Performance Based Seismic Design of Tall R.C Buildings With and Without In-Plane Flexibility of Slabs

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Abbreviations

FEMA –Federal Emergency Management Agency

ATC – Applied Technology Council

E-TABS - Extended Three Dimensional Analysis of Building Systems

ADRS - Acceleration-Displacement Response Spectra

Notations

B – Breadth for solid section and outer breadth for hollow section
D- Depth for solid section/outer depth for hollow section/diameter for solid circular section/outer diameter for circular hollow section
d - Inner depth for hollow section/inner diameter for circular hollow section
b – Inner breadth for hollow section

ABSTRACT

Earthquakes are unpredictable catastrophic events leading to loss of life and property. After the Northridge earthquake, the need to shift from the conventional codal design was felt necessary. In this context, performance based design is the new emerging technique, wherein the performance of the structure under a seismic event is predicted using non-linear analysis techniques and designed accordingly to surpass certain performance levels. In contextto performance based design, pushover analysis is gaining popularity as a simple and convenient tool to evaluate the true performance structures. Also, the floors in a building are usually modelled with a rigid floor assumption considering the deformation of the slab in its plane to be negligible. However, this assumption leads to discrepancy especially when a dynamic analysis is carried out. In the present work, a 10 story building model has been generated with three types of slab systems, viz. flat slab, grid slab and beam slab systems. Initially the in-plane stiffness of slabs is highlighted by carrying out a free vibration as well as response spectrum analysis, using two methods to model slabs. Four different types of beam sections are also used. The number of stories is varied to 20 and 30, and its effect on in-plane stiffness is highlighted. Lastly a pushover analysis for a few models is carried out to demonstrate the effect of in-plane stiffness of slabs on the inelastic behaviour of the structure. The performance points obtained from the pushover curves are used to suggest a performance based seismic design.

Keywords: In-plane flexibility, response spectrum analysis, pushover analysis, performance points, performance based design.

I. Introduction

Earthquakes have been highly disastrous natural hazards. They result in unpredictable vibrations, risking life and property. With the urban sprawl, there is scarcity of land and the buildings tend to rise higher and higher. It thus becomes inevitable to design all buildings for earthquakes. With the frequency and intensity of earthquakes increasing in various parts of the world, endangering more lives, a need to put forward certain guidelines was felt necessary such that, minimum damage occurs for buildings. Guidelines put forth by FEMA and ATC (Nitin and Mahendra, 2014) led to performance based seismic design. This new and emerging method assesses the performance of the building using non-linear techniques, such as pushover analysis, to evaluate the true behaviour of the building under earthquakes. Also, the in-plane flexibility of slabs has been neglected for a long time. The rigid floor assumption, neglecting the in-plane stiffness of slabs, is accurate for most buildings. However, for buildings with slender plans or with shear walls, this assumption leads to discrepancy in the results, mainly for dynamic analysis.

II. Literature Survey

It has been said that if the in-plane stiffness of the slabs is totally ignored, the lateral displacements may be overestimated and base shear may be significantly underestimated for buildings with shear walls. The natural periods of vibrations are shorter when flexural stiffness is considered. (Kehila et al., 2013).It was studied that the buildings without shear walls, the rigid floor assumption is accurate but for structures with long thin floor plans and perimeter and lateral resisting elements, this assumption is inaccurate(Moeini et al., 2008).The spectral displacement and drift ratios are lower for flexible floors when compared to rigid floors.Even with an opening, similar effect is seen. (Ankita et al., April 2015 “a”).Out of the several approaches for performance based seismic design method, the results obtained from direct design method are closer to the final design with less computational effort, which in turn leads to the evolution of performance based plastic design method (Dalal et al., 2011). Performance based design usingpushover analysis is a popular tool to evaluate the actual performance of the structure.A comparative study has been done for base shear, story drift, spectral acceleration, spectral displacement, story displacement for a structure with shear wall and was found that thebase shear and displacement decrease(Nitin and Mahendra, 2014).In case of pushover curves, the floors modelled as flexible floors depicted the true nature of the slab system when compared to floors modelled as rigid floors (Raghu Prasad et al., March 2015 “b”).

III. Objectives

With reference to the research work shown in the literature survey section, it is seen that work has been carried out for accounting the effect of in-plane flexibility of slabs for buildings with shear walls. However, the influence of in-plane flexibility on a simple building plan without shear walls has not been carried out. Also, hollow beam sections have not been used, and its effect on in-plane flexibility of slabs also is not shown. The influence of in-plane flexibility on the pushover curves and the performance points is also not carried out so far. Therefore, the effect of hollow beam sections as compared to solid beam sections, on the in-plane stiffness of slabs and the effect of in-plane flexibility on the pushover curves and performance points are the objectives for the present work. Also, the effect on in-plane stiffness of slabs, when number of stories is increased is also demonstrated.

IV. Methodology

The present work consists of a building model with G+9 floors, modelled using E-TABS software.Three types of slab systems had been considered, i.e., flat slab, grid slab and the conventional beam slab system.The c/c distance between the grid beams is 9m.The floors were modelled as rigid floors and flexible floors for every model, to highlight the in-plane stiffness of slabs. In E-TABS software, this is done by assigning floors as membrane, neglecting the in-plane stiffness of slabs and as thin shell elements, considering the in-plane stiffness of slabs.

