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Performance Based Seismic Design of Buildings

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*Abstract***:** *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 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. In this context pushover analysis which is an iterative procedure shall be looked upon as an alternative for the orthodox analysis procedures. This study focuses on pushover analysis of multi-storey RC framed buildings subjecting them to monotonically increasing lateral forces with an invariant height wise distribution until the preset performance level (target displacement) is reached. The promise of performance-based seismic engineering (PBSE) is to produce structures with predictable seismic performance. To turn this promise into a reality, a comprehensive and well-coordinated effort by professionals from several disciplines is required.*

1. Introduction

Performance based engineering is not new. Automobiles, airplanes, and turbines have been designed and manufactured using this approach for many decades. Generally in such applications one or more full-scale prototypes of the structure are built and subjected to extensive testing. The design and manufacturing process is then revised to incorporate the lessons learned from the experimental evaluations. Once the cycle of design, prototype manufacturing, testing and redesign is successfully completed, the product is manufactured in a massive scale. In the automotive industry, for example, millions of automobiles which are virtually identical in their mechanical characteristics are produced following each performance-based design exercise. What makes performance-based seismic engineering (PBSE) different and more complicated is that in general this massive payoff of performance-based design is not available. That is, except for large-scale developments of identical buildings, each building designed by this process is virtually unique and the experience obtained is not directly transferable to buildings of other types, sizes, and performance objectives. Therefore, up to now PBSE has not been an economically feasible alternative to conventional prescriptive code design practices. Due to the recent advances in seismic hazard assessment, PBSE methodologies, experimental facilities, and computer applications, PBSE has become increasing more attractive to developers and engineers of buildings in seismic regions. It is safe to say that within just a few years PBSE will become the standard method for design and delivery of earthquake resistant structures. In order to utilize PBSE effectively and intelligently, one need to be aware of the uncertainties involved in both structural performance and seismic hazard estimations. The recent advent of performance based design has brought the nonlinear static pushover analysis procedure to the forefront. 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 behaviour and load reversals being estimated by using a modified monotonic force-deformation criteria and with damping approximations. Static pushover analysis is an attempt by the 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.

2. Advantages of performance based Seismic Design

In contrast to prescriptive design approaches, performance-based design provides a systematic methodology for assessing the performance capability of a building. It can be used to verify the equivalent performance of alternatives, deliver standard performance at a reduced cost, or confirm higher performance needed for critical facilities [2].

It also establishes a vocabulary that facilitates meaningful discussion between stakeholders and design professionals on the development and selection of design options. It provides a framework for determining what level of safety and what level of property protection, at what cost, are acceptable to stakeholders based upon the specific needs of a project.

Performance-based seismic design can be used to:

- Design individual buildings with a higher level of confidence that the performance intended by present building codes will be achieved.
- Design individual buildings that are capable of meeting the performance intended by present building codes, but with lower construction costs.
- Design individual buildings to achieve higher performance (and lower potential losses) than intended by present building codes.
- Assess the potential seismic performance of existing structures and estimate potential losses in the event of a seismic event.
- Assess the potential performance of current prescriptive code requirements for new buildings, and serve as the basis for improvements to code-based seismic design criteria so that future buildings can perform more consistently and reliably.

3. Literature Review

X.-K. Zou et al. (2005)[8] present 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. This paper presents an effective computer-based technique that incorporates pushover analysis together with numerical optimization procedures to automate the pushover drift performance design. Steel reinforcement, as compared with concrete materials, appears to be the more cost-effective material that can be effectively used to control drift beyond the occurrence of first yielding and to provide the required ductility of RC building frameworks. In this study, steel reinforcement ratios are taken as design variables during the design optimization process. Using the principle of virtual work, the nonlinear inelastic seismic drift responses generated by the pushover analysis can be explicitly expressed in terms of element design variables. An optimality criteria technique is presented in this paper for solving the explicit performance-based seismic design optimization problem for RC buildings. Two building frame examples are presented to illustrate the effectiveness and practicality of the proposed optimal design method.

The design optimization procedure for limiting performance-based seismic drifts of an RC building structure is listed as follows:

Establish an initial design with optimal member dimensions, which can be obtained from the elastic seismic design optimization by minimizing the concrete cost of an RC structure subjected to a minor earthquake loading using the elastic response spectrum analysis method [9].

