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A RESILIENCE-BASED ASSESSMENT OF THE PERFORMANCE OF RESIDENTIAL COMMUNITIES SUBJECT TO HURRICANE HAZARD

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Hurricanes are among the most devastating and costliest natural hazards. This devastating impact urged governments and policymakers to implement mitigation plans and strategies that can enhance the community's resilience against hurricanes. A fundamental step to gauge the performance and effectiveness of these mitigations plans is to develop computational frameworks that can provide a probabilistic assessment of the resilience of the community. Therefore, this paper presents a framework to probabilistically estimate the resilience of residential wooden buildings against hurricane winds. The framework estimates the post-hurricane damage due to dynamic wind pressure and the impact of windborne debris using an engineering-based hurricane vulnerability. The building recovery function is then estimated by integrating the estimated damage with a building-level recovery model. By aggregating building recovery functions, the community recovery function is obtained. The Monte Carlo simulation method is used to account for uncertainties related to the hazard intensity, community vulnerability, and recovery process. The framework is applied to a residential neighborhood in Miami, FL. This framework can help decision-makers to compare current community resilience with target levels, identify the gap, and set strategies to improve community resilience.

Keywords: Natural hazards, Residential communities, Community resilience, Windborne debris, Monte Carlo simulation.

1 INTRODUCTION

The urgent need to mitigate hurricane-imposed risks has prompted researchers to develop vulnerability models that are capable of estimating post-hurricane damage and losses (Pita *et al.* 2015, He *et al.* 2017). On the other hand, governments and policymakers have adopted policies and strategies to increase the resilience of the community against hurricanes. To quantify the impact of these policies and strategies on enhancing community resilience, computational frameworks are required to be developed (e.g., Abdelhady *et al.* 2019a , Lin *et al.* 2019). These computational frameworks need to comprehensively model the response of the community to hurricanes by estimating the immediate damage and losses as well as the recovery trajectory of the community.

While existing literature focuses on estimating the immediate damage and losses (Pita *et al.* 2015, He *et al.* 2017), this paper presents a framework that integrates the estimated post-hurricane damage of residential wooden buildings with a probabilistic recovery model. Damage due to hurricanes can occur as a result of strong winds, flooding, and/or storm surge (Grayson *et al.*

2013, Masoomi *et al.* 2019, Do *et al.* 2020, Nofal and Van De Lindt 2020). This paper focuses on the damage due to strong winds and the associated windborne debris to residential wooden buildings as they constitute more than 60% of hurricane losses as reported by (Congressional Budget Office 2019). The output of the framework is a probabilistic quantification of the resilience of residential wooden buildings against hurricane winds. The framework is applied to a residential neighborhood in Miami, FL while considering two construction cases to show the framework's capabilities.

2 PROBLEM SETTING

Mathematically, the community resilience measure of interest is defined as shown in Eq. (1):

$$R = \frac{1}{T_R} \int_{t_E}^{t_E+T_R} Q(t)\, dt \tag{1}$$

where t_E is the time of event occurrence (i.e. hurricane impact); T_R is the community recovery time; and $Q(t)$ is the community recovery function at time t.

The estimation of both $Q(t)$ and T_R hinges on the hazard intensity, the community vulnerability, and the subsequent recovery activities (Abdelhady *et al.* 2020). Modeling uncertainties associated with all of these parameters is a key aspect to understanding community resilience. To this end, $\mathbf{X} = \{X_1, X_2, \cdots, X_n\}$ is defined as a random vector of the parameters required to model the hurricane hazard, community vulnerability, and recovery activities. To assess the resilience of a given community probabilistically, the cumulative distribution function of R can be estimated as follows:

$$F_R(r) = \Pr\,[R \le r] = \int \cdots \int_{D_R} f_{X_1,\cdots,X_n}(X_1, \cdots, X_n) dx_1 \cdots dx_n \tag{2}$$

where $f_{X_1,\cdots,X_n}(X_1, \cdots, X_n)$ is the joint probability density function of the random variables; $D_R = \{\mathbf{X} \in \mathbb{R}^n | g(\mathbf{X}) \le r\}$; and g is the resilience function that maps $\mathbf{X}$ to R (i.e. $R = g(\mathbf{X})$). Deriving a closed-form solution for Eq. (2) is intractable, therefore a stochastic simulation approach is proposed to solve Eq. (2).

