

# Performance Based Inelastic Seismic Analysis of Buildings

Dr. S. N. Tande

*Associate Professor & Head., Department of Applied Mechanics,  
Walchand college of Engineering, Sangli, Maharashtra, India*

Reshama M. Karad

*Research Scholar, Department of Applied Mechanics,  
Walchand college of Engineering, Sangli, Maharashtra, India*

**Abstract - Occurrence of the earthquake is unpredictable, but we can adopt preventive measures to overcome problems during earthquake. In this case, various organizations in the earthquake threatened countries have come up with documents, which serve as guidelines for assessment of the strength, expected performance and safety of existing buildings as well as for carrying out the necessary strengthening required.**

**The present paper deals with detailed discussions on non-linear static analysis methods various structural performance levels of building. Seismic evaluation followed by information about various strengthening techniques for beam and column. The study includes the Pushover Analysis of G+6 storey building using SAP 2000 with default and user-defined hinges. And conclude that model with user-defined hinge properties is more successful for capturing hinging mechanism.**

**Keywords – Pushover Analysis, Performance, Default and User-defined Hinges.**

## I. INTRODUCTION

Earthquakes have the potential for causing the greatest damages, amongst the other natural hazards. Earthquakes are perhaps the most unpredictable and devastating of all natural disasters. Earthquake causes great destruction in terms of human casualties and also a tremendous economic impact on the affected area. The concern about seismic hazards has led to an increasing awareness and demand for structures designed to withstand seismic forces. The building, which appeared to be strong enough, may crumble during earthquake and deficiencies may be exposed. Performance based analysis is used to produce structure with predictable seismic performance. Performance based analysis is the ability to assess seismic demands and capacities with a reasonable degree of certainty.

For seismic performance evaluation, a structural analysis of the mathematical model of the structure is required to determine force and displacement demands in various components of the structure. Several analysis methods, both elastic and inelastic, are available to predict the seismic performance of the structures. The force demand on each component of the structure is obtained and compared with available capacities by performing an elastic analysis. Elastic analysis methods include code static lateral force procedure, code dynamic procedure and elastic procedure using demand-capacity ratios. These methods are also known as force-based procedures which assume that structures respond elastically to earthquakes.

Structures suffer significant inelastic deformation under a strong earthquake and dynamic characteristics of the structure change with time so investigating the performance of an analytical procedures help to understand the actual behavior of structures by identifying failure modes and the potential for progressive collapse. Inelastic analysis procedures basically include inelastic time history analysis and inelastic static analysis which is also known as pushover analysis. In this paper, building model is analyzed by using inelastic static analysis. Inelastic static analysis, or pushover analysis, has been the preferred method for seismic performance evaluation due to its simplicity. It is a static analysis that directly incorporates nonlinear material characteristics. Inelastic static analysis procedures include Capacity Spectrum Method, Displacement Coefficient Method and the Secant Method. (sermin, 2005).

## II. PUSHOVER METHODOLOGY

The recent advancement of performance based design has brought the nonlinear static, Pushover analysis procedure. Pushover analysis is a static, nonlinear procedure in which the magnitude of the structural loading is incrementally increased in accordance with a certain predefined pattern with the increase in the magnitude of the loading, weak links and failure modes of the structure are identified. The loading is monotonic with the effects of the cyclic behavior and load reversals, being estimated by using a modified monotonic force deformation criteria and with damping approximations. Static pushover analysis is an attempt by structural engineering profession to evaluate the real strength of the structure and it promises to be a useful and effective tool for performance based design.

Local non-linear effects, such as flexural hinges and shear hinges, assumed to occur at the ends of the members, should be appropriately modelled. Redistribution of internal forces occurs with progressive plastic hinge formation, and at some hinge locations, local collapse may occur due to the plastic deformation limit being exceeded. The structure is pushed until global collapse, which is triggered when adequate number of plastic hinges forms to developed collapse mechanism or when the system cannot mobilise load paths to sustain force equilibrium (after local hinge break-downs). The main output of the pushover analysis is in the form of a force-displacement curve, called pushover curve. It is a plot of the base shear (total lateral load) versus the lateral displacement (drift) at some point at the roof level, including all the stages of lateral load/ displacement increments.

Pushover analysis results are obtained in terms of response demand versus capacity. If the demand curve intersects the capacity envelope near the elastic range, Figure 1a, then the structure has a good resistance. If the demand curve intersects the capacity curve with little reserve of strength and deformation capacity, Figure 1b, then it can be concluded that the structure will behave poorly during the imposed seismic excitation and need to be retrofitted to avoid future major damage or collapse.