Determine the design spectra, corresponding to different earthquake demand levels, which will be used in the nonlinear pushover analysis.

Conduct a static virtual load analysis to obtain the member internal forces that will be used in formulating inelastic drift responses by employing the principle of virtual work.

R. K. Geol. and A. K. Chopra presented an improved Direct Displacement-Based Design Procedure for Performance-Based seismic design of structures. Direct displacement-based design requires a simplified procedure to estimate the seismic deformation of an inelastic SDF system, representing the first (elastic) mode of vibration of the structure. This step is usually accomplished by analysis of an equivalent linear system using elastic design spectra. In their work, an equally simple procedure is developed that is based on the well-known concepts of inelastic design spectra. This procedure provides: (1) accurate values of displacement and ductility demands, and (2) a structural design that satisfies the design criteria for allowable plastic rotation. In contrast, the existing procedure using elastic design spectra for equivalent linear systems is shown to underestimate significantly the displacement and ductility demands. In this work, it is demonstrated that the deformation and ductility factor that are estimated in designing the structure by this procedure are much smaller than the deformation and ductility demands determined by nonlinear analysis of the system using inelastic design spectra. Furthermore, it has been shown that the plastic rotation demand on structures designed by this procedure may exceed the acceptable value of the plastic rotation.

J. B. Mander (2001) [12] reviewed from an historical perspective past and current developments in earthquake engineered structures. Based on the present state-of-the-practice in New Zealand, and a world-view of the state-of-the-art, he argued that in order to make progress towards the building of seismic resilient communities, research and development activities should focus on performance-based design which gives the engineer the ability to inform clients/owners of the expected degree of damage to enable a better management of seismic risk. To achieve expected performance outcomes it will be necessary to supplement, current force-based design standards with displacement-based design methodologies. Improved design methodologies alone will not lead to a significantly superior level of seismic resilient communities, but rather lead to a superior standard of performance-based engineered structures where the post-earthquake outcome will be known with a certain degree of confidence. This paper gives two philosophical approaches that are referred to as Control and Reparability of Damage (CARD), and Damage Avoidance Design (DAD).

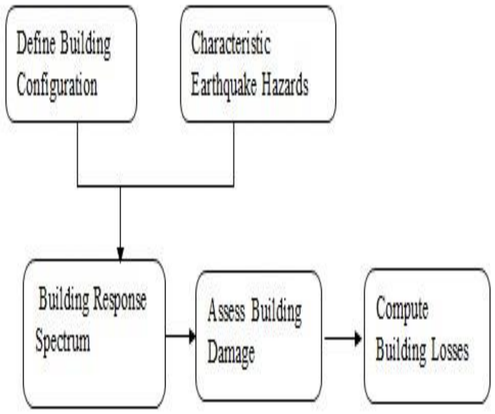


Figure 1 Procedures for Performance Assessment

4. Proposed Method

The main objective of performance based seismic design of buildings is to avoid total catastrophic damage and to restrict the structural damages caused, to the performance limit of the building. For this purpose Static pushover analysis is used for various Response Reduction factors (R) to evaluate the real strength of the structure and it promises to be a useful and effective tool for performance based design.

All modern national seismic design codes converge on the issue of design methodology. These are based on a prescriptive Force-Based Design approach, where the design is performed using a linear elastic analysis, and inelastic energy dissipation is considered indirectly, through a response reduction factor (or behavior factor). This factor, along with other interrelated provisions, governs the seismic design forces and hence the seismic performance of code-designed buildings. However, different national codes vary significantly on account of various specifications which govern the design force level. The response reduction factor, as considered in the design codes, depends on the ductility and over strength of the structure. Building codes define different ductility classes and specify corresponding response reduction factors based on the structural material, configuration and detailing. Another important issue, which governs the design and expected seismic performance of a building, is control of drift. Drift is recognized as an important control parameter by all the codes; however, they differ regarding the effective stiffness of RC members. Further, the procedures to estimate drift and the allowable limits on drift also vary considerably.

Response reduction is used to scale down the elastic response of the structure [14]. The structure is allowed to be damaged in case of severe shaking. Hence, structure is designed for seismic force much less than what is expected under strong shaking if the structure were to remain linearly elastic. It is simply represents the ratio of the maximum lateral force, V_e which would develop in a structure, responding entirely linear elastic under the specified ground motion, to the lateral force, V_d which has been designed to withstand.

