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Component damage models for detailed seismic risk analysis using structural reliability methods

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ABSTRACT

A probabilistic approach to modeling the seismic damage incurred by structural and nonstructural components is developed in this study. The resulting models are intended for use in detailed risk analysis of structures through structural reliability methods. The proposed modeling approach employs Bayesian linear regression to characterize the epistemic uncertainty in the model. In this approach, regressors are selected and constructed based on the mechanics of damage. In turn, the probability distributions of the model parameters and the model error are quantified by Bayesian linear regression using real-life data from laboratory experiments and/or post-earthquake inspections of damaged components. The paper presents in detail the stepwise procedure of collecting the observations, quantifying the repair costs, developing model forms, performing model diagnostics, and conducting model reduction, i.e., eliminating the inconclusive terms from the model. Subsequently, a library of Bayesian damage models are developed using the proposed approach for structural components, such as concrete moment frame joints, and nonstructural components, such as partition walls and traction elevators. For this purpose, the data of a host of past experimental studies are collected for Bayesian regression analysis. The proposed Bayesian damage modeling approach provides a number of insights into the parameters that are influential on damage that are discussed for the proposed models.

1. Introduction

This paper proposes a probabilistic modeling approach for prediction of seismic damage in structural and nonstructural components using Bayesian linear regression. The resulting models are intended for use in detailed seismic risk analysis of structures through structural reliability methods. The advent of reliability methods was for computing the probability of structural failure. These methods comprise the first- and second-order reliability methods (FORM and SORM) [1] and a multitude of sampling methods [2]. Risk analysis is a modern application of reliability methods [3–5]. A risk analysis in which the probability distribution of losses is computed using structural reliability methods is hereafter referred to as "reliability-based risk analysis." This is an alternative approach to the conventional methods of total probability integration to compute the probability distribution of loss, such as the one proposed by the Pacific Earthquake Engineering Research (PEER) Center [6]. The use of reliability methods for risk analysis requires the models to follow a set of rules, as enumerated by Mahsuli and Haukaas [7], the most important of which are:

(1) The uncertainty in the model is described by random variables that are input to the model
(2) Given the realization of random variables, the model produces a unique physical measurable output, *not* a probability; this contrasts the conditional probability models, such as fragility curves, in the likes of the PEER approach that produce a probability as output
(3) The model produces responses that are continuously differentiable with respect to the input random variables; this is crucial for gradient-based reliability methods, such as FORM

In reference to Fig. 1, three levels of refinement are envisioned for seismic risk analysis comprising region, building, and component levels. The first two levels focus on computing the regional loss exceedance probabilities using preliminary, observable data from a region or a portfolio of buildings. Simple models are employed for this purpose. For instance, as shown in Fig. 1, the ground motion is modeled at the spectral level through ground motion prediction models. In addition, simple models are employed to compute the overall response, damage, and loss at the building and region level. Mahsuli and Haukaas [3,7] presented the models and the framework for such analyses with an application to the Vancouver metropolitan region in Canada. The present study takes the reliability-based risk analysis approach to the next level, which is more refined and is denoted by the "component

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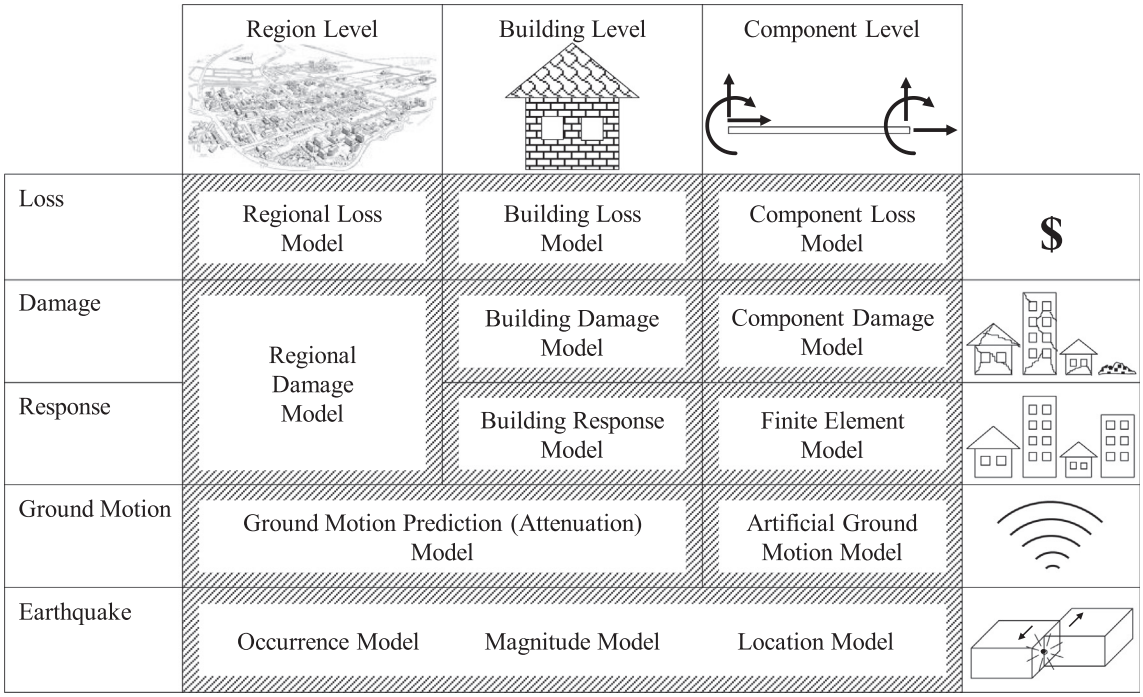

