

Research Article

## Performance Based Seismic Design

Pravin P. Kokate<sup>†\*</sup>

<sup>†</sup>Department of Civil Engineering, University of Pune, Asst.Prof. VACOE, Ahmadnager, 414001, India

Accepted 05 March 2015, Available online 15 March 2015, Vol.5, No.2 (April 2015)

### Abstract

*The various design procedures, which are adopted in practical applications to evaluate the seismic response, are usually based on linear elastic structural behavior. However these procedures cannot compute the damage levels of the buildings effectively, for this purpose more accurate methods of analyses, which can predict the real behavior of building under strong seismic actions, are required. The non-linear dynamic analysis is the most rigorous method, but it is too complex and time consuming method for practical application. The non-linear static pushover analysis seems to be a more rational method for estimating the lateral strength and the distribution of inelastic deformations. There has been increasing trend toward the use of pushover analysis as a tool for evaluating the earthquake resistance and safety of structure in the Earthquake Engineering field. Since earthquake forces are random in nature & unpredictable, the engineering tools needs to be sharpened for analyzing structures under the action of these forces. Performance based design is gaining a new dimension in the seismic design philosophy wherein the near field ground motion (usually acceleration) is to be considered. Earthquake loads are to be carefully modeled so as to assess the real behavior of structure with a clear understanding that damage is expected but it should be regulated. This study focuses on pushover analysis of multistory RC framed buildings subjecting them to monotonically increasing lateral forces until the preset performance level (target displacement) is reached. A performance-based design is aimed at controlling the structural damage based on precise estimations of proper response parameters.*

**Keywords:** The Earthquake, seismic response, pushover analysis, RC framed buildings, performance-based design.

### 1. Introduction

Amongst the natural hazards, earthquakes have the potential for causing the greatest damages. Since earthquake forces are random in nature & unpredictable, the engineering tools needs to be sharpened for analyzing structures under the action of these forces. Performance based design is gaining a new dimension in the seismic design philosophy where in the near field ground motion (usually acceleration) is to be considered. Earthquake loads are to be carefully modeled so as to assess the real behavior of structure with a clear understanding that damage is expected but it should be regulated. This study focuses on pushover analysis of multistory RC framed buildings subjecting them to monotonically increasing lateral forces until the preset performance level (target displacement) is reached. The promise of performance-based seismic engineering is to produce structures with predictable seismic performance. The results of analysis are compared in terms of base shear, spectral acceleration, spectral displacement and storey displacements. Determine the best possible combination of reinforcement that would be both

economical, effective and damage must be limited to Grade 2 (slight structural damage, moderate nonstructural damage) in order to enable Immediate Occupancy. Optimal design is analyzed and damage must be limited to Grade 3 (moderate structural damage, heavy nonstructural damage) in order to ensure Life Safety under MCE. Farzad Naeim, *et.al*(2009) explained the Performance based seismic engineering is the modern approach to earthquake resistant design. According to him performance based design is an attempt to predict buildings with predictable seismic performance. Therefore, performance objectives such as life safety, collapse prevention, or immediate occupancy are used to define the state of the building following a design earthquake. Xiao-Kang Zou *et.al*,(2005) explained the Performance-based design is a modern approach to seismic engineering, in which the design aim is to deliver a structure capable of meeting certain predictable performance objectives under different levels of earthquake motions. Performance-based design using nonlinear pushover analysis, which generally involves tedious and intensive computational effort, is a highly iterative process to meet designer-specified and code requirements. Andreas J. Kappos *et.al* (2004) presented a performance-based design procedure for realistic 3D

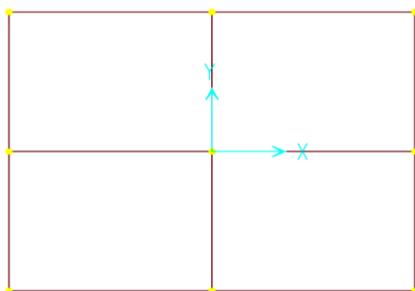
\*Corresponding author: Er. Pravin P. Kokate

