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PERFORMANCE BASED SEISMIC DESIGN OF CONCRETE BUILDINGS STRUCTURES – BASES

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Summary: *The paper reviews literature and codes related to performance-based seismic design (PBSD) of reinforced concrete building. Performance objectives such as immediate occupancy, collapse prevention, or life-safety are used to define the state (condition) of the buildings structures following a design earthquake. Some results of the analysis and provisions of seismic codes of India, Japan, EN 1998-1, and in USA (ATC-40 and FEMA 274) are described and compared.*

Keywords: *Seismic performance, RC buildings, performance objectives, analysis, design*

1. INTRODUCTION AND DEVELOPMENT OF PBD

After several powerful earthquakes that caused major damage in countries with medium and large seismic activity it has been continuously working on improving methods of design. Thus, in recent decades instead of the force based design method a new capacity design method has been introduced for the construction of buildings which gave rise to "weak beams-strong columns" as an enabling mechanism for dissipating entered energetic seismic ground motion. After a strong earthquake in Northrige 1994 (USA) and Hyogo-ken (Kobe) in 1995 significant changes followed in order to reduce damage to the new and enhancing existing facilities.

This led to the development of performance-based engineering, whose framework explicitly addresses life-safety, reparability and functional issues (damage limitation) in building at corresponding levels of seismic motions (events). The design for seismic resistance is changing from “strength“ to “performance“ [11].

The seismic design code of buildings in Japan was revised in 2000 to implement a performance-based structural engineering framework. New verification procedures of seismic structural performance were introduced: seismic design spectra defined at bedrock and evaluation of site response that form geotechnical data of surface soil layers. In addition, equivalent linearization technique uses an equivalent single-degree-of-freedom (ESDOF) system and the response spectrum analysis, while the previous procedures are based on the estimation of the ultimate capacity for lateral loads of a building [7]. Design seismic events with return periods of approximately 500 years and

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50 years are used to evaluate the seismic performance of a life safety and damage-limitation levels, respectively. Nonlinear pushover analyses are used as verification procedure for seismic performance besides ESDOF modelling of a building and site-dependent response spectrum concepts. The prediction of the maximum structural response against earthquake motions without using time history analysis is used as well.
Performance-based seismic design (PBSD) refers to the methodology in which structural design criteria are expressed in terms of achieving a set of performance objectives. A limit state is a form of performance objective. In order to ensure the desirable performance of buildings structures the strength, stiffness and ductility/deformability should be reasonably (balanced) proportioned. Conventional methods of seismic design have the objectives to provide life safety (strength and ductility) and damage control (serviceability drift limits) [5]. The performance target can be any response parameter attached to a certain threshold.
The basic concept of Performance-based seismic design (PBSD) is to provide engineers with the capability to design buildings that have a predictable and reliable performance in earthquake [6]. The term PBSD has been widely used by the engineers and researchers since 1994 Northridge Earthquake. The International Code Council (ICC) in the United States and a performance code are available for voluntary adoption since 2001 [12]. The initial documents [4] contain a range of formal performance objectives that correspond to specific levels of seismic shaking. The level generalized with descriptions of overall damage states with titles such as *operational, immediate occupancy, life safety,* and *collapse prevention.* PBSD process (Vision 2000) [13] was developed following the Northridge event SEAOC 1995 which was more generalized than the one contained in FEMA [4].
Consequently, PBSE has been defined as consisting of the selection of design criteria, appropriate structural systems, layout, proportions, and details for structure and its non-structural components [2]. Further development of the method has been described in [9]. The document [1] is limited to concrete buildings structure and emphasizes the use of the capacity and demand spectra. Therefore, the force-displacement curve of a point on the structure is determined using nonlinear static pushover analysis.
From the above definition V. Bertero in paper [2] stresses „a process that begins with the first concept of a project and lasts throughout the life of the building. It includes selection of the performance objective, determination of site suitability, conceptual design, and preliminary design, final design, acceptability checks during design, design review, quality assurance during the construction, and maintenance during the life of the building". Each step is critical to the success of the selected performance objective. Seismic hazard parameters are: ground shaking, liquefaction, landslide, settlement and fault rupture. FEMA 273 consists of 7 key technical issues: definition of performance goals and criteria; format, enforcement and implementation; risk assessment and structural reliability; structural analysis and design; performance of structural components and systems; performance of non-structural components and systems [4].
In current code design procedures, there are uncertainties concerning the seismic demand and seismic capacity of the structure. Performance-based seismic design is a more general design philosophy in which the design criteria are expressed in terms of achieving stated performance objectives when the structure is subjected to stated levels of seismic hazard [5]. Limiting damage states expressed trough performance level are

compared with permissible values. Those values depend on strength and ductility capacity.
The paper reviews literature and codes related to performance-based seismic design of reinforced concrete building. Performance objectives are used to define the condition of the concrete buildings structures following a design seismic event. Some results of the analysis and provisions of seismic codes are described and analysed. Trends and challenges are designated.

