for 5% damping. Pushover curve with performance levels and ranges are as shown in Figure 7.

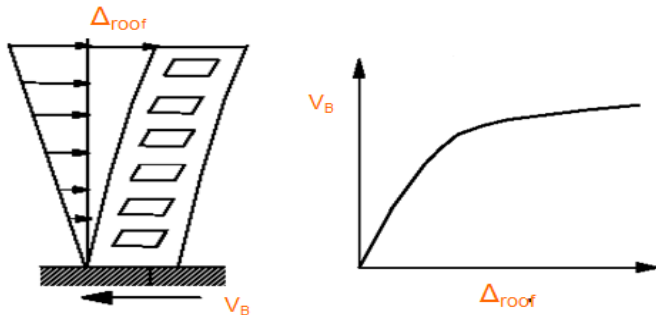


Figure 6: Building Model and Simple Pushover Curve [11]

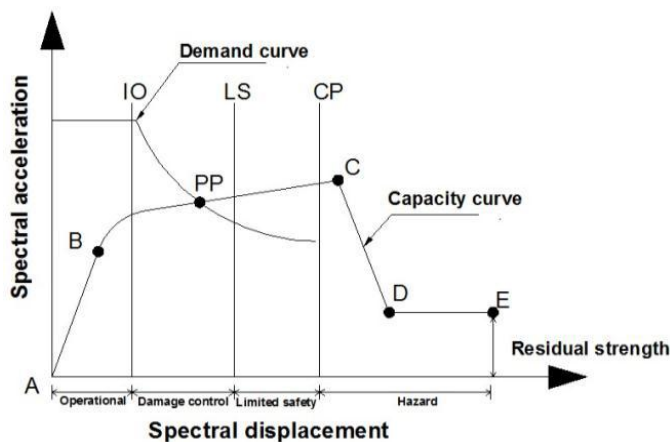


Figure 7: Capacity and Demand Spectrums with Performance Levels [11]

Here,

IO = Immediate Occupancy

LS = Life Safety

CP = Collapse Prevention

IV. MODELLING AND ANALYSIS

In the present work, various floor characteristic factors are considered to understand the behaviour of soft storey like the effect of number of floors and height of floors. Here soft storey is considered by reducing the flexural rigidity (EI) so that a range of stiffness ratios are considered from 1.0 to 0.2 and increasing the height of floor from 3m to 5m of that storey. Stiffness ratio (SR) is defined as the ratio of stiffness of column section of soft storey to that of other storeys. Soft storey is considered at ground level. Figure 8 shows the models considered by increasing the height of ground floor as 4m and 5m compared to other storeys so that making it a soft storey. For model in figure 8a five storey-single bay RC frames are considered in the analysis. Figure 9 shows the models considered to study the effect of number of floors say 3, 6 and 9 floors respectively and making the ground floor as soft storey by varying the flexural rigidity (EI) of that storey compared to others. The grade of concrete for columns and beams is taken as M25. The live load of 3kN/m² and the floor finish load of 1kN/m² are assumed. The cross section of beams and columns are assumed as 250mmx400mm and

300mmX300mm respectively for models shown in figure 9. For models considered in figure 8, the cross section of beams and columns are assumed as 200mmX300mm and 230mmX450mm.

