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Life-cycle seismic loss estimation and global sensitivity analysis based on stochastic ground motion modeling

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ABSTRACT

The assessment of seismic losses for structural systems through adoption of stochastic ground motion models for characterization of the seismic hazard is the focus of this study. An assembly-based vulnerability methodology is adopted for earthquake loss estimation that uses the nonlinear time–history response of the structure under a given excitation to estimate damages in a detailed, component level. Description of the earthquake acceleration time–history through stochastic ground motion models is considered in this context. The parameters of these models are connected to the regional seismicity characteristics (such as moment magnitude and rupture distance) through predictive relationships. Description of the uncertainty for these characteristics and for the predictive relationships, by appropriate probability distributions, leads then to quantification of the life-cycle seismic losses by its expected value. Because of the complexity of the adopted models, estimation of this expected value through stochastic simulation is suggested and techniques for improvement of computational efficiency are discussed. An innovative global sensitivity analysis is also reviewed, based on advanced stochastic sampling concepts. This analysis aims to identify the importance of each of the uncertain parameters, within the seismic hazard description, towards the overall seismic risk (life-cycle cost). The benefits in terms of detailed, versatile description of seismic risk and the computational challenges of the overall simulation-based, probabilistic framework are extensively discussed. The methodology is illustrated through application to a four-storey moment-frame concrete building for estimation of life-cycle repair cost. Emphasis is placed on the results from the sensitivity analysis for investigating the impact on the estimated repair cost of the ground motion model characteristics and of the fragility features of the different assemblies.

1. Introduction

Seismic life-cycle cost assessment requires proper integration of (i) loss-estimation methodologies for evaluating the structural performance using socioeconomic criteria, (ii) probabilistic approaches for treating the uncertainties related to the seismic hazard and to the structural behavior over the entire life-cycle of the building, as well as (iii) algorithms for efficient evaluation of the resultant multidimensional integrals ultimately quantifying seismic cost. The modeling of earthquake losses for a specific seismic event and the characterization of the earthquake hazard, describing the likelihood of occurrence of each event as well as the resultant seismic forces (in the specific format required for structural analysis, for example as ground motion time-history), constitute undoubtedly the most important components of this process. Earlier methodologies for seismic loss evaluation expressed these losses in terms of the global reliability of the structural system. Recent advances in performance-based engineering quantify more appropriately repair cost, casualties, and downtime in relation to the structural response, using fragility curves to develop such a relationship [1]. In this context, approaches have been proposed that approximately describe the nonlinear structural behavior by the static pushover response [2,3] and/or estimate earthquake losses in terms of global response characteristics [4]. Other researchers [5–7] have developed analytical tools that evaluate seismic vulnerability on a detailed, component level (such as partitions, beams and columns), using the nonlinear time–history response of the structure under a given earthquake excitation to ultimately calculate seismic damages.

This latter approach requires description of the entire ground motion time history for seismic events. The most popular methodology [8–11], to facilitate such a description relies on adoption of Intensity Measures (IMs) that represents the dominant features of the seismic excitation, and subsequent scaling/selection of ground motion records to different hazard levels (different IM values), as prescribed by a probabilistic seismic hazard analysis. These ground motions are taken to represent samples of possible future ground motions for each hazard level (a limited number of such

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levels is typically considered). To reduce computational burden a small number of ground motions is used (for each level) and some probability distributions is fitted over the samples of the structural response to obtain their statistical description for the specific hazard level [6]. An alternative approach, gaining increased interest within the structural engineering community [12–15], especially in light of recent concerns related to ground motion scaling [16], is to use stochastic ground motion models [17,18]. Such models modulate a high-dimensional stochastic sequence through functions that address spectral and temporal characteristics of the excitation, to ultimately provide samples of the earthquake acceleration time–history. The parameters of these functions, for example, duration of strong motion, can be related to earthquake (type of fault, moment magnitude and rupture distance) and site characteristics (shear wave velocity, local site conditions) by appropriate predictive relationships [12,19]. Description of the uncertainty for the earthquake characteristics (moment and rupture distance) and for these predictive relationships, through appropriate probability models, leads then to a complete and detailed probabilistic description of potential future ground-motion time–histories. The focus of these studies has been, though, primarily on development of stochastic ground motion models. Limited attention has been given to the impact of such a seismic hazard characterization within the context of performance-based engineering and life-cycle cost estimation.