2. PERFORMANCE OBJECTIVES

Performance-based seismic design explicitly evaluates how a building is likely to perform; given the potential hazard it is likely to experience, consider uncertainties inherent in the quantification of potential hazard and uncertainties in assessment of actual building response [1] and [6]. Identifying and assessing the performance capability of a building is an integral part of the design process. It is an iterative process that begins with the selection of performance objectives. Each performance objective is a statement of the acceptable risk of incurring specific levels of damage, and the consequential losses that occur as a result of this damage, at a specific level of seismic hazard [6].
Eurocode 8 [3] includes two performance levels: (a) local collapse endangering lives and (b) limitation of damage in structural and non-structural elements. M. Fardis in [10] compared code in US and Eurocode 8. In Europe performance levels (CEB Model Code) are associated to limit state. They are termed ultimate limit state (ULS) if they concern the safety of people or structures, or serviceability limit state (SLS) normal function and use of the structure, the comfort of occupants, or damage to property. In [3] two-level seismic design with explicit performance objectives are: (1) protection of life under a rare seismic action, by preventing collapse of the structure or parts of it and ensuring structural integrity and residual load capacity; (2) limited property loss in a frequent earthquake, via limitation of structural and non-structural damage.
The goal is to minimize earthquake –related costs to the building owner over the life of the building. This is done by considering a set of design objectives. The core of PBD method is the selection of seismic performance objectives defined as the coupling of expected performance level with expected levels of seismic ground motion. The performance levels are defined [11]:

- Fully operational (facility continues in operation with negligible damage).
- Operational (facility continues in operation with minor damage and minor disruption in nonessential services).
- Life safe (is substantially protected, damage is moderated to extensive.
- Near collapse (life safety is at risk, damage is severe, structural collapse is prevent.

A performance design objective couples expected or desired performance levels with levels of possible seismic hazards. The relationship between these performance levels and earthquake design level is summarised in Matrix (Fig. 1).
Eurocode 8, for structures of ordinary importance, recommends though the following: A seismic action for local collapse prevention – termed design seismic action – with 10% exceedance probability in 50 yrs (return period 475 yrs); a 10% in 10 yrs serviceability

earthquake for damage limitation (mean return period 95yrs). Enhanced performance of essential or large occupancy facilities is achieved not by upgrading the performance level for earthquake level, as in US codes, but by modifying the hazard level for which the performance level is pursued [10].
FEMA documents [4] deal with multi-level performance with associated probabilistic ground motion and a variety of performance objectives. Proposed earthquake hazard levels are different form Eurocode 8 and comprise earthquake frequency (frequent, occasional, rare, very rare, extremely rare) with return period in years (43, 72. 475, 970 and 2475) respectable and with probability of exceedence [4] and [5].

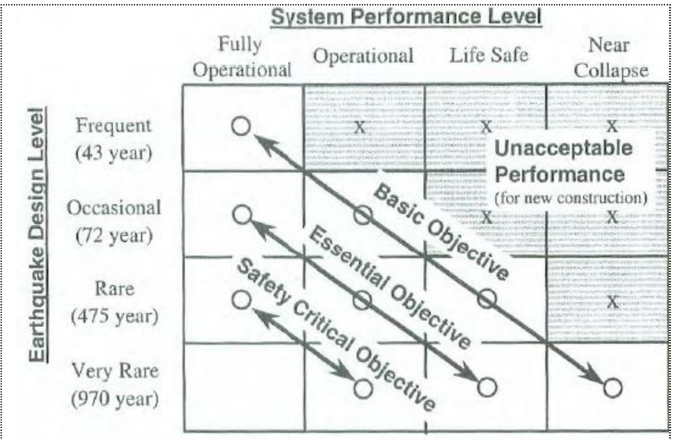

Figure 1. Performance matrix 2000 vision, after [13]

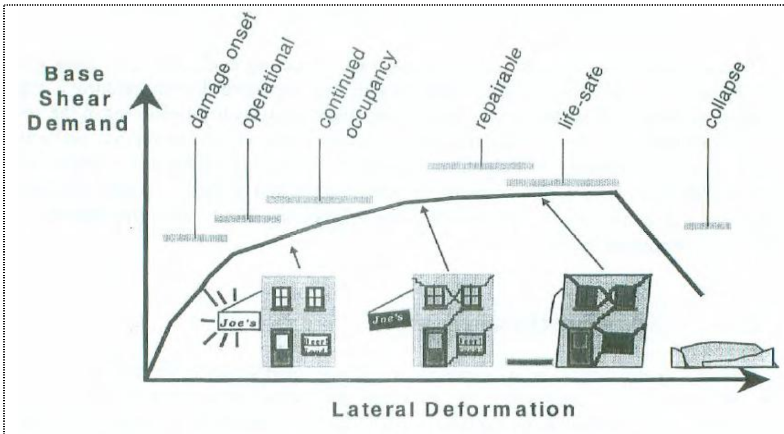

Figure 2. Performance levels relative damage [5] and (fib)