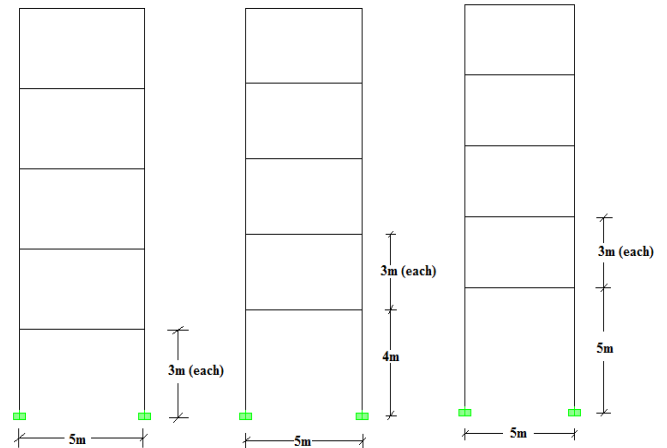


Figure 8: Models Considered by Increasing the Height of Soft Storey

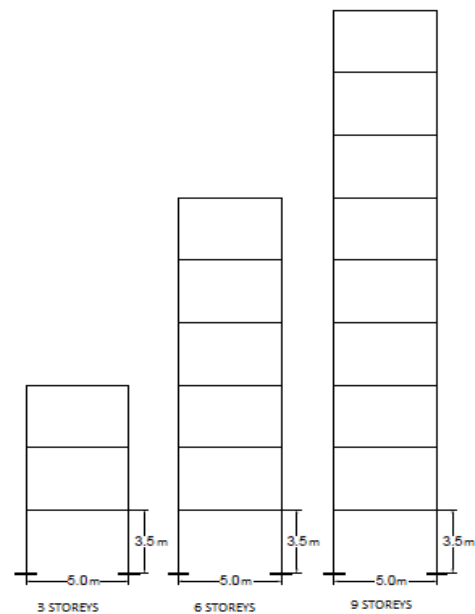


Figure 9: Models Considered with Different Number of Floors Initially, the models are analyzed and designed as per IS 456: 2000 for gravity loads. Default hinge properties available in ETABS [3] as per ATC-40 are used to assign hinge properties (material non linearity). Hinges are considered at both the ends of beam and column elements. The hinge properties assigned are M3 (only moment) and PMM (axial force and biaxial moments) for beams and columns respectively. The pushover analysis is carried out, pushover curves are obtained, the status of performance point is also been studied and ductility characteristics are assessed from ductility ratio. Ductility ratio is the ratio of ultimate displacement to yield displacement. Then the fragility analysis is carried out using predefined values of spectral displacement, Table 1 shows the predefined values for the identification of global damage

states [4]. Then the vulnerability index is obtained by multiplying the probability of expedience of a damage state with cost fraction associated with the damage state. Table 2 shows an example of cost fractions for various damage states.

Table 1: Predefined Values for the Identification of Global Damage States [4]

Damage State	Threshold Value
Slight Damage	S_{dy}
Moderate Damage	$1.5 S_{dy}$
Extensive Damage	$0.5 (S_{dy} + S_{du})$
Complete Damage	S_{du}

Here in the Table 1,

S_{dy} = Spectral displacement at the effective yield

S_{du} = Maximum spectral displacement

Table 2: Cost Fractions for Various Damage States [4]

Damage State	Cost Fraction
No Damage	0
Slight Damage	2%
Moderate Damage	10%
Extensive Damage	50%
Collapse	100%

V. RESULTS AND DISCUSSIONS

A. Effect of Varying the Floor Height at the Soft Storey Level

An attempt is made to understand the behaviour of soft storey by considering ground floor as soft and by varying the height of that storey. Here Zone V and soil type II are assumed for the analysis.

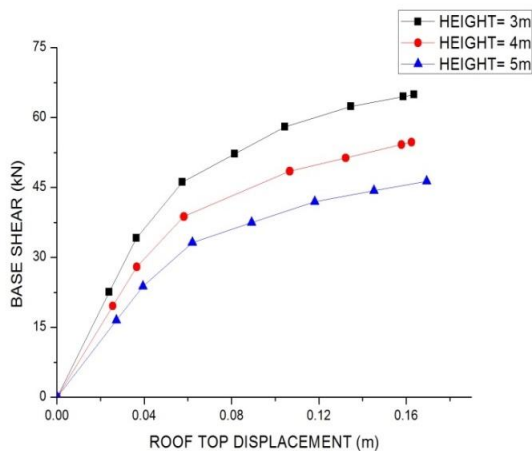


Figure 10: Pushover Curves Various Floor Height of Soft Storey

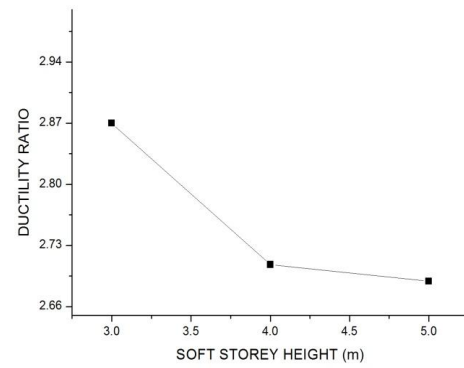


Figure 11: Variation of Ductility Ratio with Soft Storey Height

Figure 11 show the pushover curves which are obtained for various floor heights of soft storey. As the floor height of soft storey increases, there is decrease in base shear carrying capacity of the frames. Also with increase in floor height of soft storey, there is reduction in ductility demand of the structure (Figure 12). Hence as the structure becomes soft, there is decrease in base shear capacity and ductility demand of structure.