reinforced concrete (R/C) buildings, which involves the use of advanced analytical tools. The proposed method was then applied to a regular multistory reinforced concrete 3D frame building and was found to lead to better seismic performance than the standard code procedure, and in addition led to a more economic design of transverse reinforcement in the members that develop very little inelastic behavior even for very strong earthquakes. X.-K. Zou *et al* (2005) presents an effective computer-based technique that incorporates pushover analysis together with numerical optimization procedures to automate the pushover drift performance design of reinforced concrete (RC) buildings. Performance-based design using nonlinear pushover analysis is a highly iterative process needed to meet designer-specified and code requirements. The scope of present study aims at evaluation of R/C buildings (designed according to IS 456:2000) using Pushover Analysis and redesigning by changing the main reinforcement of various frame elements and again analyzing. The performance based seismic engineering technique known as Non-Linear Static Pushover analysis procedure has been effectively used in this regard. The pushover analysis has been carried out using SAP2000, a product of Computers and Structures International. A total of 19 cases for a particular four storey building located in Zone-III have been analyzed, changing reinforcement of different structural elements, i.e. Beams and Columns, in different combinations as well as at different storey levels.

**2. Experimental**

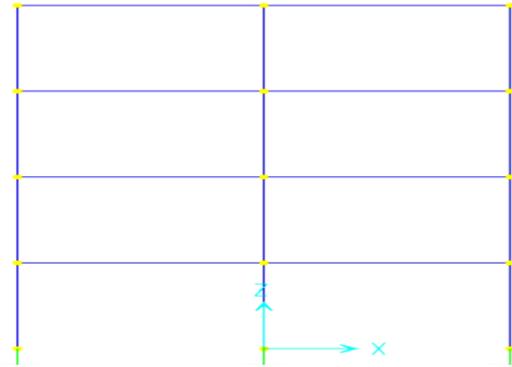
*2.1 Description of Building*

In the present work, a four storied reinforced concrete frame building situated in Zone III, is taken for the purpose of study. The plan area of building is 10 x 8 m with 3.5m as height of each typical storey. It consists of 2 bays of 5m each in X-direction and 2 bays of 4m each in Y-direction. Hence, the building is symmetrical about both the axis. The total height of the building is 14m. The building is considered as a Special Moment resisting frame. The plan of building is shown in fig. 2.1 and the front elevation is shown in fig. 2.2

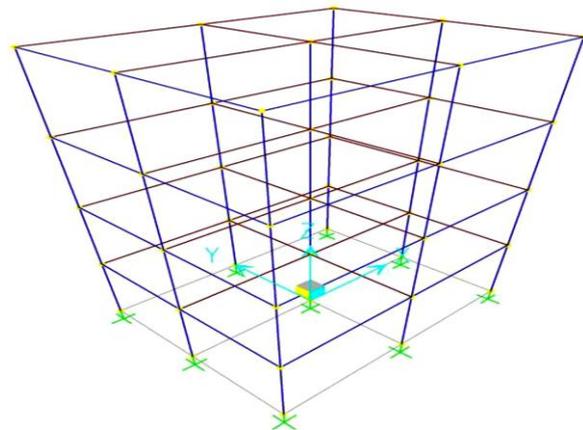


2 Bays @ 5 m = 10 m

**Figure 2.1** Plan of Building



**Figure 2.2** Elevation of Building



**Figure 2.3** 3D View of Building

The choice of a regular and relatively simple structure as a design example was mainly dictated by the need to identify any problems that may arise in applying the proposed procedure, other than those of the complexity of the structure, and obtain a idea of the relative performance of the procedure in the case of regular frame buildings.

*2.2 Determination of lateral loads for pushover analysis*

The maximum design lateral force, **Qi**, was computed for each storey level and was distributed at each node. The calculation of this force is illustrated below:

**2.2.1 Calculation of seismic Weight of Structure**

Seismic weight of roof is calculated as under:  
 Slab =  $0.200 \times 10 \times 8 \times 25 = 400$  KN  
 Beams =  $54 \times 0.350 \times 0.5 \times 25 = 232.87$  KN  
 Columns =  $0.350 \times 0.350 \times 1.75 \times 25 \times 9 = 48.23$  KN  
 Live load = 0 KN  
**Total = 681.1 KN**  
 Seismic weight of one floor is calculated as under:  
 Slab =  $0.200 \times 4 \times 5 \times 25 \times 4 = 400$  KN  
 Beams =  $54 \times 0.345 \times 0.5 \times 25 = 232.87$  KN  
 Columns =  $0.350 \times 0.350 \times 3.5 \times 25 \times 9 = 96.46$  KN  
 Live load =  $10 \times 8 \times 3.5 \times 0.5 = 140$  KN  
**Total = 869.33 KN**  
**Hence Total Seismic weight = 3289.09 KN**