In case of models with flat slab system, beams were absent. However for models with beam slab and grid slab systems, four types of beam sections were considered; these were rectangular solid, rectangular hollow, circular solid and circular hollow beam sections. Every beam section was proportioned considering three beam areas, following a pattern to proportion them. Figure 1 shows a flowchart for the models considered for free vibration and response spectrum analyses. The beam sections mentioned in the flowchart, i.e., RS, RH, CS and CH stands for rectangular solid, rectangular hollow, circular solid and circular hollow beam sections respectively.The number of stories was further increased to 20 and 30 for each case.

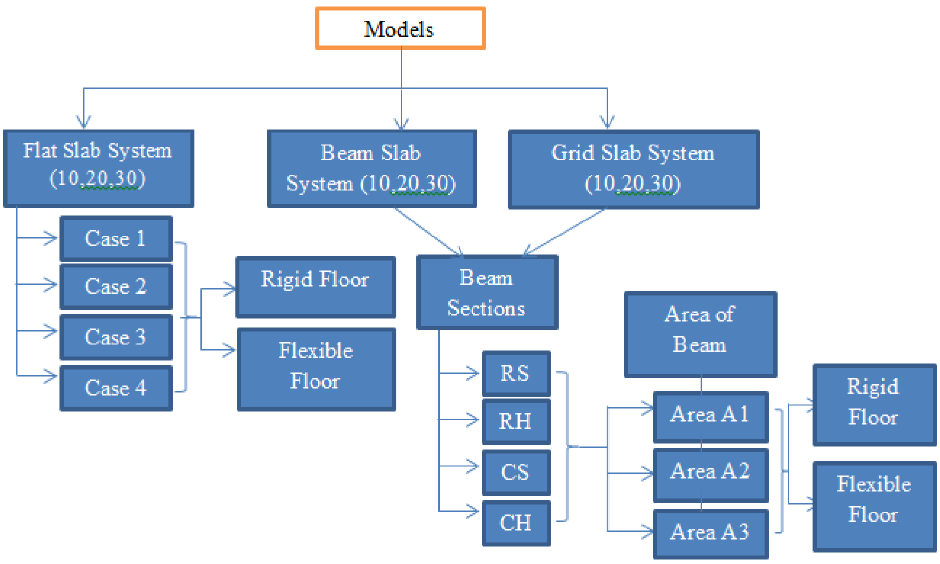


Figure 1: Models considered for free vibration and response spectrum analysis

The cases considered for models with flat slab system are shown in table 1.

Table 1: Cases for flat slab models

Case 1	Flat Slab System without drop
Case 2	Flat Slab with Shear wall every alternate floor
Case 3	Flat Slab with 1/4th drop
Case 4	Flat Slab with full drop

The pattern in proportioning the beams for rectangular sections,both solid and hollow, was such that as the area increased for the beams, the moment of inertia decreased. This was done since the accelerations for the structure depends on the accelerations of the beam which depends on AE/l, where A stands for area of the beam section, E – Modulus of Elasticity and l – length of the beam, whereas, the bending stiffness of beams depends on EI/l, where I –moment of inertia. Therefore, if the area increases, the accelerations of the structure increase and as the moment of inertia decreases, the bending stiffness of beams decreases.However, for circular beam sections, as the area of beams was increased, the moment of inertia also increased, since for circular sections, one can alter only the radius of the beam section, keeping the area constant, which resulted in the moment of inertia increasing with the increasing area. The influence of these patterns on the in-plane flexibility of slabs is highlighted. Table 2shows the beam sizes considered.

Table 2: Beam Sections

Sl. No.	b (mm)	B(mm)	d (mm)	D (mm)	Area of Beam Section (mm^2)	Moment of Inertia (mm^4)
1	Rectangular Solid Beam Section					
		200		800	160000	8.53E+09
		300		600	180000	5.4E+09
		625		400	250000	3.33E+09
2	Rectangular Hollow Beam Section					
	120	250	750	1000	160000	1.66E+10
	200	400	700	800	180000	1.14E+10
	1000	1200	230	400	250000	5.39E+09
3	Circular Solid Beam Section					
				451.352	160000	2.04E+09
				478.73	180000	2.58E+09
				564.1896	250000	4.98E+09
4	Circular Hollow Beam Section					
			395.325	600	160000	5.16E+09
			439.783	650	180000	6.93E+09
			701.2975	900	250000	2.03E+10

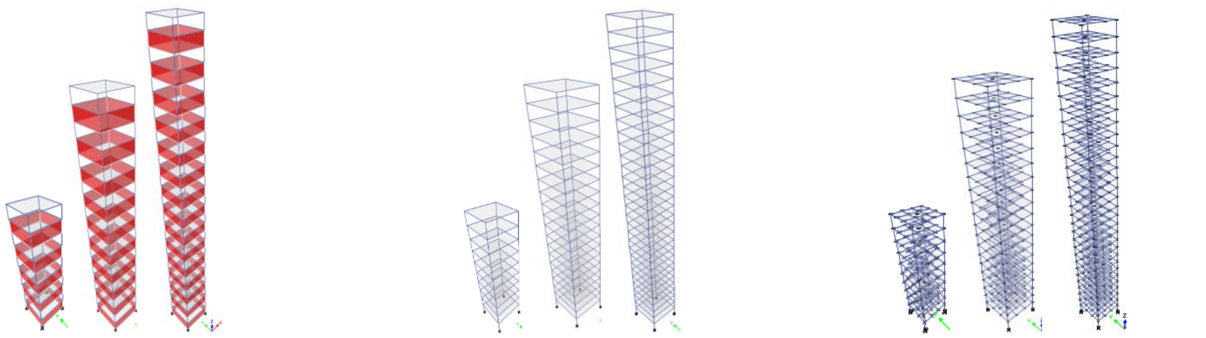
As seen from table 2, keeping the area of beam constant, the moment of inertia for every beam section is designed such that, as the area is increased, the moment of inertia reduces, for rectangular sections and increases for circular sections.