Table 3: Values of maximum base shear and ductility ratio varying of height of soft storey

Height of Soft Storey (m)	V_{Bmax} (kN)	Δ_u (m)	Δ_y (m)	DR
3	64.9371	0.1636	0.057	2.870
4	54.7183	0.1625	0.060	2.708
5	46.3074	0.1694	0.063	2.689

Here in Table 3,

V_{Bmax} = Maximum Base Shear

Δ_u and Δ_y = Ultimate and Yield Displacement

DR = Ductility Ratio

Table 3 shows the values of maximum base shear capacity, displacements at ultimate and yield points and ductility demand of the structure.

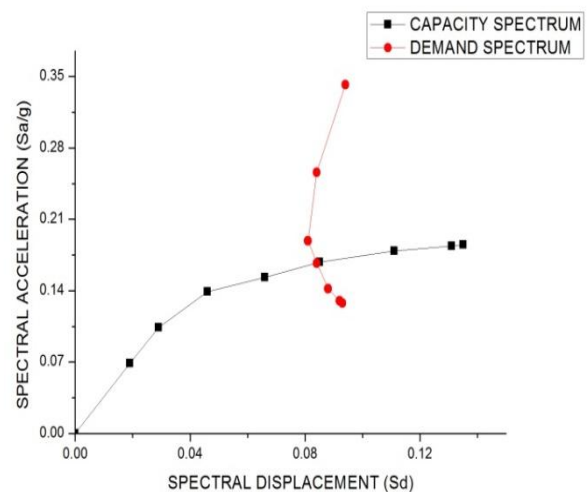


Figure 12: Performance Point for Soft Storey Height=3m

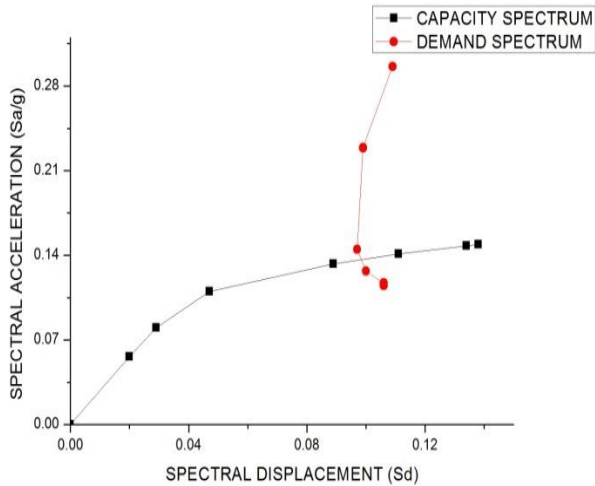


Figure 13: Performance Point for Soft Storey Height=4m

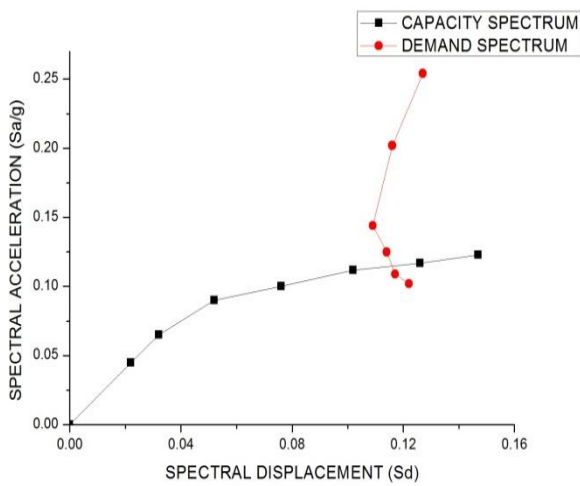


Figure 14: Performance Point for Soft Storey Height=5m

Table 4: Coordinates of Performance Points for Varying Height of Soft Storey

Height of Soft Storey (m)	S_a	S_d	V_B (kN)	Δ_R (m)
3.0	0.168	0.084	57.739	0.103
4.0	0.136	0.098	49.701	0.118
5.0	0.115	0.116	43.294	0.134

Table 4 show the values of spectral acceleration, spectral displacement, base shear and roof top displacement at performance points for varying floor heights of soft storey. Figure 12, figure 13 and figure 14 shows the global performance point of the structure for varying height of 3m, 4m and 5m respectively of soft storey. There is shift of performance point towards the higher spectral displacement showing that soft storey structures are more vulnerable compared to regular structures.