### 2.2.2 Calculation of base shear

The following parameters were taken:

Zone Factor,  $Z = 0.16$

Importance Factor,  $I = 1.0$

Response Reduction Factor = 5.0

Time Period is calculated from:

$$T_s = 0.075 h^{0.75} = .075 \times 14^{0.75} = 0.5428 \text{ seconds}$$

Hence,  $S_a/g = 2.5$  (For Medium Soil Conditions)

$$\text{Hence, } A_h = (.16/2) \times (1/5) \times 2.5 = .04$$

$$\text{Thus } V_b = .04 \times 3289.09 = 131.56 \text{ KN}$$

$$\sum W_j h_j^2 = 282585.69$$

$$\text{Now, } Q_i = \frac{V_b W_i h_i^2}{\sum W_i h_i^2}$$

$$\text{Hence, } Q_4 = (131.56 \times 681.1 \times 14^2) / 282585.69 = 62.15 \text{ KN}$$

$$\text{Similarly, } Q_3 = 44.62 \text{ KN}$$

$$Q_2 = 19.83 \text{ KN} \quad Q_1 = 4.95 \text{ KN}$$

**Table 2.1:** Structural details (As Per IS 456:2000)

Element	Dimension (m)	Reinforcement Area in mm <sup>2</sup>
Corner Columns	0.350 x 0.350	472
Mid-face Columns	0.350 x 0.350	1018
Interior Column	0.350 x 0.350	1527
Beams 1 <sup>st</sup> storey	0.350 x 0.500	657 (top) 614 (bottom)
Beams 2 <sup>nd</sup> storey	0.350 x 0.500	657 (top) 614 (bottom)
Beams 3 <sup>rd</sup> storey	0.350 x 0.500	657 (top) 614 (bottom)
Beams 4 <sup>th</sup> storey	0.350 x 0.500	657 (top) 614 (bottom)

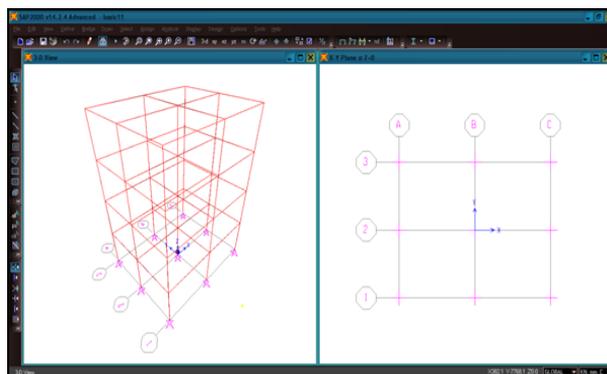
### 2.3 Pushover Analysis using SAP2000

The following steps are included in the pushover analysis. Steps 1 to 4 are to create the computer model, step 5 runs the analysis, and steps 6 to 10 review the pushover analysis results.

1. Create the basic computer model (without the pushover data) .The graphical interface of SAP2000 makes this quick and easy task. Assign sectional properties & apply all the gravity loads i.e. Dead load and Live load on the structure. For changing reinforcement, define frame section from the Define menu as shown in Fig.

2. Define properties and acceptance criteria for the pushover hinges as shown in Figure. The program includes several built-in default hinge properties that are based on average values from ATC-40 for concrete members and average values from FEMA-273 for steel members. In this analysis, PMM hinges have been defined at both the column ends and M3 hinges have

been defined at both the ends of all the beams. Locate the pushover hinges on the model by selecting all the frame members and assigning them one or more hinge properties and hinge locations as shown in Figure.



