Accumulation of damage in a hurricane vulnerability model of Florida residential construction

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SUMMARY

Vulnerability models are tools that provide estimates for a community's financial risk to exposure to various hazards. The Florida Public Hurricane Loss Model (FPHLM) is a probabilistic risk model designed to evaluate the vulnerability of Florida's infrastructure to hurricane wind-induced hazards. This model uses a Monte Carlo simulation, wherein the capacities of probabilistic building components are evaluated against wind loads to develop damage matrices over a range of wind speeds. A repair-cost algorithm uses these damage matrices to produce damage ratios as a function of wind speed. The Monte Carlo simulation is built around a repeated process of assembling a model structure with randomized component capacities, exposing those components to wind loads, and evaluating the damage. For each wind speed, thousands of simulations are performed, each with a new model structure. This paper discusses the development and implementation of a damage model variant which tracks the accumulation of damage across a series of wind speeds and directions. For each simulation in the proposed methodology, a model structure would be generated with randomized component capacities, undergo exposure to wind loading from a set wind speed and direction, then be evaluated for damage. Rather than assembling a "newly built" structure, that same model would then be exposed to the next set of wind conditions and the accumulated damage would be evaluated; this process would repeat for each combination of wind conditions. This methodology allows for the development of vulnerability curves which account for gradually increasing wind speeds, rather than assuming the immediate onset of high wind speeds. This methodology would also allow for the direct simulation of structures in historical hurricanes by inputting historical records of wind speeds and directions.

Keywords: hurricane, risk modelling, vulnerability

1. BACKGROUND

The Florida Public Hurricane Loss Model (FPHLM) is a probabilistic risk model which produces estimates of insured losses from hurricane wind-induced damage to residential structures in the state of Florida. This model consists of three major components. The meteorological hazard module utilizes a stochastic set of 50,000+ simulated hurricanes; the 10m peak wind speed at each location in Florida is derived for each of these storms. In the vulnerability module, a Monte Carlo simulation and cost-repair algorithms are used to develop vulnerability matrices for various model structure types. These matrices describe the relationship between damage ratio (ratio of the cost of repair to building value) and wind speed. The actuarial module uses the vulnerability and hazard outputs to produce the average annual insured loss for a given portfolio of structures.

The vulnerability matrices produced by the model describe the expected damage ratio for a given structure exposed to a 3-second gust over a range of wind speeds. These matrices can be expressed graphically as vulnerability curves (Figure 1). In order to account for the variety of structures in the population of Florida buildings, curves are developed for structures varying in function (personal residential, commercial low-rise), building material (timber-frame, masonry block), construction age, and roof shape. While the primary purpose of the FPHLM is to produce estimates for annual insured losses, the model has been used for a variety of other studies. A validation study was performed by comparing insurance portfolios from three major storms to predicted loss outputs by the model (Pinelli et al., 2008). Another study used the FPHLM to model the probable maximum loss for 30 hypothetical hurricanes in Florida (Hamid et al., 2011). The effectiveness of mitigation techniques (e.g. gable-end bracing, shuttered windows) was evaluated by performing a cost-benefit analysis on structures based on region and structure type (Torkian et al., 2014).

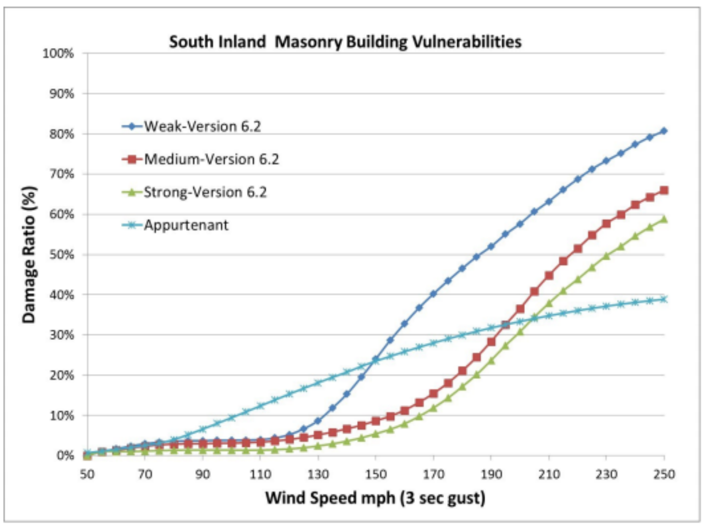

Figure 1. Comparison of four vulnerability curves

One limitation of the FPHLM is that the vulnerability curves are based on peak 3-second gust wind speeds. Any wind event is defined by its maximum wind speed, meaning that the duration of the storm has no impact on the modelled damage. This study proposes a methodology to model the accumulation of damage over a range of wind conditions. By restructuring the architecture of the vulnerability module, the FPHLM can output vulnerability curves that represent the gradual onset of damage. In addition, wind events could be represented by a time history of wind speeds and directions, rather than only by the peak wind speed.

