

Tree-Induced Damage Vulnerability Model for Low-Rise Buildings

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ABSTRACT: Windstorms are a significant natural hazard that can cause severe damage to both natural and built environments. In regions with dense tree coverage, the risk is especially high as strong winds can uproot or break trees, which then damage buildings and infrastructure. This threat is particularly pronounced in urban and suburban areas, where trees are often planted close to buildings, increasing the likelihood of tree-induced damage during hurricanes. This study develops a vulnerability model to assess the risk of tree-induced damage to low-rise buildings. The model incorporates various variables, including different tree species, tree densities, and wind conditions, to simulate potential damage outcomes under various scenarios.

KEYWORDS: Vulnerability modeling, risk assessment, wind-induced tree fall, Monte Carlo simulations, Florida Public Hurricane Loss Model (FPHLM)

1 INTRODUCTION

Severe wind events, especially hurricanes, continue to present major risks to infrastructure and communities throughout the United States. Since 1980, the country has experienced more than 400 weather and climate disasters, each generating losses of at least \$1 billion and together totaling over \$2.785 trillion. In 2024 alone, up to November 1, there were 24 billion-dollar disasters, including 17 severe storms and 4 tropical cyclones, which caused 418 deaths and significant economic impacts. The frequency of such costly disasters has risen sharply, averaging 20.4 events per year over 2019–2023, compared with 8.5 annually since 1980 (NOAA, 2024).

Florida is among the most heavily impacted states, with 93 weather and climate disasters surpassing \$1 billion in damages since 1980. These include 35 tropical cyclones, 33 severe storms, and other major events. Due to its geographic setting and climate, Florida is highly vulnerable to hurricanes, which inflict damage both directly—through intense winds—and indirectly through secondary hazards such as falling trees (NOAA, 2024).

Tree failures during hurricanes intensify the damage caused by high winds, adding further destruction to buildings, power lines, and other infrastructure. Following Hurricane Andrew in 1992, the University of Florida’s Institute of Food and Agricultural Sciences (UF/IFAS) began extensive research on hurricane impacts to urban forests (Duryea, 2007). Their studies across ten hurricanes showed that urban forest losses ranged from 11% to 38%, with higher wind speeds strongly linked to increased tree failure (Duryea, 2007). As shown in Figure 1, tree vulnerability

risers sharply with wind intensity—demonstrating that stronger hurricanes substantially increase the likelihood of tree loss.

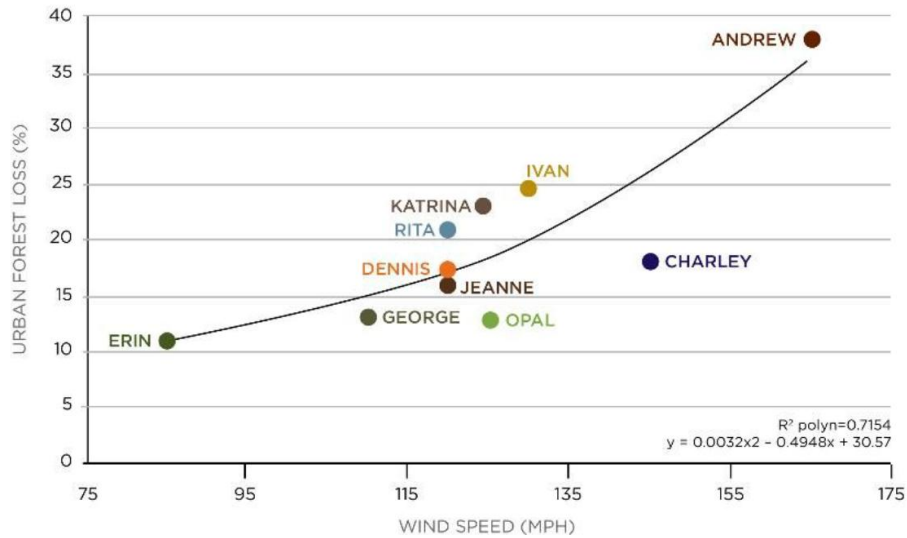


Figure 1: Urban Forest loss (%) at different wind speeds (mph) in 10 hurricanes ((Duryea, 2007)).

