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Probabilistic Sensitivity Analysis of Earthquake-induced Loss Estimates in Buildings

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ABSTRACT

The degree of uncertainty associated with earthquake-induced loss predictions is significant. In this study, we perform a probabilistic sensitivity analysis to identify how the uncertainty in seismic losses is affected by uncertainty in variables used as inputs at different stages of the performance-based earthquake engineering framework, i.e., structural response, damage, and loss analyses. We adopt a variance-based sensitivity analysis procedure to compute input variables' relative importance in terms of the Sobol index for two seismic loss measures: the probability of irreparable damages, and the expected repair costs. Sobol indices measure the contribution of the variance of each input variable to the variance of an output variable. The assessments are performed for a 12-story modern reinforced concrete shear wall building archetype under 100-year, 475-year, 975-year, and 2475-year return period ground shaking intensity levels. The results indicate that the variance in the size of modeling uncertainty added to the simulated demand distribution is a major contributor to the variance in seismic losses at all, but the highest hazard level. At the 2475-year intensity level, the variance in building replacement cost becomes the primary contributor due to the high probability of irreparable damage. The analyses presented in this study increase our understanding of the implicit relationships between parameters in complex seismic risk assessments and help prioritize research in computational modeling to better support disaster risk management.

Keywords: Seismic loss, uncertainty quantification, variance-based sensitivity analysis, Sobol indices.

INTRODUCTION

The performance-based earthquake engineering framework aims to quantify earthquake-induced losses by integrating the results of hazard, structural, and damage analyses [1]. This procedure was established on a probabilistic basis in order to acknowledge the inherent uncertainties at each step of the calculations. It is therefore essential to understand the impact of uncertainties in the underlying assumption on the output variables, i.e., seismic losses. In this regard, researchers endeavored to measure the sensitivity of building seismic loss predictions to uncertainty in modeling assumptions. For instance, Porter et al. [2] conducted a deterministic sensitivity analysis for a high-rise reinforced concrete moment-frame building to evaluate to most important input variables that can influence earthquake-induced repair cost estimates. Although past studies have provided insights into the key contributing factors to uncertainty in seismic risk, they have primarily concentrated on evaluating uncertainty associated with the hazard parameters by exclusively using deterministic and local sensitivity analysis methods. To gain a more comprehensive understanding of the input-output interaction in probabilistic seismic performance assessment, it is critical to utilize global or probabilistic sensitivity analysis approaches. Unlike local sensitivity analysis, which evaluates the sensitivity of a model to changes in individual input variables around a specific point, global sensitivity analysis accounts for the overall behavior of the model across the entire range of possible input values [3]. Previous research on the application of variance-based sensitivity analysis in seismic risk analysis is limited. For example, Cremen and Baker [4] carried out variance-based sensitivity analyses for FEMA P-58 loss estimates by considering ground shaking intensity, building period, occupancy, lateral system, and nonstructural building quantities as input variables. Although their research increased our understanding of consequence predictions of the FEMA P-58 methodology, it did not explore important assumptions regarding the calculation of irreparable damage and component-level fragility functions. To address these shortcomings, this study performs a variance-based sensitivity analysis of seismic losses in terms of the probability of irreparable damages and expected repair costs by considering a wide range of input variables as defined in the performance-based earthquake engineering framework. We performed analyses at four distinct seismic hazard levels to highlight how the outcomes are affected by the changes in typical assumptions at different levels of ground shaking.

METHODOLOGY

In this study, we adopt a variance-based sensitivity analysis [5] method to quantify each input variable's impact on the overall variability of the model output. The method is a common type of global sensitivity analysis that is based on decomposing the total variance of output into the contributions of variance in each input variable and their interactions. Sobol [6] indices are derived to identify the relative importance of input variables. The Sobol index (S_i) for the input variable (X_i) represents the expected reduction in the output variance if X_i is fixed while all other input variables follow their prescribed distributions. In this article, we focus on first-order Sobol indices that do not account for interactions between input variables. These indices are always non-negative and the sum of them can never exceed 1.0 since the total output variance cannot be less than the sum of the variances explained by the input variables. When the relationship between inputs and the output is complex or cannot be represented with a closed-form solution, data-driven approaches can provide approximate values for Sobol indices. Monte Carlo-based sampling methods are robust and efficient for such purposes [7]. We sample N realizations from the distribution of each input variable (n_p in total) and use these samples to construct the so-called sampling and resampling matrices. These matrices are used to perform $N \times n_p$ damage and loss simulations following the Monte Carlo-based procedure outlined in the FEMA P-58 methodology [8]. The approximate equation suggested by Saltelli et al. [9] is employed to estimate Sobol indices by utilizing the results obtained from each FEMA P-58 simulation.

