

## СЕЙСМОСТОЙКОСТЬ СООРУЖЕНИЙ SEISMIC RESISTANCE

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RESEARCH PAPER

### Performance-Based Seismic Design for buildings

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#### Abstract

Structures are designed using current seismic design codes which are mostly based on Force-Based Design approach. **The aim of the work** is to implement the Performance-Based Seismic Design (PBSD) approach in concrete buildings. PBSD, which is a new concept in seismic design of structures, is a reliable approach capable of providing more detailed information on the performance levels of both structural and non-structural elements. **Methods.** In this study Performance-Based Seismic Design has been utilized on reinforced concrete irregular frame. In order to do this pushover analysis was done. Story drift ratios were chosen as deformation limits to define the performance levels for specific earthquake hazard levels. **The results** of this study show that Performance-Based Seismic Design gives a structure with better seismic load carrying capacity, thereby achieving the objective of performance as well as economy. It is also possible to conclude that PBSD obtained by above procedure satisfies the acceptance criteria for immediate occupancy and life safety limit states for various intensities of earthquakes.

**Keywords:** Performance-Based Seismic Design (PBSD), pushover analysis, example building

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### Introduction

Viewed through the historical prism of the past 100 years, seismic structural design can be seen to have been in constant evolution – much more so than design for other load cases or actions such as gravity, wind, traffic, etc. Initially, following structural damage in the seminal earthquakes of the early 20<sup>th</sup> century (Kanto, Long Beach, Napier), seismic attack was per-

ceived in terms of simple mass-proportional lateral forces, resisted by elastic structural action. In the 1940's and 50's the influence of structural period in modifying the intensity of the inertia forces started to be incorporated into structural design, but structural analysis was still based on elastic structural response. Ductility considerations were introduced in the 1960's and 70's as a consequence of the experimental and empirical evidence that well detailed structures could survive levels of ground shaking capable of inducing inertia forces many times larger than those predicted by elastic analysis. Predicted performance came to be assessed by ultimate strength considerations, using force levels reduced from the elastic values by somewhat arbitrary force-reduction factors, that differed markedly between the design codes of different seismically-active countries. Gradually this led to a fur-

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ther realization, in the 1980's and 90's that strength was important, but only in that it helped to reduce displacements or strains, which can be directly related

to damage potential, and that the proper definition of structural vulnerability should hence be related to deformations, not strength [1].

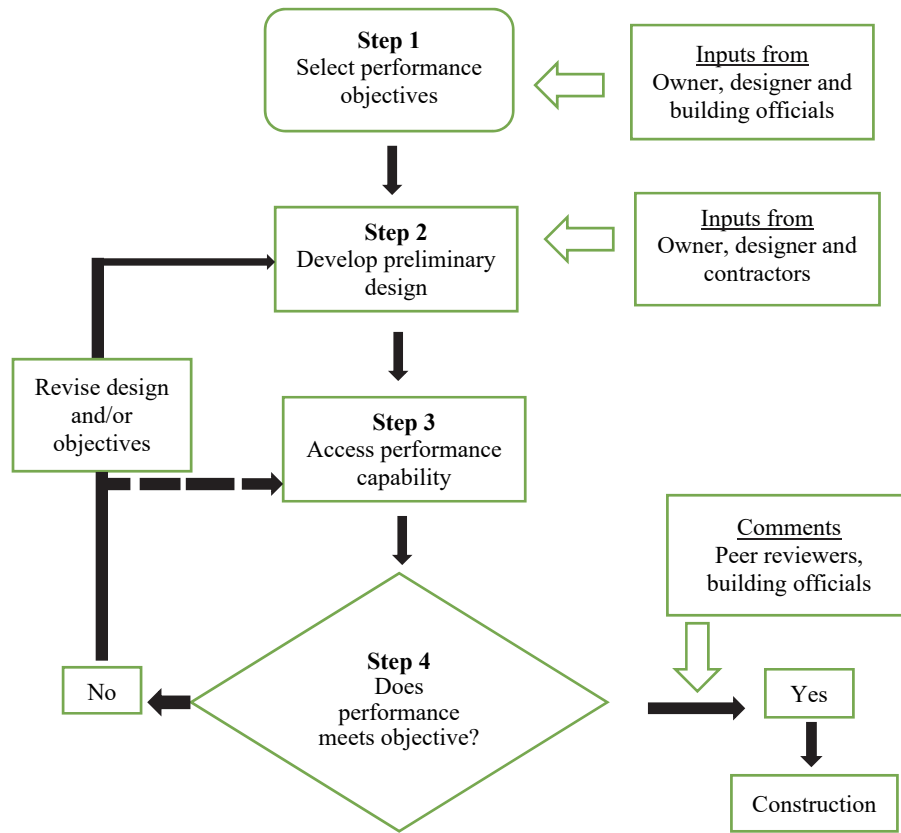


Figure 1. Performance-Based Seismic Design flow diagram [2]