Taken together, trees in residential communities are a major cause of damage to low-rise buildings, power lines, and other infrastructure during hurricanes (Jason Cole, 2021). Also, they contribute to serious traffic interruptions and pose safety hazards, complicating emergency response and recovery efforts.

To address these challenges, this paper presents the development of a probabilistic vulnerability model for assessing tree-induced building damage during hurricanes. While the focus here is on the formulation and validation of the tree-damage model, its integration into catastrophe modeling frameworks—such as the Florida Public Hurricane Loss Model—is envisioned as a future extension. Incorporating tree risk into portfolio analyses will ultimately enable more comprehensive evaluation of hurricane losses by accounting for both wind effects and tree failures, thereby improving insurance loss estimation and supporting more effective risk management strategies.

2 METHODOLOGY

First, the team developed tree vulnerability and fragility curves for seven tree species, categorized into deciduous and coniferous (Ahmed, F. et al. 2022; Ibrahim, H. A. et al. 2025). Second, the team developed a scenario-based approach to assess wind-induced tree damage on various building classes with different building strengths and materials. For each scenario, the tree density goes from 1 tree to 20 trees in one tree increments for a given tree species. These densities are also categorized into low, medium, and high density. Each scenario maximum wind speed at 10m over actual terrain varies from 50 to 250 mph in 5 mph increments, and the wind direction from 0° to 360° in 45° increments. For each building class, tree species, tree density, and combination of wind direction and speed, the model performs 2000 Monte Carlo simulations (Figure 3).

In each simulation, for each tree quantity (e.g., 3), we randomize the location and crown diameter for each tree in that group (e.g. trees 1, 2, and 3). If trees fall, and if they strike the house, we record the impact energy, which is then used to derive the building damage ratio through a predefined damage function. These functions relate the impact energy to the expected damage based on physical tests conducted at Clemson University (HAZUS-MH 2022). In cases where multiple trees hit the house, we accumulate the damage caused by each fallen tree to estimate the total impact on the structure. This approach ensures that both individual and combined tree impacts are considered in the overall damage assessment.

The simulations result in damage vectors, for each combination of wind speed and direction, where each row corresponds to the output of an individual simulation. The vectors for the different wind directions, given a wind speed can be combined.

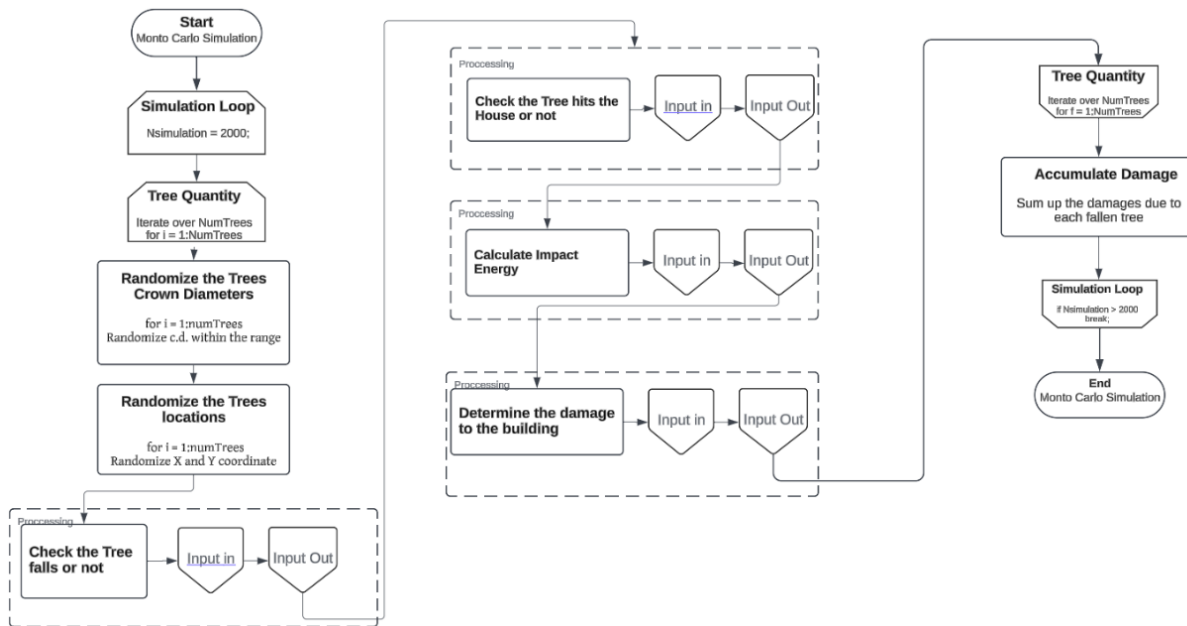


Figure 2: Vulnerability model for tree-induced damage to buildings- MC simulations: Random variables