Response reduction factor R, is expressed by the equation:

$$R = V_e / V_d$$

Where, V_e = Linear Elastic lateral Force, V_d = Design lateral Force

Ductility may be broadly defined as the ability of a structure or member to undergo inelastic deformations beyond the initial yield deformation with no decrease in the load resistance. The displacement ductility demand for a given earthquake load is obtained from the pushover curve and is calculated by the following equation,

$$\mu = \frac{\Delta_m}{\Delta_y}$$, Where,

Δ_m , Δ_y is maximum displacement and yield displacement.

Inter-storey drift is defined as the ratio of relative horizontal displacement of two adjacent floors and corresponding storey height (h). It is calculated by equation,

$$\delta = \frac{\delta_i}{\delta_{i-1}}$$, Where,

δ_i, δ_{i-1} is displacement at i and i-1 storey.

DESCRIPTION OF BUILDINGS

In the present work, an eight storied and sixteen storied reinforced concrete frame building situated in Indian Seismic Zone V and Soil type medium is taken for the purpose of study with different R values. The plan area of building is 20 x 12 m with 3.0 m as height of each typical storey. It consists of 4 bays of 5m each in X-direction and 3 bays of 4m each in Y-direction. The total height of the building is 25.5 m and 49.5 m for eight and sixteen storey building respectively. The response spectrum used in the analysis is shown in fig.4.9.

The two problems chosen are

1. Problem 1: Eight storey R.C. building with response reduction factors 3, 5, 8.
2. Problem 2: Sixteen storey R.C. building with response reduction factors 3, 5, 8.

Problem 1: 8 storey R.C. Building

Table 4.1 Design data for 8 Storey building

Grade of concrete	M20
Grade of steel	Fe415
Live load on roof	1.5kN/m^2
Live load on floors	3 kN/ m^2
Roof finish	1kN/ m^2
Floor finish	1kN/ m^2
Brick wall on internal beams	150mm
Brick wall on external beams	230mm
Density of concrete	25kN/ m^3
Density of concrete wall including plaster	20 kN/ m^3

The seismic criteria considered for this building is:

i. Response reduction factor :3, 5 and 8
ii. Importance factor :1
iii. Zone factor for zone V:0.36

Table Preliminary Sizes of columns and beams for 8 storey building

Column		Beam	
External frames middle	300X500	Roof and floor beam (1)	300X600
Corner column	400X400	Roof and floor beam (2)	300X400
Interior column	400X500	Plinth beam (1)	300X400
		Plinth beam (2)	300X350
Slab thickness		125mm	

Figure 2. Procedures for Performance Assessment

Loads assigned

Wall load: External wall load intensity : 11.73kN/m
Internal wall load intensity : 7.65kN/m
Parapet wall load intensity : 4.6kN/m
Slab load (Dead Slab): Intensity of slab load : 3.125kN/m
Floor finish load (Dead FF): Intensity of floor finish : 1kN/m
Roof treatment load: Intensity of roof treatment load : 1.5kN/m
Live load: Intensity of live load : 3kN/m
1.5kN/m

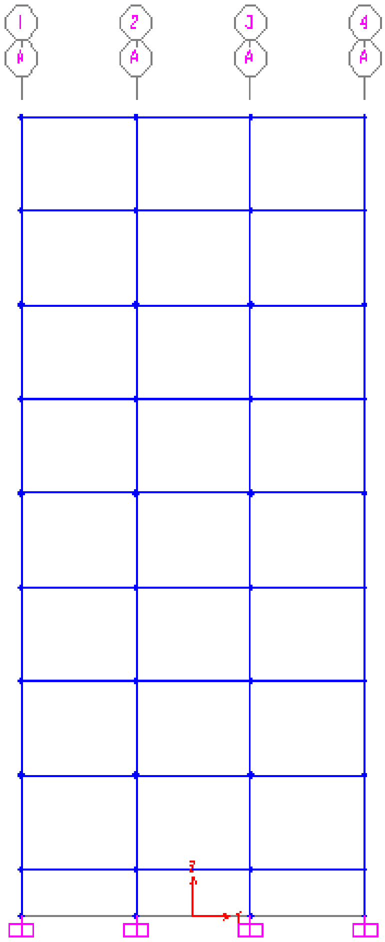


Figure 3. Elevation of 1-4 frames of 8 storied RC Building

Table 4.3 Design data for 16 Storey building

Grade of concrete	M20
Grade of steel	Fe415
Live load on roof	1.5kN/m^2
Live load on floors	3 kN/ m^2
Roof finish	1kN/ m^2
Floor finish	1kN/ m^2
Brick wall on internal beams	150mm
Brick wall on external beams	230mm
Density of concrete	25kN/ m^3
Density of concrete wall including plaster	20 kN/ m^3