3 PROPOSED SIMULATION-BASED FRAMEWORK

An overview of the simulation strategy is shown in Figure 1. The framework estimates the post-hurricane damage to the buildings using the engineering-based vulnerability model outlined in (Abdelhady *et al.* 2019b). This estimated damage is used as an input to a building-level recovery model which identifies the building recovery function (shown in Figure 2) based on its pre-defined resilience limit state. More details about this process can be found in (Abdelhady *et al.* 2020).

The community recovery function is then obtained by aggregating building recovery functions. Uncertainties associated with the hurricane hazard, the community vulnerability, and the recovery activities are handled using the Monte Carlo simulation method. The result is a probabilistic quantification of the resilience measure (R) for any given community where F_R is estimated as shown in Eq. (3):

$$F_R(r) = \Pr\,[R \le r] \approx \frac{1}{N_{MC}} \sum_{l=1}^{N_{MC}} \mathcal{I}^{(l)}(R_l) \tag{3}$$

where N_{MC} is the number of samples in the Monte Carlo simulation method, and $\mathcal{I}$ is the indicator function which is defined as follows (Eq. 4)):

$$\mathcal{I}^{(l)} = \begin{cases} 1, & R_l \leq r \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

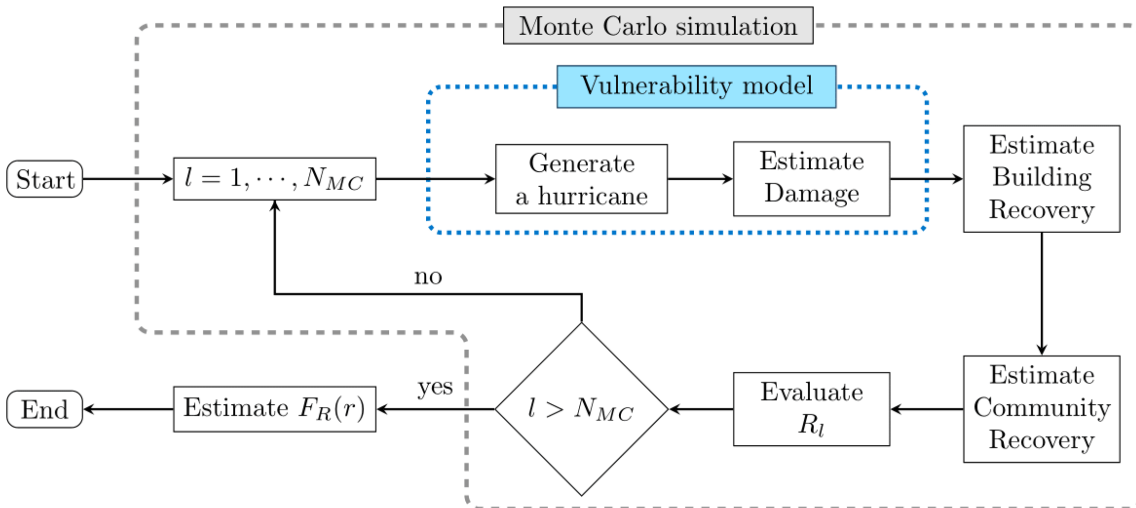

Figure 1. Flowchart of the proposed framework.