3 FINDINGS AND IMPLICATIONS

The results are presented as a damage matrix, where each row corresponds to the output of an individual simulation. The columns of the matrix represent three-second gust wind speeds. Aggregated damage ratios are used to develop unweighted vulnerability matrices, where each cell represents the conditional probability of a specific building damage ratio, given a particular wind speed interval. Then the vulnerability curves are simply the mean values of the probability mass functions as a function of wind speed. Furthermore, a structured nomenclature has been developed, to provide a standardized way to reference and distinguish between different scenarios, variables, and outputs (such as tree species, building types, and density levels) across simulations, facilitating easier interpretation, reproducibility, and collaboration in the research.

Below, some examples of the vulnerability curves are presented, conditioned on building class, tree types, and numbers, and wind conditions:

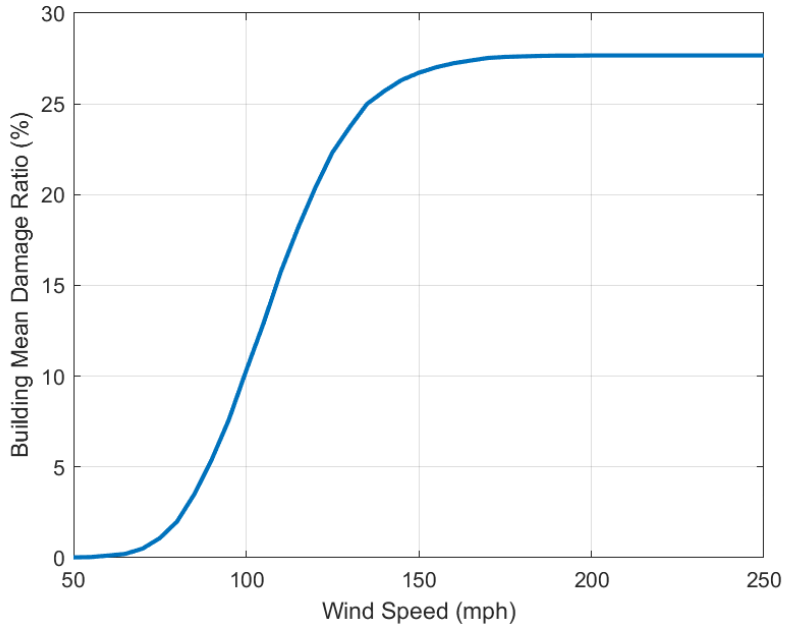


Figure 3: Vulnerability curve for Loblolly Pine with a single tree – 1-story timber building

