Journal of Building Engineering 2 (2015) 36–43

Contents lists available at ScienceDirect

Journal of Building Engineering

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

Condition-based updating of the fragility for roof covers under high winds

Bejoy Paruthyvalappil Alduse [a], Sungmoon Jung [a,*], O. Arda Vanli [b]

[a] Department of Civil and Environmental Engineering, Florida A&M University – Florida State University College of Engineering, Tallahassee, FL 32310, USA
[b] Department of Industrial and Manufacturing Engineering, Florida A&M University – Florida State University College of Engineering, Tallahassee, FL 32310, USA

ARTICLE INFO

Article history:
Received 17 February 2015
Received in revised form
7 April 2015
Accepted 11 April 2015
Available online 14 April 2015

Keywords:
Fragility
Winds
Hurricanes
Bayesian approach
Asphalt shingles
Unsealing
Force sensor

ABSTRACT

Fragility modeling is a commonly used approach to quantify the risk of a structure subjected to high winds. In order to overcome a limitation of conventional fragility models where the performance of the roof cover is assumed to be fixed, we propose a new framework for obtaining the fragility of roof covers under high winds. The approach models the capacity related terms as functions rather than fixed values. Therefore, it can describe gradual increase of failure probability as the roof cover degrades over time. The parameters for the capacity functions are obtained from sensor measurements. In order to overcome the uncertainties associated with the limited measurements, a Bayesian approach is employed. Although the proposed framework can be applied to any type of roof covers, an illustrative example is given for asphalt shingles. Results show the importance of considering degradation of the roof cover in obtaining the fragility. The proposed approach provides much more comprehensive fragility functions than conventional approaches by considering the degradation of the roof cover.

1. Introduction

The insured value of properties continues to rise in the U.S., which now exceeds $10 trillion in the coastal counties alone [1]. These counties often experience financial loss due to hurricanes. A roof cover is the main barrier against wind and rain for the roof of a building. However, many damage surveys report that roof covers can fail prematurely during a severe wind event [10,12,22,32]. An example of such failures is shown in Fig. 1 (RICOWI 2007). Roof cover damage can cause financial loss of up to 59% of the interior value of the house due to water intrusion and replacement cost ratios up to 6% of the value of the house (Florida Public Hurricane Loss Projection Model 2005). Jain [23] also reports that roof cover failure induces water penetration which causes damage to interior and contents.

Fragility modeling is a commonly used approach to quantify the risk of the roof cover subjected to hurricanes. A fragility is the conditional probability of failure of a structural member (or a system) for the given wind speed [28,31]. Fragility analysis has been widely used for various structures subjected to high winds such as wood-frame buildings [42], tall buildings [39], industrial buildings [29], and long-span bridges [37]. The fragility approach has also been adopted by the insurance industry [17,18].

While many researchers studied the fragility analysis under high winds, existing approaches have a major limitation. In obtaining the fragility, these approaches assume that building components maintain their initial conditions at the time of construction. Such assumptions stem from the research in earthquake engineering where structural performance of a building component (ex: a concrete column) experiences limited change over time. However, such assumptions are not valid for the roof covers that may experience significant performance degradation over time [40]. Another reason is lack of experimental data to develop more advanced fragility models. Recently, researchers in wind engineering began to work on this issue. Examples of new experiments are asphalt shingle research in University of Florida [13,14] and roof paver research in Florida International University [3,34]. These new efforts are expected to advance the fragility modeling under high winds.

The objective of this paper is to propose a new framework for obtaining the fragility of roof covers under high winds, considering gradual degradation of the roofing material. The proposed approach integrates the condition-based fragility model and monitoring [25] (and updating) of the condition using sensors. Such an idea has been studied for fragility updating considering corrosion [9,20,33], but not for wind engineering applications. On the other hand, wind engineering community has used sensors to assess the condition of the structure [21,30,43], but without using the fragility model. In this paper, we seek merits of both approaches to enhance the fragility assessment of roof covers.

Although an illustrative example for the proposed method is

* Corresponding author. Fax: +1 850 410 6142.
E-mail address: sjung@eng.fsu.edu (S. Jung).

http://dx.doi.org/10.1016/j.jobe.2015.04.003
2352-7102/

Fig. 1. Shingle loss during Hurricane Katrina, Photo#2.05-1, Courtesy: RICOWI (2007), Photographer: Bas Baskaran and John Goveia.

presented for asphalt shingles, the proposed framework can be applied to any type of roof covers. In addition, the degradation mechanism considered in this study is sealant detachment, which is the most commonly observed degradation mode and relatively easy to quantify using sensors.

