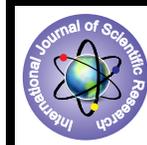


## Performance-Based Seismic Design of Structures



### Engineering

**KEYWORDS :** Seismic design, Performance based design

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### INTRODUCTION

In the recent years it has been observed that many countries are opting for seismic design with prime importance. The important reason for this need is the buildings are designed to existing design codes perform well in earthquakes with respect to safety of human life, loss of economy, usage and extent of damage to structures. The cost of repairing for these damaged structures is very high.

Conventional process of seismic design have the objectives to provide safety of life (strength & ductility) and to control damage (limit state of serviceability). The criteria for design are defined by limiting the stresses and calculation of member forces from prescribed levels of applied lateral forces. In the current design procedures (codal) there are some uncertainties regarding the seismic demand and seismic capacity of the structure.

In Performance based design the design criteria is expressed in terms of getting stated performance when the structure is subjected to stated levels of seismic hazards. The performance target may be a level of stress not to be exceeded, a displacement, a load, a limit state or a target damage state.

The idea of performance based design is not new. A limit state is a form of performance objective. The structural response in terms of displacement can be related to strain based limit state, which in turn is assumed to be related to the level of damage. For a defined performance of a structure in terms of a state of damage, strain and deformation give better indicators of damage than stresses [2]. The use of serviceability limit strains enables a consistent level of assessment to be achieved. In effect, performance based-design is a powerful approach that includes traditional methods of seismic design with significant upgrades. There have been different interpretations of what is meant by performance-based design [3-5]. The most appropriate definition is that performance-based design refers to the methodology in which structural design criteria are expressed in terms of achieving a set of performance objectives.

Performance-based design and displacement-based design have been used interchangeably. This is based on the idea that performance objectives can be related to the level of damage to the structure, which in turn can be related to displacements and drift. However, this assumption is an oversimplification since the level of damage is influenced by several other parameters such as the accumulation and distribution of structural damage, failure mode of elements and components, the number of cycles and duration of the earthquake, and the acceleration levels as in the case of secondary systems.

An attempt to develop a procedure to correlate damage of various structural systems to drift, taking into account various ground motion characteristics, was made through the use of a damage index [7]. For effective design criteria, the correlation between damage and drift must be calibrated against the performance of structures in actual earthquakes. The performance target can be any response parameter attached to a certain threshold. A single design parameter such as displacement or drift may not adequately control all performance objectives for structural and non-structural systems [8]. For example, force or stress-based criteria are more appropriate for short period structures, when trying to achieve pre-yield limit state, than displacement-based criteria.

The general methodology for performance-based design may include various approaches. In one approach, traditional force-based analysis is conducted and, after the design is completed, the deformation and damage may be estimated and checked against established displacement limits. Other approaches may start by establishing the displacement or drift associated with a certain performance, proportion the structure and then conduct the response analysis [10]. The objective of this study is to evaluate the state of development of performance-based design, present a summary of trends and challenges, and review the most important contributions in the field.

### STATE OF DEVELOPMENT

There is increasing agreement among researchers and professionals that future seismic design needs to be based on achieving multiple performance objectives. However, there are divergent viewpoints on the meaning of performance-based design and its methods of implementation. Three documents are credited with laying the foundation for performance-based design concepts: SEAOC Vision 2000 [3]; ATC 40 [4]; and FEMA273 and 274 [5]. The documents attempted to develop procedures that can be used as seismic provisions in building codes.

The goal of SEAOC Vision 2000 [3] is to develop the framework for procedures that lead to design of structures of predictable seismic performance and is able to accommodate multiple performance objectives. The document presents the concepts and addresses the performance levels for structural and non-structural systems. Five performance levels are described with specified limits of transient and permanent drift. It is suggested that capacity design principles should be applied to guide the inelastic response analysis of the structure and to designate the ductile links or forces in the lateral force resisting system. Possible design approaches include various elastic and inelastic analysis procedures such as: (1) conventional force and strength meth-

ods; (2) displacement-based design; (3) energy approaches; and (4) prescriptive design approaches.

In the Applied Technology Council ATC 40 document [4], performance-based design refers to the methodology in which structural criteria are expressed in terms of achieving a performance objective. The document is limited to concrete buildings and emphasizes the use of the capacity spectrum method. The procedure involves determining the capacity and demand spectra. To construct the capacity spectrum, the force displacement curve of a point on the structure is determined using nonlinear static (pushover) analysis. The forces and displacements are converted to spectral accelerations and spectral displacements using an equivalent SDOF system. The demands of the earthquake are defined by highly damped elastic spectra. At the performance point the seismic capacity is assumed equal to the demand, which provides an estimate of acceleration (strength) and displacement (demand). The probability of occurrence of the earthquake may be related to the risk of occurrence of the associated damage state. Not all the components of the procedure are well established. For example, an attempt was made to develop relationships between ductility and damping using perfect, hardening and softening models [8]; however, further research and development are required. Although the capacity spectrum is simple, the theoretical basis and physical interpretations are questionable [3,6].