The material properties, geometric properties, load parameters and earthquake parameters considered for the models are mentioned in table 3. The loads are considered referring IS 875 Part 5, 1987 and the earthquake parameters are as per IS 1893 part 2, 2002.

Table 3: Different parameters considered for modelling

Grade of concrete	Beams and Slab – M40 Columns – M50
Grade of steel	Fe 415
Density of concrete	25 kN/m^3
Floor to floor height	3m
Size of bay	9mX9m, 11.25mX11.25m
Slab thickness	150mm, 225mm
Drop thickness	475mm
Size of columns	600mmX600mm
Thickness of shear wall	225mm
Loads considered	Live load – 3 kN/m^2 Floor Finishes – 1.5 kN/m^2
Earthquake Parameters	a) Zone – V b) Importance Factor – 1 c) Response Reduction Factor – 5 d) Soil Type - I

The three dimensional view of the models has been shown in figure 2. The model with flat slab system with case 2 has been shown in the figure for flat slab system model.



a. Model with FSS **b. Model with BSS** **c. Model with GSS**

Figure 2: 3D view for models with flat, beam slab and grid slab respectively with 10,20 and 30 stories

All the models consideredfor free vibration and response spectrum analyses have been not been considered for pushover analysis. The models considered for pushover analysis is shown in figure 3.

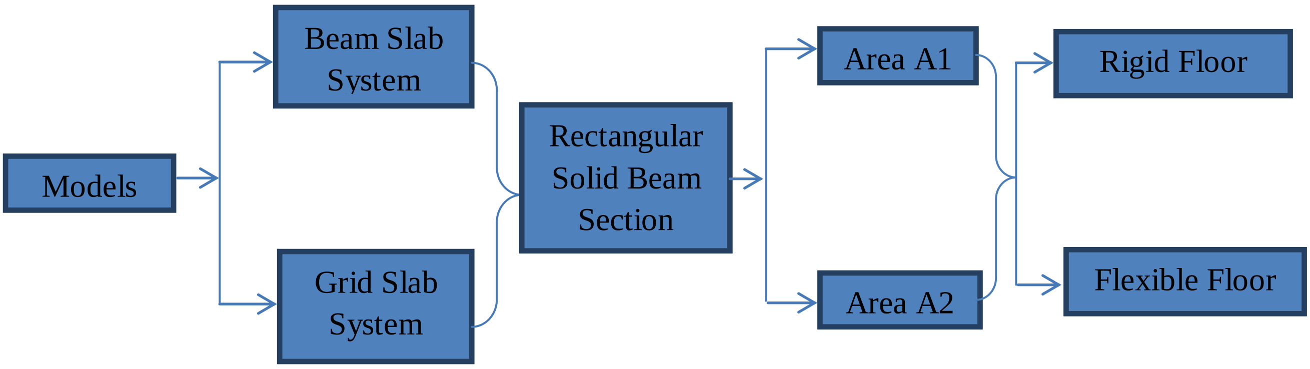


Figure 3: Models for pushover analysis

V. Results and Discussions

5.1 Natural Time Periods

Results obtained from free vibration analysis have been shown in table 4 for the 1st mode for models with flat slab system and table 5 for models with beam slab and grid slab system.In alltables, I stands for models with rigid floors and II – stands for models with flexible floors.

In case of models with beam slab and grid slab systems, only the values for model with 10 stories is shown, as with the increase in number of stories, the difference between the two methods to model slabs, follows similar trend as seen for a 10 story building model for time periods as well as spectral displacement and base shear values.

Table 4: Natural time periods for the 1st mode for different model cases for flat slab system

Flat Slab System								
	Time Period (sec)							
Number of Stories	Case 1		Case 2		Case 3		Case 4	
	I	II	I	II	I	II	I	II
10 story	8.224	5.626	0.556	0.555	9.657	2.907	12.785	2.55
20 story	31.653	15.633	1.477	1.476	37.086	5.609	46.816	5.498
30 story	70.304	24.011	2.919	2.918	82.299	8.87	97.256	10.153

Table 5: Natural time periods for the 1st mode for different models with beam slab and grid slab system for 10 story building model

	Beam Slab System		Grid Slab System	
Sections and areas	I	II	I	II
	Rectangular Solid Beam Section			
A1	1.68	1.65	1.84	1.82
A2	2.02	1.92	2.23	2.18
A3	2.53	2.32	2.87	2.77
	Rectangular Hollow Beam Section			
A1	1.33	1.31	1.44	1.43
A2	1.53	1.49	1.62	1.6
A3	2.12	1.99	2.15	2.09
	Circular Solid Beam Section			
A1	2.89	2.571	2.86	2.7
A2	2.68	2.421	2.67	2.55
A3	2.17	2.04	2.24	2.17
	Circular Hollow Beam Section			
A1	1.99	1.89	2.05	2.01
A2	1.81	1.74	1.89	1.86
A3	1.30	1.29	1.45	1.45

As seen from tables 4 and 5, the time periods are shorter for models with flexible floors than for models with rigid floors. Especially in case of models with flat slab system with cases 1,3 and 4, with rigid floors, the time periods are very long, which become too large with increase in the number of stories.