**Figure 2.4** Basic Model in SAP2000

4. Define the pushover load cases, figure 5.8(a) and (b). In SAP2000 more than one pushover load case can be run in the same analysis. Also a pushover load case can start from the final conditions of another pushover load case that was previously run in the same analysis. Typically the first pushover load case was used to apply gravity load and then subsequent lateral pushover load cases were specified to start from the final conditions of the gravity pushover. Pushover load cases can be force controlled, that is, pushed to a certain defined force level, or they can be displacement controlled, that is, pushed to a specified displacement. Typically a gravity load pushover is force controlled and lateral pushovers are displacement controlled. In this case a Gravity load combination of DL+0.25LL has been used. This combination has been defined as PUSH. The lateral loads, as calculated in 5.6.1, have been applied to a case called PUSHPAT.

5. Run the basic static analysis. Then run the static nonlinear pushover analysis.

6. The Pushover curve was made for control nodes at each storey level. This was done by defining a number of pushover cases in the same analysis, and displacement was monitored for a different node in each case.

7. The pushover curve was obtained as shown in Fig. 2.5. A table was also obtained which gives the coordinates of each step of the pushover curve and summarizes the number of hinges in each state (for example, between IO and LS, or between D and E). This table is shown in Fig. 2.5

8. The capacity spectrum curve obtained is shown in Fig. 2.6. The magnitude of the earthquake and the damping information on this form can be modified and the new capacity spectrum plot can be obtained immediately. The performance point for a given set of values is defined by the intersection of the capacity

curve and the single demand spectrum curve. Also, a table was generated which shows the coordinates of the capacity curve and the demand curve as well as other information used to convert the pushover curve to Acceleration-Displacement Response Spectrum format (also known as ADRS format). See Fig. 2.6.



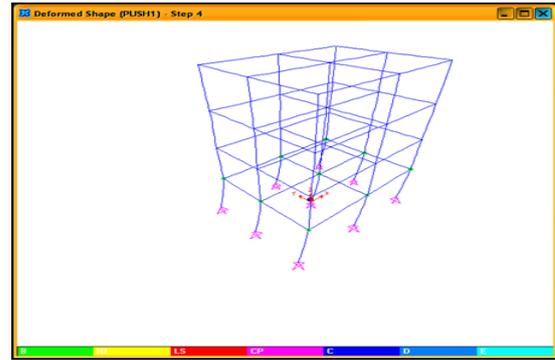
Figure 2.5 Pushover Curve



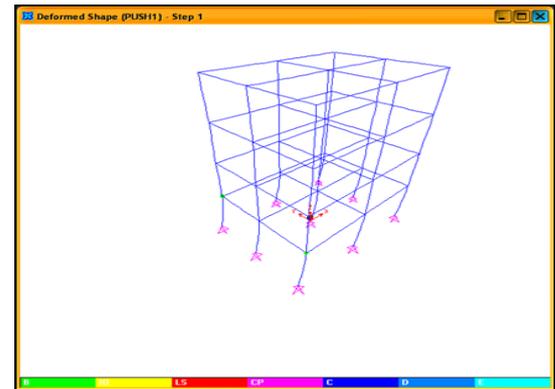
Figure 2.6 Capacity Spectrum Curve

9. The pushover displaced shape and sequence of hinge information on a step-by-step basis was obtained and is shown in the Figure 2.7.

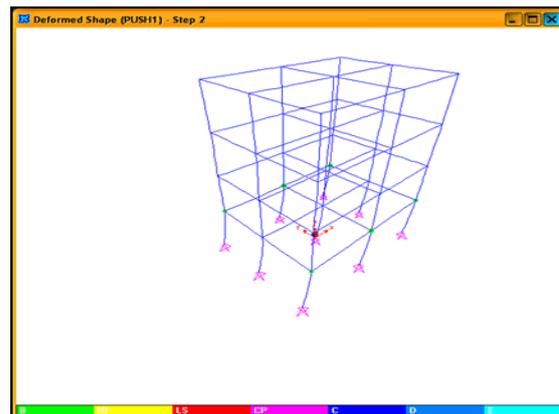
10. Output for the pushover analysis can be printed in a tabular form for the entire model or for selected elements of the model. The types of output available in this form include joint displacements at each step of the pushover, frame member forces at each step of the pushover, and hinge force, displacement and state at each step of the pushover.



