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Application of endurance time method in performance-based optimum design of structures

Mohammad Ch. Basim *, Homayoon E. Estekanchi

Sharif University of Technology, Tehran, Iran

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A B S T R A C T

In this research, application of the Endurance Time (ET) method in performance-based design of structures with and without consideration of uncertainties is investigated and a practical optimum design procedure is proposed. The ET method is used as an analytical assessment tool because of its capabilities in response estimation with an affordable computational demand. In the first step of the proposed method, ET analysis is implemented in a multi-objective optimum design procedure in order to achieve a set of Pareto optimal designs. Optimization is conducted with respect to initial cost and expected life cycle cost using a deterministic approach. For each design alternative the median damages due to probable earthquakes in its life time is estimated by the ET method, and the expected cost of earthquake consequences is calculated using Life Cycle Cost Analysis (LCCA). In the next step, a comprehensive performance assessment is carried out on a candidate optimal design considering inherent uncertainties in the framework of FEMA-P-58. It is also proposed to use the ET method as the response assessment tool in this framework. Expected damage costs, fatalities and probability of collapse are estimated using a Monte Carlo approach to account for uncertainties. The candidate design can then be altered to another optimal design from the Pareto set in the case of undesirable performance. The advantages and shortcomings of the method are investigated by comparing the results from the ET method and recommended procedure using a suite of ground motions. The results provide a pathway towards practical use of the ET analysis method in state of the art performance-based design and probabilistic estimation of losses.

1. Introduction

Performance-Based Design (PBD) of structures has been recognized as an effective approach to limit or reduce earthquake losses to acceptable levels. PBD makes it possible for design professionals, owners and stakeholders to cooperate in identification of the desired building performance characteristics. In the first generations of performance-based design procedures, the concept of performance was defined in terms of discrete levels of damage in a number of hazard intensity levels. However, some limitations in these early procedures have motivated researchers to plan for more improved methodologies in the Next-Generation Performance-Based Seismic Design [1].

Many sources of uncertainties exist in the nature of earthquake hazards and their consequences. These uncertainties vary from uncertainties in ground motion and seismic demand parameters to uncertainties in structural capacity parameters and modeling assumptions. If these uncertainties are not considered, large variability in seismic performance may affect the reliability and safety of the achieved design. Therefore, a migration is necessary from deterministic procedures towards reliability based design criteria. As well, one of the major goals of PBD is to provide meaningful measures of performance for decision makers and owners to facilitate their discussions with design professionals on the development of design options. For this purpose, realistic understandings of the probable risk of casualties, occupancy interruption, and economic losses are required. The most recent generation of performance based design provided by FEMA-P-58 [2] accounts for the uncertainties inherent in factors affecting seismic performance and defines more sensible performance measures. However, the method involves repetitive response estimation analyses at multiple hazard levels and can hardly be implemented in initial design stages.

Numerous studies have been conducted on uncertainty sources and their corresponding effects on structural responses. Among many others, Kwon and Elnashai [3] probed the effects of ground

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* Corresponding author at: Department of Civil Engineering, Sharif University of Technology, P.O. Box 11155-9313, Azadi Ave, Tehran, Iran. Tel.: +98 9125764730; fax: +98 2166014828.

E-mail addresses: mch_basim@mehr.sharif.edu (M.Ch. Basim), stkanchi@sharif.edu (H.E. Estekanchi).

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motion input and material variability on the vulnerability of structures, indicating more significant effects of randomness in strong-motion characteristics than in material response parameters. On the other hand, some researches have emphasized uncertainties related to the parameters of the structural model. Jalayer et al. [4] tried to characterize the uncertainties in material properties and in construction details and to propagate them to estimation of the structural performance. Liel et al. [5] and also Ibarra and Krawinkler [6] showed that uncertainties in structural parameters can have more significant effects on collapse performance of structures. A more detailed review of the recent literature on reliability assessment can be found in a work by Kazantzi et al. [7]. They examined the effects of the model parameter uncertainties on the seismic performance of a steel frame, revealing that the consideration of model parameter uncertainties can be safely ignored for global behavior of the frame. However, they showed significant effects of these uncertainties on local component damages and loss assessment. Therefore, there is a general agreement on the need for probabilistic evaluation of performance for damage or loss assessment, the latter requiring a comprehensive study of both local and global damages and also collapse capacity of the structure.