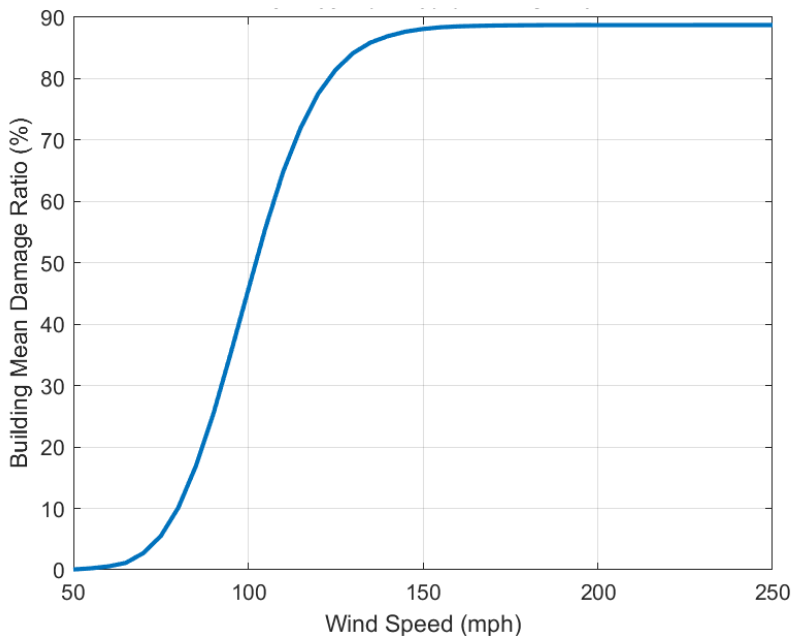


Figure 4: Vulnerability curve for Pine Shortleaf with 10 trees - 1-story timber building

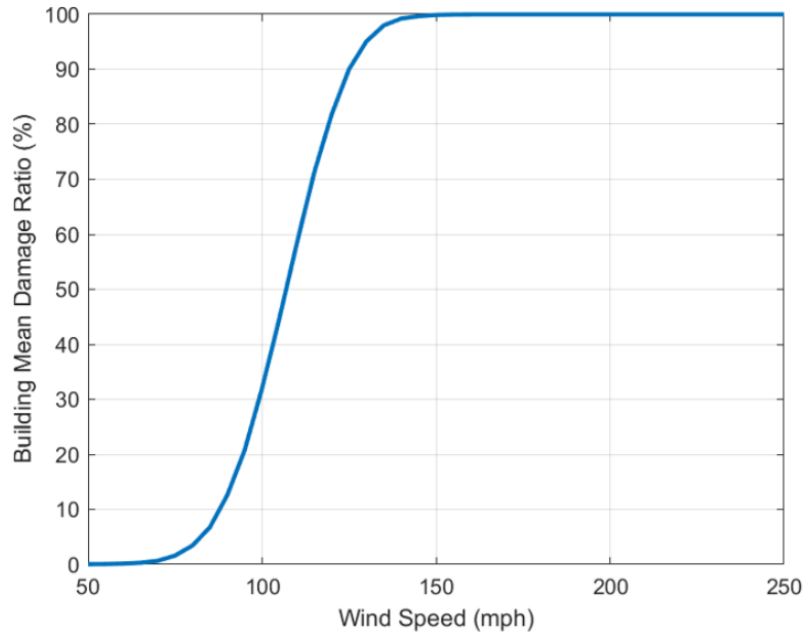


Figure 5: Vulnerability curve Slash Pine with 20 trees. - 1story timber building

Also, weighted vulnerability matrices are derived by combined the vulnerability matrices for different combinations of species (e.g. deciduous vs. coniferous), and different tree density levels (e.g. low, medium, or high), after calibrating, and validating the initial unweighted curves. Weighted vulnerability curves are shown for a 2-story, medium-strength timber structure, considering coniferous tree species under varying tree densities (low, medium, and high) (Figure 7). These weighted curves can provide a more generic representation of tree building vulnerability across different scenarios.