This paper discusses a simulation-based, comprehensive computational approach that aims to bridge this gap. It focuses on seismic loss estimation through adoption of stochastic ground motion models for the seismic hazard description and investigates the potential benefits in terms of detailed, versatile description of seismic risk as well as the challenges in terms of computational efficiency. A probabilistic framework for assessment of life-cycle repair cost is initially presented based on the concepts discussed above for loss estimation and probabilistic earthquake hazard description. In this context, life-cycle seismic cost is quantified by its expected value over the established probability models and stochastic simulation is suggested for its evaluation. Techniques for improvement of computational efficiency are examined and suggestions are provided for their implementation in practical applications. An innovative probabilistic global sensitivity analysis is also reviewed, based on advanced stochastic sampling concepts. This analysis, demonstrated for seismic risk applications first in [20] and recently extended in [21] to groups of parameters (not necessarily constrained to individual scalar parameters), aims to identify the importance of the various risk-factors (i.e., uncertain model parameters) towards the overall performance of the structural system. This analysis is implemented here in the context of seismic loss estimation, i.e., not constrained to simplified performance evaluation in terms of system reliability as in the aforementioned two studies.

2. Probabilistic quantification of life-cycle seismic losses

For evaluation of seismic cost, adoption of appropriate models is needed for the structural system itself, the earthquake excitation (in particular a stochastic ground motion model is adopted for this purpose), and for loss evaluation (Fig. 1). The combination of the first two models provides the structural response and in the approach adopted here this is established in terms of nonlinear time–history analysis. The loss evaluation model quantifies, then, earthquake performance in economic terms based on that response. Note that this approach is consistent with the Pacific Earthquake Engineering Research (PEER) center's framework (see, for example, [6]) which is divided into four main steps; (i) hazard analysis, (ii) structural analysis, (iii) damage analysis and (iv) loss analysis. The modeling framework adopted here simply establishes a formal system theoretic context (distinction between excitation, system and performance evaluation models) and integrates the last two steps of the PEER approach into a common loss evaluation model.

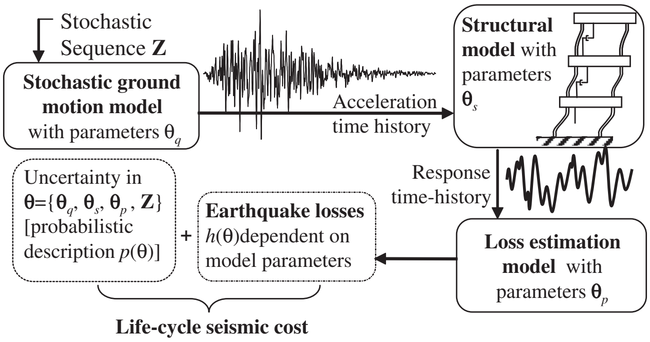

Fig. 1. Augmented system description for life-cycle seismic cost estimation.

The characteristics of the models in Fig. 1 are not known, though, with absolute certainty. Uncertainties may pertain to (i) the properties of the structural system, for example, related to stiffness or damping characteristics; to (ii) the variability of future seismic events, i.e., the moment magnitude or the rupture distance; to (iii) the predictive relationships about the characteristics of the excitation given a specific seismic event, for example duration of strong ground motion or peak acceleration; or to (iv) the parameters related to the performance of the system, for example, thresholds defining fragility of system components. A probability logic approach [22] provides a rational and consistent framework for quantifying all these uncertainties through the entire life-cycle of the structure [13]. To formalize this idea, let $\boldsymbol{\theta} \in \Theta \subset \Re^{n_\theta}$, denote the augmented vector of model parameters where Θ represents the space of possible model parameter values. Vector $\boldsymbol{\theta}$ is composed of *all* the model parameters for the individual structural system, $\boldsymbol{\theta}_s$, excitation, $\boldsymbol{\theta}_q$, and loss evaluation, $\boldsymbol{\theta}_p$, models as illustrated in Fig. 1 and it further includes the stochastic sequence $\mathbf{Z}$. The uncertainty in these model parameters is quantified by assigning a probability model $p(\boldsymbol{\theta})$ to them, which incorporates our available prior knowledge about the system and its environment into the model and it addresses future variability for both the seismic hazard, as well as for the structural system and its performance. Note that though the focus on this paper will be on seismic hazard the framework can address the uncertainties for the structural or for the loss estimation models. A significant benefit of the modeling approach of Fig. 1, utilizing a stochastic ground motion model for description of the seismic hazard, is the fact that all uncertainties related to the life-cycle structural behavior are described within a common probabilistic framework. There needs to be no distinction between the probabilistic methodologies introduced to address the seismic hazard variability and those used to address structural or performance evaluation uncertainties. Also though one can distinguish between epistemic and aleatoric uncertainties [23] (as is frequently established in earthquake engineering) such a distinction is not necessary within the proposed approach; both types of uncertainties are treated in a common modeling/assessment framework.

Let, now, the overall cost, for a specific structural configuration and seismic excitation, described by model parameter vector $\boldsymbol{\theta}$, be expressed by the performance function (representing ultimately the risk consequence measure) $h(\boldsymbol{\theta})$. This function will be related to (i) the earthquake losses that can be calculated based on the estimated response of the structure as well as to (ii) assumptions made about the rate of occurrence of seismic events and to (iii)