Structural Safety 52 (2015) 113–120

Contents lists available at ScienceDirect

Structural Safety

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

Building portfolio seismic loss assessment using the First-Order Reliability Method

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ARTICLE INFO

Article history:
Received 12 February 2014
Received in revised form 23 September 2014
Accepted 28 September 2014
Available online 23 October 2014

Keywords:
Reliability
Portfolio
Earthquake
Building
Retrofit
Community
Seismic

ABSTRACT

The aggregate loss to a portfolio of buildings given a seismic event is of interest to parties such as insurance companies, developers, political organizations and community planners. Regional level estimations tend to be more complex than site-specific assessments due to the correlation that exists between the performances of spatially distributed buildings within a single hazard. This paper presents a new reliability-based approach to quantify seismic risk for a portfolio of buildings, while incorporating this correlation. The proposed framework uses the First-Order Reliability Method (FORM) to evaluate a probability distribution of loss for a suite of spatially distributed buildings. It is applied to a San Francisco neighborhood building inventory to estimate the distribution of total repair cost given a scenario earthquake and prioritize cost-effective retrofit schemes in terms of reducing portfolio loss. The information provided by using the proposed method is expected to facilitate more efficient risk management and mitigation decision-making.

1. Introduction

An informed decision-making process with optimal resource allocation is needed to reduce hazard risk efficiently, and this requires the aid of reliable and quantitative risk assessment tools. These are often desired at a regional level as many private and public entities are concerned with the impact of an earthquake to a portfolio of buildings as opposed to that for a single site. Assessing potential losses for a portfolio of buildings is more complex than for a single site because of the correlations that exist between building performances (i.e., characterized by building damage or loss) in a seismic event. Therefore, portfolio loss assessments are often characterized by the expected value of loss and the variance of loss; the latter being sensitive to correlations in excitations and building characteristics within a region.

Many commercial loss assessment tools, such as HAZUS-MH, use the expected value of economic losses, casualties, etc. as the measure of risk [1]. Although minimizing expected loss is consistent with reducing regional risk, the uncertainty around this loss is not quantified. According to Schubert and Faber [2], decision makers often prefer decisions that yield a low probability of experiencing large losses, since they tend to dominate earthquake repair costs over time. The probability of such a phenomenon can only be estimated accurately if the uncertainties and correlations between the building performances are included in the loss assessment process.

The correlation between the performances of spatially distributed buildings (referred to as spatial correlation) is a function of shared effects from the seismic source, site effects, and similarities in structural components [2]. For example, sites in close proximity to each other and with similar soil conditions will experience similar ground motion time histories due to shared seismic source conditions and commonality of wave paths [3]. Disregarding the spatial correlation in ground motion intensity has been shown to significantly reduce the variance in loss, as well as influence the prioritization of cost-effective retrofit schemes [4–8].

The primary focus of this paper is in developing a method for estimating probabilistic seismic-induced losses for a suite of buildings, while incorporating this spatial correlation and variance in loss. Significant efforts have been made previously to predict the seismic risk to infrastructure portfolios, including many recent academic studies that utilize simulation techniques to quantify the loss as a probability distribution [4,5,9]. While simulation methods, such as Monte Carlo Simulation (MCS), can provide accurate portfolio loss estimates, they are often criticized as being computationally intensive. In addition, the evaluation of sensitivities within a system (i.e., variables that are most influential to the loss estimate) can be time intensive as it requires a large number of simu-

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http://dx.doi.org/10.1016/j.strusafe.2014.09.005
0167-4730/

lations to reduce the variability in the reliability comparison required for a sensitivity analysis [10]. Algorithmic approaches have also been developed based on individual building characteristics to optimize mitigation strategy [11].

Because of these drawbacks, the research reported in this paper proposes the use of the First-Order Reliability Method (FORM) to quantify the potential loss to a portfolio of buildings given either a known or probabilistic earthquake scenario. The basic theory behind FORM is to approximate the limit state failure surface (i.e., performance threshold) by a linearized surface to compute the failure probability. The approximate failure surface is fit to the original at a "design point," which is characterized by the most likely combination of variables that cause failure. As most of the failure probability contribution is located within close proximity to the design point when there is a single dominant failure mode, FORM usually provides accurate results, and unlike traditional MCS, is very computationally efficient [10,12]. Sensitivity measures are easily computed within the FORM evaluation, and are used in this study to prioritize the most cost-effective retrofit scheme with respect to reducing portfolio loss.

The proposed method overcomes limitations in current methodologies by providing an efficient loss estimation tool intended to be generic and replicable for different building portfolios. Specifically, it offers three important advantages over many previous techniques used to quantify loss: (1) it is analytical and stochastic; (2) it accounts for spatial correlations between building performances; and (3) it provides a framework to prioritize the most cost effective retrofit schemes in terms of reducing portfolio loss. The following section provides a description of the reliability approach developed to evaluate loss, followed by a review of the proposed FORM analysis and application to a San Francisco building portfolio.