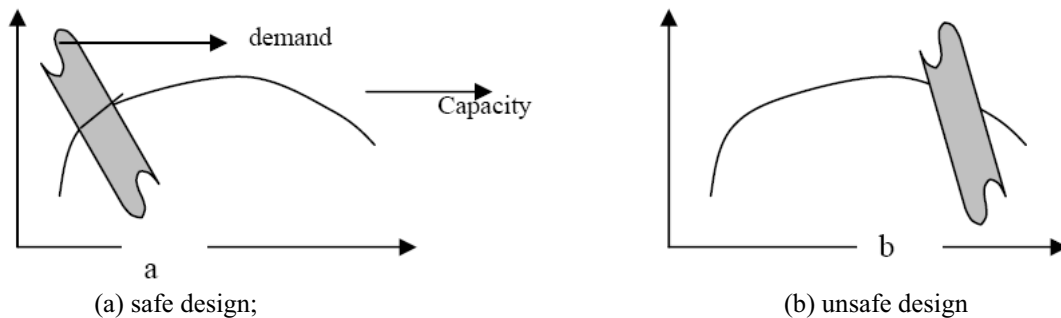


Figure 1. Typical seismic demand versus capacity

### A. Documents Related To Pushover Analysis

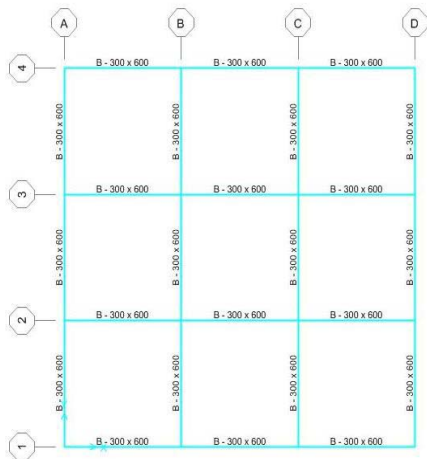
The non-linear static pushover procedure was originally formulated and suggested by two agencies namely, federal emergency management agency (FEMA) and applied technical council (ATC), under their seismic rehabilitation program and guidelines. This is included in the documents FEMA-273, FEMA-356 and ATC-40.

## III. DESCRIPTION OF FRAME STRUCTURE

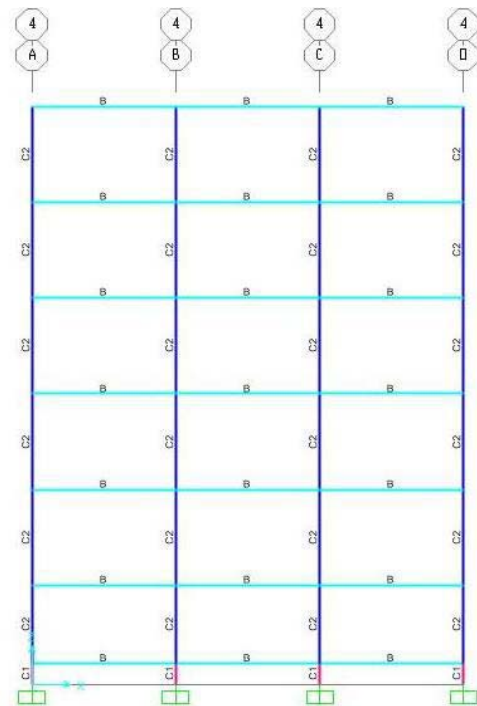
A six storey building for a commercial complex has plan dimensions as shown in Figure 2. The building is located in seismic zone III on a site with medium soil. Design the building for seismic loads as per IS 1893 (Part 1): 2002.

1. Live load : 4.0 kN/m<sup>2</sup> at typical floor  
: 1.5 kN/m<sup>2</sup> on terrace
2. Floor finish : 1.0 kN/m<sup>2</sup>
3. Water proofing : 2.0 kN/m<sup>2</sup>

4. Terrace finish : 1.0 kN/m<sup>2</sup>
5. Location : Vadodara city
6. Wind load : As per IS: 875-Not designed for wind
7. load, since earthquake loads exceed the wind loads.
8. Earthquake load : As per IS-1893 (Part 1) - 2002
9. Depth of foundation below ground : 2.5 m
10. Type of soil : Type II, Medium as per IS:1893
11. Allowable bearing pressure : 200 kN/m<sup>2</sup>
12. Average thickness of footing : 0.9 m, assume isolated footings
13. Storey height : Typical floor: 5 m, GF: 3.4 m
14. Floors : G.F. + 5 upper floors.
15. Ground beams : To be provided at 100 mm below G.L.
16. Plinth level : 0.6 m
17. Walls : 230 mm thick brick masonry walls only at periphery.
18. Grade of concrete is M25 and Grade of steel is Fe415.



