A Scenario-based Approach for Hurricane-Induced Wind Risk Analysis in Urban Areas

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ABSTRACT: This study presents a new framework for simulating hurricane-induced winds of a scenario event to predict community-level building damage and socioeconomic losses. The approach employs historical hurricane data to identify storm trajectories and determines peak gust wind speeds at building sites using an empirical model to account for the spatial variation of wind intensities. The building damage states are then simulated stochastically using HAZUS fragility functions, gust wind speed, and randomly generated numbers. Building damage information is then used for evaluating social consequences using potential household dislocation, employment disruption, and school closures. The application of the framework is demonstrated using a virtual testbed that is built based on the hurricane-prone community of Onslow County, North Carolina. Results can be used for risk-based decision-making to improve coastal community resilience.

KEYWORDS: Hurricane-induced winds, vulnerability analysis, loss estimation, social impacts.

1 INTRODUCTION

Hurricanes pose a great threat to coastal communities and often result in severe damages to the buildings and substantial social and economic disruptions (Kakareko et al. 2017). Recent hurricanes (e.g., Hurricane Matthew, Hurricane Florence, Hurricane Michael) severely impacted underprepared communities indicating the need for reliable hurricane risk prediction at the community level to better prepare for future events. Post-disaster studies highlight research needs to mitigate (e.g., NIST 2017) the risk of natural hazards. Accurate estimation of the damage that hurricanes can pose to buildings at the community level is a major challenge (Deierlein et al. 2020). The majority of past research has focused on assessing damage and loss following a hurricane instead of developing methods for simulating hazardous winds considering spatially varied winds at the community scale. Past studies have contributed to better understanding the performance of various structures against hurricane hazards (Pinelli et al. 2004; Li and Ellingwod 2006; Xu and Brown 2008; Salman and Li 2018). However, most of these studies (e.g., Pinelli et al. 2004; Vickery et al. 2006; Li and Ellingwood 2006; Kakareko et al. 2017; Salman and Li 2018) that estimate hurricane damage and loss are limited to evaluating individual structure's performance. Moreover, current design standards and building codes focus on analyzing individual building performance and do not specify any guideline to estimate the building damage portfolio at a community scale (Adhikari et al. 2021).

To mitigate the consequences of future hurricane hazards for a community, the possible impacts of a potential hurricane need to be estimated considering spatially varying wind intensities. A scenario-based analysis is preferable for developing the community-level building damage portfolio as it allows the modeling of spatially distributed wind intensities. Hence, this study formulated a scenario-based hurricane risk assessment framework to estimate the community-level building damage portfolio considering spatially distributed hurricane wind speeds. While hurricanes typically cause heavy rainfall and high storm surges alongside strong winds, this paper only discusses wind-induced impacts. Direct economic losses are estimated based on physical building damage. In addition to economic loss, important social consequences of physical building damage are estimated in this study, including household dislocation, employment disruption, and students' school disruption. These social impacts significantly affect the community's recovery trajectory (Masterson et al. 2014), whereas most existing hurricane risk assessment models estimate physical damages to the built environment and their direct economic losses only (e.g., Pinelli et al. 2004; Vickery et al. 2006; Kakareko et al. 2017; Adhikari et al. 2021). The framework is demonstrated using a virtual testbed of the hurricane-prone community of Onslow County, North Carolina.

2 METHODOLOGY

The proposed framework is developed utilizing recent research on hurricane wind field modelling and wind fragility functions for building to estimate likely damage. The framework also integrates occupancy data to estimate the likely social and economic impacts of a severe hurricane on a coastal community. The framework consists of three modules: (1) hazard analysis, (2) vulnerability analysis, and (3) loss estimation modules, as illustrated in Figure 1. In the hazard analysis module, building-specific peak gust wind speeds are determined for a hurricane scenario where characteristics of the hurricane are obtained from the HURDAT2 database, including path trajectory and wind speed distribution. In the vulnerability analysis module, the probability of exceeding four damage states (i.e., minor, moderate, severe, and complete) of a building is determined using HAZUS fragility functions and peak gust wind speed. A damage state is then assigned to each building stochastically by comparing the peak gust wind speed, damage state probabilities, and a randomly generated number. Finally, in the loss estimation module, direct economic losses resulting from physical damages are evaluated using building damage ratio and building replacement values. Social impacts are assessed by estimating the number of dislocated households, potential employment disruption, and the number of students who are likely to lose their access to school.