The performance target can be a specified limit on and response parameter such as stress, strains, displacements, accelerations, etc. Usually drift levels are associated with specific damage categories. Some of the subjected performance levels can group in

equivalent categories as listed in Table 1 [4] and [13]. Structural system performance can also be quantified using a reliable damage index such as that based on displacement ductility and hysteretic energy [5]. Performance levels relative damage of concrete rigid elements (walls) is shown in Figure2 (the performance includes reparability of damage).
In [3] the drift limit under the 10% in 10 years serviceability earthquake is 0.5% if non-structural elements are brittle and attached to the framing, 0.75% if they are ductile, and 1% if they are not forced to follow structural deformations or do not exist. The 1% drift limit is to protect also structural members from significant inelastic deformations under serviceability earthquake. Drift demands are calculated on the basis of the equal-displacement rule (and in concrete buildings for 50% of uncracked gross section stiffness) [10].

Table 1. Definition of performance levels from Vision-2000

Performance level	Performance description	Story drift
Fully operational	Continuous service, negligible damage	<0.2 %
Operational	Safe for occupancy, light damage, repairs for Non-essential operation	<0.5 %
Life safety	Moderate damage, life safety protection, repair may be possible but impractical	<1.5 %
Near collapse	Severe damage, collapse prevented, falling Non-structural elements	<2.5 %
Collapse		>2.5 %

3. DESIGN EVALUATION

In Japan [7] the middle level earthquake forces used in the conventional seismic design practice (case of moderate earthquakes –return period ~50years). The motion of rare earthquake (once in~500 years) is at the life-safety limit state. The level of maximum earthquake motions to be considered corresponding to the category of requirement for service life safety and it is assumed to produce the maximum possible effects on the structural safety of a building. The level of the earthquake ground motion used for the seismic design at the damage-limitation limit state should be reduced to a fifth of that for life safety. The verification procedures involve the application of the ESDOF, and the application of a nonlinear pushover analysis and modal analysis.
Analysis methods for the calculation of deformation demands and criteria of applicability [3] have adopted a fully displacement-based approach. The seismic action is given by the 5%- damped elastic response spectrum. The quantities of interest derived from it: the target displacement for nonlinear static analysis, or acceleration time-histories for nonlinear dynamic analysis. If linear analysis is applied, internal forces in “brittle” members are estimated as in “capacity-design”, i.e. all beams, columns and walls are capacity-designed against brittle-shear failure. Force capacities are estimated from expected values of material strengths derived from the available information, multiplied by a “confidence factor” greater than 1,0 that depends on the amount and reliability of information on the as-built structure. Factors defining different performance states include residual displacement as a key performance limit.

Restriction of deformation-shift is an indicator of the damage degree. It is generally accepted as damage for structural member, or drift for non-structural components. The development and verification of displacement-based analysis methods are key steps to the development of performance-based seismic design [14]. The concept of structure design which achieves specific performance defined by the strain or drift limits under specific level of seismic intensity was introduced first in New Zealand (Priestley, 1993). After that considerable research attention were paid in Europe and US. The designed structures were compatible with the concept of uniform-risk spectra.
The provisions of FEMA 273 limit global displacement of the performance level under consideration (e.g. Immediate Occupancy, Life Safety, Collapse Prevention) to that at which any single component researches its acceptability limit (Fig. 3). Global displacement limits component acceptability by using FEMA 273. The acceptability limits were developed according to FEMA 273 to identify and mitigate specific seismic deficiencies in buildings to improve anticipated performance.