5.2 Spectral Displacements for roof and Base Shear

Base shear is an approximation of the maximum expected lateral force that will occur at the base of the structure due to seismic ground motion. Base Shear thus is the value which the building provides to resist the lateral loads it is subjected to.

In the present study, response spectrum analysis has been carried out and the values obtained for spectral displacement, base shear and drift ratios in the x-direction are tabulated. The values in only x-direction are considered since the building plan is symmetrical and would have same values in the y-direction.

The spectral displacement and base shear values for models with flat slab system is shown in table 6 andfor beam slab and grid slab system is shown in table 7. In case of models with beam slab and grid slab system, the results for a 10 story model are shown since similar results have been obtained for a 20 and 30 story model.

Table 6: Spectral Displacement and base shear values for models with flat slab system

Flat Slab System								
	Spectral Displacement (mm)							
Stories	Case 1		Case 2		Case 3		Case 4	
	I	II	I	II	I	II	I	II
10 story	2082.3	1080.8	10.6	8.9	2904.9	218.2	538.7	30
20 story	34326.6	8371.5	80.4	63.9	47465.2	1024.8	12397.7	149.9
30 story	148409.2	18610.1	311.1	306.9	235586	2596.7	32252.6	315.7
	Base Shear (kN)							
Stories	Case 1		Case 2		Case 3		Case 4	
	I	II	I	II	I	II	I	II
10 story	565.73	657.01	1018.46	854.5	781.84	1054.76	201.62	316.68
20 story	1207.24	1356.61	2008.79	1598.99	1647.41	2137.69	298.35	373.02
30 story	1548.78	2075.1	2818.28	2740.16	2455.93	3206.14	440.19	523.3

Table 7: Spectral Displacement and base shear values for models with beam slab and grid slab systems for 10 story building model

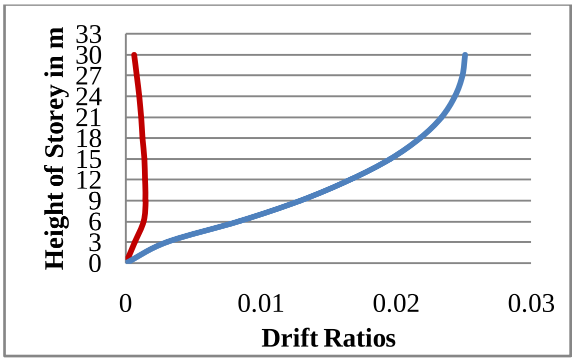
Area of Beams	Beam Slab System				Grid Slab System			
	Spectral Displacement in mm		Base Shear in kN		Spectral Displacement in mm		Base Shear in kN	
	I	II	I	II	I	II	I	II
Rectangular Solid Beam Section								
A1	90.6	84.5	998.28	961.48	108.9	106.7	1226.25	1236.2
A2	132.2	114.2	1022.03	976.79	160.7	154.7	1268.32	1279.05
A3	210.4	168	1099.59	1054.37	268.8	251.6	1439.6	1453.05
Rectangular Hollow Beam Section								
A1	57.4	53	1013.68	969.31	66.3	65.9	1232.28	1250.27
A2	71.4	68.6	1033.83	990.57	84.5	82.9	1292.78	1301.26
A3	145.6	122.3	1114.56	1063.83	148.1	140.8	1356.03	1368.13
Circular Solid Beam Section								
A1	277.6	207.7	965.61	929.07	268.4	238.8	1191.53	1202.68
A2	236.6	183.3	999.64	960.06	232	211.6	1251.19	1264.77
A3	153.3	128.9	1112.51	1064.65	159.6	152	1469.25	1478.55
Circular Hollow Beam Section								
A1	128.8	110.6	1124.65	1074.45	135.1	130	1488.6	1497.15
A2	105.6	93.1	1177.23	1127.24	114.4	111.5	1596.49	1606.63
A3	55.3	51.5	1396.41	1334.09	64	68.3	1902.03	2043.48

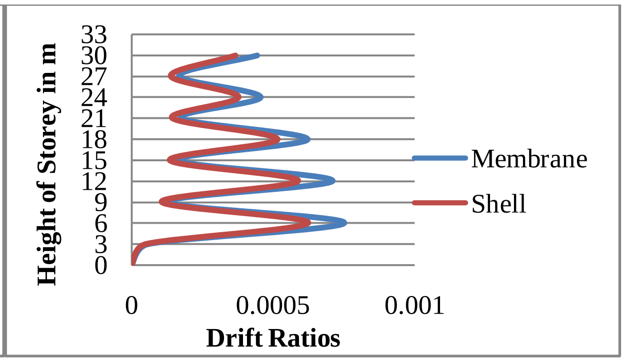
Models with all the three slab systems show lesser displacements for models with flexible floors than that of rigid floors. However, for models with flat slab system, cases 1,3 and 4, the displacement values for models with rigid floors are very high, especially for 20 and 30 stories. The difference between the two methods to model floors is the maximum for model with flat slab system. The base shear values are higher for models with flexible floors for all the cases for model with flat slab system, other than case 2. Similarly, the values base shear are higher for models with flexible floors for grid slab system models, but for models with beam slab system, models with rigid floors have higher values when compared to models with flexible floors.