2. Proposed approach

The proposed approach is composed of the condition-based fragility model, estimation of the capacity using sensors, and estimation of the demand. These will be explained in Section 2.1. A challenge in the capacity estimation is that the bulk of data is from the literature (that has capacity measurements but without sensor measurements) whereas additional data with the sensor measurement is limited. We employed a Bayesian approach to deal with this challenge, which will be explained in Section 2.2.

2.1. Condition-based fragility model

Fragility formulations quantify conditional probability of failure of a structural member (or a system) for the given loading [15,16,27,28]. A commonly used fragility formulation in wind engineering is:

$$F_R(y) = \Phi\left(\frac{\ln(y/m_R)}{\zeta_R}\right) \tag{1}$$

in which y is the demand variable, m_R is the median capacity, and ζ_R is the logarithmic standard deviation. $\Phi(\cdot)$ represents the standard normal probability integral. This model is based on the assumptions that (1) the capacity and the demand follow the lognormal distribution, and that (2) only the demand can change (ex: increase in member force due to the increase in wind speed) whereas the capacity does not change. The first assumption has been shown to be valid for many wind engineering problems (ex, see [31]), whereas the second assumption generally is not true for roof covers as explained in the introduction.

We adopt fragility updating models used in the corrosion modeling [9,20,33] so that degradation of the roof covers is reflected in the fragility estimation:

$$F_R(y, s) = \Phi\left(\frac{\ln(y/m_R(s))}{\zeta_R(s)}\right) \tag{2}$$

in which $F_R(y, s)$ is the fragility considering the degradation of the structure, s is the condition index measured from the sensor, $m_R(s)$ is the median capacity for the given condition, and $\zeta_R(s)$ is the logarithmic standard deviation for the given condition.

As evident from Eq. (2), the proposed approach needs to update

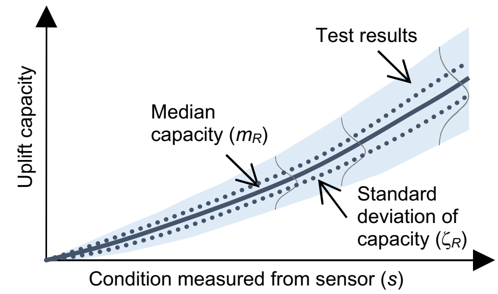

Fig. 2. Schematic illustration of the relation between sensor reading and uplift capacity.

capacity estimation using sensors. In particular the median and logarithmic standard deviation of capacity will be updated with new sensor data. Fig. 2 illustrates the relation between actual capacities of the roof cover (shaded area) and statistical representation of the capacity to be used with the fragility model (solid line: median, dotted line: standard deviation). Force sensors will be used to monitor and update the condition of the roof cover. Using the sensor measurement, the uplift capacity will be estimated. Further details will be explained when we present an illustrative example.

The demand y is typically estimated using the design code such as ASCE 7 (ASCE 2010). For a low-rise building, the demand on the component under study can be computed using the pressure:

$$p = q_h\left[(GC_p) - (GC_{pi})\right] \tag{3}$$

in which q_h is the velocity pressure evaluated at the mean roof height, GC_p is the external pressure coefficient, and GC_{pi} is the internal pressure coefficient. This equation can be used to estimate the demand on roof covers. However, the illustrative example that will be presented later uses asphalt shingles, and special equations are needed due to the pervious nature of them. These equations will be explained when we present the example.

2.2. Bayesian approach to integrate existing data and measured data

A challenge in the capacity estimation is that the bulk of data is from the literature whereas additional data with the sensor measurement is limited. Bayesian approach provides a rigorous framework to integrate available knowledge from the literature and observations made about an outcome of an event (in this paper, sensor data collection and uplift capacity testing) [4,19]. The prior knowledge and observed data can be used to generate posterior distributions, which are representative of possible outcomes. In other words, the posterior distribution is a weighted outcome of the prior and observed data. A closed form solution is preferred in implementing the Bayesian approach to save the computation time [19]. Hence in this study, the prior and posterior are assumed to be conjugate pairs, implying that both distribution belongs to the same category. Past research on wind engineering problems have shown the log-normal nature of capacities of different materials [31,41]. Hence this study uses log-normal distribution for the capacities.

The prior and posterior are assumed to be conjugate pair distributions. The prior distribution of the median uplift capacity before observation of the condition (sensor data) is assumed to follow a log-normal distribution:

$$f\left(m_R \mid \xi_R^2, R_1\right) = LN\left(\mu_0, \xi_R^2/\kappa_0\right) \tag{4}$$

in which μ_0 and κ_0 are the parameters of the prior, to be determined by the user from a set of historical capacity data R_1. The