The seismic criteria considered for this building is:

i. Response reduction factor :3, 5 and 8
ii. Importance factor :1
iii. Zone factor for zone V:0.36

Table: Preliminary Sizes of columns and beams for 16 storey building

Column		Beam	
External frames middle	300X500	Roof and floor beam (1)	300X600
Corner column	400X400	Roof and floor beam (2)	300X400
Interior column	400X500	Plinth beam (1)	300X400
		Plinth beam (2)	300X350
Slab thickness		125mm	

Loads assigned

Wall load: External wall load intensity : 11.73kN/m

Internal wall load intensity : 7.65kN/m

Parapet wall load intensity : 4.6kN/m

Slab load (Dead Slab): Intensity of slab load : 3.125kN/m

Floor finish load (Dead FF): Intensity of floor finish : 1kN/m

Roof treatment load: Intensity of roof treatment load : 1.5kN/m

Live load: Intensity of live load : 3kN/m

Live roof load: Intensity of live roof load : 1.5kN/m

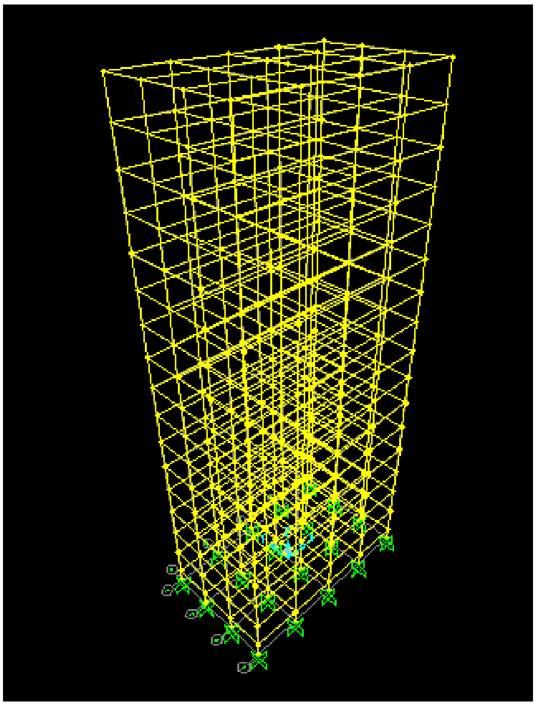


Figure 4. 3D Model of 16 story R.C. building

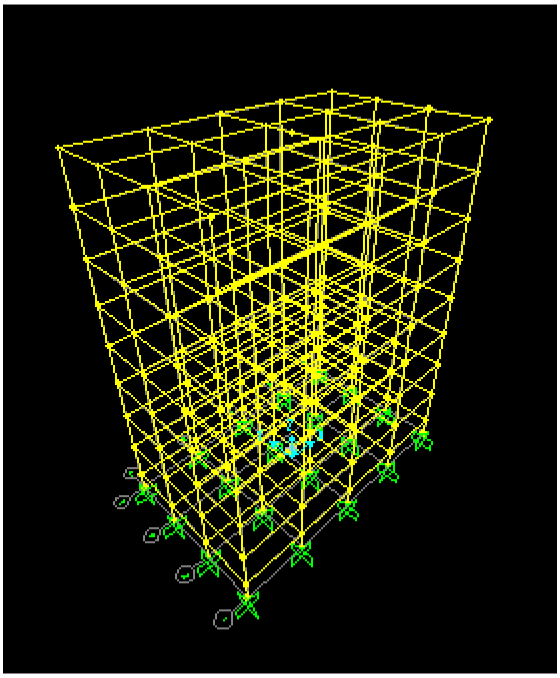


Figure 5. 3D Model of 8 story R.C. building

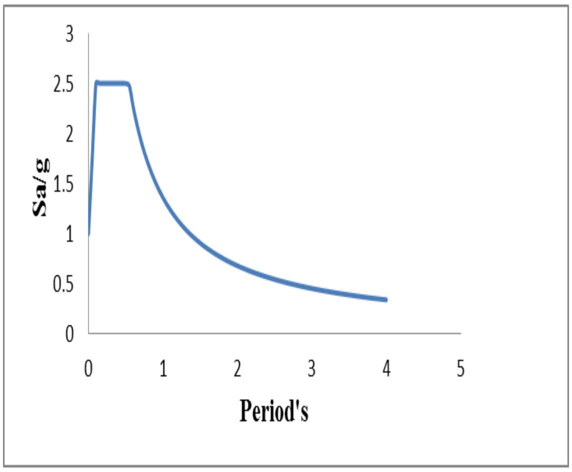


Figure 6. Response spectrum curve

ANALYSIS PROCEDURE

1. In this study, the preliminary sections chosen are given in Table 4.2 and 4.4 for eight storied and sixteen storied building.
2. Then the model is done according to the sections chosen, and loads are also assigned as given above for the model.
3. First using response reduction factor as 8 and response spectrum as shown in fig. 4.9 the linear analysis (Response spectrum) is done for model and designed using IS 456: 2000.
4. In each model some members are overstressed, so the sections for these members are changed and made sure that it is not overstressed.

5. Then the steps 2 and 3 are repeated for various response reduction factors say 3, 5, and 8 to get total of 6 models.
6. After linear analysis is done the pushover load cases are defined and auto hinges are assigned to beams and columns as per FEMA 356 for each model.
7. Nonlinear static pushover analysis is done for each model.