Plan



Elevation

### Section Properties

#### Column

- a) C1 = 600 x 600  
Cover = 40mm  
Longitudinal steel = 12 no's 25mm  $\Phi$   
Transverse steel = 2 legged stirrups of  $\Phi 10 @ 200$ mm
- b) C1 = 500 x 500  
Cover = 40mm  
Longitudinal steel = 12 no's 20mm  $\Phi$   
Transverse steel = 2 legged stirrups of  $\Phi 10 @ 200$ mm
- c) B = 230 x 600  
Cover = 25mm

**Gravity load calculation**

Dead load of members

$$C1 = 0.6 \times 0.6 \times 25 = 9 \text{ Kn/m}$$

$$C2 = 0.5 \times 0.5 \times 25 = 6.3 \text{ Kn/m}$$

$$B = 0.23 \times 0.6 \times 25 = 3.45 \text{ Kn/m}$$

$$\text{Slab}(100\text{mm thick}) = 25 \times 0.1 \times 1 \times 1 = 2.5 \text{ Kn/m}$$

$$\text{Brick wall (230mm thick)} = 0.23 \times 19 \text{ (wall)} + 2 \times 0.012 \times 20 \text{ (plaster)} = 4.9 \text{ Kn/m}^2$$

$$\text{Floor wall (height 4.4m)} = (5 - 0.6) \times 4.9 = 21.6 \text{ Kn/m}$$

$$\text{Ground floor wall (height 3.5)} = (4.1 - 0.6) \times 4.9 = 17.2 \text{ Kn/m}$$

$$\text{Dead slab} = 2.5 \times \frac{7.5}{2} = 9.375 \text{ Kn/m}$$

$$\text{Dead roof treatment} = 2 \times \frac{7.5}{2} = 7.5 \text{ Kn/m}$$

$$\text{Dead floor finish} = 1 \times \frac{7.5}{2} = 3.75 \text{ Kn/m}$$

$$\text{Live} = 4 \times \frac{7.5}{2} = 15 \text{ Kn/m}$$

$$\text{Live roof} = 1.5 \times \frac{7.5}{2} = 5.625 \text{ Kn/m}$$

## IV. MODELLING APPROACH

The general finite element package SAP 2000 has been used for the analyses. A three dimensional model of the structure have been created to undertake the non linear analysis. Beams and columns are modeled as nonlinear frame elements with lumped plasticity at the start and the end of each element. SAP 2000 provides default and user-defined hinges which recommends PMM hinges for columns and M3 hinges for beams as described in FEMA 356.

## V. PUSHOVER ANALYSIS

After designing and detailing the reinforced concrete frame structure, a nonlinear pushover analysis is carried out for evaluating the structural seismic response. The pushover analysis consists of the application of gravity loads and representative lateral load pattern. The lateral loads were applied monotonically in a step-by-step nonlinear static analysis. The applied lateral loads were accelerations in the x direction representing the forces that would be experienced by the structures when subjected to ground shaking. Under incrementally increasing loads some elements may yield sequentially. Consequently, at each event, the structure experiences a stiffness change as shown in figure 3, IO, LS and CP stand for immediate occupancy, life safety and collapse prevention respectively.

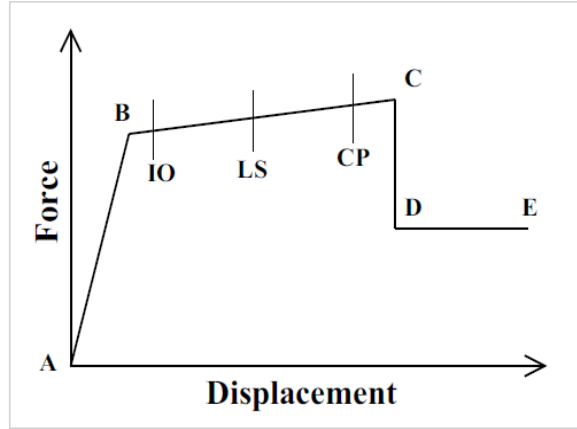


Figure 3. Load-Deformation curve

VI. RESULTS AND DISCUSSION

a) Case I) Analysis Of Building By Using Default Hinges

After running the analysis, Now the pushover curve is obtain as shown in figure 4. A table also obtain which gives the coordinates of each step of the pushover curve and summarizes the number of hinges in each state (for example, between IO, LS, CP or between D and E). This data is shown in Table. 5.1.