Performance-Based Seismic Design (PBSD) is a generalized design philosophy in which design criteria are expressed in terms of achieving stated performance objectives when the structure is subjected to the stated levels of seismic hazard. PBSD permits the design and construction of buildings with a realistic and reliable understanding of the risk to life, occupancy, and economic loss that may occur because of future seismic events. PBSD is an iterative process, which begins with the selection of performance objectives (that are defined by the owners, designers, and building officials), followed by the development of a preliminary design (considering stated set of performance objectives), an assessment of whether the design meets the performance objectives, and finally redesign and reassessment, if required, until the desired performance level is achieved. The methodology provides a framework for determining the levels of safety and property protection, and the cost acceptable to owner, designer, and building officials for the project according to the specific project requirement [2].

*PBSD procedure:*

- Generally, a team of decision makers, including the building owner, design professionals, and building officials, will participate in the selection of performance objectives for a building.
- Once the performance objectives are set, a series of simulations (analyses of building response to loading) are performed to estimate the probable performance of the building under various design scenario events.
- If the simulated performance meets or exceeds the performance objectives, the design is complete otherwise it has to be redesigned. Figure 1 displays the flowchart representing key steps in the PBSD procedure.

**1. Methods of analysis**

Generally, for analyzing the structure the following analysis methods are used depending upon the requirements [3]: linear static procedure, linear dynamic pro-

cedure, nonlinear static procedure (pushover analysis, capacity spectrum method), nonlinear dynamic procedure (time history analysis).

Pushover analysis is the one, which is suitable for the performance based seismic design, because elastic analyses are insufficient, therefore they cannot realistically predict the force and deformation distributions after the initiation of damage in the building. Inelastic analytical procedures become necessary to identify the modes of failure and the potential for progressive collapse.

## 2. Evaluation of Performance-Based Design

The essential difference between the design of new buildings and the evaluation of existing buildings is the point of view. In design, the objective is to create a new building, which can resist the expected forces (horizontal and vertical) with an appropriate safety margin. Starting from a structural model of the building and the expected applied forces the required sections of the structural elements have to be determined for a chosen material. It is common practice to choose a slightly conservative model, i.e. to neglect the positive influence of some elements, firstly to simplify the model and secondly to be on the safe side. Also, the material strength is usually multiplied by a certain strength reduction factor; whereas the expected applied forces are enhanced to take into account uncertainties [4].

The choice of the strength reduction factors and the design forces are governed by the aim for economic optimization, however they are usually chosen to keep the risk of damage extremely low, i.e. in building design this compares with an accepted annual probability for achieving the ultimate capacity of about 0.01%. In earthquake engineering a rational design becomes more important accepting a higher risk of damage [5; 6].

Here the annual probability for achieving the ultimate capacity can be as high as 1 to 3%. In evaluation the objective is to determine how an existing building will respond to given forces. This corresponds to an analysis of a building structure where the structural elements, the materials and the dead loads are given. It is not desired to calculate a worst-case scenario by choosing a conservative model and making conservative assumptions on the material properties but to assess the most probable behavior of the building subjected to the applied action. Thus, the real material properties and the real loading have to be taken without any safety factors as these would falsify the results. Also the model should be as close as possible to

reality taking into account all structural elements that help to support the applied forces.

The evaluation of existing buildings plays an important role in earthquake evaluation projects where the risk of damage in a certain area is estimated in order to decide on appropriate risk reduction strategies.

## 3. Development of Performance-Based Earthquake Engineering

Seismic loading provisions in the existing building codes focus on the minimum lateral seismic forces for which the building must be designed, but don't explicitly incorporate the demand and response characteristics. However, the specifications of the lateral forces alone is not enough to ensure the desired level of protection in a building when subjected to expected earthquakes of different intensities [6].