ARCHETYPE BUILDING AND HAZARD LEVELS

For the sensitivity analysis in this study, we consider a 12-story modern residential reinforced concrete shear wall building. Marafi et al. [10] detailed the lateral load-resisting system in the archetype building using special reinforced concrete shear walls per ACI 318-14 [11] designed to meet the minimum seismic design requirements as outlined in ASCE 7-16 [12] for a site in downtown Seattle (47.60° N, −122.30° W). The typical floor size for the archetype building is 30.5 m × 30.5 m (100 ft × 100 ft), and the story height is 3.05 m (10 ft). Marafi et al. developed a finite element model and assessed the structural response for the archetype using nonlinear dynamic analyses with ground motion records representing 100-year, 475-year, 975-year, and 2475-year hazard levels consistent with the 2014 National Seismic Hazard Model (NSHM) [13]. At each hazard level, 100 ground motion records were selected to represent the contribution of three types of source mechanisms (i.e., crustal, intraslab, and interface) to the total hazard. The acceleration time histories were scaled to minimize the error between the mean and variance of the spectra corresponding to the selected records and the target spectrum for the site [14].

INPUT AND OUTPUT VARIABLES

The input variables considered in this study represent various underlying assumptions related to both demands and capacities in FEMA P-58. When quantifying seismic losses, we also incorporate the probability of irreparable damage that is primarily controlled by residual drifts. The residual drift ratio in this study is calculated using the approximate equation recommended in FEMA P-58. These drift estimates (demands) are evaluated against a repair fragility (capacity) characterized by a lognormal cumulative distribution function. We leverage the building performance model developed by Kourehpaz et al. [15] and use Pelicun, SimCenter's open-source software [16, 17], to simulate damage and losses in the building by generating 2000 Monte Carlo realizations.

Table 1. Input variables definition.

Symbol	Definition	Typical Value	Range
Med_{RF}	Median of the repair fragility	1%	[0.8% , 2.5%]
σ_{RF}	Dispersion of the repair fragility	0.3	[0.1 , 0.8]
SDR_Y	Yield drift ratio	0.5%	[0.2% , 0.6%]
β_m	Additional uncertainty on demands	0.35	[0.15 , 0.56]
C_{rep}	Building replacement cost per square foot	$230	[$125 , $300]
δ_{rcw}	Shift in median drift capacity of shear wall fragility	0	[-0.47% , +0.47%]
δ_{sc}	Shift in median drift capacity of slab-column connection fragility	0	[-1.1% , +1.1%]
δ_{st}	Shift in median drift capacity of staircase fragility	0	[-2.0% , +2.0%]
δ_{fc}	Shift in median drift capacity of facade fragility	0	[-1.0% , +1.0%]
δ_{elev}	Shift in median acceleration capacity of elevator fragility	0	[-0.195g , +0.195g]

Table 1 summarizes the input variables, their typical value, and the ranges considered in the sensitivity analysis. The upper and lower bounds were determined primarily based on values found in the literature. We use a truncated normal distribution for all random variables with the mean of the original normal distribution set to match typical values commonly used in standard practice. The dispersion for each distribution is chosen in such a way that the coefficient of variation falls within the range of 0.3 to 0.5. For instance, past studies have indicated that the yield drift ratio for reinforced concrete shear walls varies between 0.2% to 0.6%; nevertheless, it is improbable for the yield drift ratio to be below 0.3% [20, 21, 22]. Thus, we set the coefficient of variation of the probability distribution of the yield drift ratio to 0.3 in order to achieve approximately a 10% probability of sampling values below 0.3%.

ANALYSIS RESULTS

We produce a total of 20000 Monte Carlo samples (N=2000, n_p=10) to compute first-order Sobol indices for the building's irreparable damage probability and expected repair costs at four ground shaking intensity levels ranging from 100 to 2475 years. Note that each of these Monte Carlo samples is the result of a FEMA P-58 damage and loss simulation with a sample size of 2000. Figure 1 depicts the probability of irreparable damage across the ground motion intensity levels. The probability of irreparable damage at the 100-year hazard level is negligible, i.e., less than 0.1% of damage realizations are irreparable in 94% of the cases. With the increase in hazard level, the likelihood of building irreparability becomes more prominent. At the 2475-year intensity level, the probability of irreparable damage is at least 70%, and in approximately 85% of the cases, more than 90% of the damage realizations are irreparable. At the two intermediate return periods, the probability of irreparable damage is highly variable and ranges from approximately 0 to 70% and 10% to 90%, for 475-year and 975-year intensity levels, respectively.