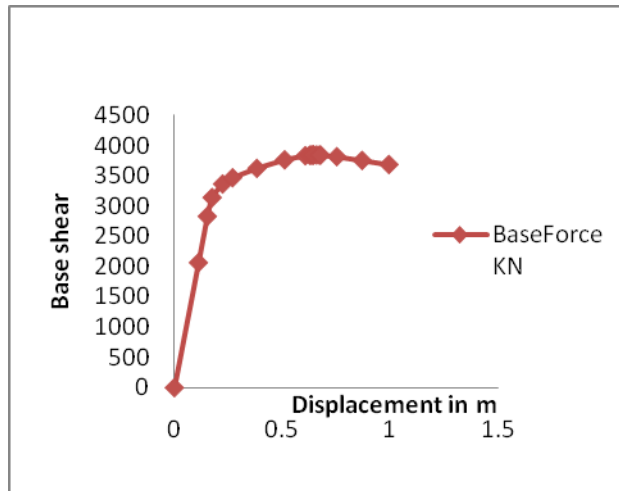


Figure 4. Pushover curve

Yield Values (V,D) = 1841.96, 0.1  
 Ultimate Values (V,D) = 3745.27, 0.5

**Results According To ATC-40**

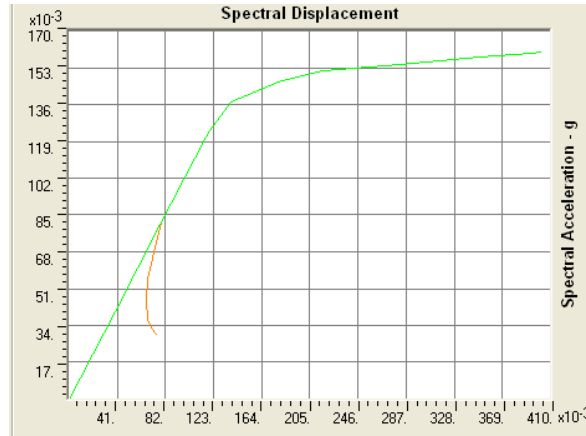


Figure 5 Capacity Spectrum Curve

Performance point is the intersection of capacity and demand spectra.

$V, D = 1856.712, 0.101$

$S_a, S_d = 0.081, 0.078$

$T_{eff}, B_{eff} = 1.969, 0.050$

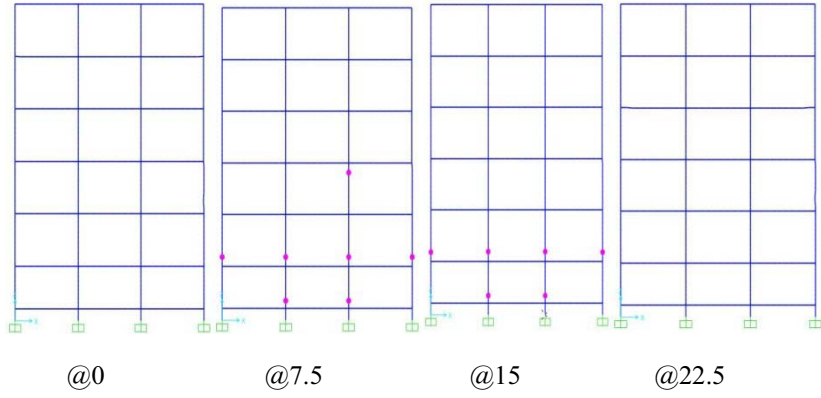
The performance point of the structure can be now determined by using the pushover curves obtained. The performance point is the point where the capacity and demand of the structure are equal. The performance point is determined automatically by SAP 2000, using the procedure c mentioned in ATC-40.

The point at which the capacity curve intersects the reduced demand curve represents the performance point at which capacity and demand are equal. As displacement increase, the period of the structure lengthens and reduces demand. Hence, optimum point should have a higher capacity for a lesser displacement.

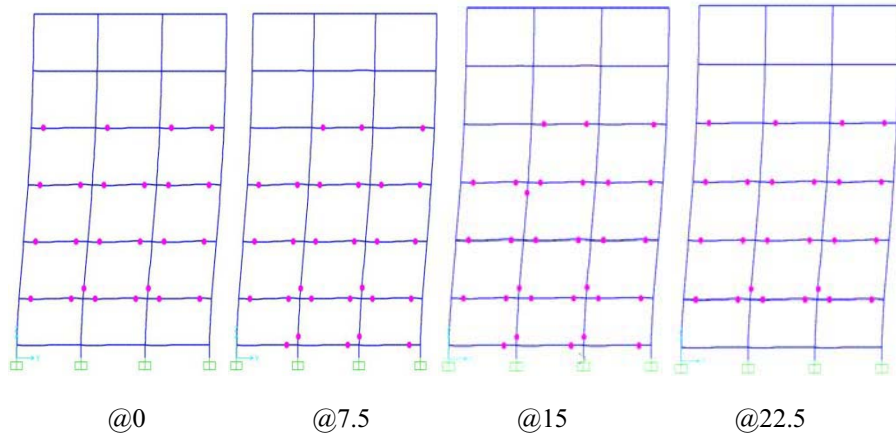
Table 1. Tabular data for capacity spectrum curve