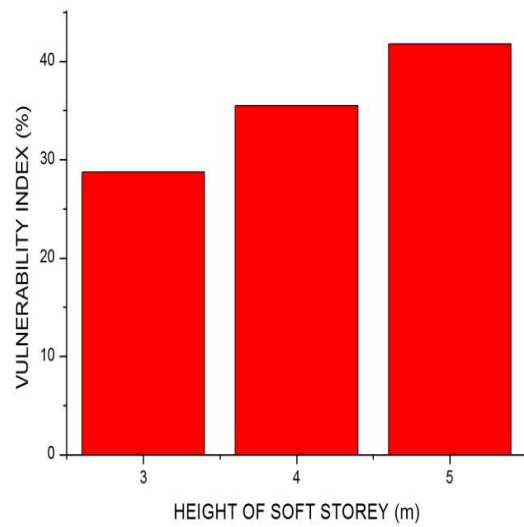


Figure 15: Vulnerability Index for Varying Height of Soft Storey

Figure 15 shows the variation of vulnerability index for varying floor height of soft storey. There is increase in vulnerability index with increase in floor height of soft storey. Hence soft storey structures are most vulnerable to seismic excitation compared to regular structures.

B. Effect Number of Floors on Soft Storey

An attempt is made to study the effect of number of floors on soft storey, thus 3, 6 and 9 storey RC frames are considered. Here the soft storey is considered by varying the flexural rigidity (EI) of that storey and is at ground level. Stiffness ratio is varied as 1.0, 0.8, 0.6, 0.4 and 0.2 respectively. Zone V and soil type II are assumed for the analysis.

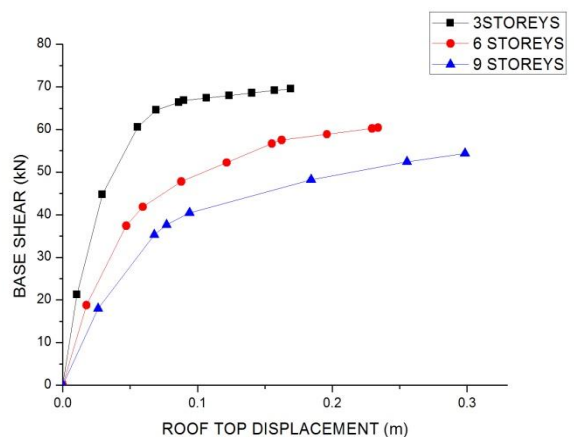


Figure 16: Pushover Curves for SR= 0.6

Table 5: Values of Maximum Base Shear and Ductility Ratio for Varying Number of Floors and Stiffness Ratios

SR	3 Storeys		6 Storeys		9 Storeys	
	V _{Bmax} (kN)	DR	V _{Bmax} (kN)	DR	V _{Bmax} (kN)	DR
1.0	78.9752	6.232	66.8821	5.496	59.0321	4.109
0.8	73.9598	5.697	64.2977	5.175	56.6836	3.900
0.6	69.5504	5.121	60.4059	4.586	54.3630	3.684
0.4	64.5309	4.829	57.2336	4.155	50.8019	3.510
0.2	56.9697	4.060	50.3795	3.640	44.2997	2.976

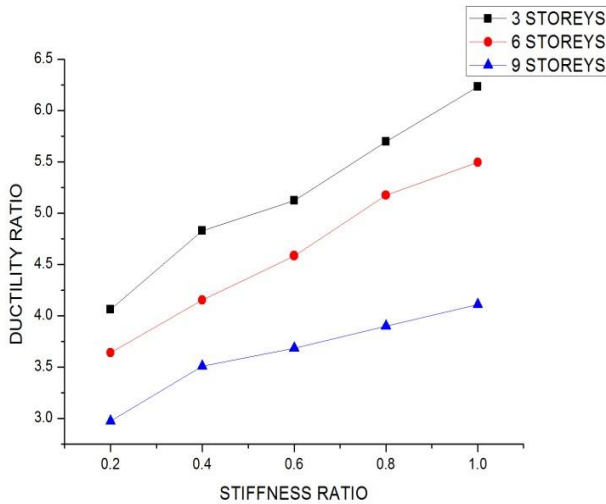


Figure 17: Variation of Ductility Ratio with Stiffness Ratio for Different Number of Floors

The resulting pushover curves are obtained for varying stiffness ratios and for different numbers of floors. Figure 16 shows the pushover curves for SR= 0.6 and for varying number of floors. Table 5 shows the values of maximum base shear capacity and the ductility ratios for varying stiffness ratios and number of floors. There is reduction of base shear carrying capacity of the frames with higher number of floors and with decrease in stiffness ratio. Figure 17 shows the variation of ductility ratio with stiffness ratio for different number of floors. There is decrease in ductility demand of the frames as the number of floors increases with lower stiffness ratio.

