Integrated Risk Assessment of Tree-Induced and Wind-Induced Damage to Low-Rise Buildings in Hurricane Scenarios

Mohammad Bakhshandeh[1], Jean-Paul Pinelli[2], Amal Elawady[3]

[1]*Florida Institute of Technology, Melbourne, FL 32901, USA, mbakhshandeh2023@my.fit.edu*
[2]*Florida Institute of Technology, Melbourne, FL 32901, USA, pinelli@fit.edu*
[3]*Florida International University, Miami, FL 33174, USA, aelawady@fiiu.edu*

SUMMARY:
Windstorms are a significant hazard that can severely damage buildings, especially in areas with dense tree cover. Strong winds can break trees, which may fall on nearby structures. This risk is even higher in urban and suburban areas, where trees are often located close to buildings, increasing the chance of damage during hurricanes. This study presents a vulnerability model that evaluates the risk of tree-induced damage to low-rise buildings by incorporating factors such as tree species, densities, and wind conditions to simulate potential damage across different scenarios. In addition to assessing structural damage, the model also considers interior and content damage, offering a more comprehensive evaluation of total losses. Once tree-induced damage is calculated, it is combined with wind-induced damage in the Florida Public Hurricane Loss Model (FPHLM) to provide a comprehensive estimate of overall hurricane-related losses, including exterior, interior, and content damage.
Keywords: Vulnerability modeling, risk assessment, wind-induced damage, tree-induced damage, Monte Carlo simulations, Florida Public Hurricane Loss Model (FPHLM)

1 METHODOLOGY

The team developed a vulnerability model using a scenario-based approach to assess the potential damage to different building classes caused by wind-induced tree falls. The output are vulnerability curves that give mean damage ratios against wind speeds for different tree densities and species. Below are the key steps in the methodology:

1.1 Tree Fragility Curves

Fragility curves for seven tree species: oak live, oak water, mahogany, pine shortleaf, loblolly pine, American sweet gum, and slash pine, yield the probability of tree failure under varying wind speed. (Ahmed, F.et al. 2022)

1.2 Tree impact energy model

Tree impact energy during blowdowns is calculated by estimating the potential energy of the tree's trunk and crown using parameters like Diameter at Breast Height (DBH) and tree height, assuming it falls due to gravity. Larger DBH leads to higher impact energy, which correlates with greater structural damage upon impact (FEMA, 2022).

1.3 **Damage Function**

Limited data, based on incomplete tests conducted at Clemson University in the 1990's (FEMA 2022), relate qualitatively damage states (DS) for timber and masonry walls to the impact energy from falling trees (Tables 1&2).

Table 1. One and two-story Timber building damage states due to impact energy in HAZUS

Damage State #		1	2	3	4	5	6	7	8
One-Story Wood	Impact Energy (foot-pound) (1)	250	2,000	5,600	6,400	8,800			
	Example Tree Height (2) (feet)	30.0	46.9	57.5	59.0	62.6			
	Damage State Description	Surface damage	Roof deck crack	Top-plates rupture	One-Fourth Cut into wall	Cut through wall			
Two-Story Wood	Impact Energy (foot-pound)	250	2,000	5,600	6,400	8,800	14,400	15,200	17,600

Table 2. One and two-story Masonry building damage states due to impact energy in HAZUS

Damage State #		1	2	3	4	5	6	7	8
	Example Tree Height (feet)	32.0	50.2	61.3	62.8	66.6	72.5	73.3	75.2
	Damage State Description	Surface damage	Roof deck crack	Top-plates rupture	One-Fourth Cut into upper wall	Cut through upper wall	Floor-plates rupture	One-Fourth Cut into lower wall	Cut through lower wall
One-Story Masonry	Impact Energy (foot-pound)	250	2,000	11,000	13,000	19,000			
	Example Tree Height (feet)	30.0	46.9	65.2	67.2	72.0			
	Damage State	Surface damage	Roof deck crack	Bond-beam rupture	¼ Cut into wall	Cut through wall			
Two-Story Masonry	Impact Energy (foot-pound)	250	2,000	11,000	13,000	19,000	30,000	32,000	38,000

The authors transformed the wall DS from Tables 1&2 into quantitative overall building damage ratios for each estimate of impact energy, based on engineering judgment. Polynomial damage functions were then fitted to the ensemble of pairs of (impact energy, and damage ratio) to model the relationship between the impact energy of a falling tree and the resulting overall damage to the building for both weak-strength timber and masonry buildings (see Figure 1). Further research shall validate these preliminary curves and expand to the case of medium- and high-strength buildings.

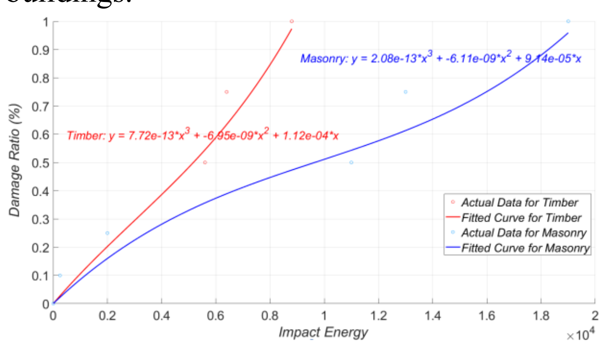

Figure 1. Building Damage Functions for Timber and Masonry 1-story Building

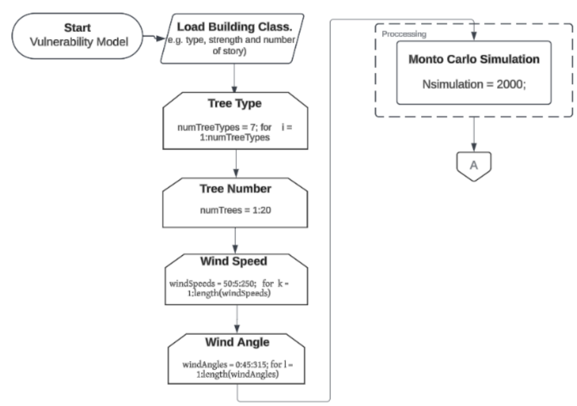

Figure 2: Vulnerability Flowchart for tree-induced damage to buildings – Define Scenarios