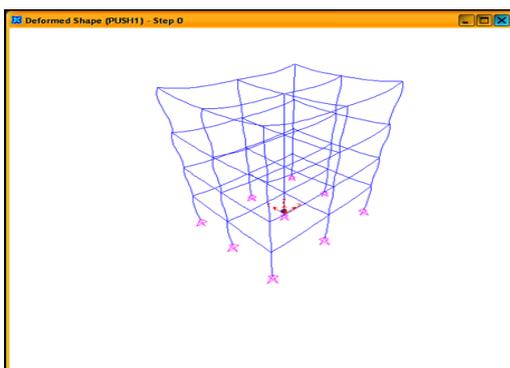
STEP 1



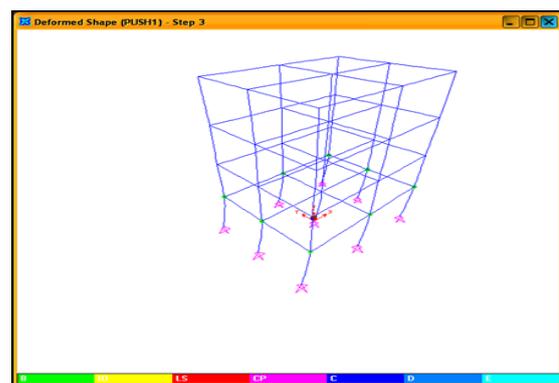
STEP 2



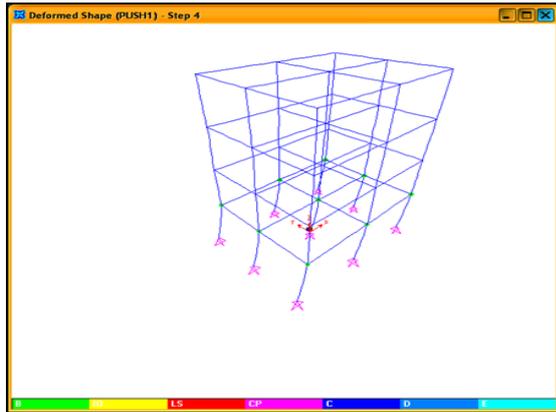
STEP 3



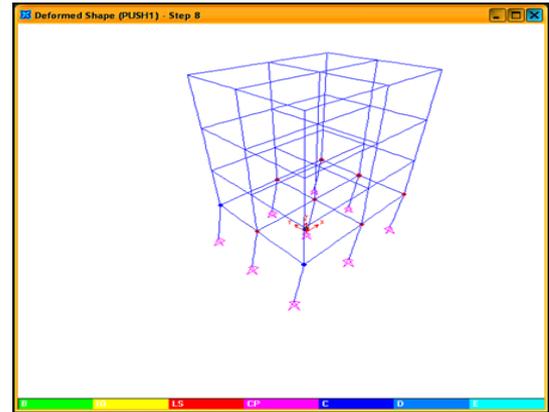
STEP 0



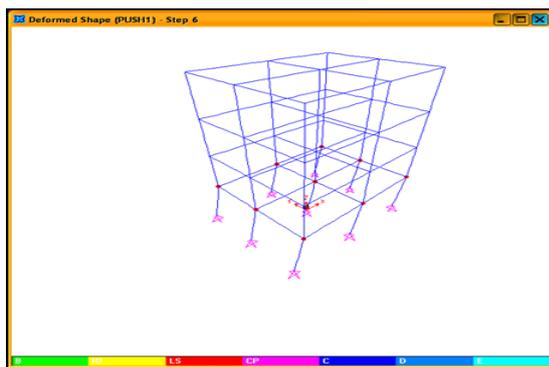
STEP 4



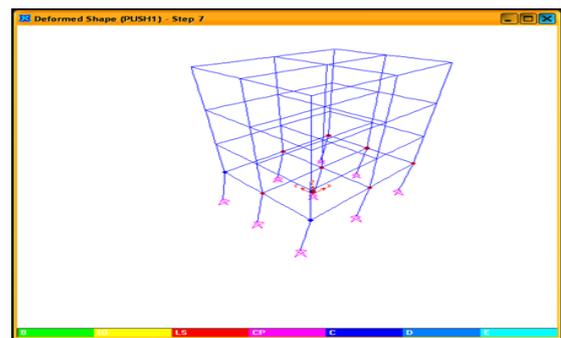
STEP 5



STEP 7



STEP6



STEP8

Fig 2.7 Step By Step Deformations for Pushover

Table: 3.1 Comparison of Base Shear

Structural Elements	Cases	%Increase In Reinforcement	Base Shear (KN)	Percentage Change In Base Shear
Basic structure			<b>196.061</b>	
Beams of 1 <sup>st</sup> Storey	Case 1	5	196.061	0.00
	Case 2	10	196.061	0.00
	Case 3	15	196.061	0.00
	Case 4	20	196.061	0.00
	Case 5	25	196.061	0.00
	Case 6	50	196.061	0.00
Beams of 2 <sup>nd</sup> Storey	Case 7	20	196.061	0.00
Beams of 3 <sup>rd</sup> Storey	Case 8	20	196.064	0.0015
Beams of 4 <sup>th</sup> Storey	Case 9	20	196.007	-0.028
Beams of 1 <sup>st</sup> & 2 <sup>nd</sup> Storey	Case 10	20	196.068	0.004
Beams of 3 <sup>rd</sup> & 4 <sup>th</sup> Storey	Case 11	20	196.061	0.00
Columns of 1 <sup>st</sup> Storey	Case 12	Corner-4.17, Mid-12.5, Int.-28	213.734	9.01
	Case 13	Corner-38, Mid-40, Int.-28	234.216	19.46
	Case 14	Corner-50, Mid-50, Int.-50	250.270	27.65
Columns of 1 <sup>st</sup> & 2 <sup>nd</sup> Storey	Case 15	Corner-4.17, Mid-12.5, Int.-28	213.734	9.01
	Case 16	Corner-38, Mid-40, Int.-28	234.216	19.46

	Case 17	Corner-50, Mid-50,Int.-50	250.270	27.65
Beams and Columns of 1 <sup>st</sup> Storey	Case 18	Beams-20, Column-corner- 4.17, Mid-12.5, Int- 28	213.734	9.01
Beams of 1 <sup>st</sup> &2 <sup>nd</sup> Columns of 1 <sup>st</sup> Storey	Case 19	Beams-20, Column-corner- 4.17, Mid-12.5, Int- 28	230.443	17.54

**Table 3.2** Comparison of Roof Displacement

Structural Elements	Cases	Percentage Increase In Reinforcement	Roof Displacement (mm)	Percentage Change In Roof Displacement