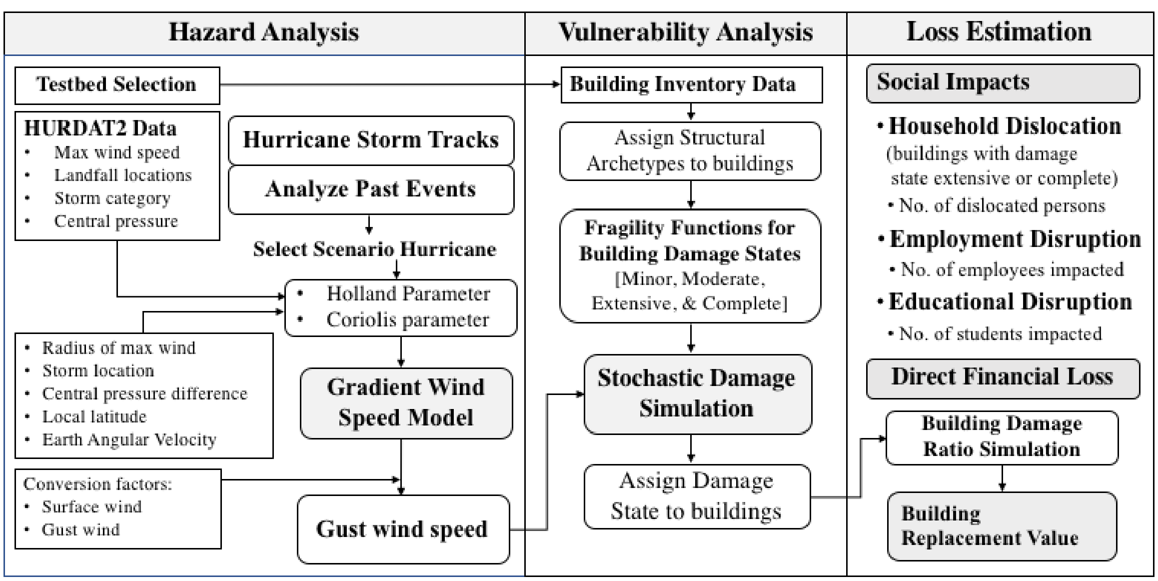

Figure 1: Hurricane risk analysis framework

2.1 *Hurricane Wind Hazard*

Evaluation of hurricane damage to buildings requires estimation of peak gust wind speed at each building site. The wind field model allows estimating the spatial variation of the wind speed over a large area (Salman and Li 2018). The Holland pressure profile parameter is used for estimating the peak wind speed for buildings at any time instant during a hurricane. The strongest hurricane wind occurs at the hurricane eye wall, and wind intensity decays as the location moves away from the hurricane center (Xu and Brown 2008). Gradient wind speed at building location is estimated using the radial wind profile model provided by Holland (1980), as follows:

$$V_G = \left[\left(\frac{R_{max}}{r}\right)^B \cdot \left(\frac{B\Delta p \cdot \exp\left[-\left(\frac{R_{max}}{r}\right)^B\right]}{\rho}\right) + \frac{r^2 f^2}{4}\right]^{\frac{1}{2}} - \frac{rf}{2} \tag{1}$$

where R_{max} is the radius of the maximum wind speed, r is the distance from hurricane eye to the building site, B is the Holland pressure profile parameter, Δp is the central pressure difference estimated subtracting central pressure from atmospheric pressure of 1013 millibars, ρ is the air density, and f is the Coriolis parameter (=$2\Omega \cdot \sin\varphi$, where φ is the latitude, Ω is the earth's angular velocity) (Xu and Brown 2008). The radius of the maximum wind is estimated using the model provided by FEMA (2012), as below:

$$\ln R_{max} = 2.556 - 0.000050255\Delta p^2 + 0.042243032\psi \tag{2}$$

where ψ is the storm latitude and Δp is the central pressure difference. Holland pressure profile parameter is estimated using the model developed by Powell et al. (1998), as follows:

$$B = 1.881 - 0.00557R_{max} - 0.01097\psi \tag{3}$$

A conversion factor that ranges from 0.8 to 0.86 depending on weaker to strong hurricanes is used to convert gradient wind speed to surface wind speed (Vickery et al. 2000). Building damage during due to hurricane is generally associated with the peak gust wind speed. Hence, the surface wind speed is further converted to 3-s gust wind speed, multiplying surface wind speed by a gust wind factor of 1.287 (Xu and Brown 2008; Salman and Li 2018).

2.2 *Vulnerability Analysis*

The vulnerability analysis involves assessing the expected physical damage to each building conditioned on wind speed (Pita et al., 2004). Wind fragility functions provide the probability of exceeding various structural damage states given wind speeds for different building types. Four potential damage states defined in the HAZUS Hurricane model are used for damage analysis of buildings (FEMA 2012) in this study. Figure 2(a) provides simplified definitions of four damage states. The probability of exceeding these four damage states of an individual building is estimated using fragility functions, as shown in Figure 2(b), which provides the probability of exceeding minor, moderate, severe, and complete damage states given the peak gust wind speed. A community's building portfolio is often composed of a large set of structural archetypes. HAZUS Hurricane Model offers a wide range of fragility functions for various archetypes developed based on damage statistics of hurricane simulation (FEMA 2012). Hence, fragility functions provided in HAZUS were fitted to lognormal distributions to obtain fragility parameters.

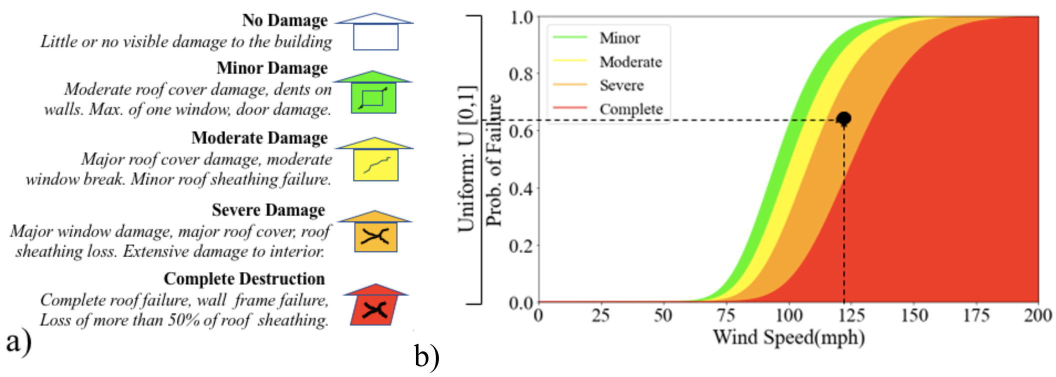

Figure 2: a) Damage states; b) Damage simulation

2.3 *Damage Simulation*

After estimating the peak wind speeds for a building, the probability of damage is generated using the appropriate fragility functions for the building structural archetype. The expected damage state is then assigned to the building stochastically based on the maximum peak wind speed, and a random number generated on a uniform distribution U[0,1] (Mazumder et al. 2020). The intersection point of x-axis (i.e., maximum peak wind speed) and y-axis (i.e., random number) values indicate the damage state for a particular building for a single realization, as shown in Figure 2(b).