5.3 Story Drifts

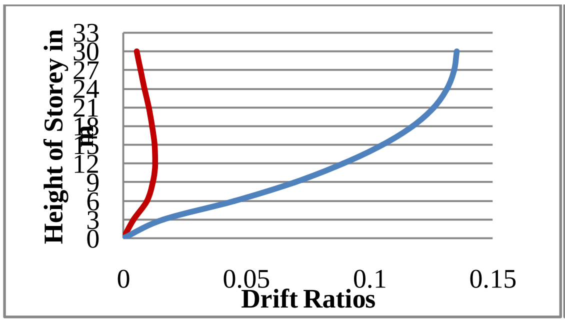
Inter- story drift ratio is defined as the relative horizontal displacement of two adjacent floors in a building. The sway in the building can be understood by observing the story drifts and should not exceed 0.004 times the storey height according to IS 1893Part 1, 2002.

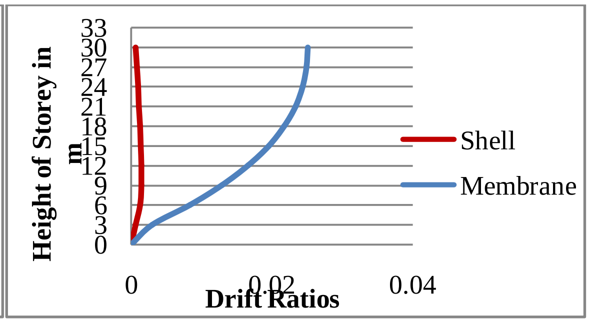
Figure 4 shows the drift ratio values obtained for the flat slab models.





a. Case 1 **b. Case 2**

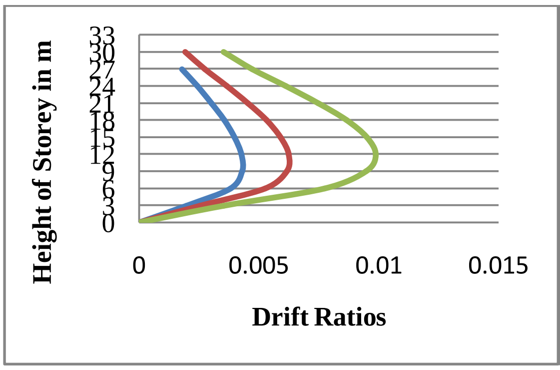


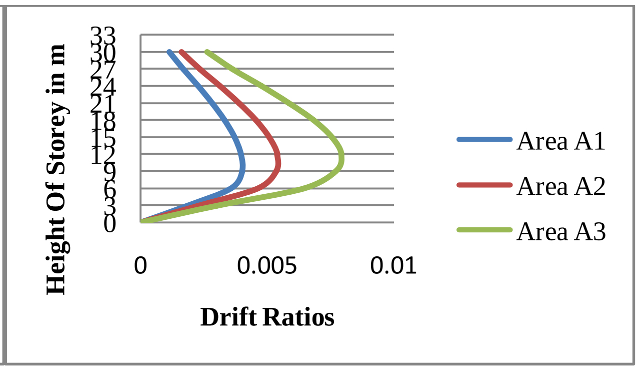


c. Case 3 **d. Case 4**

Figure 4: Drift ratios for models with flat slab system

Similar trend of drift ratios can be observed for flat slab system, when number of stories is increased to 20 and 30. They are lesser for flexible floors than rigid floors.Figures 5 and 6 show the drift ratios obtained for the different beam sections for beam slab system.

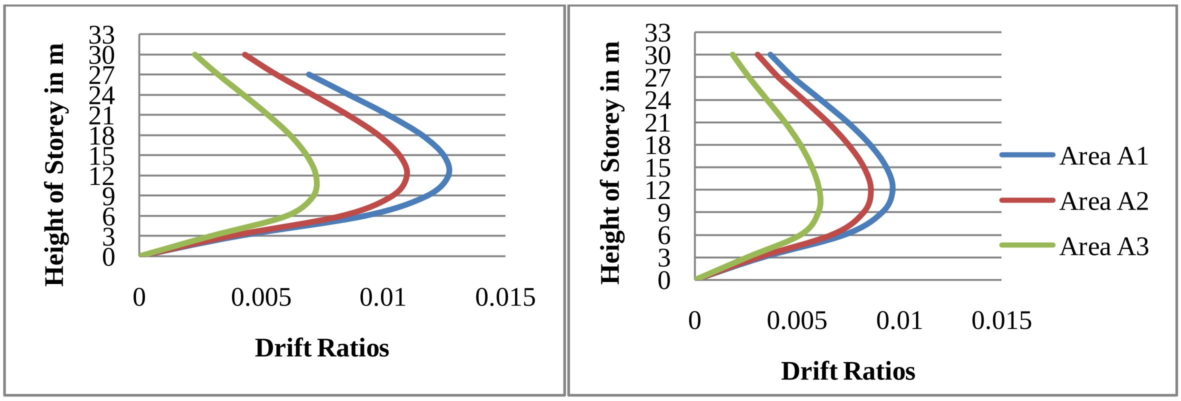




a. Rigid Floor **b. Flexible Floor**

Figure 5: Drift ratios for model with beam slab system with 10 stories for rectangular solid beam section