Basic structure			92.633	
Beams of 1 <sup>st</sup> Storey	Case 1	5	92.633	0.00
	Case 2	10	92.633	0.00
	Case 3	15	92.633	0.00
	Case 4	20	92.633	0.00
	Case 5	25	92.633	0.00
	Case 6	50	92.633	0.00
Beams of 2 <sup>nd</sup> Storey	Case 7	20	92.633	0.00
Beams of 3 <sup>rd</sup> Storey	Case 8	20	92.634	0.001
Beams of 4 <sup>th</sup> Storey	Case 9	20	92.618	-0.016
Beams of 1 <sup>st</sup> & 2 <sup>nd</sup> Storey	Case 10	20	92.635	0.002
Beams of 3 <sup>rd</sup> & 4 <sup>th</sup> Storey	Case 11	20	92.633	0.00
Columns of 1 <sup>st</sup> Storey	Case 12	Corner-4.17, Mid-12.5, Int.-28	93.996	1.47
	Case 13	Corner-38, Mid-40, Int.-28	97.643	5.41
	Case 14	Corner-50, Mid-50, Int.-50	98.956	6.83
Columns of 1 <sup>st</sup> & 2 <sup>nd</sup> Storey	Case 15	Corner-4.17, Mid-12.5, Int.-28	93.996	1.47
	Case 16	Corner-38, Mid-40, Int.-28	97.643	5.41
	Case 17	Corner-50, Mid-50, Int.-50	98.956	6.83
Beams and Columns of 1 <sup>st</sup> Storey	Case 18	Beams-20, Column-corner- 4.17, Mid-12.5, Int-28	93.996	1.47
Beams of 1 <sup>st</sup> &2 <sup>nd</sup> Columns of 1 <sup>st</sup> Storey	Case 19	Beams-20, Column-corner- 4.17, Mid-12.5, Int-28	94.714	2.25

**3. Result and Discussion**

*3.1 Base Shear*

The base shear for the four-storey building with different combination of element reinforcement at various floor levels is presented in Table 3.1 It is observed that with increase in reinforcement of beams only, there is a quite percentage change in the base shear varying from 0.004% to -0.028%, which the structure can carry. However, with the increase in

reinforcement of storey columns, there is measurable change in the base force carrying capacity of the structure. The combination of change of reinforcement in beams and columns both show a small increase in base force capacity.

