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Hurricane loss estimation in wood-frame buildings using Bayesian model updating: Assessing uncertainty in fragility and reliability analyses

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ABSTRACT

This paper proposes a Bayesian model updating method for quantification of uncertainty in the analytical capacity predictions of roof-to-wall connections of wooden structures. The ultimate goals are to construct fragility models for various mitigation options accounting for uncertainties due to model discrepancy and experimental error and to determine the most cost-effective option under a potential hurricane in terms of aggregate loss estimates based on total probability of failure. The proposed approach is applied to both hurricane-clips (mitigated specimen) and toenails (unmitigated specimen) and the exceedance probability of different aggregated loss scenarios are found using both the proposed method and the existing log-normal approach. The advantage of the two-stage Bayesian model is that it provides the uncertainty bound on the exceedance probability which gives a measure of the factors unaccounted for in the capacity estimation process.

1. Introduction

The insured value of properties continues to rise in the U.S., especially for coastal regions that are prone to hurricane hazards. Catastrophic failures of one and two story, light-frame residential buildings are the most frequently observed types of loss in a hurricane. The failure of roof-to-wall connections is a dominant cause of the breach of the building envelope (roof sheathing). Breach of the building envelope constitutes a significant component of hurricane loss because possible subsequent water and wind damage to the interior and the contents of the building can be very high.

An effective approach to lessen damages due to the hurricane is hardening or mitigation of homes. Mitigation actions also improve resilience of the coastal communities because more residential and commercial buildings will remain functional even after the storm, or quickly recover compared to unmitigated buildings. One of the main challenges in assessing the benefits of mitigation actions from available loss data is that due to the large uncertainties in building performance against hurricanes based solely on past loss data it is very difficult to perform an effective cost-benefit analysis. Therefore, researchers have developed physics-based failure prediction functions for structural components to aid the analysis.

In wind engineering, fragility functions, or conditional probability of failure under a given wind loading, are used to model the variation in failure occurrence. Failure is assumed to occur when the wind pressure exceeds the component capacity for a given mode of failure. Fragility curve for residential structures depend on many factors, including shape of roof (gable or hip), frame material (wood or masonry), number of stories, roof to wall connection type (toe-nail or hurricane clip) and terrain roughness. For example, HAZUS – MH 2.1 (Vickery et al., [34]), a commonly used hazard analysis software package for loss estimate analysis, contains hundreds of fragility curves for single family residential structures, depending on the combination of these factors. Furthermore, there are large errors in fragility estimates, especially for segments that correspond to higher wind uplift forces, which represent rare but powerful hurricanes. This large uncertainty arises due to the lack of available data both for wind speeds and component performance. This region is referred to as the low-probability high-consequence event and is thought to have significant influence in a cost-benefit assessment [16,9,18].

This paper presents a Bayesian model updating approach to develop fragility functions of building components and determine failure probability against wind loading while considering uncertainties. A model updating approach is proposed to quantify discrepancy in capacity prediction of an analytical model based on experimental capacity data. Roof system components representing

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mitigation actions (hurricane clips) and no mitigation (toe-nailing the rafters) are considered to evaluate the benefit of mitigations. The Bayesian posterior distribution of the capacity is used to develop posterior distribution and confidence bounds of fragility functions, total failure probability and aggregate hurricane loss.

2. Relevant literature

The probability of failure P_f of a structural component for a certain limit state is defined as:

$$P_f = \int F_v p(v) dv \tag{1}$$

in which $p(v)$ is the probability density function of the hurricane wind speed v and F_v is the fragility function, the probability that the structure fails at this wind speed. Fragility analysis using this equation uncouples the hazard (probability distribution of wind load) from the structure reliability (fragility function), thus, the analyses for determining hazard likelihood and fragility of various components can be conducted separately. It is often the case that accurate information on hazard is not available, hence it is desirable to make safety decisions against a range of hazard intensities through the use of fragility analysis [17].

The parameters of both functions $p(v)$ and F_v need to be determined from data and therefore are subject to estimation error. In this paper we represent the fragility function in terms of random parameters using a Bayesian approach and evaluate the integral in Eq. (1) with respect to the posterior distribution of the parameters. The approach enables one to quantify the uncertainty in total probability of failure and the aggregate loss estimates. By contrast, the traditional approaches assume that the fragility function is known with certainty and hence cannot account for estimation uncertainty.