Similar Results are obtained for model with beam slab system with rectangular hollow beam section.



a. Rigid Floor **b. Flexible Floor**

Figure 6: Drift ratios for model with beam slab system with 10 stories for circular solid beam section

Similar drift ratios are obtained for model with beam slab system with circular hollow beam section

As seen in figures 4-6, the values of drift ratios are lower for models with flexible floors for all the cases for flat slab system and all the beam sections and beam areas for beam slab, when compared to models with rigid floors. In case of models with beam slab system, as the area of beam increases, the drift ratios increases for rectangular beam sections and reduces for circular beam sections.

Similarly, drift ratios were found for grid slab system, with the different beam sections and area of beams.

With the increase in number of stories, the drift ratios also increased. However, as seen for a 10 story building, similar results were seen for 20 and 30 story buildings.

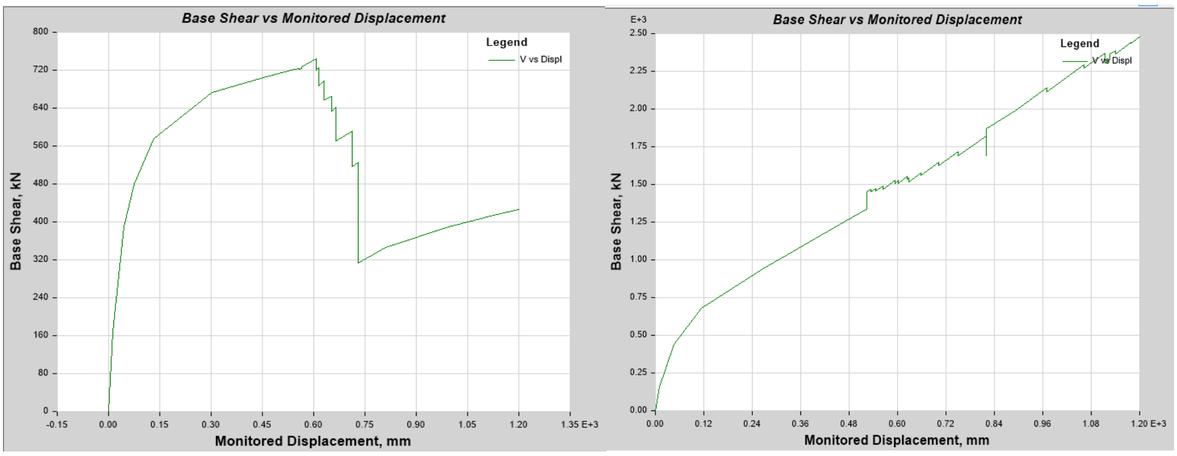
5.4 Pushover analysis

Pushover analysis is an approximate method in which the structure is subjected to monotonically increasing lateral forces with a predefined height-wise distribution until a target displacement is reached. Pushover analysis consists of a series of sequential elastic analysis, superimposed to approximate a force-displacement curve of the overall structure.

In the present study, the building models with rigid and flexible floors were pushed till a target displacement of 1200mm. The effect of in-plane stiffness of slabs on the pushover curves is demonstrated using the load vs displacement curves.

The analysis results for load vs displacement plot, formation of hinges and ADRS curves is shown only for model with beam slab system with area of beam A1. The results for model with beam slab system with area of beam A2, was similar to that of beam area A1 and the models with grid slab system with area of beams A1 and A2 were similar to models with beam slab system and areas of beam A1 and A2 respectively.

The pushover curves for load vs displacement are shown in figure7.



a. Rigid Floor **b. Flexible Floor**

Figure 7: Load vs displacement curve for beam slab system with area of beam A1 modelling floor as rigid floor

Models with beam slab system and beam area A1 is shown in figure7. It can be seen that the building models with rigid floors,collapsed before target displacement was reached, whereas the building models with flexible floors were pushed till target displacement without collapse of structure.

Table 8 gives the displacement and base shear values the building models reached for the various models considered.

Table 8: Displacement and base shear from the load vs displacement graphs

Type of slab system/ area type	Performance Points			
	Displacement		**Base Shear**	
Beam Slab System	**I**	**II**	**I**	**II**
Area A1	606.88	1200	744.82	2478.42
Area A2	578.77	1200	674.05	2463.93
Grid Slab System				
Area A1	558.15	1200	758.59	2387.79
Area A2	579.85	1200	655.87	2214.29