8. Then Pushover curves, inter-story drift has been calculated for each model and compared with graph.

5. RESULTS

Reinforced concrete building frameworks used for performance evaluations in this present study are described in chapter 4. Analyses results of R.C. building frames modeled and analyzed in chapter 4 for the assigned response spectrum are tabulated in the present chapter for the result discussion. Based on the analysis performed for three different response reduction factors to eight and sixteen storied RC Building, the results for Pushover Curve, Inter-storey drift ratio and displacement ductility are compared for various performance levels.

As explained in chapter 4 when linear analysis is done some members are overstressed. The sections are changed for those members namely Frame nos. 1, 2 , 3, 16, 17, 18, 21, 41, 61, 81, 82, 83, 26, 27, 28, 29, 46, 47, 48, 49, 66, 67, 68, 69, 31, 32, 33, 34, 51, 52, 53, 54, 71, 72, 73, 74, 96, 97, 98, 36, 46, 76 in eight storied building.

The members changed in sixteen storied building are 1, 81, 21, 22, 23, 24, 25, 383, 41, 42, 43, 44, 45, 319, 61, 62, 63, 64, 65, 335, 16, 96, 36, 32, 38 , 39, 40, 315, 56, 57, 58, 59, 60, 331, 76, 77, 78, 79, 80, 347, 11, 12, 13, 14, 15, 91, 92, 93, 94, 95, 31, 32, 33, 34, 35, 51, 52, 53, 54, 55, 71, 72, 73, 74, 75, 6, 7, 8, 9, 10, 26, 27, 28, 29, 30, 46, 47, 48, 49, 50, 66, 67, 68, 69, 70, 86, 87, 88, 89, 90.

Tables 5.1 to 5.4 correspond to base shear versus displacement and Table 5.5 and 5.6 corresponds to inter-storey drift ratio of eight and sixteen storey reinforced concrete building frame. Figures 5.1 to 5.4 corresponds pushover curve and Figures 5.5 to 5.8 corresponds inter-storey drift ratio for 8 & 16 storey reinforced concrete building frame.

Result Discussions

The fact that ductility of the structure has major contribution to response reduction factor which highlights the importance of critical consideration of structural ductility in the seismic analysis process of the structure.

