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Preventive maintenance of wood-framed buildings for hurricane preparedness

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ABSTRACT

This paper presents a time-dependent reliability modeling and optimal maintenance planning approach for residential buildings subject to hurricane winds. A gamma process is employed to model the stochastic degradation of building components. The time-dependent fragility function and the failure probability of the roof system obtained from the degradation model are used to determine the retrofit timing of components that optimize an average cost per cycle time. The method is illustrated on determining the retrofit times of roof-to-wall connections based on actual component failure and hurricane wind load data. Effectiveness of the optimal retrofit age is compared to a replacement based on time-invariant failure probabilities. A simulation approach is presented to quantify the effect of wind speed uncertainty on maintenance cost.

1. Introduction

Damages to residential wood-framed buildings due to extreme winds constitute a major economic loss in coastal communities during hurricanes. In hurricane events, the failure of roof-to-wall connections is the main failure mode that often leads to the complete breach of the building envelope and interior water damage and therefore has a dominant effect on the overall economic loss. See Kakareko et al. [15], for a recent analysis of failure of roof-to-wall connections. An effective approach to lessen damages due to the hurricanes is hardening or mitigation of homes. Most current efforts for assessing benefits of mitigation rely on insurance claims or loss data. However, with limited number of historical hurricane events and due to large uncertainties of building performance, it is often not possible to show significant benefits of mitigation actions merely based on historical loss data. To aid the loss analyses, researchers often resort to physics-based failure prediction functions for structural components. Pita et al. [23] provide a detailed discussion of both physics-based models and data-based models for hurricane loss analysis.

In this research we propose a new reliability approach to determine the optimal retrofit time of aging components in wood-framed buildings subject to hurricane winds and to quantify the uncertainty in the maintenance cost due to wind speed variability. A stochastic degradation model and a time-varying fragility curve is estimated from the capacity data of aging roof-to-wall (RTW) connections. From the degradation model of the connections, the approach estimates the fragility curve of a roof system that consists of a set of connections and the time-dependent failure probabilities for various damage severities of the roof under a given wind speed probability distribution. Using the time-dependent failure probabilities, a life-cycle cost function is developed to determine the optimal retrofit age of the components of the roof system. The approach is useful for decision makers in conducting more accurate cost-benefit analyses of preventive mitigation options against specified hurricane hazards by allowing to balance the risk of early collapse against the cost of replacing components that have remaining useful life.

The remainder of the paper is organized as follows. Relevant literature on optimal preventive maintenance and fragility analysis is reviewed in Section 2. Section 3 presents the proposed time-dependent fragility modeling approach based on gamma-process degradation analysis. Section 4 presents the proposed optimal maintenance planning approach using the fragility curves. Section 5 presents an illustration of the replacement scheduling approach based on capacity data from literature.

2. Relevant literature

Optimum maintenance scheduling has been studied extensively in the reliability engineering literature. Two major methods in preventive maintenance are condition-based and age-based. In the condition-based

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case, a degradation measure of a unit is observed at regular time intervals and if found to exceed a predetermined threshold then it is replaced preventively (Wang [33]). In the age-based case, the unit is replaced if its age is older than a predetermined age (Glasser [10]). Grall et al. [11] proposed a method that jointly determines the threshold and the length of inspection intervals in condition-based maintenance by minimizing the total cost of failure and cost of maintenance. Wang [33] proposed a random coefficient model to model the degradation behavior and determine the failure threshold and the monitoring intervals that minimize the total cost. Robinson and Crowder [26] studied a Bayesian growth curve model to incorporate nonlinearity and parameter uncertainty in degradation modeling. Elwany and Gebraeel [9] and Armstrong and Atkins [2] developed renewal process based replacement and inventory control approaches. Noortwijk [32] discussed application of gamma process in degradation modeling and maintenance analysis.

In the structural engineering literature, Wen [34] and Ellingwood and Wen [7] utilized reliability analysis to formulate expected life-cycle cost functions and determine optimal design parameters of civil infrastructure (buildings, bridges) against earthquake loading. These approaches, sometimes called the performance based design (PBD), are the basis of many standards for structural design, including minimum design loads for buildings and structures (ASCE [1]). PBD allows one to determine the building design parameters and mitigation options (e.g., design loads and resistance) to optimize the structural performance during the design life based on the exceedance probabilities of certain limit states at a specific point in time (Barbato et al. [3]). Majority of the earlier studies in the PBD literature have used time-invariant fragility curves in the life-cycle cost calculations. However, some recent research have incorporated time-variant fragility functions within the PBD framework, including Ramanathan et al. [24] and Bisadi and Padgett [5], who develop fragility functions for use in optimal design of concrete bridges against earthquake hazards. The contribution of the method proposed in this paper is in the area of time-variant fragility modeling, by explicitly accounting for the deterioration of structural resistance and failure probability throughout the lifetime to determine the optimal retrofit time of aging components.

