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Innovative seismic design optimization with reliability constraints

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A B S T R A C T

Performance-Based Design (PBD) methodologies is the contemporary trend in designing better and more economic earthquake-resistant structures where the main objective is to achieve more predictable and reliable levels of safety and operability against natural hazards. On the other hand, reliability-based optimization (RBO) methods directly account for the variability of the design parameters into the formulation of the optimization problem. The objective of this work is to incorporate PBD methodologies under seismic loading into the framework of RBO in conjunction with innovative tools for treating computational intensive problems of real-world structural systems. Two types of random variables are considered: Those which influence the level of seismic demand and those that affect the structural capacity. Reliability analysis is required for the assessment of the probabilistic constraints within the RBO formulation. The Monte Carlo Simulation (MCS) method is considered as the most reliable method for estimating the probabilities of exceedance or other statistical quantities albeit with excessive, in many cases, computational cost. First or Second Order Reliability Methods (FORM, SORM) constitute alternative approaches which require an explicit limit-state function. This type of limit-state function is not available for complex problems. In this study, in order to find the most efficient methodology for performing reliability analysis in conjunction with performance-based optimum design under seismic loading, a Neural Network approximation of the limit-state function is proposed and is combined with either MCS or with FORM approaches for handling the uncertainties. These two methodologies are applied in RBO problems with sizing and topology design variables resulting in two orders of magnitude reduction of the computational effort.

1. Introduction

In deterministic optimization problems randomness and uncertainty are considered through several safety factors introduced into the constraints of the optimization problem. On the other hand, non-deterministic performance measures are increasingly being taken into consideration in many contemporary engineering applications that involve various reliability requirements. In structural optimization, non-deterministic performance measures can be taken into account using two distinct formulations: robust design optimization (RDO) [1,2] and reliability-based design optimization (RBO) [3–5].

The modern conceptual approach to structural design under seismic loading is based on the principal that a structure should meet performance-based objectives for a number of different hazard levels, ranging from earthquakes of small intensity with small return period, to more destructive events with large return period. This approach constitutes the Performance-Based Design (PBD) concept which has been introduced in order to increase the safety against natural hazards. According to PBD the structures should be able to resist earthquakes in a quantifiable manner and to preset levels of desired possible damage. The current state of practice in performance-based engineering can be found in US guidelines such as FEMA-350 [6] and FEMA-356 [7].

The structural performance during an earthquake depends highly on a number of structural parameters which are inherently uncertain. Such parameters are, among others, the material properties, the workmanship, the hysteretic behaviour of structural members and joints. The intensity and the earthquake ground motion characteristics are also random. Furthermore, uncertainty is also involved in the analysis procedure that would be adopted and in the numerical simulation of the structure. In order to account for as many as possible of the above uncertainties, a reliability-based in conjunction with a performance-oriented approach should be considered. For earthquake engineering applications, the reliability problem can be defined as a problem of two separate types of variables, representing the demand and the capacity. This concept is adopted in the reliability-based design procedure suggested in the SAC/FEMA project [8]. The SAC/FEMA methodology allows the consideration of uncertainties on both capacity and demand. However, for the calculation of the limit-state probabilities,

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prior knowledge of the distribution and the variance of the capacity and the demand is necessary.

A limited number of studies have been published in the past, where the PBD concept is implemented in a structural optimization problem considering uncertainties. These studies are restricted to relatively small-scale structures due to the increased computational cost. Aleatory and epistemic uncertainties are introduced in a structural optimization environment by Beck et al. [9]. In the work by Wen [10], the issue of the proper consideration of the uncertainty in the demand and capacity and the balance of reliability against cost is investigated based on the minimization of the expected life-cycle cost. The concept of Performance-Based Design within the context of robust design optimization for the design of structures is examined by Lagaros and Fragiadakis [11]. In the work by Foley et al. [12] a state-of-the-art model code Performance-Based Design methodology is proposed. This design methodology is applied to multiple-objective optimization problems for single storey and multi-storey structural frameworks with fully and partially restrained connections.