1.4 **Scenario-Based Approach for Tree-Induced Damage:**

A scenario-based approach assesses wind-induced tree damage on various building classes with varying structural strengths and materials (weak, medium, and strong), and different height (1-story and 2-story buildings). For each scenario, tree quantity ranges from 1 to 20, in one tree increment. Wind speed ranges from 22.4 to 111.8 -m/s in 2.24 m/s increments at a height of 10 meters, with wind directions spanning from 0° to 360° in 45° increments. Figure 2 presents a flowchart which is part of the vulnerability model illustrating the scenario definition for tree-induced damage to buildings, and serves as input for the Monte Carlo simulation

1.5 Monte Carlo Simulations:

For a given building class, for each combination of tree species, tree quantity, wind speed, and direction, 2000 Monte Carlo simulations are conducted. In each simulation, tree locations and crown diameters are randomized. The model then determines if trees fall and calculates the accumulated impact energy from all the trees that strike the building. This energy is used to estimate the building's damage ratio. 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.

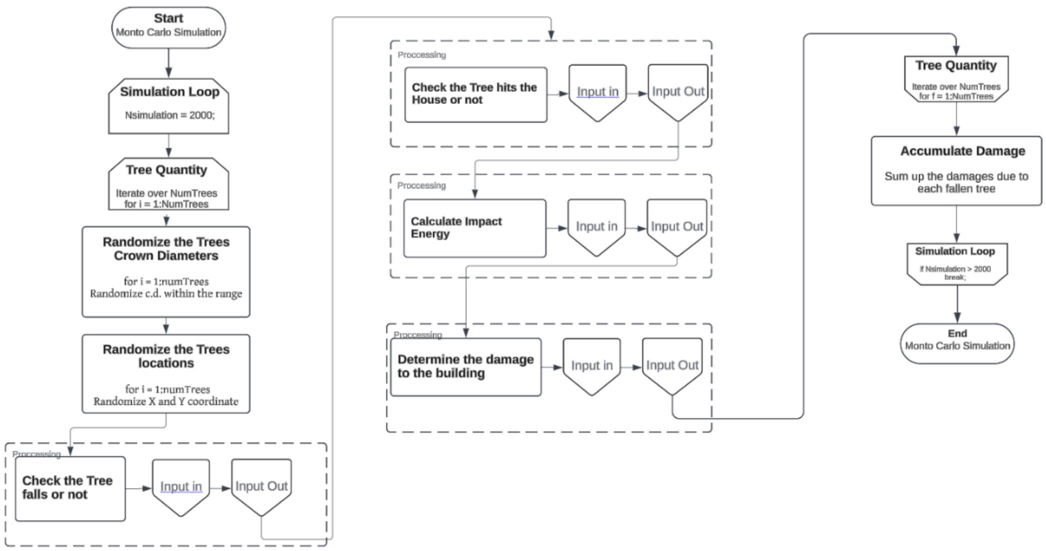

Figure 2: Vulnerability model for tree-induced damage to buildings- MC simulations: Random variables

1.6 Tree damage vulnerability matrices and curves

The results of the simulation model 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 a vulnerability matrix, 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. Also, weighted vulnerability matrices can be derived by combining the vulnerability matrices for different combinations of species (e.g. deciduous vs. coniferous), and different tree density levels (e.g. low, medium, or high).

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.

1.7 Estimation of Interior and Content Damage

We do not have data on damage to buildings due to falling trees, which makes estimating interior and contents damage challenging, but several options exist. The current adopted approach considers an overall building damage function (Figure 1), which projects the total damage to the building, including both exterior and interior components. Another semi-engineering option is to separate the estimates of exterior and interior damage. The model can project envelope breaches to the walls and floors due to the tree impact, which can lead to water ingress and subsequent interior and contents damage. But this presupposes a component-based model. In the absence of such a model, an alternative option would be to derive statistics that would relate envelope breaches to interior and contents damage and evaluate statistically the possible interior and contents damage. These options are currently under evaluation, and they will be discussed at the conference.

1.8 Integration of Tree-induced and Wind-Induced Vulnerability Models

The Florida Public Hurricane Loss Model (FPHLM) is a tool for estimating insured losses in the state of Florida (FPHLM, 2023; Pinelli et al., 2020). The tree-induced building damage vulnerability model described above is combined with the wind-induced building damage vulnerability model of the FPHLM. Tentatively, this integration uses the following formula:

$$\text{Total Damage} = \text{Wind Damage} + \text{Tree Damage} - (\text{Wind Damage} \times \text{Tree Damage}) \quad (1)$$

This formula is provided to combine the two independent damage estimates while accounting for potential overlap, ensuring that the same damage is not counted twice. The main advantage of this approach is indeed its simplicity.

2 CONCLUSION:

This is a work in progress. The authors have generated a preliminary library of tree-induced building damage vulnerability matrices and curves. The next step involves validating and calibrating the model using reconnaissance data from previous hurricanes, followed by combining tree and wind models in the FPHLM. At the conference, the authors will present and compare these vulnerability curves, and they will show the impact of combining tree- and wind-induced damage estimates on overall portfolio loss projections in tree-covered areas.

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