In wind engineering, the fragility function, or the conditional probability of failure at a given load, is commonly used to model the variation in failure occurrence under wind loads. Failure is assumed to occur when the wind pressure exceeds the component capacity for a given mode of failure. Fragility functions are often assumed to follow certain probability functions, where the lognormal distribution is one of the most commonly used probability distribution (Rosowsky and Ellingwood [27], Li and Ellingwood [17]). In most of the earlier studies the degradation of structural capacity over the lifetime is not considered and for estimating the fragilities, the resistance of new construction is used (Li and Ellingwood [17]). Recently, some studies considered component degradation for developing time-variant fragility. Dong and Li [6] and Salman et al., [30] studied the fragility of roof panels and power system poles, respectively. The former work is limited to developing time-varying fragility curves only (with no focus on retrofitting). However, the latter work is very similar to our proposed method in terms of the objectives and the scope, in that a formal preventive maintenance planning approach was presented by linking time-variant fragility of power system poles with life-cycle cost calculations. A major difference in our approach, however, is that our work provides a formal framework to account for the effects of uncertainty of wind loads in maintenance costs.

In structural maintenance literature, Jain and Davidson [14] studied how to forecast changes in wind vulnerability of a region's building inventory due to component aging, in addition to demolition and changes in building codes. Ellingwood and Wen [7] considered earthquake events and presented a PBD formulation to design buildings that achieve an optimal balance between costs and risks of failure while considering uncertainties in fragility models. Kappos and Dimitrakopoulos [16] applied life-cycle cost analysis to determine the optimal retrofit level for mitigating the earthquake risk. However, these approaches consider the static problem (capacity of new construction is used in the analyses) and the degradation of component capacity due to aging was not considered. Few approaches consider aging phenomena in structures. Barone and Frangopol [4] compared point-in-time performance indicators (similar to PBD) and lifetime distribution based approaches for maintenance of deteriorating bridges and suggested that an advantage of lifetime distributions is dealing with closed-form expressions, while annual performance indicators require approximate numerical methods such as First Order Reliability Method (FORM).

This paper takes a lifetime distribution based approach to maintenance of aging wooden buildings. The unique contributions of the proposed research are that it allows one (*i*) to determine the timing of mitigation actions by considering the capacity degradation over the lifetime due to aging by contrast to the existing approaches in wind engineering literature (*ii*) to estimate failure probability against rare hurricane events efficiently using an importance sampling approach and (*iii*) to quantify the uncertainty in the life-cycle costs due to variations in hurricane wind loading, by contrast to the existing approaches in structural maintenance literature which do not model maintenance cost uncertainty.

3. Proposed approach for estimating time-dependent fragility

In this section we present a new methodology to represent fragility curves of aging building components subjected to hurricane wind loading as a function of age. As illustration, toe-nail type roof-to-wall (RTW) connections are considered. A gamma-process based degradation model is used to model the capacity of aging RTW connections and to determine the fragility curve at a given age. Fragility curve of an individual connection is used to develop fragility curve of a roof-system that consists of a set of connections.

A commonly used alternative of gamma process in degradation modeling is Wiener process, which is defined as a Brownian motion with drift (Mishra and Vanli [21]). However, a limitation of Brownian motion is that because it is based on a Gaussian random variable that takes both positive and negative values it would not be a realistic approach for modeling the degradation in the capacity that monotonically decreases with the passage of time. For monotonic degradation processes that can be modeled as non-negative random variables, however, gamma processes have been used successfully in many applications (Van Noortwijk et al. [32]). In addition, the gamma process is very flexible and provides a generic formulation to most common random processes: when the value of the shape parameter is 1, the probability density function is equivalent to the exponential distribution; when the shape parameter is very large the density function approaches the Gaussian distribution and for the intermediate values of the shape parameter it provides an alternative to the lognormal distribution. Iervolino et al. [13] have used gamma capacity degradation model as the lifetime distribution and develop maintenance policy of buildings against earthquakes.

While most current structures use hurricane clips or straps as the roof-to-wall connection, toe nails are more common in older structures (built before hurricane Andrew 1992, often located in north or central parts of Florida). The proposed methodology is used to determine the most cost effective age of the roof to perform the retrofitting. It is assumed that a toe-nail type roof to wall connection is retrofitted to a much stronger roof-to-wall connection type, such as a hurricane clip. However, as the retrofitting procedure is rather labor intensive, it assumed that retrofitting is done once for the lifetime of the roof structure. Experimental data from Shanmugam et al. [31] for aging toe-nail roof to wall connections are used to formulate the models.