2. Description of the reliability approach

Since FORM is a method of linear approximation relative to each random variable of interest, an increase in random variables results in an increase in required computation time as well as difficulty in characterizing limit state nonlinearities. Therefore, it is useful to minimize the number of random variables used in FORM reliability assessments to increase accuracy. In this study, two random variables are used to evaluate the distribution of seismic-induced loss at each building site: (1) the natural logarithm of the spectral intensity demand ($\ln S_a$); and (2) a parameter that captures the uncertainty in structural response (γ_{IDR}). The variables for each site are combined to compute loss for a suite of buildings, given the modeling assumptions discussed in the following sections.

2.1. Seismic intensity random variable

The uncertainties and correlation between seismic intensities at each site must be accounted for in order to capture the spatially distributed seismic demand across a region. These parameters relate to uncertain characteristics in the seismic source, site-to-source distance and orientation, and site effects. Following Jayaram & Baker [5], the seismic intensity in this study is defined by the following multivariate seismic intensity model:

$$\ln(S_{a_{ij}}) = \ln(\bar{S}_{a_{ij}}) + \sigma_{ij}\varepsilon_{ij} + \tau_j\eta_j \tag{1}$$

where $(S_{a_{ij}})$ denotes the spectral acceleration at the period of interest at site i during earthquake j, $\bar{S}_{a_{ij}}$ is the predicted median spectral acceleration determined by ground motion prediction equations (GMPEs) (see, e.g., [13–17]), ε_{ij} and η_j are the normalized intra-event (between sites) and inter-event (between earthquake events) residuals, and σ_{ij} and τ_j are the corresponding standard deviations of the residual terms, also determined by GMPEs.

For a probabilistic earthquake scenario, a simulation procedure motivated by the approach proposed by Jayaram and Baker [4] is used to compute simultaneous ground motion intensities at each site. Magnitude, epicenter location and shear wave velocities specific to each site based on the soil properties in the top 30 m (V_{s30}) are simulated and used in GMPEs to compute realizations of $\bar{S}_a$. The intra- and inter-residual terms in Eq. (1) are simulated from a multivariate normal distribution with correlation determined from empirical relations proposed in recent literature. These empirical models have been developed to predict correlations in ground motion residual terms as a function of inter-site distance [4,5,18] as well as the fundamental building period [3,18]. The models proposed in the latter two studies are used in this paper to characterize correlations between the inter- and intra-event residual terms.

Simulated spectral intensities can be used to model a multivariate distribution representing the joint seismic intensity at all sites of interest. Since the computed seismic intensity is a function of many uncertain variables, it is not clear whether the samples follow a particular distribution. Results in Miller et al. [7], however, show that the normal distribution fits the simulated $\ln S_a$ values well. From these results it is assumed that the combination of site-specific normal distributions can be modeled by a multivariate normal distribution. Using a linear regression analysis, the correlation between $\ln S_a$ at each site can be calculated based on the simulated seismic intensity values. Fig. 1 shows $\ln S_a$ simulations and the computed correlation between simulated seismic intensities for two representative sites. It should be noted that the expected values of $\ln S_a$ were the same at both sites in this example; which of course is frequently not the case. The fitted distribution contours are shown, representing one, two and three standard deviations.

This simulation procedure can be circumvented by starting with a deterministic earthquake scenario and soil properties. The multivariate distribution of site-specific seismic intensities can then be characterized by expected median spectral accelerations determined by GMPEs and the following covariance matrix:

$$COV(\ln S_a) = COV(\tilde{\varepsilon}) + COV(\tilde{\eta}) \tag{2}$$

where $\tilde{\varepsilon}$ is the multivariate distribution of intra-event residuals ($\tilde{\varepsilon}_i = \sigma_i\varepsilon_i$ for site i) and $\tilde{\eta}$ is the multivariate distribution of inter-event residuals ($\tilde{\eta} = \tau_i\eta_i$ specific to each unique building period at

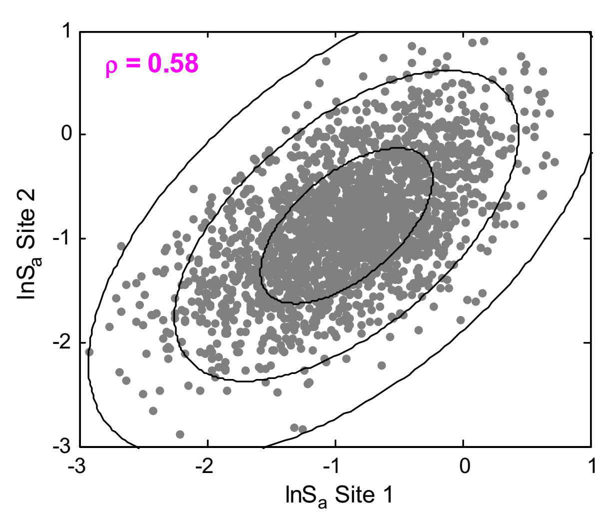

Fig. 1. Grey dots represent the simulated $\ln S_a$ data for Site 1 and Site 2 with the estimated bivariate normal distribution contours and correlation between sites shown.