Engineering Structures 151 (2017) 206–220

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Probabilistic comparative investigation on introduced performance-based seismic design and assessment criteria

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ARTICLE INFO

Article history:
Received 16 May 2017
Revised 10 August 2017
Accepted 14 August 2017

Keywords:
Performance-based seismic design
Design criteria
Probability-based seismic design
Reliability of structures

ABSTRACT

Despite all valuable progresses resulted by modern seismic design approaches from reducing fatalities to prevent catastrophic failures, still higher demands are imposed by society. Therefore, another generation of methodologies so-called Performance-Based Seismic Design (PBSD) was introduced. Satisfying all objectives of this method requires developing precise predicting tools and introducing reliable thresholds. These criteria not only should represent structural/non-structural damage states at desired hazard level, but also should strongly correlate with economic aspects, residence safety and functionality. In this regard, a variety of recommendations were proposed in the literature which can be classified into two general groups, i.e. at section/component level (local) or at story/building level (global). In this article, the priority of these two groups regarding each other, their relation and reliability of proposed recommendations are investigated. In this regard, diversity of outcomes related to the employed analysis method, type of the subjected ground motion record, building's height and desired performance level is reported. On the other hand, key parameters such as the influence of allowed percentage of elements to surpass from local limits on maximum experienced inter-story drift and amount of reserved capacity at components when global criteria controls the performance are investigated. Later, analytical approaches are followed to extract global limits and compare with those from the literature. Finally, the probability of exceeding local threshold at any desired inter-story drift/performance level and their safety indices is studied. In this regard, previously obtained outcomes and conventional safety levels are used to evaluate reliability of presented conclusions. Considering all, it is concluded that the global criteria controls performance of the building at all levels; but using local thresholds on higher levels may lead to less conservative designs. Therefore, it seems essential for global thresholds to be revised in development of PBSD to make it more compatible with its objectives.

1. Introduction

Conventional seismic design provisions follow capacity-based approaches by providing required strength and ductility. Their philosophy stands on minimizing occurrence of major damages in frequent earthquakes and prevention of fatalities in rare events. In addition to significant advancements in securing lives and preserving man-made facilities, contemporary regulations seem to be incapable of satisfying induced diverging expectations, coming from economical point of view and also modern life standards. On the other hand, it was shown that the buildings designed based on current seismic design regulations may experience high damages even in cases subjected to their target hazard level [1]. Previously experienced earthquakes have approved some of these deficiencies, such as undergoing large inelastic deformations, inaccurate prediction of prescribed lateral forces, ambiguous performance under different earthquake levels, considering strength as synonyms of stiffness and undesirable damages (both structural and non-structural components). Moreover, large uncertainties coming from different sources (such as ground motion or characteristics of the building) arise in the current seismic designs which they are still not incorporated or implicitly considered [2–7]. Therefore, major studies have begun worldwide to shift ongoing seismic design methods to the one so-called as Performance-Based Seismic Design (PBSD).

The principal objective of PBSD is enabling engineers with more reliable tools to predict future earthquakes, response of buildings, their influences and introducing appropriate thresholds for multi-

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http://dx.doi.org/10.1016/j.engstruct.2017.08.029
0141-0296/

Nomenclature

α_c	post-capping stiffness ratio
α_s	hardening stiffness ratio
β	reliability (safety) index
ϵ_{su}	steel strain at ultimate strength
η	ratio of chord rotation to corresponding threshold value at desired performance limit
λ	the mean annual frequency of decision variable exceeding desired value
Φ	standard normal distribution function
ρ_{sm}	required confinement proposed by the code
ρ_s	existing confinement reinforcement
ρ_v	volumetric ratio of transverse reinforcement
θ	local criteria value at desired performance level
$\theta_{cap.pl}$	plastic chord rotation from yield point to the cap
θ_c	chord rotation at peak capacity
θ_{pc}	post-capping plastic-rotation capacity
θ_y	chord rotation at yielding
ξ_{DR}	design requirements-related uncertainty
ξ_{MDL}	modeling-related uncertainty
ξ_{PTR}	record-to-record uncertainty
ξ_{TD}	test data-related uncertainty
ξ_{tot}	total system uncertainty
D	global response parameter
DM	damage measure
DV	decision variable
EDP	engineering demand parameter (such as inter-story drift, and floor acceleration)
f'_{cc}	compressive strength of confined concrete
$F_R(x)$	probability of exceeding local performance criteria when the global response parameter equals as x
f_{yh}	yield strength of transverse reinforcement
$IDDR$	ratio of inelastic displacement to the ultimate inelastic displacement capacity
IM	intensity measure (characteristic parameter of probable future earthquake at site)
K_c	post-capping stiffness
K_e	initial secant stiffness up to the yield point
K_s	hardening stiffness
M_c	moment capacity
M_y	yield moment
P_f	probability of failure
P_i	total gravity load in ith story
R	local response parameter
S_a	spectral acceleration
V_i	total shear force in ith story