In order to describe performance measures in a vocabulary that can be better understood by decision makers, the consequences of damages may be expressed in terms of potential casualties, occupancy interruption, and induced repair costs. Economic measures can provide useful information for many decisions associated with real property. In order to directly incorporate the economic concerns in design or decision making process, Life Cycle Cost Analysis (LCCA) has been applied in structural engineering. LCCA is used to evaluate the performance of structures during their life span in economic terms by estimating costs due to future earthquakes [8,9]. This analysis can be accompanied by an optimization algorithm to achieve a design with the least total cost [10].

The basic procedure in performance-based design involves development of a preliminary design and then revising the design until the satisfactory performance level is reached. This procedure can be automated by optimization methods to achieve optimal structural designs [11,12]. Commonly, in single objective structural optimization problems, initial cost is considered as the only objective whereas building code and other project requirements are treated as constraints. A more comprehensive decision making study on design alternatives may be achieved by the use of multi-objective optimization procedures and resultant Pareto optimal design alternatives. Multi-objective optimum seismic design has been utilized by various researchers [13–16]. Life cycle and initial costs are introduced as optimization objectives in most of these researches. Rojas et al. [17] used a multi-objective optimization procedure to minimize both weight and expected annual loss for a steel framing system assuming exposure to three seismic hazard levels. Liu et al. [18] used a robust performance based design approach for a multi-objective optimization using genetic algorithm subjected to uncertainties and provided a set of Pareto optimal designs. Commonly, evolutionary algorithms are employed to solve structural optimization problems owing to their complexity [16]. In this study, NSGA-II [19] is used for solving the defined multi-objective optimization problem. This multi-objective genetic algorithm is a population based optimization method that has appropriate capability to identify Pareto optimal designs with a computationally efficient procedure.

One of the most important obstacles in optimum design procedures is accurate response estimation with an acceptable computational effort. Loss assessments require calculation of structural responses in multiple hazard levels. A reliable performance assessment would be attained by response-history based analyses and considering a realistic numerical model of the structure. Simplified analysis methods that have been introduced to be used in optimization procedures usually involve considerable loss of accuracy.

In this study, the endurance time (ET) method is applied to estimate the response of the structure at various hazard intensity levels [20]. In the ET method, the structure which is to be assessed is analyzed subjected to specially designed intensifying acceleration functions instead of a set of progressively scaled up ground motion records, and its performance is assessed based on its response at different excitation levels in a single response-history analysis. Therefore, the required computational demand is considerably reduced while the major benefits of a complete response history analysis, i.e., accuracy and insensitivity to model complexity, are maintained [21]. Application of the ET method in loss assessment and LCC analysis is formulated in a work by Basim and Estekanchi [10].

A two-stage procedure is proposed here to practically use the reliability based performance measures in the optimum design of structures utilizing the potential benefits of the ET method:

First stage: The procedure begins with a multi-objective optimization problem to achieve a set of Pareto optimal designs with respect to initial and expected life cycle cost. A deterministic approach with a relatively simple cost model is used in the first stage for the sake of computational efficiency. The ET method, as a dynamic response history procedure, is used to estimate demand parameters as a continuous function of intensity measure in a specified range of interest. The proposed procedure is used in optimum design of an example five story steel frame subject to ANSI/AISC360-10 LRFD design recommendations. The reduced computational effort in ET analyses provides the applicability of optimization procedures in the first design stage (i.e., selecting design sections). The median damages due to probable earthquakes in the life time of the structure is estimated by the ET method, and the expected costs of earthquake consequences are calculated using LCCA.

Second stage: In the next step, a detailed performance model of the building under study is constructed, and a reliability based performance assessment is performed on a number of selected optimal designs considering inherent uncertainties in the framework of FEMA-P-58. The main goal in the second stage is to perform a comprehensive study on the performance of the candidate designs and select the one that best matches the design objectives. In a case where the candidate alternatives fail to meet the desired objectives another alternative optimum design with better performance can be selected from the Pareto instead of blind search among too many possible designs. In this research, the assessment is carried out on a selected design alternative, and meanwhile it is proposed to use the ET method as response assessment tool in this framework. A Monte Carlo approach is used to estimate the expected damage costs, fatalities and probability of collapse considering uncertainties. Results from the ET method and from a selected suite of ground motions are compared and discussed.

2. Endurance time method (ET)

Endurance time method is a response history based procedure in which intensifying accelerograms are applied as loading functions. In this procedure, structural responses are monitored through time while the intensity of the applied dynamic loading is increasing. In these simulated acceleration functions, excitation starts with a low intensity and the excitation intensity grows gradually until structural collapse. In this way, the structural responses can be observed through the entire range of intensities [22].

Indeed, analysis time in the ET method is associated with excitation intensity. In ET analysis, the concept of acceleration response spectrum is conveniently used to characterize excitation