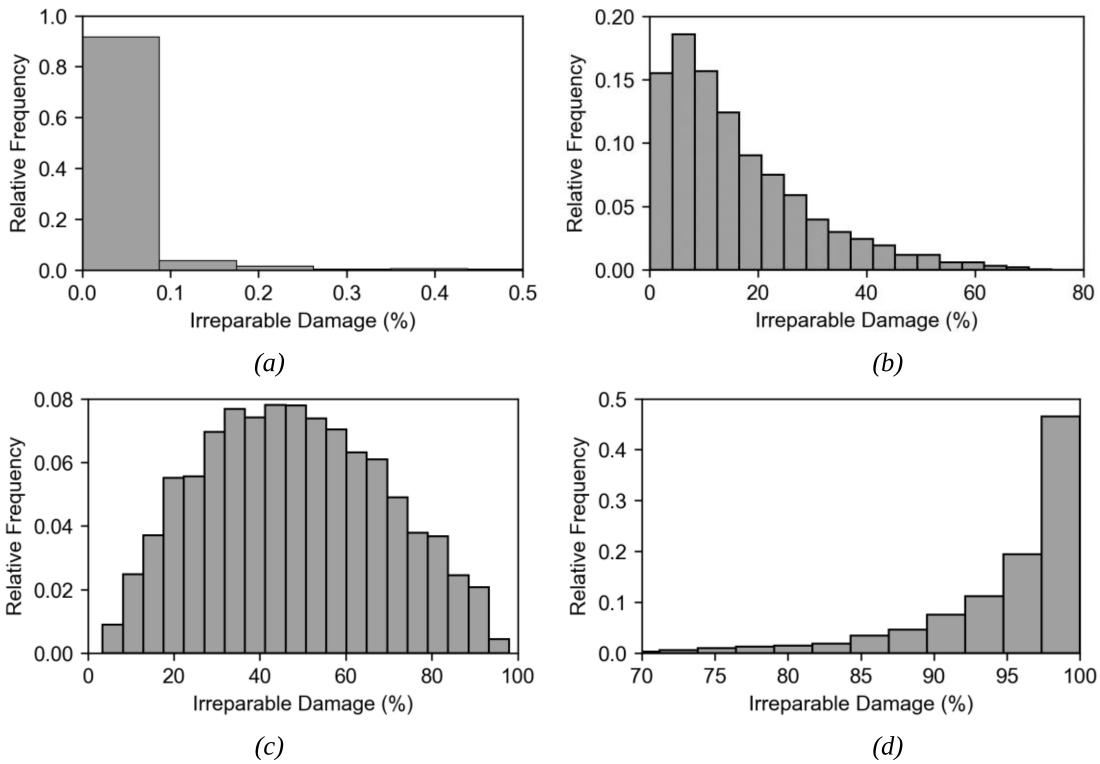

Figure 1. Distribution of the probability of irreparable damage across 20000 simulations performed at four different ground shaking intensity levels: (a) 100-year, (b) 475-year, (c) 975-year, and (d) 2475-year.

The variance-based sensitivity analysis for the building's irreparability highlights the impact of assumptions in the FEMA P-58 methodology used to estimate irreparable damages that are caused by excessive residual drifts. Figure 2 shows the relative importance of the input variables expressed in terms of first-order Sobol indices for the probability of irreparable damage. The Sobol indices are not available at the 100-year hazard level due to the extremely low number of irreparable cases observed. The figure indicates that the median of the repair fragility (Med_{RF}) becomes more important as the hazard level increases, and its variance contributes more than 40% to the output variance at the highest intensity level, i.e., 2475-year. On the other hand, the yield story drift ratio (SDR_Y) and the additional uncertainty on demands (β_m) are the main contributors to the overall output uncertainty at 475 and 975 years and they become less important as the hazard level increases. In other words, at low hazard levels, the input variables related to demands are the governing factors, while at higher hazard levels, the results are more sensitive to the variables controlling the capacities. To understand the rationale behind this observation, let us look at the 2475-year hazard level, for example. Due to high residual drift demands the building is most likely irreparable (refer back to Figure

1d). The corresponding input variables (SDR_Y and β_m) modify the demand distribution but do not change the median demand. Since the majority of demand realizations are beyond the median capacity, the results are not affected significantly by changes in the dispersion of the demand distribution. However, changes in the variables corresponding to the capacity side (Med_{RF} and σ_{RF}) can modify the median capacity and have a substantial impact on the probability of the building's irreparability.