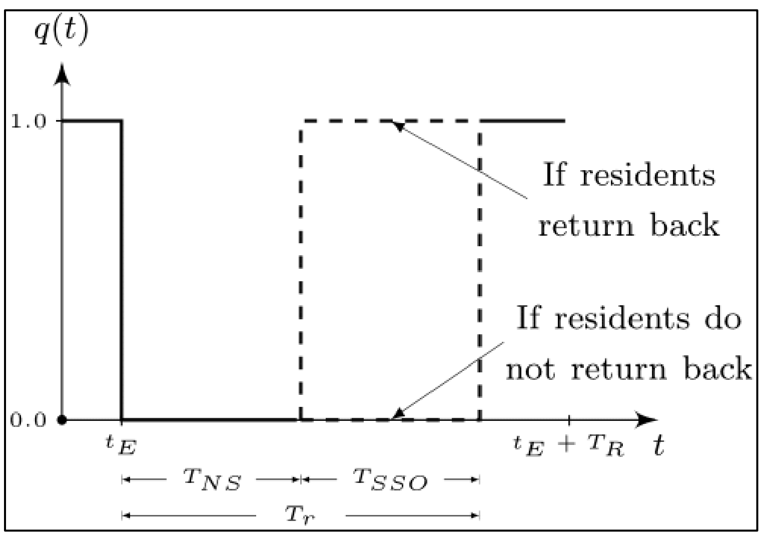

Figure 2. Conceptual representation of the building recovery function.

4 CASE STUDY

4.1 Description

The presented framework is applied to a residential neighborhood in Miami-Dade County, FL to assess its resilience to hurricane winds, as shown in Figure 3. The residential neighborhood consists of 513 buildings. To accurately estimate damage from windborne debris the buildings surrounding the considered community are modeled as a source of potential windborne debris. Two construction cases are considered which are summarized in table 1: (1) as-built: which is representative of the building stock in Florida; and (2) enhanced: in which enhancements have been applied to the wall-roof connection capacity as well as the building envelope components (e.g., roof sheathing, covering, windows, doors, etc.).

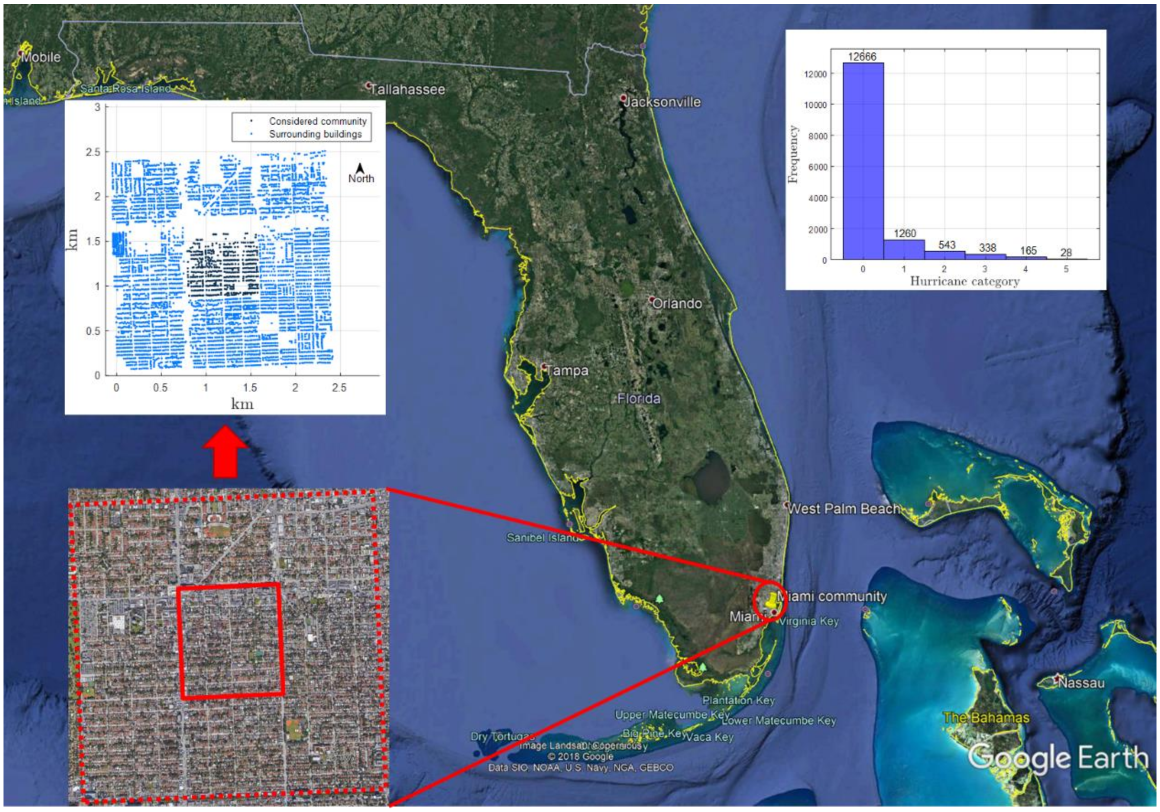

Figure 3. The community layout and hurricane distribution.