Experience shows that once an approach and the corresponding procedures are introduced in a standard and code, it is very difficult and time demanding to make any changes. It is believed that before any of the so-called simplified approaches for Performance-Based Seismic Design and their corresponding methodologies are implemented in a building code, they should be thoroughly calibrated. The question then is, calibrate against what? There is no doubt that it would be ideal to calibrate them using the most sophisticated and reliable approach and procedure for Performance-Based Seismic Design that can be developed. Starting about 1990, the international design community began to be interested in the development of performance-based design concepts. Whereas current building code provisions are prescriptive in nature and require that buildings be designed with minimum specified strength and stiffness, performance based procedures permit the designer to directly demonstrate that a design is capable of meeting certain standard performance objectives, independent of meeting prescriptive strength and stiffness criteria [5–7].

Documents published by SEAOC (1995, 1996, 1999) (Structural Engineers Association of California, USA), ATC-40 (1996) (Applied Technology Council, USA) [16], FEMA-273, 274 (1997), FEMA-356 (2000), FEMA-350 (2000) (Federal Emergency Management Agency, USA) have given guidelines regarding how to apply the concept of PBSB to new and existing constructions. Furthermore, FEMA-302, 303 (1997) and FEMA-368 (2001) cover the 'NEHRP Recommended Provisions for Seismic Regulations for Buildings and other Structures' (National Earthquake Hazards Reduction Program, USA) and recent codes such as ICC (2000 and 2003) (International Code Council) and NFPA 5000 (2003) (National Fire Protection Associa-

tion, USA) contain provisions that permit use of the Performance-Based Seismic Design concept.

The above publications have contributed significantly toward a better understanding of what performance based seismic design and particularly PBSO are, and already some of the guidelines and particularly the ICC (2000) have provided specific quantification of the different Performance-Based Seismic Design Objectives (PBSO), and provisions for the application of PBSO concept.

*SEAOC Vision 2000 (Structural Engineers Association of California, USA)*. A promising approach toward the above development has been proposed by the Vision 2000 Committee of the structural Engineers Association of California (SEAOC) in 1995 in its report entitled “Performance-Based Seismic Engineering of Buildings” and which will be denominated as the “Performance-Based Seismic Engineering” (PBSE), although it is also called “Performance-Based Earthquake Engineering” (PBEE). The above report presents a conceptual framework for PBSE, as well as the different methodologies that have been proposed for the application of such framework to the design, construction, occupancy and maintenance, with particular emphasis on the design that has been denominated as “Performance-Based Seismic Design” (PBSO).

#### 4. Case study

In order to develop the application conception of pushover analysis, ideal regular building will be studied. 4-story building with the following specifications is modeled as shown in Figure 2.

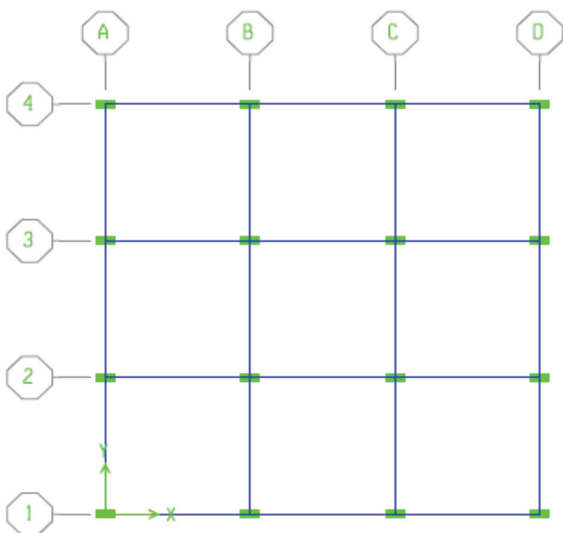


Figure 2. Plan of ideal buildings

A reinforcement concrete with Structural Frame System building with square plan 12×12 m is used.

The total height of the building is 3 m. All beams section are 0.45×0.2 m and all columns section are 0.5×0.2 m. 10 KN/m dead load and 10 KN/m live load applied to all beams. Default ETABS nonlinear frame hinge properties was used. Figure 3 shows the model of the 4-story building which developed by ETABS.