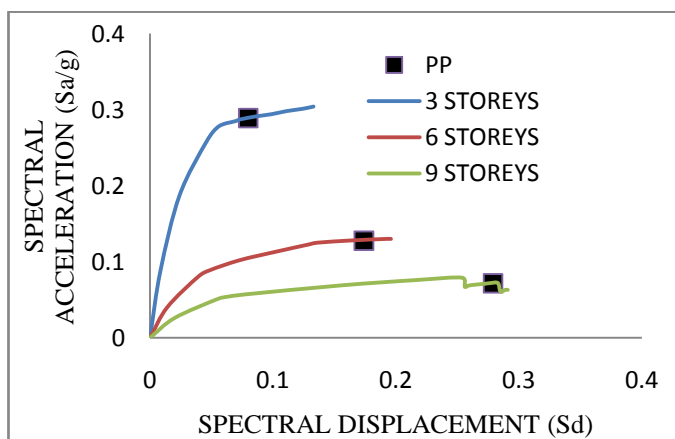


Figure 18: Performance Point for SR=0.6

Table 6: Coordinates of Performance Points for Varying Stiffness Ratios and Different Number of Floors

SR	NO OF STOREYS	Sa	Sd	V _B (kN)	Δ _R (m)
		0.336	0.071	75.624	0.090
1	3	0.336	0.071	75.624	0.090
	6	0.144	0.161	64.626	0.194
	9	0.088	0.260	58.960	0.307
0.8	3	0.310	0.075	71.099	0.094
	6	0.137	0.166	62.249	0.200
	9	0.074	0.267	50.605	0.313
0.6	3	0.289	0.080	67.151	0.100
	6	0.128	0.174	59.339	0.208
	9	0.072	0.279	49.824	0.324
0.4	3	0.264	0.088	62.564	0.108
	6	0.122	0.184	57.178	0.219
	9	0.042	0.465	29.948	0.524
0.2	3	0.224	0.106	55.185	0.125
	6	0.094	0.212	45.816	0.245
	9	N/A			

Figure 18 shows the performance point for stiffness ratio 0.6 and for increased number of floors. There is shift of performance point towards the collapse stage with increased number of floors. Table 6 shows the values of spectral acceleration, spectral displacement, base shear and roof top displacement at performance points for varying stiffness ratios and different number of floors. There is shift of performance point towards higher spectral displacement with higher number of floors and with lesser stiffness ratios showing shift of performance point towards collapse stage. Hence tall structures with least stiffness ratio are most vulnerable to seismic excitation.

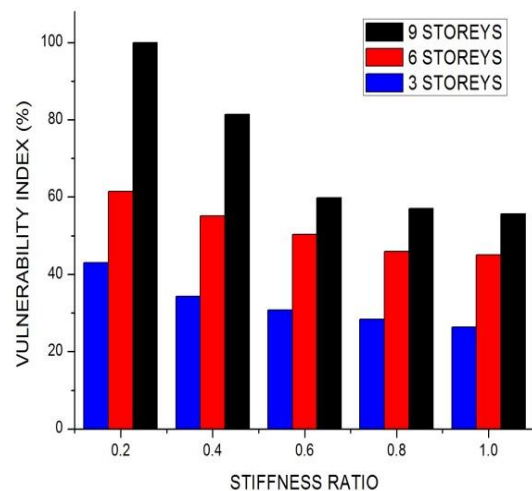


Figure 19: Vulnerability Index for Different Stiffness Ratios and Varying Number of Floors

Figure 19 shows variation of vulnerability index for different stiffness ratios and also for varying number of floors. There is increase in vulnerability index for 9 storeys RC frame with $SR= 0.2$ compared to regular 3 storeys RC frame. Hence the structure with higher number of floors and least stiffness ratio is most vulnerable.

VI. CONCLUSIONS

In the present study, an attempt has been made to study the effects of various parameters that influencing the seismic behavior of soft storey RC frames. Following are the conclusions drawn from the present study.

- The base shear carrying capacity of the structure reduces with the decrease in stiffness ratio, higher number of floors and increased floor height of soft storey.
- Ductility demand of the structure reduces when the structure becomes irregular and when the structure is taller.
- Performance point shifts more towards collapse stage when the structure becomes more irregular, structures with higher number of floors and increased floor height of soft storey.
- Vulnerability index is more for structures with lesser stiffness ratio, higher floor height of soft storey and higher number of floors.
- Hence tall structures with soft storey are most vulnerable to seismic excitation compared to low height structures.

The present study emphasizes the importance of study on soft storey structures with increased floor heights and number of floors. Soft storey can be overcome by infills, bracings, increasing the flexural rigidity (EI), addition of extra columns or by adding external buttresses to the columns in that storey.

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