4.2 Results and Discussion

The upper right inset in Figure 3 shows the distribution of hurricane category for the generated hurricanes, $N_{MC} = 15{,}000$. In this case study, three target resilience levels are used to assess the performance of the community against various hurricane categories: (1) $r_T = 60\%$, (2) $r_T = 80\%$, and (3) $r_T = 90\%$. Figure 4 summarizes the performance of the community using the probability of exceeding r_T (i.e. $1 - F_R(r_T)$).

As the hurricane category increases the probability of the community exceeding the target resilience level decreases, Figure 4. the effect of the mitigation plans applied to the enhanced case is reflected in the increased probability of resilience target exceedance. As the severity of the hurricane increases, the performance gap between the as-built and the enhanced case increases. For example, at $r_T = 60\%$ the performance gap is 0%, 5%, 64% for category 0/1, 2/3, and 4/5, respectively. This variation in the performance gap across hurricane categories implies the need to convolute the community performance with the site-specific hurricane hazard curve to determine the efficiency of applying any mitigation plan.

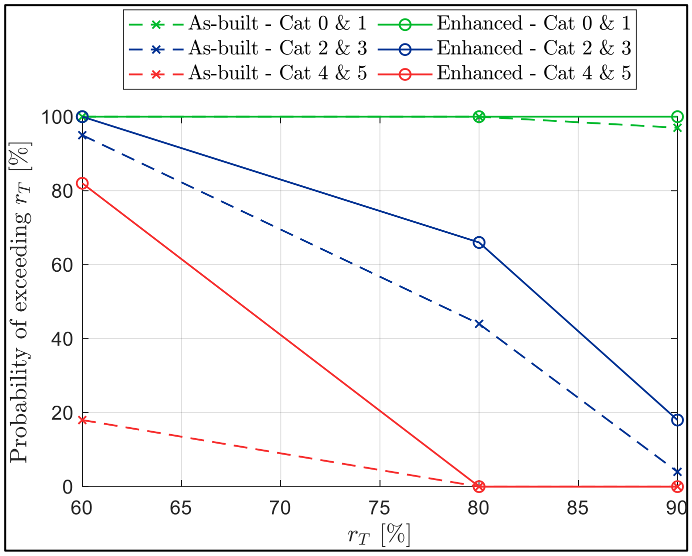

Figure 4. Probability of exceeding the predefined target resilience levels.

Table 1. The building components' resistance for the as-built and enhanced construction cases.

Building Component	Mean resistance		COV	Distribution
	As-built	Enhanced		
Wall sheathing	6.00 kPa	8.70 kPa	0.40	Normal
Roof sheathing	7.20 kPa	8.70 kPa	0.40	Normal
Wall cover	3.20 kPa	6.20 kPa	0.20	Normal
Roof cover	3.35 kPa	6.20 kPa	0.40	Normal
Windows	2.50 kPa	2.50 kPa	0.20	Normal
Doors	4.80 kPa	4.80 kPa	0.20	Normal
Roof-wall connection	16.50 kN	20.00 kN	0.20	Normal

5 CONCLUSIONS

A stochastic simulation-based framework for the quantification of the resilience of residential wooden buildings probabilistically is presented. The framework is based on the integration between an engineering-based vulnerability model with a novel recovery model to assess the performance of the community based on the resilience measure, R. Modeling uncertainties in the hazard intensity, the community vulnerability as well as recovery activities are achieved using the Monte Carlo simulation method. Applying the framework to assess the performance of a residential neighborhood in Miami, FL shows the significance of the probabilistic quantification in understanding community resilience. This framework provides insightful information for researchers and policy-makers that can help to enhance the community's resilience against hurricanes and identify strategies to mitigate hurricane-imposed risks.

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