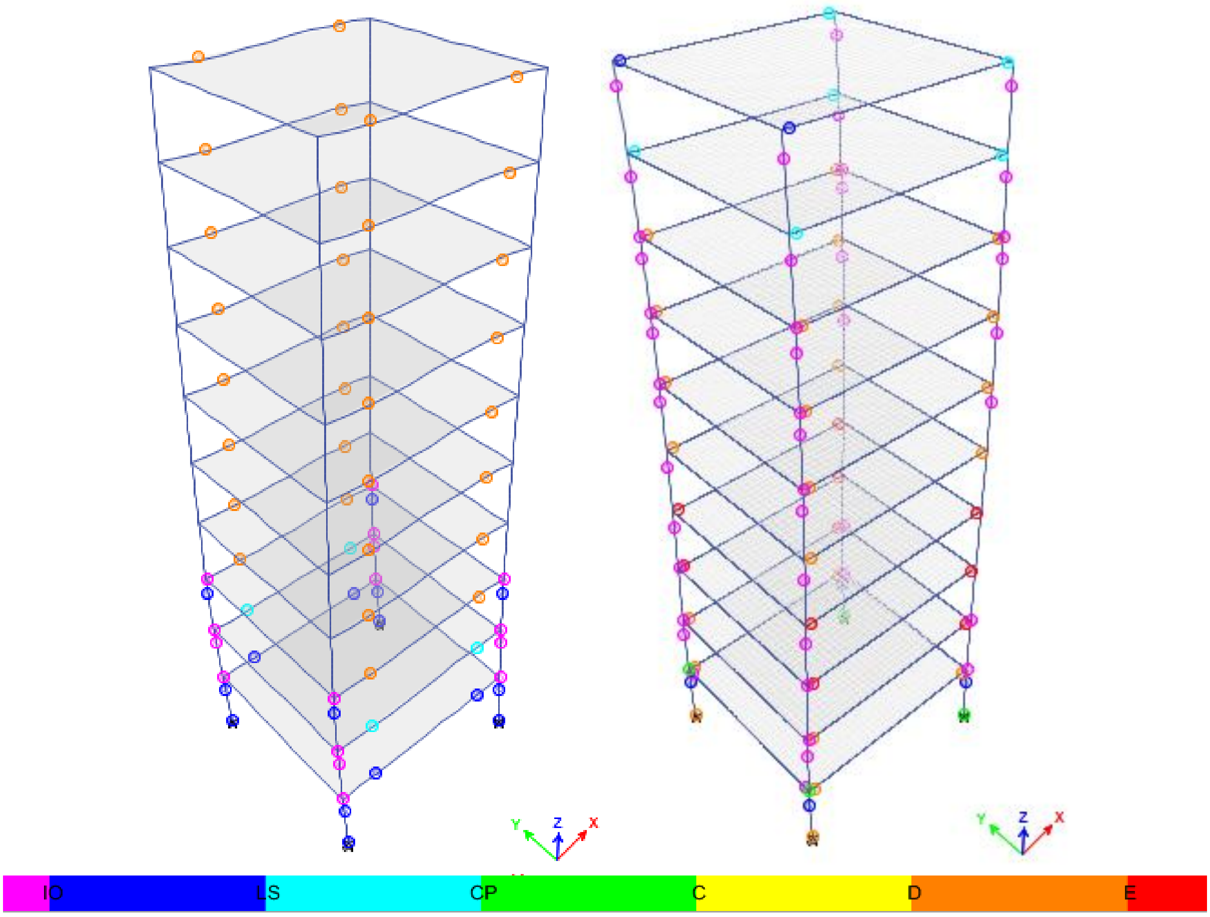
5.5 Performance Evaluation

The main concept of Performance Based Seismic Design is to provide structural engineers with the capability to design buildings that have a predictable and reliable performance during earthquakes. Performance based seismic design is a method in which probable performance of the building under input ground motions is predicted and design is carried out based on certain performance levels, that the building must satisfy when it is subjected to earthquake forces.

Four performance levels have been described commonly for the seismic design of structures. These are the operational, immediate occupancy, life safety, and collapse prevention levels, as per FEMA 273. The performance point is the point where the capacity spectrum curve and demand spectrum curve of the structure meet. The performance point as prescribed by ATC-40 has been plotted also known as the Acceleration-Displacement Response Spectra method (ADRS).

In the present study, the building has been pushed to 1200mm using pushover analysis. E-TABS defines hinge formation in a series of band levels in correlation with FEMA 440 and ATC 40. Performance points are obtained using the ADRS graphs and suggestions are made based on these performance points to surpass performance levels. The hinge results also explain about the performance of the building.

Figures 8shows the hinge locationswhen the target displacement is reached for model with beam slab system with area of beam A1. Similar results are seen for the other models.