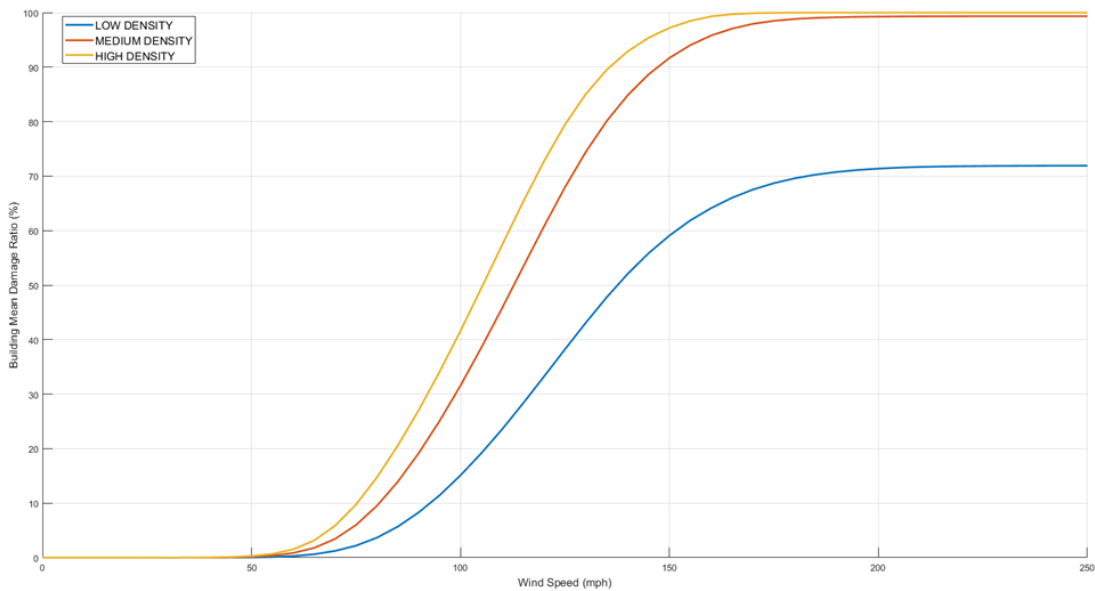


Figure 7: Weighted vulnerability curves (2-Story Medium-Strength Timber Structure), Tree species (coniferous), and Tree Density (Low, Medium, High)

4 VALIDATION AND CALIBRATION

The calibration and validation of the model using reconnaissance data from previous hurricane datasets, such as detailed damage reports from Hurricane Michael (2018) focusing on tree-induced building damage, is currently under evaluation (Roueche et al., 2020). The damage assessment data gathered through Fulcrum offers comprehensive insights into tree-induced building damage and wind effects during Hurricane Michael (2018), documenting structural features, damage conditions, and environmental hazards observed on-site. (Roueche et al., 2020; NHERI DesignSafe, 2018) The following data, derived from Fulcrum, can be accessed in the archive at StEER. The building, a two-story single-family home built in 1974, sustained severe damage, including 40% roof cover loss, 20% roof structure damage, and 10% wall structure damage (Figure 8)



(a)



(b)

Figure 6: Tree damage to building – Hurricane Michael - Blounstown, FL. (a) south-facing perspective; (b) north-facing perspective.

The damage ratios obtained from the collected data represent physical damage ratios and must first be converted into monetary damage ratios. In addition, the assessment is expanded to account for interior damage to the building. The case will then be assigned the corresponding wind speed at which the damage occurred, using a Jupyter-based tool developed for this purpose. The final step involves verification and validation of the results to ensure consistency and reliability of the model. All these tasks are currently in progress.

5 FUTURE WORK

This is a work in progress. The resulting library of vulnerability curves offers a way to project damage due to tree fall during hurricanes, providing that tree density and species make-up are known at the peril's location. A tree hazard characterization study is underway, to gather statistics on tree hazard at any given location.

The accuracy of the damage functions depends to a large extent on the relationship between damage and tree impact energy. The current relationship between damage and energy comes from crude steel pipe drop tests at Clemson University from the 1990's. These tests results suffer from lack of documentation and various uncertainties, and a lot of engineering judgment is needed to extrapolate them to real conditions. A better understanding of the impact energy of falling trees, the contribution of the kinetic energy from the wind, and its effect on different construction types is essential to develop a reliable model. That includes a realistic estimate of size of tree-induced envelope breaches, which is also critical to estimate interior and contents damage due to rain ingress.

6 CONCLUSION

A probabilistic vulnerability model quantifies the risk of tree-induced damage to low-rise buildings during hurricanes. By incorporating species-specific fragility curves, tree densities, wind conditions, and building characteristics into a Monte Carlo simulation framework, the model provides a structured methodology for evaluating the compound effects of wind and tree failure on the built environment. Initial results demonstrate the model's capacity to generate vulnerability curves and matrices across diverse scenarios.

Ongoing calibration of the model using reconnaissance data from hurricanes such as Michael (2018) is in progress, which are essential for validating and improving the accuracy of the model. This model should enable more realistic loss projections and serve as a foundation for integrating tree-induced damage into broader catastrophe models, such as the Florida Public Hurricane Loss Model (FPHLM). By addressing a critical gap in current risk assessments, the approach has the potential to enhance insurance portfolio analyses, support urban resilience planning, and ultimately reduce the economic and societal impacts of future hurricanes.

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