The Federal Emergency Management Agency FEMA 273 document [5] presents a variety of performance objectives with associated probabilistic ground motions. Analysis and design methods for the multi-level performance range from linear static to inelastic time history analysis. The document defines performance levels for non-structural elements and systems and proposes drift limits for various lateral load resisting structural systems at different performance levels.

**PERFORMANCE OBJECTIVES**

Performance objectives are statements of acceptable performance of the structure. The performance target can be specified limits on any response parameter such as stresses, strains, displacements, accelerations, etc. It is appealing to express the performance objective in terms of a specific damage state or the probability of failure against a prescribed probability demand level [12]. Various documents [3-5] promote the same concepts but differ in detail and specify different performance levels. Some of the suggested performance levels can be grouped in equivalent categories as listed in Table 1.

**Table 1- Performance levels, corresponding damage state and drift limits**

Performance level [3-5]	Damage state	Drift [3]
Fully operational, Immediate occupancy	No damage	< 0.2%
Operational, Damage control, Moderate	Repairable	< 0.5%
Life safe , Damage state	Irreparable	< 1.5%
Near collapse, Limited safety, Hazard reduced	Severe	< 2.5%
Collapse	-	> 2.5%

It is recognized that drift levels associated with specific damage categories may vary considerably with the structural system and construction material. An attempt was made to define drift levels for different structural systems and materials [3]. However, more research is needed, particularly in the development of realistic and quantitative estimates of drift damage relationships. In addition, design criteria that apply to various parameters may be required by different performance objectives. To implement performance-based design, there is a need for consensus on the number and definition of performance levels, associated damage

states, and design criteria.

Structural system performance can also be quantified using a reliable damage index such as that based on displacement ductility and hysteretic energy. The performance of the contents of the structure and secondary systems may be quantified using damage indices based on different parameters such as floor acceleration levels. Performance levels are associated with earthquake hazard and design levels. Some of the proposed earthquake hazard levels are listed in Table 2.

**Table 2 - Proposed earthquake hazard levels [16]**

Earthquake frequency	Return period in years	Probability of exceedance
Frequent	43	50 % in 30 years
Occasional	72	50 % in 50 years
Rare	475	10 % in 50 years
Very rare	970	100 years
Extremely rare	2475	2 % in 50 years

There are unresolved issues concerning the need to improve our quantitative understanding of site-specific ground motion characteristics, their likely effects on structures, and some aspects of near-field effects. This research will lead to reduced uncertainties and the development of improved procedures for prediction of seismic demands.

**DESIGN EVALUATION**

Acceptable procedures for design evaluation include: (1) elastic analysis; (2) component-based elastic analysis procedure; (3) simplified nonlinear analysis methods; and (4) dynamic nonlinear time history analysis. Simplified nonlinear analysis methods are based on pushover analysis to determine capacity and on design spectrum to represent demand. Some of the recent developments include inelastic spectra, yield point spectra and the N2 method. At each design step, design evaluations may involve response parameters such as the stresses, drift and deformation, structural accelerations, ductility demand ratios, and energy dissipation in terms of demand versus capacity. Typical limiting values for these response parameters need to be established for each performance level through research including laboratory testing of specific components. The limiting values may be calibrated by analysing buildings that have experienced measurable damage in seismic events for which strong motion records are available. The most realistic verification process is the prediction of deformation and forces from inelastic time history analysis. For the analysis to be reliable and credible, it is necessary to ensure that:

- appropriate site-specific ground motion with specified hazard level can be generated with confidence
- the structural model is realistic
- the cyclic load-deformation model for each element is representative of the behaviour
- analysis procedures and interpretation tools are reliable
- identification of modes and sequence of element and component failure are also realistic

The static nonlinear pushover analysis may provide much of the needed information. In the pushover analysis, the structure is loaded with a predetermined or adaptive lateral load pattern and is pushed statically to target displacement at which performance of the structure is evaluated. The target displacements are estimates of global displacement expected due to the design earthquake corresponding to the selected performance level. Recent studies addressed limitations of the procedure [13] and the selection of lateral load distribution including adaptive techniques to account for the contribution of higher modes in long period structures [14].