| Step | $T_{eff}$ | $B_{eff}$ | $S_d$ Capacity<br>m | $S_a$ Capacity | $S_d$ Demand<br>m | $S_a$ Demand | Alpha    | PFPhi    |
|------|-----------|-----------|---------------------|----------------|-------------------|--------------|----------|----------|
| 0    | 1.969429  | 0.050000  | 0.000000            | 0.000000       | 0.078275          | 0.081242     | 1.000000 | 1.000000 |
| 1    | 1.969429  | 0.050000  | 0.038827            | 0.040298       | 0.078275          | 0.081242     | 0.690381 | 1.287778 |
| 2    | 1.969429  | 0.050000  | 0.077653            | 0.080597       | 0.078275          | 0.081242     | 0.690381 | 1.287778 |
| 3    | 1.969429  | 0.050000  | 0.116480            | 0.120895       | 0.078275          | 0.081242     | 0.690381 | 1.287778 |
| 4    | 1.969429  | 0.050000  | 0.119190            | 0.123708       | 0.078275          | 0.081242     | 0.690381 | 1.287778 |
| 5    | 2.007224  | 0.064366  | 0.137214            | 0.137103       | 0.074777          | 0.074716     | 0.690940 | 1.282833 |
| 6    | 2.211433  | 0.130712  | 0.177995            | 0.146521       | 0.066912          | 0.055080     | 0.692713 | 1.262642 |
| 7    | 2.397225  | 0.175931  | 0.216058            | 0.151353       | 0.065500          | 0.045884     | 0.691264 | 1.254934 |
| 8    | 2.709310  | 0.230215  | 0.281698            | 0.154492       | 0.066832          | 0.036653     | 0.698948 | 1.245812 |
| 9    | 2.988548  | 0.252344  | 0.349945            | 0.157732       | 0.071011          | 0.032007     | 0.703293 | 1.240601 |
| 10   | 3.145504  | 0.260339  | 0.392632            | 0.159751       | 0.073771          | 0.030016     | 0.705802 | 1.241213 |
| 11   | 3.180401  | 0.261755  | 0.402660            | 0.160256       | 0.074419          | 0.029618     | 0.705983 | 1.241743 |

Figure 5 shows that performance point is at  $T_{eff} = 1.969$  sec which is close value of  $T_{eff}$  at Step No. 4. Hence, it is required to see the hinge formations at Step No. 4. From Figure 6, it also becomes clear that hinges formed in beams and columns are below immediate occupation level. Hence, structure is very safe to use.



(a) Step 4 Hinging mechanism in x-z direction



(b) Step 4 Hinging mechanism in y-z direction

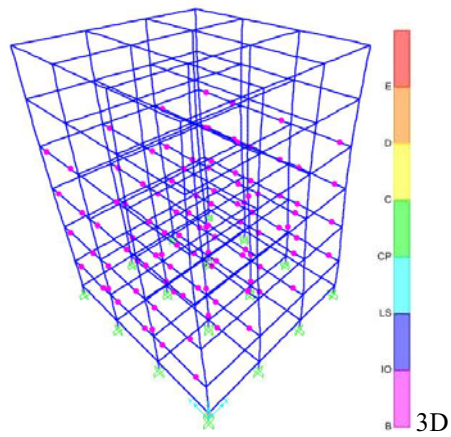


Figure 6. Step 4. Hinging Mechanism in x-z and y-z direction

Results According To FEMA 356 (Coefficient Method)

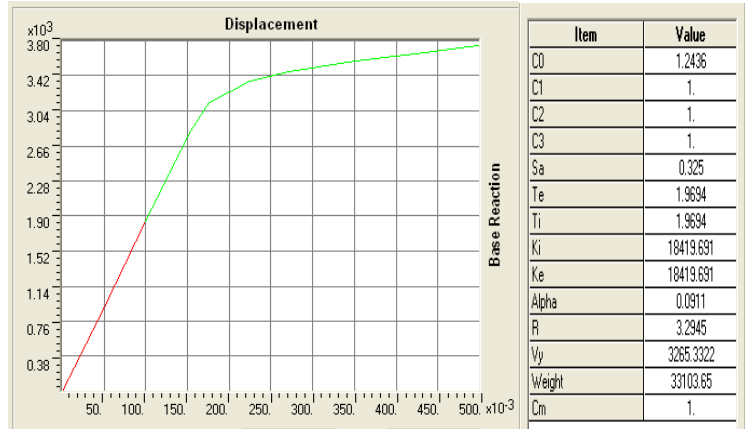


Figure 7 . Displacement Coefficient Curve & some calculated values

Target Displacement (V,D) 1840.893, 0.100

ANALYSIS OF BUILDING BY USING USER-DEFINED HINGES

In case of user-defined hinge properties, column interaction curve is plotted according to section property and provided steel for respective column by using Response 2000. And in case of beam balanced moment is calculated and assigned to the building. After assigning user defined hinges base shear vs displacement curve is obtained.