a. Rigid Floor b. Flexible Floor

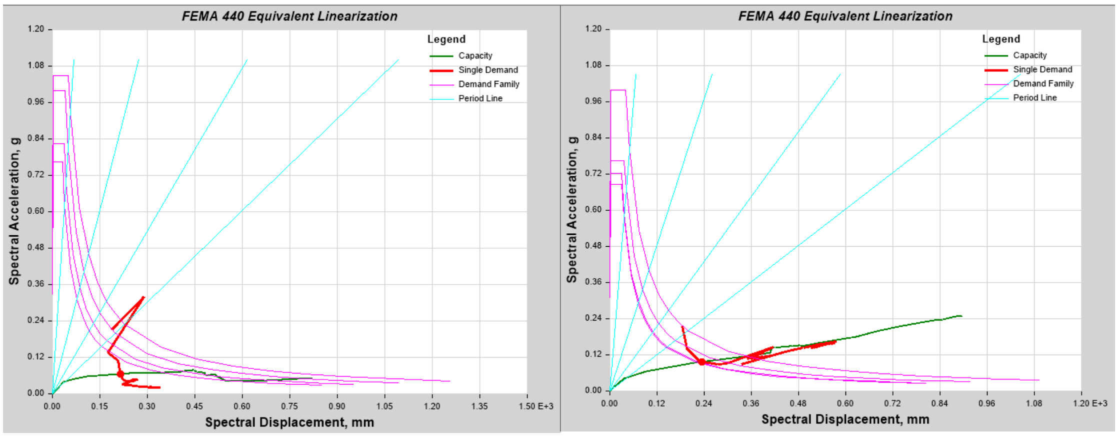
Figure 8: Model with beam slab system with area of beam A1

In figure 8, the coloured band signifiesspecific performance level. IO stands for Immediate Occupancy level, LS for Life Safety and CP for Collapse Prevention.Hinges formed in different colours illustrate the performance level it surpasses.The number of hinges formed for the two models is shown in table 9.

Table 9: Displacement and base shear from the load vs displacement graphs

	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	>E	Total
I	16	16	4	0	0	32	0	68
II	43	6	6	4	0	24	8	91

The model with rigid floors has lesser number of hinges when compared to the model with flexible floors. Also, maximum hinges formed are in the B-IO range. The hinges formed in the D-E band for both the models are for beams, as seen from figure 10, which shows that a few beams have collapsed. Even for the hinges in >E band are formed in beams for model with shell elements. However, the columns for models with both methods are in the B-IO range.This shows that floors modelled as flexible floors show satisfactory results than floors modelled as rigid floors. Also, the performance of the building shown in case of floors modelled as rigid floors is much different to that shown by floors modelled as flexible floors, which explains that the true behaviour of the structure is affected by the behaviour of slabs with in-plane stiffness for lateral loads. In case of models with grid slab system, similar trend is followed. Figure 9 shows the performance points obtained using ADRS curves.



a. Floor modelled as membrane **b. Floor modelled as shell**

Figure 9: ADRS graphs for model with beam slab system and area of beam A1

Table 10 shows the performance points.

Table 10: Performance points

Type of slab system/ area type	Performance Points			
	Displacement		Base Shear	
Beam Slab System	Membrane	Shell	Membrane	Shell
Area A1	265.6	291.8	0.6527	0.982
Area A2	318.2	362	0.5914	0.9952
Grid Slab System				
Area A1	301.8	350.5	0.6742	1.1116
Area A2	364.3	400.6	0.6005	1.0755

Observations from table 10 suggest that, the building displacements and base shears are within limits and the risk to life and property is minimum.The building models surpass the immediate occupancy level, as seen from the hinge formation results.

VI. Conclusions

Various models were prepared varying parameters using flexible and rigid floor assumption. They were analysed to highlight the in-plane flexibility of slabs.The following conclusions can be drawn.

- All the models showed shorter time periods and lower values for spectral displacement and drift ratios for models with flexible floors when compared to models with rigid floors.
- Three types of slab systems were considered. It was seen that difference for the two methods to model slabs was the highest for flat slab system with respect to all the parameters considered. Also, it is seen that for building with flat slab system, rigid floors do not have an efficient load transfer and therefore, for building with flat slab, the floors should be necessarily modelled as shell elements.
- In case of the four beam cross sections, for rectangular sections, as the areas increased, the drift ratios, time periods and spectral displacements increased. However, for circular sections, as the area increased, the drift ratios, time periods and spectral displacements decreased. However, in case of all the models, flexible floors showed lesser values when compared to rigid floors.
- It was seen that, hollow beam sections gives lesser drift ratios and spectral displacement values when compared to solid beam sections.
- With the increase in the number of stories, significant difference between the two methods to model slabs is seen only for model with flat slab system. In case of beam slab and grid slab system, prominent difference between the two methods is not seen, for all the beam sections.
- The models with beam slab system for a particular beam section and constant area, gave lower values for spectral displacements and drift ratios and shorter time periods for beam slab system when compared to grid slab system.
- The base shear values are found higher for models with flexible floors than rigid floors for grid slab system, and the other way round for beam slab system.
- Pushover analysis results depicted, that the models with rigid floor assumption reached collapse loads even before the building was pushed to the target displacement. However, for building with floors modelled as thin plate or shell elements, could be pushed till the set target displacement. This shows floors modelled with rigid floor assumption, fail to portray the actual behaviour of slabs which is interconnected with the actual behaviour of the structure. Therefore, for seismic evaluation of new and old buildings, floors need to be necessarily modelled as thin shell elements, not ignoring the in-plane stiffness of floors. In the present study, most of the hinges formed were in the operational level performance criteria, thus resulting in no risk to life safety.
- As seen from the formation of hinges, a few beams have hinges in the D-E and >E range for models with both flexible and rigid floors. However, all the columns have hinges in the B-IO range, which makes the building safe for Immediate Occupancy performance level.
- In case of performance based design, all the models considered, had performance points satisfying the required performance objectives. A performance based design was achieved.
- In general, it can be said that the neglecting the in-plane flexibility of slabs can lead in underestimating the base shear and over estimating the displacement and drift ratio values.

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