Fig. 1. Levels of refinement in seismic risk analysis.

level" in Fig. 1. As shown, detailed models are utilized at this level of refinement to simulate the ground motion as well as the response, damage, and loss of each component of the building.

As opposed to spectral analysis, detailed seismic risk analysis at the component level is commonly conducted using a nonlinear response history analysis of the structure. This, in turn, is carried out using an ensemble of naturally recorded ground motions or a probabilistic model to generate artificial ground motion. Several models are available in the literature for artificial ground motions, such as Rezaeian and Der Kiureghian [8] and Yoshifumi and Baker [9] among others. Moreover, the response model for risk analysis at the component level is commonly a detailed finite element model of the structure that yields the key responses of components. It is acknowledged that model classes other than those described above are available for risk analysis of buildings. The combination of reliability methods with finite element analysis, referred to as finite element reliability analysis, has been the subject of numerous studies; see [10–13] for instance. In a reliability-based risk analysis, such phenomena as degradation and deterioration can be taken into account through response models and damage models. While the example for damage models is presented later in this paper, two examples for response models are mentioned here. First, the authors [14] presented the reliability-based seismic risk analysis of a building in which cyclic degradation of the structure was accounted for in the response model. As another instance, Mahsuli and Haukaas [15] presented the reliability-based risk analysis of a reinforced concrete moment frame structure in which the cross-section area of the reinforcing bars in the response model diminishes over time due to corrosion.

Despite response models, component damage models that are used to ultimately predict repair costs and conform to the rules required for use in structural reliability methods such as FORM and SORM, are not available in the literature. This is a gap that is addressed in the present paper by putting forward a Bayesian regression approach to develop such models. For the remainder of this paper, unless specified otherwise, the term "model" refers to "Bayesian linear regression component damage model."

The proposed damage models in this study have as input the characteristics of a component as well as the demand and yield a damage ratio, defined as the cost of repair divided by the maximum repair cost, usually, the cost of replacing the component. Demand, in this context, refers to the local response under the seismic excitation that governs the damage incurred by the components, such as the inter-story drift ratio or the peak floor acceleration. Damage ratio is a computationally convenient and straightforward metric that directly connects the structural responses, i.e., demands, to the repair cost of the component, and thus, readily facilitates computing the risk, i.e., the probability distribution of repair costs. Bayesian linear regression is an appealing approach to develop such damage models. This modeling approach is based on mechanics and observed data. The mechanics of the problem determines the model variables and the model form. In other words, the literature on the mechanics of damage for a given component specify the variables, and the combinations thereof, that are deemed influential on the seismic damage of the component. Section 4.3 later in this paper will expand on how this is accomplished and presents examples. The resulting model form is then calibrated to real-world observations. This provides the opportunity to employ the bulk of experimental studies and post-earthquake reconnaissance reports to develop models. No such model does provide a perfect prediction of the reality; hence, the model is uncertain. Bayesian regression characterizes the model uncertainty through random variables that are input to the model, which is another desirable characteristic for use of such models in reliability-based risk analysis [7]. The probability distribution of these random variables are updated as new data emerge. This makes it possible to reduce the epistemic model uncertainty with more experiments and data-gathering over time.

To develop damage models for a given component, a five-step approach is proposed in this paper. The first step is to collect observations from laboratory experiments on the given component or from real-world instrumented buildings in past earthquakes that comprised the given component. The information to be collected include the characteristics of the component, such as geometry and material properties, seismic demands on the component as recorded by sensors, and the description/images of the damage incurred by the component at each level of demand. The second step is to quantify the repair cost of those components by determining the method of repair, and to normalize the quantified repair cost by the cost of replacing the component to

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