2.4 *Direct Economic Loss*

Direct Economic loss caused by hurricane winds is determined using the expected damage ratio, and building replacement value. Damage ratios for none, minor, moderate, severe, or complete damage states are assumed as 0%, 2%, 10%, 50%, and 100%, respectively (FEMA 2012, p 7-11). These damage ratios represent the percentage of total building value losses. Uncertainty in damage ratio for each building is modeled using a normal distribution with a mean damage ratio and a coefficient of variation (COV) of 0.05. Total direct financial loss for a community is estimated as follows:

$$\mathrm{Cost}(\$) = \sum_{\mathrm{i}}^{\mathrm{n}} \%\ \mathrm{of\ damage}|\mathrm{DS}_i|\mathrm{v}_i \times \mathrm{BRV}_i \tag{4}$$

where DS_i , v_i and BRV_i are the damage state, the peak gust wind speed and the building replacement value for *i*-th building, respectively, and *n* is the total number of buildings.

2.5 *Social Consequences*

The proposed framework evaluates social consequences using the number of dislocated housing units, the number of commercial buildings and schools experiencing severe and complete damage to predict the number of community members who may face employment disruption and the students likely to lose access to school. The number of dislocated persons was estimated by multiplying the average household size (i.e., 2.72 per household) by the number of dislocated housing units (U.S. Census Bureau 2021). Employment interruption is assessed using the number of employees estimated for each commercial building damaged severely or completely thus prohibiting use of the building. Education loss is evaluated using the number of students attending each school building damage severely or completely. For general office, retail, industrial, recreation, education, and other buildings, the number of occupants is estimated based on the number of users per building footprint from the U.S. Green Building Council (USGBC 2019) and National Fire Protection Association Life Safety Code (NFPA 2021). Table 2 presents the details and references used to compute the number of occupants for each building type.

Table 2: Occupancy counts

Occupancy Type	
Residential Buildings	***Number of residences per building***
Duplex, Beach Duplex	2 units × (2.72 occupants per unit *)
Beach House, Mixed-Use (Residential /Commercial), Multi-Section MH, Single-Family, Singlewide M/H	1 unit × (2.72 occupants per unit)
Beach Condo, Beach Town Home, Condominium, Town Home	Number of tax parcels assigned to these buildings × (2.72 occupants per tax parcel)
Apartment, Multi-Family	No. of units × (2.72 occupants per unit)
Commercial Buildings	***Gross square feet per employee *****
Medical Building	225
Offices/Services	250
Restaurant	435
Retail	550
Auto Service	600
Conversion, Public Buildings	750
Theater/Recreation, Hotel/Club, Motel	1500
Special/Institutional	3000
Education, Daycare (DC)	630
Education, K-12	1300
Education, Postsecondary (PS)	2100
Warehouse/Industrial, Distribution	2500
Warehouse/Industrial, Storage	20000
Educational Buildings	***Gross square feet per student *****
Education, Daycare (DC)	550
Education, K-12	140
Education, Postsecondary (PS)	150

* US Census Bureau (2021)

** U.S. Green Building Council (2019) and NFPA (2021)

3 EXAMPLE COMMUNITY: ONSLOW COUNTY, NORTH CAROLINA

The proposed framework is examined through its application to the community of Onslow County, NC. The county is home to more than 197,000 people with an area of nearly 2,000 km^2 (Onslow County 2021). Onslow County has experienced 17 hurricanes in the past 40 years (NOAA 2021), making it an important area for hurricane risk analysis. The Onslow testbed contains 72,089 buildings assigned 22 HAZUS building structural archetypes, including residential buildings, manufactured homes, commercial and industrial buildings. The Onslow testbed is developed in this study using information obtained from the county government website, ReferenceUSA, OpenStreetMap, and Google Map. Hurricane Helene (1958), the strongest hurricane to pass within a 100 km radius of Onslow County in the past 160 years, was adopted here for estimating the potential damage and losses. Figure 3 provides the spatial distribution of building structural archetypes, hurricane track, peak gust wind intensity map, and building damage portfolio.