*3.2 Roof Displacement*

The Roof displacement for the four-storey building with different combination of element reinforcement at various floor levels is presented in Table 3.2. It is

observed that by increasing the reinforcement of beams only, there is no increase in the roof displacement for 1<sup>st</sup>&2<sup>nd</sup> storey, it is slightly increased for 3<sup>rd</sup>storey and then decreases for 4<sup>th</sup>storey. The percentage change varies from -0.016% to 6.83%. The combination of increase of reinforcement of beams and columns both, show a little increase in the roof displacement.

### 3.3 Pushover Curve

The Pushover curve is the curve which is plotted between the Base force and Roof displacement. This curve shows the overall response of the structure in case of incremental seismic loading. The structure is applied an inverted triangular loading. This loading is increased monotonically, in small increments, till there is a failure in the structure at any level. As the loading is increased, a curve between the base force and roof displacement is plotted. This curve is known as the pushover curve.

### 3.4 Performance Point

The performance point of the structure can be now determined by using the ADRS pushover curves obtained. The performance point is the point where the capacity and demand of the structure are equal. Hence, it can be termed as a measure of economy of the reinforcement system. The performance point is determined automatically by SAP2000, 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. This is reflected directly in the capacity spectrum. Displacements increase damping and reduce demand. Hence, the optimum point should have a higher capacity for a lesser displacement.

## 4. Performance Based Design

Specified deformation states are often taken as a measure of building performance at corresponding load levels. For example, the US Federal Emergency Management Agency identifies operational, immediate-occupancy, life-safety and collapse-prevention performance levels, and adopts roof-level lateral drift at the corresponding load levels as a measure of the associated behavior states of the building. The increasing degrees of damage that a building experiences at the various performance levels are associated with earthquakes having increasing intensities of horizontal ground motion. For the Performance based design the frame should bear maximum base shear & should give minimum displacement for the same case.

**Table 3.3:** Target Roof Lateral Displacement ratios at various performance levels

Performance level	Operational	Immediate Occupancy	Life-Safety	Collapse-Prevention
Lateral Drift ratio ( $\delta/h$ ) %	0.37	0.7	2.5	5

Where,  $\delta$  is Lateral Roof Displacement and  $h$  is total height of building Performance based design is obtained by increasing the main reinforcement of various frame elements by hit and trail method, so that the building performance level, (after performing Pushover Analysis) lies in Immediate Occupancy level i.e., roof displacement of building is 0.7% of total height of building.

Target Roof Displacement =  $0.007 \times 14m = 0.098m = 98mm$  Design thus obtained is subjected to triangular loading corresponding to MCE, (Maximum Considered Earthquake) so that the structural damage is limited to Grade 3 (moderate structural damage, heavy nonstructural damage) in order to ensure Life Safety i.e., roof displacement of building is 2.5% of total height of building.

Target Roof Displacement =  $0.025 \times 14m = 0.35m = 350mm$

**Table 3.4** Comparison of reinforcement area in mm<sup>2</sup> in beams and columns for all Designs

Element	IS 456:2000	Performance based Design
Corner Columns 1 <sup>st</sup> storey	452	628
Corner Columns 2 <sup>nd</sup> storey	452	452
Corner Columns 3 <sup>rd</sup> and 4 <sup>th</sup> storey	452	452
Mid-Frame Columns 1 <sup>st</sup> storey	804	1130
Mid-Frame Columns 2 <sup>nd</sup> , 3 <sup>rd</sup> and 4 <sup>th</sup> storey	804	804
Interior Column 1 <sup>st</sup> and storey	1260	1608
Interior Column 2 <sup>nd</sup> , 3 <sup>rd</sup> and 4 <sup>th</sup> storey	1260	1260
Beams 1 <sup>st</sup> storey	657 (top) 614 (bottom)	657 (top) 614 (bottom)
Beams 2 <sup>nd</sup> storey	657 (top) 614 (bottom)	657 (top) 614 (bottom)
Beams 3 <sup>rd</sup> storey	657 (top) 614 (bottom)	657 (top) 614 (bottom)
Beams 4 <sup>th</sup> storey	657 (top) 614 (bottom)	657 (top) 614 (bottom)