## CHALLENGES AND FUTURE TRENDS

There are several challenges to be addressed before procedures for performance-based design can be agreed upon and generally accepted. These challenges are in the areas of design criteria; probabilistic characterization of capacity and performance; development of general design procedures for multi-performance and hazard levels; and analysis and modelling of the inelastic behaviour of structures for the realistic determination of transient and residual deformations. Although several documents [3-5] attempted to provide procedures that can be used as seismic provisions of building codes, these developments require much supporting research in several areas [14]. Some of the cited reasons are the current limited ability to accurately predict deformation demands and to accurately predict the inelastic building behaviour. There are several sources of uncertainties inherent in the performance-based design process. The expectation that the approach will produce structures with predictable performance may be only achieved in probabilistic terms.

### 5.1. DESIGN CRITERIA

A fundamental question in performance-based design is to validate the appropriateness of the selected performance levels, the specific parameters used to define their minimum performance, and the seismic hazard definitions. For the case of three performance levels (serviceability, damage control and life safety or collapse prevention), three corresponding structural characteristics (stiffness, strength and deformation capacity) dominate the performance as illustrated in Fig. 1.

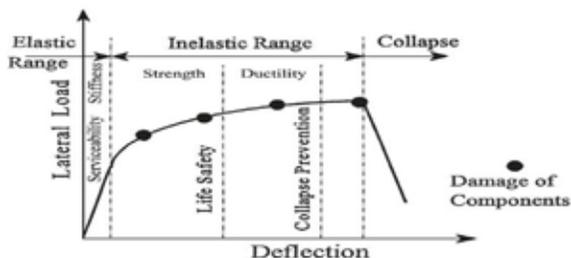


Fig. 1. Typical performance curve for the structure

If more intermediate performance levels are selected, then it becomes difficult to define which structural characteristics dominate the performance. It can be argued that different performance objectives may impose conflicting demands on strength and stiffness [13]. Much research is needed to associate the displacement or drift limits with the damage states and the stated general performance objectives. The displacements or drift limits are also functions of the structural system and its ability to deform (ductility). Design criteria may be established on the basis of observation and experimental data of deformation capacity. For example, near the collapse point, the drift limits of structural walls are different from a moment-resisting frame, which suggest that different structural systems will undergo unequal displacements. Other issues related to the damage evaluation are the quantification of the relationship between building restoration time/costs and earthquake hazard level. It is of interest to identify the damage level at which building restoration becomes impractical, which represents the state of irreparable damage.

### 5.2. DESIGN METHODOLOGY

A major challenge to performance-based design is to develop an efficient and effective general methodology for the design of structures at multiple performance and hazard levels. Improved procedures are needed for the assessment of strength and deformation capacities of structural elements, components and systems at all performance levels. Addressing multiple performance objectives will require more complex and time consuming analytical techniques to evaluate the building performance to more than one earthquake demand level.

This is expected to increase building development and design cost. These analysis procedures need to be calibrated and their adequacy verified [15]. Eventually, consideration needs to be given to the complete soil foundation structure system, all non-structural systems and components and the building contents. Appropriate acceptance criteria for site performance in terms of permissible foundation settlements, lateral spreading, liquefaction and faulting will need to be established for each performance objective.

### 5.3. DEFORMATION-CONTROLLED DESIGN

The most suitable approach to achieve the objectives of performance-based seismic design with displacement based performance objectives appears to be the deformation-controlled design approach. It is anticipated that deformation-controlled design will be implemented in future codes, both by enhancing force-based design through verification of deformation targets and by the development of direct deformation-based design procedures [10].

Computer tools are needed to predict the inelastic dynamic response of complex structures. Extensive efforts are believed to be necessary to develop versatile and robust, yet efficient, numerical standard programs to simulate seismic response of three-dimensional structures taking into account various nonlinearities. It is necessary that these tools be design oriented rather than Research oriented.

The general design methodology may have to go beyond the methods that assume a single-degree of freedom representation of the structure. This assumption results in severe restrictions on the reliability of the estimated performance. At the risk of sacrificing simplicity, it is important to obtain a good estimate of the local displacements within the structure, take higher mode effects into consideration, and account for the sequence of element damage. Nonlinear static pushover analysis coupled with new methods (other than SDOF-based spectra) to determine demand, or nonlinear inelastic dynamic analysis, may provide a more reliable prediction of the performance.

## CONCLUSIONS

The summary of this paper can be given as the future seismic designs to be based on different performance objectives and related earthquake hazards. The main advantage of performance based design is the predictable seismic performance with uniform risk. The reliability of this approach may ultimately depends on the development of explicit and quantifiable performance criteria that can be related to the calculated response parameters such as stress, strain, displacement, acceleration.

The developments in performance-based design in seismic engineering will be directed towards a general design methodology that permits performance-based design at multiple performance and hazard levels, and with due consideration given to the complete soil foundation structure system, non-structural systems and components and the building contents.

The framework for a unified seismic design approach could be based on performance-based design concepts for multiple performance levels. However, much research and development remain to be done before such a design methodology can be implemented.

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