IN-VENTO 2026
International Conference of the Italian Association for Wind Engineering
Bari, September 13th – 16th, 2026

BARI

Integrated Hurricane Vulnerability Assessment of Low-Rise Buildings Considering Tree- and Wind-Induced Damage

Mohammad Bakhshandeh[1], Jean-Paul Pinelli[1], Fouad Elazaka[2], Haitham A. Ibrahim[2], Amal Elawady[2]

[1]*Florida Institute of Technology, Melbourne, FL, USA*
[2]*Florida International University, Miami, FL 33174, USA*

SUMMARY
Hurricanes can cause severe building damage through both direct wind forces and the impact of falling trees. Strong winds may cause tree failures, and falling trees often strike nearby structures, increasing overall hurricane losses. Conventional vulnerability models generally consider these hazards independently, potentially underestimating damage in communities with substantial tree cover. This study evaluates an integrated vulnerability framework that combines tree-induced and wind-induced damage within the Florida Public Hurricane Loss Model (FPHLM) to provide a more comprehensive assessment of hurricane risk.
The tree-induced component accounts for tree species, density, wind speed, and wind direction using Monte Carlo simulations to estimate tree failure, impact energy, and resulting exterior and interior building damage. These results are integrated with the wind-induced vulnerability model of the FPHLM to produce combined damage matrices and vulnerability curves representing the overall hurricane response of low-rise buildings.
This study evaluates alternative approaches to combining damage and introduces a framework for integrating tree- and wind-induced damage to quantify overall building vulnerability. The proposed framework enables a more comprehensive assessment of hurricane losses and provides an improved basis for catastrophe modeling, hurricane risk assessment, mitigation planning, and resilience analysis.

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

1. Introduction

Hurricanes are among the most destructive natural hazards in the United States, causing extensive damage to buildings and infrastructure every year (NOAA, 2024). Although hurricane damage is commonly associated with strong wind loading, post-event investigations following hurricanes such as Irma (2017), Michael (2018), and Ian (2022) have shown that falling trees also cause substantial damage to residential buildings. During extreme wind events, trees may fail through uprooting or stem breakage and strike nearby structures, increasing both the severity and cost of hurricane losses (Roueche et al., 2020; Ibrahim et al., 2025; Bakhshandeh et al., 2025a).

Current hurricane catastrophe models mainly focus on wind-induced building damage, while tree-induced damage is often neglected or treated separately. As a result, building vulnerability may be underestimated in neighborhoods with significant tree cover. Recent studies have improved the understanding of tree failure under extreme winds (Ahmed et al., 2022; Ibrahim et al., 2025), but practical approaches for integrating tree- and wind-induced damage within a regional catastrophe model remain limited (Bakhshandeh et al., 2025b).

This study presents an integrated vulnerability framework that combines the Tree-Induced Damage Vulnerability Model with the Florida Public Hurricane Loss Model (FPHLM). The proposed framework estimates tree-induced damage using probabilistic Monte Carlo simulations and integrates it with the wind-induced vulnerability model implemented in the FPHLM. Alternative damage-combination approaches are evaluated to quantify overall building vulnerability and improve hurricane loss estimation for low-rise buildings in tree-rich environments.

2. Methodology

This study presents an integrated vulnerability framework that combines a probabilistic Tree-Induced Damage Vulnerability Model with the wind-induced vulnerability model implemented in the Florida Public Hurricane Loss Model (FPHLM). The framework estimates tree-induced and wind-induced building damage separately and then integrates the two components to quantify the overall hurricane vulnerability of low-rise residential buildings.

2.1.Induced Damage Vulnerability Model

The Tree-Induced Damage Vulnerability Model estimates building damage caused by falling trees during hurricanes using a probabilistic Monte Carlo framework. The model considers one- and two-story residential timber and masonry buildings representative of the Florida building exposure. Each building class is further classified into weak, medium, and strong construction levels to account for differences in structural capacity.

Simulation scenarios are defined using wind speed, wind direction, tree species, and tree density representative of Florida conditions. Wind speeds range from 22.35 to 111.75 m/s (3-second gust) with eight wind directions, while tree exposure is represented by seven common Florida tree species and densities ranging from one to twenty trees surrounding the building. For each scenario, thousands of Monte Carlo simulations are performed to account for the natural variability in tree location, crown diameter, and failure behavior. Species-specific fragility curves are used to estimate the probability of tree failure as a function of wind speed (Ahmed et al., 2022; Ibrahim et al., 2025). When a tree fails, the model evaluates its fall trajectory and determines whether it impacts the building.