## Conclusion

Based on the present study, the following conclusions can be drawn:

1. Performance increases on increasing reinforcement of columns only resulting into an appreciable decrease in the maximum roof displacement.
2. The increase in reinforcement of columns only results into a nominal increase in base shear, for R.C. building. It is observed that changing reinforcement of 1<sup>st</sup>storey affects base shear more than other storey's.

3. Performance of the building decreases when the sectional sizes of beams and columns are reduced while keeping same reinforcement.
4. Increasing reinforcement of beams and columns both result in an appreciable decrease in roof displacement.
5. The performance based seismic design obtained by above procedure satisfies the acceptance criteria for immediate occupancy and life safety limit states for various intensities of earthquakes.
6. Performance based seismic design obtained leads to a small increase in steel reinforcement when compared to code based design (IS 456:2000).

As a closing remark, one can say that performance based seismic design gives a structure with better seismic load carrying capacity, thereby achieving the objective of Performance as well as Economy and there is certainly room for further improvement in the aforementioned method.

## Reference

- ASCE 2000, Prestandard and Commentary for the Seismic Rehabilitation of Buildings, FEMA 356 Report, prepared by the American Society of Civil Engineers for the Federal Emergency Management Agency, Washington, D.C
- ATC 1997, NEHRP Guidelines for the Seismic Rehabilitation of Buildings, FEMA 273 Report, prepared by the Applied Technology Council for the Building Seismic Safety Council, published by the Federal Emergency Management Agency, Washington, D.C.
- ATC 1997b, NEHRP Commentary on the Guidelines for the Seismic Rehabilitation of Buildings, FEMA 274 Report, prepared by the Applied Technology Council, for the Building Seismic Safety Council, published by the Federal Emergency Management Agency, Washington, D.C.
- ATC 2006, Next-Generation Performance-Based Seismic Design Guidelines: Program Plan for New and Existing Buildings, FEMA 445, Federal Emergency Management Agency, Washington, D.C
- Chan CM & Zou XK, 2002, Optimal inelastic drift design of reinforced concrete structures under pushover loading. In: The second China-Japan-Korea joint symposium on optimization of structural and mechanical systems.
- Chopra AK., *et.al*, 1995, Dynamics of structures--theory and applications to earthquake Engineering. New Jersey: Prentice-Hall.
- Chintanapakdee C, *et.al*, 2001, Comparing response of SDF systems to near-fault and far-fault earthquake motions in the context of spectral regions. Earthquake Engineering and Structural Dynamics; 30:1769-1789.
- Fajfar, P. *et.al*, 1997, Seismic Design Methodologies for the Next Generation of Codes, Proceedings of International Workshop held in Bled (Slovenia), Balkema, The Netherlands.
- Kowalsky M J, *et.al*, 1994, Displacement-based design, a methodology for seismic design applied to single degree of freedom reinforced concrete structures.
- Mander J.B., 2001, Future directions in seismic design and performance-based engineering, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand, NZSEE2001 Conference
- NEHRP, 2009, Research Required to Support Full Implementation of Performance-Based Seismic Design, prepared by The Building Seismic Safety Council of The National Institute of Building Sciences Washington, D.C
- Farzad Naeim, *et.al*, 2009, Performance Based Seismic Engineering.
- Andreas J., *et.al*, 2004 Performance-Based Seismic Design of 3D R/C Buildings using Inelastic Static and Dynamic Analysis Procedures. ISET Journal of Earthquake Technology, Paper No. 444, Vol. 41, No. 1, pp. 141-158.
- X.-K. Zouet *al* (2005), An Effective Computer-Based Technique that Incorporates Pushover Analysis together with Numerical Optimization Procedures.