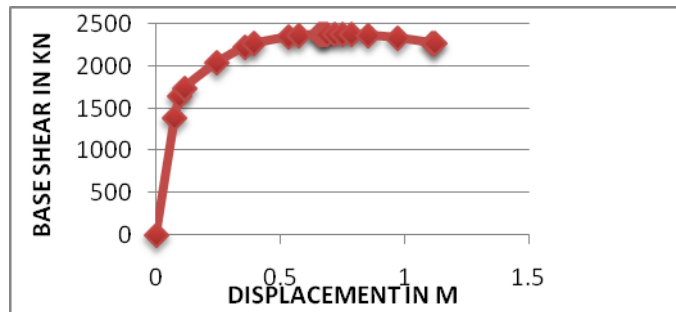


Fig. 8 Pushover curve

Yield Values (V,D) = 1636.86, 0.09532

Ultimate Values (V,D) = 2325.405, 0.5

Results According To ATC-40

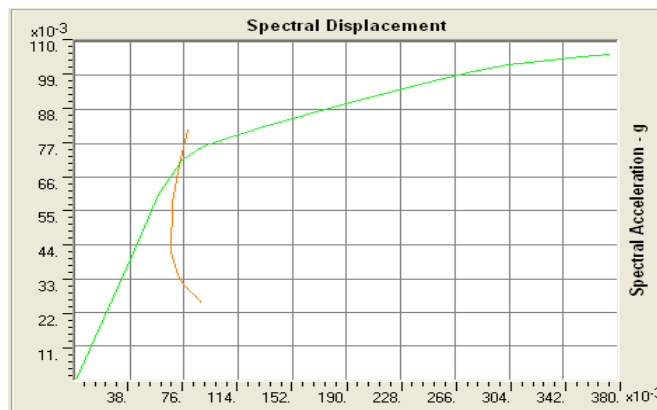




Fig. 9 Capacity spectrum curve

Performance Point (V.D) = 1618.227, 0.097

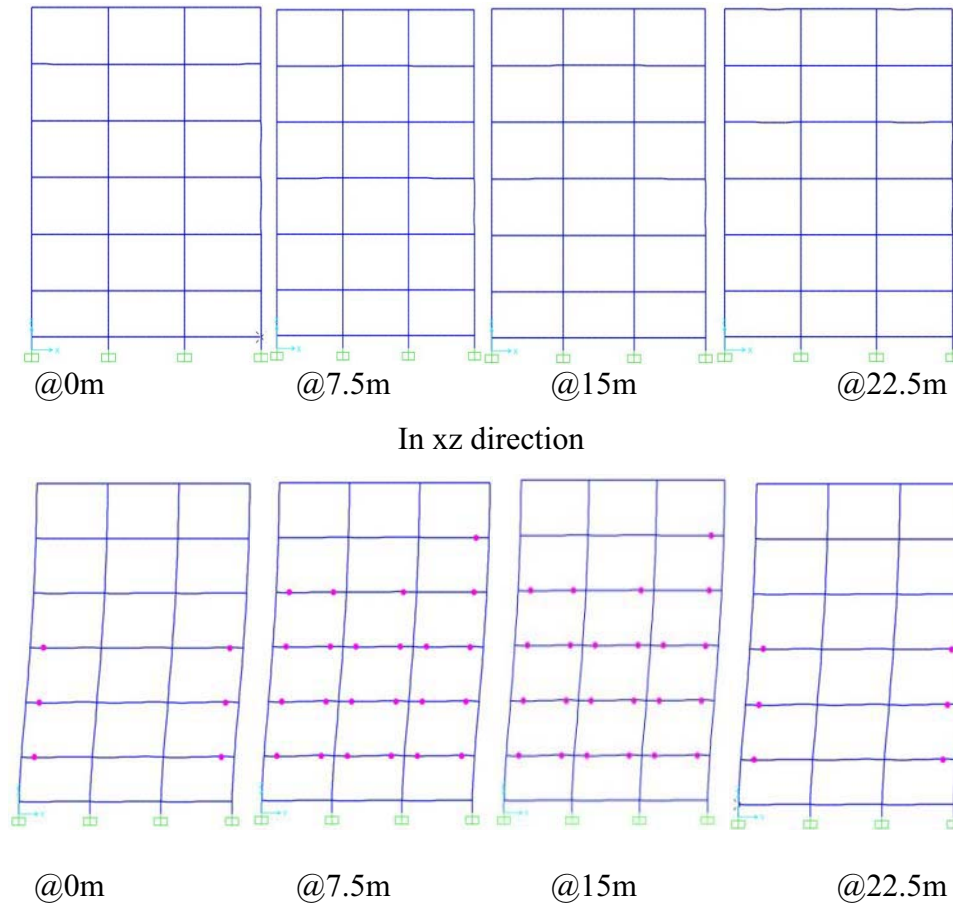
Sa, Sd = 0.071, 0.073

Teff, Beff = 2.040, 0.074

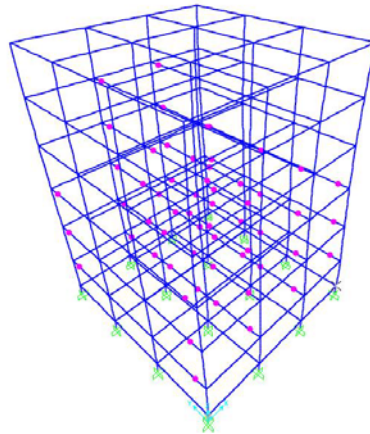
Table 2: Tabular data for capacity spectrum curve