The fragility is the conditional probability that capacity is less than a wind load D_v for a given wind speed v

$$F_v = P(c \leqslant D_v) = \int_{\beta,\eta \in \Omega} f(\beta, \eta) d\eta d\beta$$

in which $f(\beta, \eta)$ is the joint probability density function of the parameters η and β, the sets of parameters that define the capacity and wind load models, respectively, and Ω is the set of values of β, η such that $c \leqslant D_v$. The integral is usually evaluated using numerical integration or first-order reliability methods [19]. In wind engineering, fragility functions are often assumed to follow certain probability function, where the lognormal distribution is one of the most commonly used distribution [27,17]:

$$F_v = \Phi[\ln(D_v/m)/\zeta] \tag{2}$$

in which $\Phi(\cdot)$ is the standard normal probability integral, m is the median capacity, and ζ is the logarithmic standard deviation of capacity. Li and Ellingwood [17] found the fragility curves for hurricane winds but did not provide bounds on the curve. Gardoni et al. [10] and Straub and der Kiureghian [31] considered quantifying uncertainty in fragility by provided confidence bounds, however, the application was limited to earthquake loss analysis.

In a recent survey of hurricane vulnerability analysis methods Pita et al. [22] mentioned that uncertainty in the loss estimates depends on the wind speed domain under study. Uncertainty is typically larger in the lower and the higher wind speed ranges. The former uncertainty is because the claim data employed to fit the vulnerability does not include any damage lower than the deductibles, while the latter one is because there is scarce past loss data due to the rare occurrence of strong hurricanes. To circumvent issues with scarce performance data, researchers have investigated physics-based approaches to model building vulnerability. For example Ellingwood et al. [8] and Zhang et al. [35] developed capacity models of building components from which fragility curves can be found to assess the response of a light-frame wooden construction exposed to extreme winds and earthquakes. It is assumed that the severity of a catastrophe is based on annual probability of exceeding the design hazard or its return period.

Most analytical approaches to estimate the load carrying capacity of building components based on Newtonian-mechanics principles do not account for uncertainty that arises due to modeling assumptions [21]. Several assumptions made at the modeling stage can contribute significantly to model uncertainty that results in biased capacity predictions: variation of material properties during manufacture, inexact modeling of material constitutive behavior, inaccurate modeling of the boundary conditions, and insufficient refinement in spatial discretization of distributed parameters. To correct the bias between computer predicted deterministic model and experimental observations, a model-updating method is employed. The major purpose of model updating is to modify the model parameters to obtain a better agreement between numerical results and the test data. According to Straub and der Kiureghian [31] the uncertainties in the model gives rise to statistical dependence among observations and can have significant effect on fragility. Gardoni et al. [10] have used Bayesian framework for constructing univariate and multivariate predictive capacity model based on experimental observations and develop fragility curves with uncertainty bounds. Beck and Au [5] have proposed a Bayesian framework for finding probability distribution of the model parameters for structural analysis and Beck and Katafygiotis [6] have used an adaptive Markov chain Monte Carlo simulation to find updated posterior probability using a sampling based approach rather than closed-form expressions.

In engineering statistics improving the predictive accuracy of computer models with physical or experimental data has been studied extensively and referred to as model updating and model calibration [15,25,23]. Vanli and Jung [33] have used the probabilistic model updating method to improve the accuracy of damage size and location prediction of a structural health monitoring system with help of a finite element analysis method. Model uncertainty is typically categorized into the forms epistemic and aleatory uncertainty. Epistemic uncertainty derives from a lack of knowledge about the appropriate value to use for a quantity that is assumed to have a fixed value in the context of a particular analysis. Aleatory uncertainty arises because the system under study can behave in many different ways (e.g., many different accidents are possible at a power station). Thus, aleatory uncertainty is a property of the system under study and epistemic uncertainty is a property of the analysis [14]. Often, some type of random sampling through a set of event trees is used to sample from aleatory uncertainty and random sampling from the input distributions is used to sample from epistemic uncertainty. In addition, to provide a better coverage of low probability/high consequence events and enhance the effectiveness of the computational effort, importance sampling is recommended as a more effective sampling procedure than random sampling.

3. Proposed method: uncertainty quantification of failure probability against wind loading

This paper proposes a two-stage Bayesian updating approach [25] for finding the predictive distribution of the capacity of a roof-to-wall connection and finding the probability of failure against wind loading. The first stage data are the analytical capacity values and the second stage data are the experimental measurements; the posterior of the analytical model is used as the prior for the second-stage model.