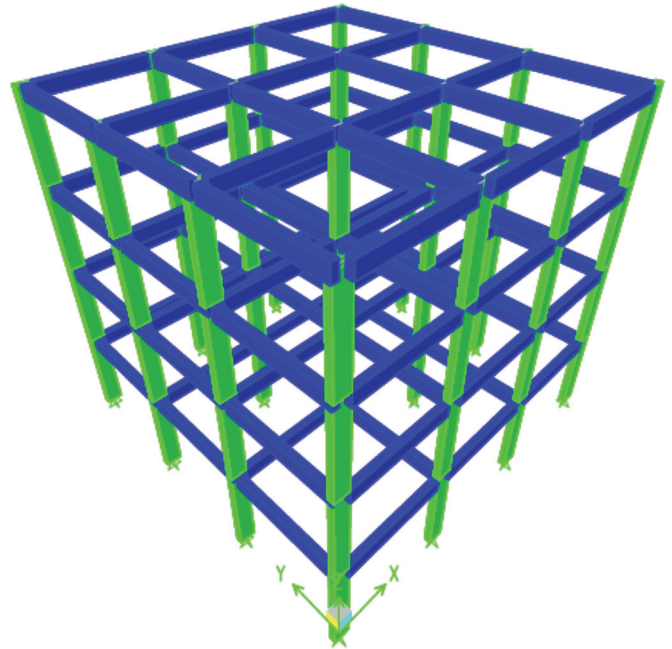


Figure 3. ETABS model of first ideal building

The building analyzed under the following cases: static linear analysis for dead, live, earthquake loads; static nonlinear analysis for dead load; and static nonlinear (pushover) analysis for lateral forces starts from the static nonlinear analysis for dead load. Lateral forces apply by ground acceleration for both sides (X, Y).

Results show that y direction is the critical direction, which reasoned by small dimension of columns section in this direction. From the static linear analysis results, base shear  $V = 190.14$  KN.

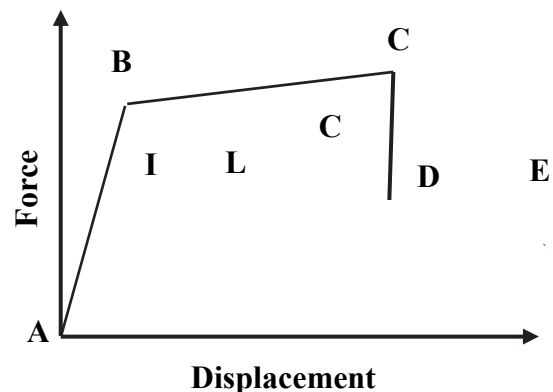


Figure 4. Load – deformation curve

Under incrementally increasing loads some elements may yield sequentially. Consequently, at each event, the structures experiences a stiffness change as shown in Figure 4, where IO, LS and CP stand for immediate occupancy, life safety and collapse prevention respectively.

ETABS results develop pushover curves show the resultant base shear vs. monitored displacement as Figure 5.

Results show that pushover acceleration leads to generate hinges in structure which work towards to lose the stability of the structure.

ETABS identify the performance point indicated to base shear of  $V = 422.99 \text{ KN}$ , and target displacement value  $D = 0.091 \text{ m}$ .

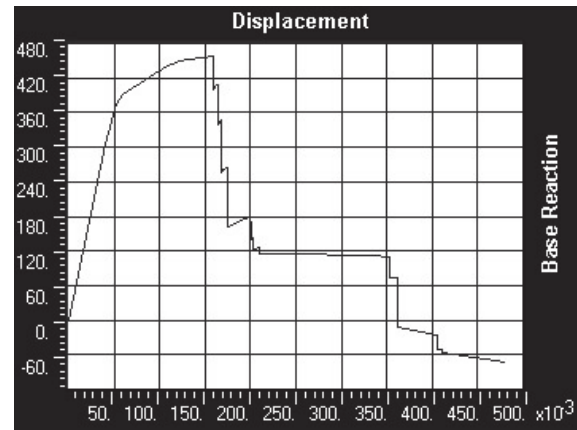


Figure 5. ETABS output of pushover curve (resultant base shear (KN) vs. monitored displacement [m])