Structural reliability analysis can be performed either with simulation methods, such as the Monte Carlo Simulation (MCS) method, or with other approximation methods. First and Second Order Reliability Methods (FORM, SORM) require prior knowledge of the mean and the variance of each random variable. Furthermore, these methods require a differentiable failure function. On the other hand, although the major advantage of MCS is that accurate solutions can be obtained for almost every problem, yet it requires excessive computational cost in many cases. Variance reduction techniques, such as Importance Sampling, Directional Simulation, Antithetic Variates or Adaptive Sampling, have been proposed in order to reduce the computational effort of MCS. The disadvantage of these methods is that they require prior knowledge of the behaviour of the structure in order to determine the most effective sampling region, which for many practical problems is not clearly identifiable. Recent results [13] reveal that variance reduction techniques still require significant number of the system response evaluations to estimate failure probabilities of the order less than 10^{-3}. Other recently proposed simulation methods, such as Line Sampling [13] and Subset Simulation [14], were proved to be very efficient in reducing the required sample size and the computational cost; however, their performance and ergodicity are sensitive to the values of certain parameters which are not known a priori.

The computational cost is the main barrier that prohibited the application of uncertain optimization methodologies considering earthquake loading. For the application of a computationally efficient MCS method to complex structural models it would be necessary to have an approximate knowledge of the limit-state function $g(\mathbf{x})$. Such an approximation contributes in reducing the excessive number of repeated finite element analyses required for the MCS. On the other hand, since complex structural reliability problems are characterized by the implicit nature of the limit-state functions, the implementation of FORM or SORM requires an explicit approximation of either the entire limit-state function $g(\mathbf{x})$ or of its limit-state surface $g(\mathbf{x}) = 0$ in the space of the random variables $\mathbf{x}$. The Response Surface (RS) method is customarily used for approximating the limit-state function. It was found, though, that the performance of the RS method is dependent on the experimental points required to define the limit-state function approximation due to the rigid and non-adaptive structure of the function implemented by the RS method [15,16]. Several attempts have been presented in the past where the limit-state function is estimated with a Neural Network (NN) approximation. These attempts, however, were limited to static loads [17,18]. In the present work innovative and efficient procedures for performing RBO are implemented, within the Performance-Based Design framework of FEMA-356 under seismic loading, for the design of real-world structural systems. Randomness and uncertainty are taken into consideration with two methodologies for reducing the computational cost. The methodologies are based on the Monte Carlo and the First Order Reliability Methods and exploit the Neural Network predictions of the limit-state function. Furthermore, sizing and topology design variables are incorporated into deterministic and probabilistic formulations of the optimization problem.

2. Performance-Based Design

The majority of the seismic design codes belong to the category of the prescriptive design codes, which take into consideration site selection and development of conceptual, preliminary and final design stages. According to a prescriptive design code the strength of the structure is evaluated at one limit-state, between life-safety and near collapse, using a response spectrum-based loading corresponding to one design earthquake [19]. In addition, the serviceability limit-state is usually checked in order to ensure that the structure will not deflect or vibrate excessively. On the other hand, PBD is a different approach for the seismic design of structural systems which includes, apart from the site selection and the consideration of the design stages, the performance of the building after construction in order to ensure reliable and predictable seismic performance over its life.

Prescriptive building codes do not provide acceptable levels of a building life-cycle performance, since they only include provisions aiming at ensuring adequate strength of structural members and, indirectly or implicitly, of the overall structural strength. The basic philosophy of a PBD procedure is to allow engineers to determine explicitly the seismic demands at preset performance levels by introducing design checks of a higher level. Performance-based seismic design has the following distinctive features with respect to a prescriptive design requirements: (i) Allows the owner in cooperation with the structural engineer to define the appropriate level of seismic hazard and the corresponding performance level where the seismic demand will be evaluated. (ii) The structure is designed to meet the requirements corresponding to a number of levels of seismic intensity.

2.1. Performance levels and objectives

The main part in a performance-based seismic design procedure is the definition of the performance objectives. A performance objective is defined as a given level of performance for a specific hazard level. In this study, three performance objectives corresponding to the "Enhanced Rehabilitation Objectives" of FEMA-356 [7] for buildings have been considered.

The first part in the definition of a performance objective is the selection of the level of structural performance. The following performance levels have been considered:

(i) *Operational level*: the overall damage is characterized as very light. No permanent drift is encountered, while the structure essentially retains original strength and stiffness.
(ii) *Life safety level*: the overall damage is characterized as moderate. Permanent drift is encountered but partial or total structural collapse is avoided. Gravity load bearing elements continue to function while there is no out of plane failure of the infill walls. The overall risk of life-threatening injury as a result of structural damage is expected to be low. It should be possible to repair the structure; however, for economic reasons this may not be practical.
(iii) *Collapse prevention level*: the overall damage is characterized as severe. Substantial damage has occurred to the structure, including significant degradation in the stiffness and