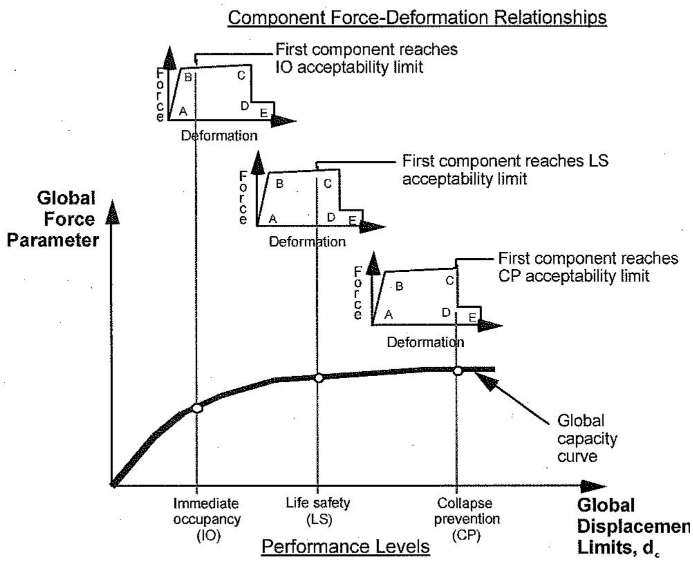

Fig. 3. Global displacement limits and component acceptability used in FEMA 273

Acceptable procedures for design evaluation include [5] and [9]: (1) elastic analysis; (2) component-based elastic analysis procedure; (3) simplified nonlinear analysis methods; and (4) dynamic nonlinear time history analysis. Simplified nonlinear analysis is based on pushover analysis to determine capacity and on design spectrum to represent demand. Among them are: the N2 method, developed by Fajfar and recommended in [3], inelastic spectra and yield point spectra. At each design step, design evaluation max involves response parameters in term of demand versus capacity. The extension of the N2 method to asymmetric building structures can be represented by 3D structural model. When taking into consideration the soil conditions and soil-structure interaction effects they are presented as accurately as possible [7].

Performance-based design approaches aimed at reduction local damage or ductility. Some authors proposed force-based design for preliminary strength determination, with inelastic time-history analyses to check inelastic deformation [2]. Capacity design principles are employed to determine required shear strength of the member and joints. The time-history analyses are also used to check storey drift, and if local inelastic deformations are within acceptable limits [11].
Force-based requires the specification of initial stiffnees of structural members. This is sometimes taken to be gross stiffness, and as a reducted stiffness to represent the influence of cracking. The linear procedure can be applied, for buildings if their height is not more than 25m. In all other cases, the modal combination method should be applied. By using a suitable modal combination, the contributions of the higher modes can be taken into account accordingly (Incremental Modal Combination Method). In the nonlinear static evaluation procedure (Pushover Analysis) idealized roads of beam and column can be considered as: concentrated plasticity with plastic hinge or nonlinear spring hinge; and distributed plasticity with finite hinge zone, fibre section and finite element (*fib: MC2010*, 2013)._The regions of potential plastic hinging should be designed according to the Section 5 of [3].
The foundation of a structure in a seismic area shall receive forces from the superstructure which are transferred to the ground without substantial permanent deformations. In general, only one foundation type shall be used for the same structure, unless the latter consists of dynamically independent units. The interaction of soil-foundations-structure depends on: foundation manner, properties of soil, foundation and structure. Characteristics of vibration caused by earthquake (frequency contents, peak acceleration, i.e.) are important and they depend on soil quality.

4. FINAL REMARKS AND CONCLUSIONS

A workshop on performance- based seismic design [10] finished with resolutions, conclusions and recommendations focused on issues important to the development of performance-based seismic design methodologies that can form the basis of practical guidelines, standards, and code implementation.
In PBSD multi-level seismic hazards are considered with an emphasis on transparency of performance objectives. Building performance is guaranteed through limited inelastic deformation in addition to strength and ductility. This method design will insure the minimum life-cycle cost of buildings [12].
The seismic performance shall be verified by comparing the predicted response values with the estimated limit value of structural members and overall buildings. The basic objective of performance-based earthquake engineering is to produce structures that respond in a more reliable manner during earthquake shaking, many engineers PBEE with overall enhanced performance [14].
Performance-based design concepts provide a suitable framework for future seismic code development. Future seismic design needs to be based on defined multiple performance objectives and associated earthquake hazard levels. That permits considerations of soil-foundation-structure systems including non-structural components [5] and [8].

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NA PERFORMANSAMA ZASNVANA SEIZMIČKA ANALIZA BETONSKIH KONSTRUKCIJA ZGRADA

Резиме: *U radu je dat kratak pregled literature i preporuka za primenu na performansama zasnovanog projektovanja (PBD) armiranobetonskih zgrada. Ciljane performanse: trenutno korišćenje, sprečavanje rušenja, ili sigurnost života se koriste za definisanje stanja konstrukcija zgrada za proračunski zemljotres. Prikazani su neki rezultati analiza i odredbi za projektovanje zasnovano na performansama iz Indije, Japana, evropskih normi i SAD (ATC-40 i FEMA 274) uz njihovo upoređenje.*

Кључне речи: *Seizmičke performase, AB zgrade, ciljne performanse, analiza, proračun*