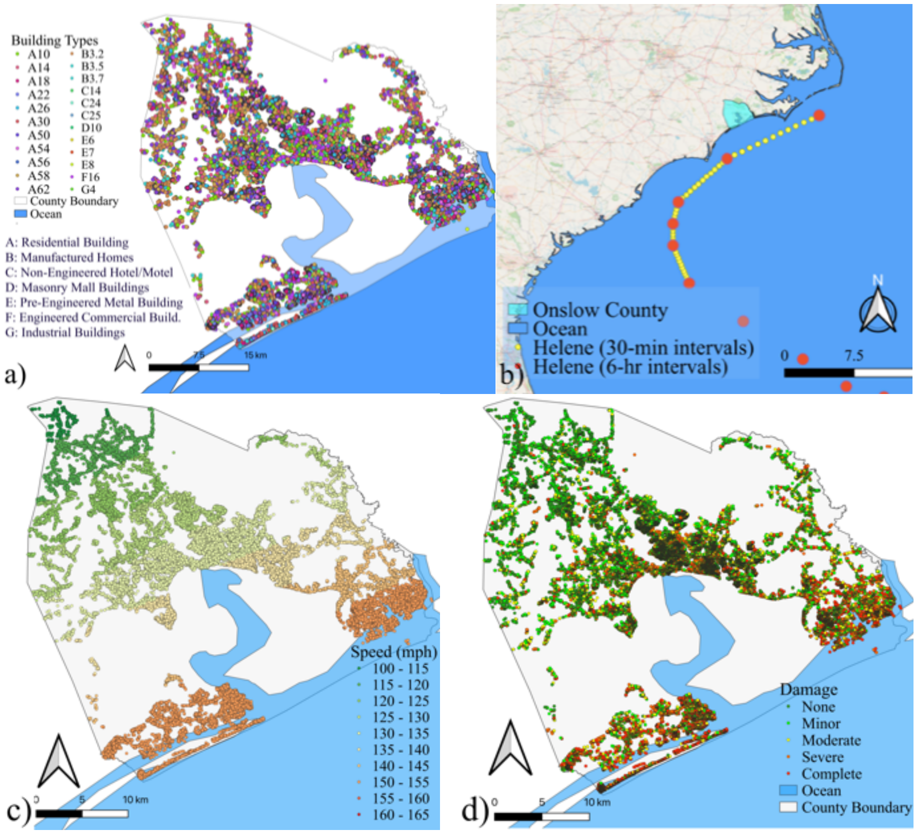

Figure 3: Onslow testbed: a) building inventory, b) Hurricane Helene track, c) max. peak gust wind speed, and d) building damage portfolio.

Onslow testbed contains 65,968 residential buildings consisting of 73,792 housing units, 5,681 commercial buildings, and 440 school buildings across the 72,089 buildings. The average maximum gust wind speed for the testbed buildings due to Hurricane Helene is 217.3 km/h. Hurricane Helene caused about 25.6% of residential buildings (23% of the total population) to experience either severe or complete damage, and \$10,350 million USD financial losses. Household dislocation, employment disruption, and school closure were used as proxies for the social impact caused by Helene. Using the numbers from Table 2, Helene caused 38,097 employment disruption and resulted in school closure for 11,492 students. People working in general office/services and retail are expected to experience significant employment disruption due to the hurricane Table 3 summarizes the estimated social consequences at Onslow County due to Hurricane Helene.

Table 3: Potential dislocated household, disrupted employment and education counts

Building Use	**No. of buildings/units**
Dislocated housing units	19,170
No. of dislocated persons	44,686
Severely/completely damaged commercial buildings	3,912
No. of employees impacted	38,097
Severely/completely damaged school buildings	156
No. of students impacted	11,492

The maximum gust wind speed due to Hurricane Helene was recorded as 241 km/h. This study simulated the maximum wind speed for Hurricane Helene is 240 km/h, which is very close to recoded maximum wind speed.

4 CLOSING REMARKS

The proposed analytical approach generates building damage portfolio, direct economic loss, and select social consequences in a community that can help prioritize resources in urban hurricane risk mitigation planning. The framework also demonstrates how building damage impacts the community's social system. While existing approaches focus on determining individual building performance, this community-level approach estimates peak gust wind speeds at building sites considering the spatial variation of wind intensities. These findings assist decision-makers in shaping future policies to improve community disaster resilience. The scenario hurricane analysis results were verified by comparing predicted wind speed intensities with recorded wind speed data. This model can be further validated for other hurricane scenarios where physical damage information is available.

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