ple performances. Furthermore, it clears owners/stakeholders about probable financial impacts and damages in case of predefined possible risks to satisfy their needing and safety expectations [8].

First steps toward such objectives were passed by publishing FEMA-273, 274 and ATC-40 which qualitative definitions of performance and hazard levels were introduced. These guidelines focus on rehabilitating and assessment of existing buildings. These type of structures do not necessarily comply with new regulations and probably will not be as ductile as expected. On the other side, financial issues and human losses are out of their scope [9,10]. Considering all, employing these regulations for design of new buildings may lead to conservative sections. Hence, the Pacific Earthquake Engineering Research Center (PEER) developed performance assessment methodology. This procedure includes estimating Decision Variables (DVs) as a function of number of casualties, length of downtime, monetary losses or collapse, by incorporating losses, damages, response and seismic hazard analyses by means of conditional and total probability theorem as indicated in Eq. (1) [11].

$$\lambda(DV) = v(DV > dv) = \iiint G(DV|DM)|dG(DM|EDP)||dG(EDP|IM)||d\lambda(IM)| \quad (1)$$

As it is evident, PBSD faces with many obstacles before being implemented in practice. Reliable prediction of probable seismic hazard, developing simplified and precise analysis tools and proposing design acceptance criteria -at the section, component and building level- corresponding to each desired performance level are some of those. These limit states must have strong theoretical, experimental and experienced-based backgrounds with high compatibility to financial and occupant safety concerns [12,13]. In this regard, two categories of criteria i.e. at component (hereafter denoted as local) and building/story (hereafter denoted as global) level are defined in the literature. Some of them will be discussed later in this article. Reviewing available references highlights their silence about the relation between these two types of thresholds. It is worthwhile to note that some of these proposed criteria (especially those global ones) have not been revised for new concepts and have been directly transferred to PBSD regulations from conventional approaches. Therefore, their blind usage may lead to designs with deficiencies same as those of force-based approaches. In other words, this issue may cause missing one of the aforementioned aims of PBSD or loosing desired safety. Thus, detailed investigations are required to evaluate efficiency and applicability of PBSD criteria before being implemented in design regulations; whereas this is not precisely explored in the literature.

In this regard, the relation between different proposed local and global criteria is investigated in the current article. First, different performance-based design or assessment criteria are collected from the literature. They are employed to check the performance of low to mid-rise moment resisting RC frames. This objective is achieved by performing pushover, nonlinear time-history and incremental dynamic analyses. In the following, the results are post-processed with two different approaches, i.e. when the performance is controlled by local criteria and in cases which global threshold controls it. In each of these cases the experienced response representing other criteria are recorded. Finally, these outcomes are used to investigate the relation between local and global criteria. This relation is also investigated using probabilistic- and reliability-based methods. Furthermore, the influence of different parameters such as height of the building and number of elements exceeding desired performance threshold are studied.

2. Review on performance-based seismic design criteria

Currently, two different groups of seismic performance criteria are introduced in the literature. The first field includes seismic assessment of existing buildings (e.g. FEMA-356, ASCE-41, FEMA-273, ATC-40, Turkish rehabilitation code and NZSEE instructors) and the second one are those have been proposed for seismic design of new buildings (e.g. recommendations of Priestley et al., draft code of Taiwan and Tall Buildings Initiative (TBI – guidelines for performance-based seismic design of tall buildings)).