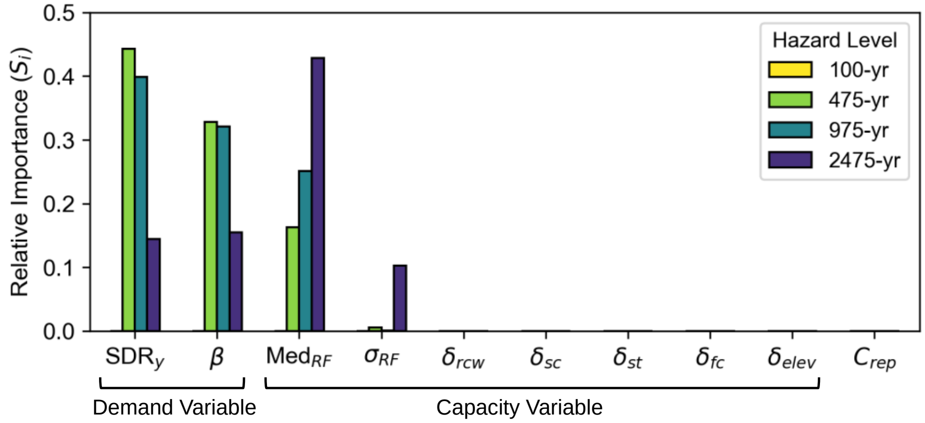

Figure 2. Sobol indices for the probability of irreparable damage at 100-year, 475-year, 975-year, and 2475-year hazard levels.

The Sobol indices are also computed to evaluate the sensitivity of earthquake-induced repair costs to input variable assumptions. Figure 3 displays the first-order Sobol indices for the expected repair cost estimated at four ground motion shaking intensities. At the lowest intensity level, the expected repair costs are largely governed by the additional uncertainty on demands (β_m) and the rotation capacity of the slab-column connections (δ_{SC}). At the 475-year and 975-year hazard levels, the impacts of Med_{RF} and SDR_Y, (i.e., input variables associated with irreparable damage estimation) are important because of their substantial impact on the probability of irreparable damage (see Figure 2) and the significant contribution of losses associated with irreparable realizations (i.e., total replacement cost) to the expected loss. At the 2475-year hazard level, the sensitivity of the expected repair costs can solely be attributed to the replacement cost ratio (C_{rep}), due to the high probability and considerably smaller variance of irreparable damage and the substantial uncertainty in the replacement cost.

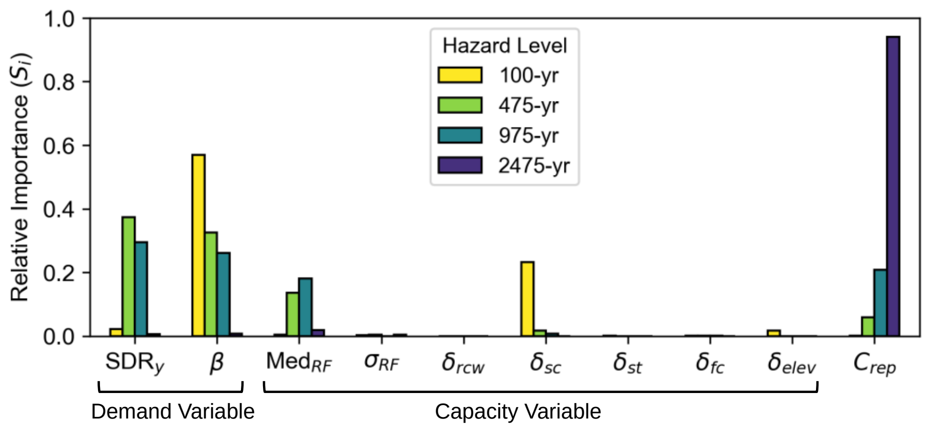

Figure 3. Sobol indices for the expected repair cost at 100-year, 475-year, 975-year, and 2475-year hazard levels.

CONCLUSIONS

The main objective of this study is to employ variance-based sensitivity analysis to evaluate how the variation in seismic loss estimates with consideration of the irreparable damage is influenced by diverse sources of uncertainty present throughout different stages of the performance-based earthquake engineering framework. Through variance-based assessments, Sobol indices are computed to rank the input variables according to their contribution to the overall uncertainty in damage and loss estimates. The Sobol indices help us identify which input variables deserve the most attention when conducting a performance assessment. The uncertainty in a variable with a small Sobol index has negligible influence on the decision variable. Uncertainty in such input variables can be safely neglected, and the variables can be treated as deterministic. The results of this study increase our understanding of seismic performance assessments and provide insights to prioritize input variables for further research to enhance the accuracy of damage and loss estimates. This study has focused on a reinforced concrete shear wall building to illustrate the procedure, but the methodology proposed is generic and it can be applied to explore other risk metrics and other structural systems. Future work by the authors will explore the sensitivity of post-earthquake recovery time estimates to these and additional input variables.

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