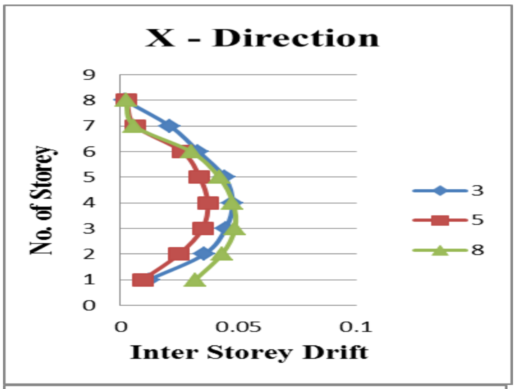
The check for inter-storey ratios for each model(as per the guidelines by FEMA-273), makes it meaningful so that the inter-storey drift is not limited to a value only at design load level and thus, it need not depend upon the ductility class of the structure.

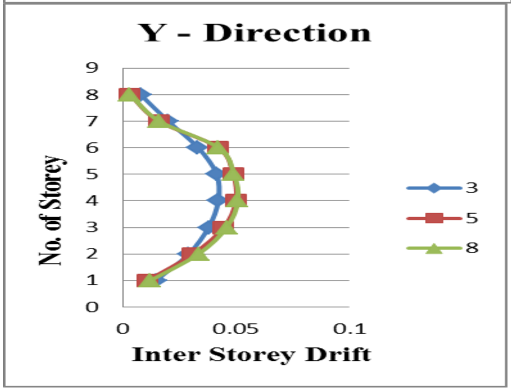
The evaluation factor like displacement ductility justify the ductile detailing of the structure as every parameter associated with it is critically evaluated for the seismic behaviour in the present study.

The determination of plastic rotations and the type of hinge formation for each performance level and their potential locations provides a useful input for providing special confining reinforcement in the structural members. The accuracy of these will depend upon the accuracy of modelling. Hence, it is necessary to establish proper guidelines or methodology for modelling in the respective seismic code, which is the limitation of present Indian seismic code, IS 1893-2002.

In the present study, the possible performance based design methodology was described by consideration of limited variable parameters. It is because of the limitation of the performance evaluation parameters in the present Indian seismic code, so some of the guidelines given by FEMA-273 are followed. To incorporate the performance based seismic design approach in the Indian seismic codes, a comprehensive study is needed to decide such performance parameters which will suit the current design and construction practices in India.

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 above mentioned method.





REFERENCES

1. CEN 1995, Eurocode 8: Earthquake Resistant Design of Structures - Part 1: General Rules, ENV1998-1, Parts 1-3, CEN, Brussels, Belgium.
2. 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.
3. 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.
4. ICC, 2001, International Performance Code for Buildings and Facilities, International Code Council, Whittier, California.
5. ATC, 1997a, 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.
6. SEAOC, 1995, Vision 2000: Performance-Based Seismic Engineering of Buildings, Structural Engineers Association of California, Sacramento, California.
7. Bertero VV. 1997, Performance-based seismic engineering: a critical review of proposed guidelines. In: Proceedings of the International Workshop on Seismic Design Methodologies for the Next Generation of Codes. Bled/Slovenia.
8. Zou XK & Chan CM. 2005. An optimal resizing technique for seismic drift design of concrete buildings subjected to response spectrum and time history loadings. Computers & Structures Volume 83, Issues 19-20, July 2005, Pages 1689-1704.
9. Xue Q, Chia-Wei Wu, Cheng-Chung Chen, Kuo-Ching Chen, 2007, Civil and Hydraulic Engineering Research Center, Sinotech Engineering Consultants Inc., Taiwan, The draft code for performance-based seismic design of buildings in Taiwan.
10. Computers and Structures SAP2000: Three Dimensional Static and Dynamic Finite Element Analysis and Design of Structures‖, Computers and Structures Inc., Berkeley, California, U.S.A.
11. Xue Q. 2001. A direct displacement-based seismic design procedure of inelastic structures. Engineering Structures; 23(11):1453–1460.
12. Mander J.B., 2001, Future directions in seismic design and performance-based
13. Magazine: Structuremag A Joint Publication of NCSEA/ CASE/ SEI, June, 2008, Performance-Based Design with Application to Seismic Hazard
14. Borzi, B. and Elnashai, A.S., “Refined Force Reduction Factors for SeismicDesign” Engineering Structures, 22, 2000.
15. IS 456. (2000). Plain reinforced concrete-code of practice, Bureau of Indian Standards, New Delhi, India.
16. IS 1893-Part1. (2002). Part I: Criteria for earthquake resistant design of structures - General provisions and buildings, Bureau of Indian Standards, New Delhi, India.