If an impact occurs, the corresponding impact energy is calculated considering tree geometry, breakage height, and failure mechanism. The calculated impact energy is converted into a building damage ratio using empirical damage functions developed from post-hurricane reconnaissance observations and physics-based impact analyses. Interior damage is subsequently estimated using the heuristic procedures adopted in the FPHLM. When multiple trees strike the same building, their individual damage contributions are accumulated to estimate the total tree-induced damage. The Monte Carlo simulations produce vulnerability matrices and vulnerability curves for different building classes, tree species, and tree density levels. Individual scenarios are subsequently combined into weighted vulnerability curves by grouping tree species into deciduous and coniferous categories and classifying tree density as low, medium, or high. These weighted curves are intended for portfolio-scale catastrophe modeling applications (Bakhshandeh et al., 2025a; Bakhshandeh et al., 2025b).

2.2.Wind-Induced Vulnerability Model

Wind-induced building damage is estimated using the vulnerability module of the Florida Public

Hurricane Loss Model (FPHLM), a regional catastrophe model developed for estimating insured hurricane losses in Florida (Pinelli et al., 2020; FPHLM, 2025). The FPHLM evaluates wind damage to individual building components using Monte Carlo simulations and component fragility functions. The model produces vulnerability matrices and mean vulnerability curves that describe expected building damage as a function of wind speed for different construction classes (Wei et al., 2024).

2.3. Integrated Tree- and Wind-Induced Vulnerability Framework

The final step of the proposed methodology integrates the tree-induced damage estimated by the Tree-Induced Damage Vulnerability Model with the wind-induced damage generated by the FPHLM. Since both hazards contribute to overall hurricane losses, several damage-combination approaches are investigated to identify a methodology that is both physically reasonable and computationally efficient for catastrophe modeling. The first approach estimates wind- and tree-induced damage independently and combines them using an additive union formulation similar to that adopted in HAZUS-MH for multi-hazard damage assessment (FEMA, 2023). This approach provides a simple and computationally efficient baseline while reducing double counting of overlapping damage (Bakhshandeh et al., 2025b; Bakhshandeh et al., 2026).

Recognizing that wind loading and tree failure are not completely independent, an improved additive formulation is also considered. This approach acknowledges that increasing wind speed simultaneously increases direct structural damage and the probability of tree failure. Furthermore, tree impacts may occur after buildings have already experienced wind damage, making the overall damage dependent on the interaction between the two hazards (Baradaranshoraka et al., 2017). Although this approach better reflects the physical behavior of hurricanes, additional calibration using post-event observations and insurance claims is required.

Finally, a unified Monte Carlo framework is evaluated as a conceptual long-term solution. In this approach, wind loading and tree impacts would be simulated simultaneously within each Monte Carlo realization. This framework would provide a more physically realistic representation of hurricane damage; however, the large number of possible combinations of wind speed, wind direction, tree characteristics, and failure timing would substantially increase computational demands. In addition, limited field observations describing the sequence of wind damage and tree failure currently prevent reliable model calibration (Masoomi et al., 2019; Nofal et al., 2021).

For these reasons, the present study adopts the additive damage-combination approach for implementation within the FPHLM while presenting the improved additive formulation and the unified Monte Carlo framework as potential directions for future research. The proposed methodology is currently under implementation. Preliminary results, including combined vulnerability curves and comparisons with conventional wind-only assessments, will be presented and discussed at the conference.

3. CONCLUSIONS:

This study presents an integrated vulnerability framework that combines tree-induced and wind-induced damage for low-rise buildings within the Florida Public Hurricane Loss Model (FPHLM). Tree- and wind-induced damage are estimated independently and combined using a practical damage-combination approach that minimizes double counting while remaining computationally efficient for catastrophe modeling. A unified Monte Carlo framework is also discussed as a potential direction for future model development. Implementation of the proposed framework is ongoing, and preliminary results will be presented at the conference.

ACKNOWLEDGEMENTS

The National Science Foundation supports the Wind Hazard and Infrastructure Performance Center (WHIP-C) through grant No. 1841523, and the WHIP-C's Industrial Advisory Board endorsed this work through grant No. WHIP2022_05. The opinions, conclusions, and results presented in this document are solely those of the authors and do not necessarily represent the views of the NSF or the WHIP-C.

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