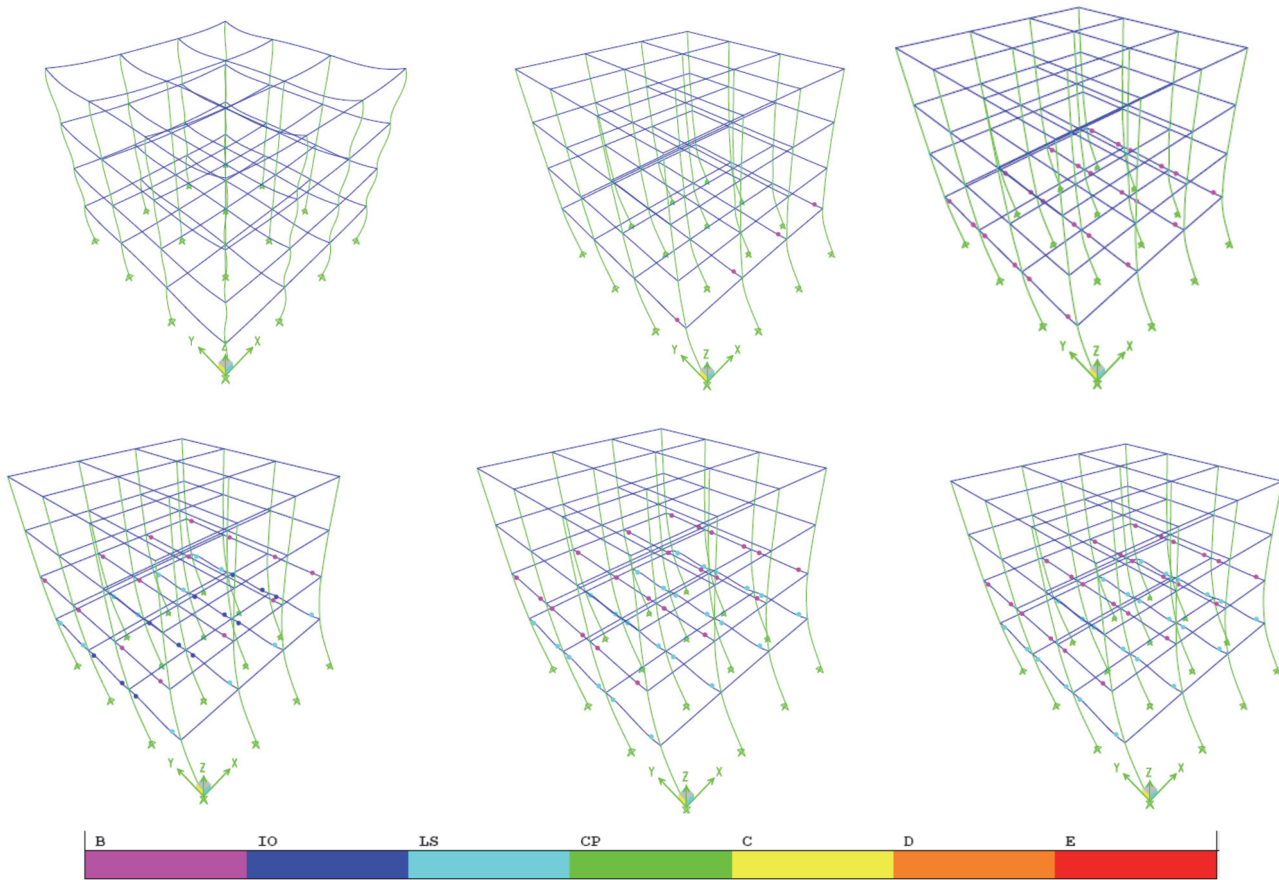


Figure 6. First six steps of pushover analysis and sequence of hinges formation (ETABS output)

### Conclusion

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

1) 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;

2) Performance-Based Seismic Design gives a structure with better seismic load carrying capacity, there-

by achieving the objective of performance as well as economy.

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НАУЧНАЯ СТАТЬЯ

## Сейсмическое проектирование зданий на основе эксплуатационных характеристик

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### Аннотация

Строительные конструкции, спроектированные с учетом современных норм сейсмостойкого строительства, в основном получены при применении силового метода проектирования сейсмостойких конструкций (Force-Based Design). **Цель** данного исследования – применить «характеристический метод» сейсмического проектирования (Performance-Based Seismic Design, PBSD) к бетонным строениям. Новая концепция сейсмического проектирования на основе характеристик PBSD является надежным подходом, способным обеспечить более детальную информацию об уровнях работоспособности как конструктивных, так и неструктурных элементов при землетрясении. **Методы.** В исследовании PBSD был применен к несимметричной железобетонной раме, для чего использовался нелинейный статический метод. Коэффициенты подошвы были выбраны в качестве предельных деформаций при определении характеристик для конкретных уровней сейсмической опасности. **Результаты.** Показано, что PBSD позволяет получить несущую конструкцию, более устойчивую к сейсмическим нагрузкам, таким образом повышая характеристики эффективности и экономичности. Опираясь на полученные данные, можно заключить, что сейсмический расчет на основе эксплуатационных характеристик, выполненный по описанной методике, удовлетворяет критериям безопасности жизнедеятельности при различной интенсивности землетрясений.

**Ключевые слова:** эксплуатационно-ориентированное сейсмическое проектирование, сейсмическое воздействие, эксплуатация сооружений, нелинейные статические методы, анализ толчков

### Для цитирования

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