| Step | Teff     | Beff     | SdCapacity | SaCapacity | SdDemand | SaDemand | Alpha    | PFPhi    |
|------|----------|----------|------------|------------|----------|----------|----------|----------|
|      |          |          | m          |            | m        |          |          |          |
| 0    | 1.969429 | 0.050000 | 0.000000   | 0.000000   | 0.078275 | 0.081242 | 1.000000 | 1.000000 |
| 1    | 1.969429 | 0.050000 | 0.038827   | 0.040298   | 0.078275 | 0.081242 | 0.690381 | 1.287778 |
| 2    | 1.969429 | 0.050000 | 0.058122   | 0.060325   | 0.078275 | 0.081242 | 0.690381 | 1.287778 |
| 3    | 2.045305 | 0.076202 | 0.074353   | 0.071552   | 0.072785 | 0.070043 | 0.691057 | 1.281985 |
| 4    | 2.177158 | 0.117648 | 0.089531   | 0.076038   | 0.068139 | 0.057870 | 0.691937 | 1.271165 |
| 5    | 2.533808 | 0.195313 | 0.131612   | 0.082525   | 0.066617 | 0.041771 | 0.688294 | 1.259566 |
| 6    | 2.925845 | 0.232093 | 0.192278   | 0.090421   | 0.071938 | 0.033830 | 0.680256 | 1.264503 |
| 7    | 3.176516 | 0.240698 | 0.241488   | 0.096346   | 0.076960 | 0.030704 | 0.675038 | 1.272955 |
| 8    | 3.357476 | 0.244700 | 0.282009   | 0.100711   | 0.080797 | 0.028854 | 0.669915 | 1.286481 |
| 9    | 3.449845 | 0.247313 | 0.303075   | 0.102516   | 0.082658 | 0.027959 | 0.668045 | 1.294632 |
| 10   | 3.688323 | 0.257057 | 0.354758   | 0.104982   | 0.086964 | 0.025735 | 0.664664 | 1.324278 |
| 11   | 3.776834 | 0.260034 | 0.374976   | 0.105825   | 0.088622 | 0.025011 | 0.663798 | 1.333418 |

Figure 5.12 shows that performance point is at Teff = 2.040 sec which is close value of Teff at Step No. 3. Hence, it is required to see the hinge formations at Step No. 3. From Fig. Step 5.11(d), it also becomes clear that hinges formed in beams are below immediate occupation level. Hence, structure is very safe to use.



In yz direction



3D

Figure 10. Step No.3 Hinging mechanism in x-z direction in y-z direction

Results According To FEMA 356 (Displacement Coefficient Method)

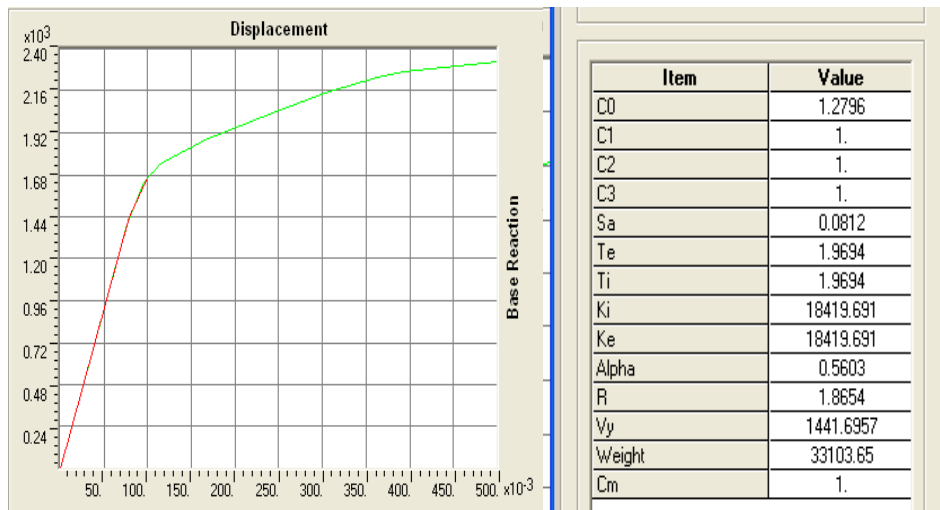


Fig 11. Displacement Coefficient Curve & some calculated values

Target Displacement (V,D) = 1660.283 , 0.099

### VII. CONCLUSIONS

The performance of reinforced concrete frames was investigated using the pushover Analysis. Based on the above results and observations the following conclusions are drawn.

- 1) The frame is modeled with default and user-defined hinges properties to study the possible differences in the results of pushover analysis.
- 2) From fig. 4 and fig. 8, the base shear capacity and hinge mechanism for models with default and used-defined hinges at yield and ultimate, a significant variation is observed.
- 3) This difference may be due to the orientation and axial load level of the columns is not properly accounted for default hinge properties..

- 4) From fig. 5 and fig. 9 as Teff of default is 1.969sec and Teff of user-defined is 2.040sec. Based on observation in the hinging mechanism compared to the user-defined hinge model is more successful in capturing the hinging mechanism compared to the model of default hinge.
- 5) The behavior of properly detailed reinforced concrete frame building is adequate as Indicated by the intersection of the demand and capacity curves and the distribution of Hinges in the beams and the columns. Most of the hinges developed in the beams and few in the columns but with limited damage
- 6) The results obtained in terms of demand, capacity and plastic hinges gives an insight into the real behavior of structures.
- 7) If the capacity and demand curve are intersected in between immediate occupancy and life safety. Such that building experiences moderate damage when subjected to pushover load.
- 8) It would be desirable to study more cases before reaching definite conclusions about the behavior of reinforced concrete frame buildings.

## REFERENCES

- [1] Abhijit Mukherjee, Amit R. Kalyani, (2004), "Seismic retrofitting of reinforced concrete frames with fibre reinforced composites", *Workshop on seismic evaluation and retrofitting of building*, pp 74-82.
- [2] Applied Technology Council (ATC). "Evaluating the seismic resistance of existing buildings." *Rep. No. ATC 14, 1987*, California.
- [3] Applied Technology Council, *ATC-40*, 1996, Seismic Evaluation and Retrofit of Concrete Buildings, Volume 1-2, Redwood City, California
- [4] American Society of Civil Engineers (ASCE). "Seismic Evaluation of Existing Buildings", 2003, *ASCE/SEI 31-03*.
- [5] A.Kadid anf A. Bourmrkik., "Pushover analysis of reinforced concrete frame structure", *Asian Journal of civil engineering (Building and housing)* Vol. 9, No.1(2008), pp 75-83
- [6] CEN (1998). "Euro code 8, 2001 : Design Provisions for Earthquake Resistance of Structures", *Comité European de Normalization*, Brussels, Belgium.
- [7] Cinitha A, Umesh P.K, Iyer N.R., " Nonlinear static analysis to assess seismic performance and vulnaribility of code – conforming RC building " January 2012, , Issue 1, Volume 7, E-ISSN : 2224-3429.
- [8] Dr Durgesh C Rai, (2005), guidelines for seismic evaluation and strengthening of existing building, Provision with commentary and explanatory examples, Indian Institute of Technology Kanpur, *Document no- IITK-GSDMA Earthquake 6, vol. 4*
- [9] Federal Emergency Management Agency (FEMA), 2000, Prestandard and Commentary for the Rehabilitation of Buildings, *FEMA-356*.
- [10] Habibullah, Ashraf. and Stephen, Pyle, —Practical Three-Dimensional Nonlinear Static Pushover *Analysis, Structure Magazine, U.S.A. , pp.1-2, 1998*
- [11] Institute for Research in Construction (NRC/IRC). "Guidelines for Seismic Evaluation of Existing Buildings". *National Research Council of Canada*, Ottawa, Ontario. 1993
- [12] N.Pillai and Devdas Menon,, Reinforced Concrete Building, *Tata McGraw Hill Education Private Limited*, New Delhi [1].
- [13] Pavan Kumar V.S.R, Rayaprolu, Polu Raju P, (2012 ), " Incorporation of Various Seismic Retrofitting Techniques and Materials for RC Framed Building Using SAP 2000", *International Journal of Emerging Trends in Engineering and Developement*, ISSN 2249-6149, Issue 2, Vol.3
- [14] P.Poluraju and P.V.S. Nageswara Rao, "Pushover analysis of reinforced concrete frame structure using SAP 2000", *International Journal of Earth Sciences and Engineering*, ISSN 0974-5904, volume 04, No. 06 SPL, October 2011, pp 684-690
- [15] Rama Raju K, Cinitha A And Iyer N.R., "Seismic Performamce Evaluation Of Existing R.C Building Designed As Per Past Codes Of Practice", *Vol.37, Part.2*, April 2012, pp.281-297.
- [16] Sermin Oguz. A thesis on "Evaluation of Pushover Analysis Procedures For Frame Structures", April,2005.
- [17] Sucuoglu H, Gur T And Gunay M.S., " Performance Based Seismic Rehabilitation of Damaged Reinforced Concrete Buildings", *Journal Of Structural Engineering*, 2004(130), pp. 1475-1486.
- [18] Tande S. N. and Kumbhar S. P., "Seismic Evaluation of Existing Buildings and Strengthening Techniques", International Conference on Natural Hazards and Disaster Management, CBIT, IC – NHDM, 12-14th Dec. 2007, Hyderabad, Andhra Pradesh, India.
- [19] Tande S. N. and Mohite P. B., "Linear and Nonlinear Seismic Response of Reinforced Concrete Frames", 4th International Conference and Exhibition by Indian Concrete Institute on 'Innovative World of Concrete 08', Dec. 11th -14th 2008, New Delhi, India.
- [20] Wenjun Guo and Raman Gilsanz., " Simple Non-Linear Static Analysis Procedure For Progressive Collapse Evaluation", proceedings, Los Angles tall buildings structural design council annual meeting Los Angles, May 2003, pp. 98-106.
- [21] Yogendra Singh, (2003), "Challenges in retrofitting of RC buildings", Workshop on retrofitting of structures, IIT Roorkee, pp 29-44.