2. FPHLM STRUCTURE

This study is concerned with modifications to the FPHLM vulnerability module. This section summarizes the function of the vulnerability component; a comprehensive description of the

FPHLM, including the hazard and actuarial modules, is publicly available (Florida International University, 2021).

2.1 Damage Estimation Component

The vulnerability module begins with the damage estimation component. In this component, simulations of wind-induced damage to the structural components of model buildings are performed. The damage estimation component makes use of Monte Carlo simulation to account for uncertainties in the calculation of wind loads and damage. For a given model type (e.g. two-story masonry block hip roof structure built in 1983), many simulations are conducted for a sequence of wind speeds and wind directions. In each simulation, the wind speed, wind direction, and model building characteristics are used to generate random wind loading and component capacity values. Then, a series of calculations are performed, representing deterministic relationships that define load paths, load sharing, and the influence of damaged components on building loads. For example, a failed roof-to-wall connection will require a redistribution of roof uplift load to the surrounding connections. The output of each simulation is an array quantifying the number of failed components (instances where load exceeded capacity). In the next simulation, a new set of wind loading and component capacity values are randomly generated, using the same wind speed, wind direction, and building characteristics. Once many simulations have been performed using this combination, the model iterates through wind speeds and wind directions. The final result is a 4-dimensional damage matrix; each row represents a simulation, each column represents a component, the 3^{rd} dimension represents wind speed, and the 4^{th} dimension represents wind angle. Each cell is a value of damage to a specific component in a given simulation. By averaging the 4-dimensional damage matrix over all simulations and wind directions, we develop a relationship of average damage to each component as a function of wind speed. By default, the FPHLM uses wind speeds of 50-250 mph 3-second gusts in 5 mph increments, 8 approach angles in 45^{o} increments, and 2,000 simulations for each combination of structure, wind speed, and wind angle. In total, there are 656,000 simulations accounted for in each damage matrix.

2.2 Interior Damage & Vulnerability Components

After the damage estimation component has produced the damage matrix, the outputs are used in the internal damage component. For each simulation, the internal damage component predicts losses caused by rain-water ingress. The internal damage component accounts for rain-water intrusion through damaged components and through rain-water pathways in undamaged components.

The final step in the vulnerability module involves converting the component and interior damage into monetary damage; these values are then used to calculate the damage ratio of repair cost to total building value. Damage ratios are aggregated into a damage matrix for each modelled structure, where each column corresponds to a 3-second gust wind speed, and each row corresponds to a range of damage ratios. Each cell is the conditional probability that a structure at the given wind speed will accrue damage within the corresponding range of damage ratios. Vulnerability curves are graphical representations of the damage matrices. For each wind speed, the weighted average of all damage ratios is taken to determine the expected damage ratio (Figure 1). This tool allows us to visualize how changes to the damage estimation component can impact vulnerability and financial losses.

3. ACCUMULATION OF DAMAGE METHODOLOGY

This study proposes a methodology for modelling the accumulation of damage over time in the FPHLM. In the current model, the Monte Carlo simulation is structured by creating 2,000 independent simulations for each combination of wind speed and wind direction. The new architecture involves building the initial model structure with randomized components, exposing it to the first combination of wind conditions, and recording the damage as normal. In the next simulation, the FPHLM would utilize the same model structure, carrying over the damage from the previous simulation, and using the next combination of wind speed and direction to generate the new wind load. After repeating this process for all desired combinations of wind speed and direction, the process would repeat, using a newly generated model structure with no damage.

This methodology would allow us to observe the effects of storm duration on vulnerability. A vulnerability curve could be generated by subjecting a structure to multiple iterations of the same wind condition, or to gradually increasing wind speeds. Another use case would be the ability to simulate historical and hypothetical storms with a time history of wind speeds and directions.

4. WORK IN PROGRESS & CONCLUSIONS

Prototypes of this methodology are currently in development. Small-scale models are being built to observe the effects of damage accumulation on individual components, in order to troubleshoot and determine the most efficient approach before developing a new model with this structure.

ACKNOWLEDGEMENTS

The authors wish to recognize the support and contributions of the FPHLM team members not directly involved with this abstract. This work is supported by the Florida Office of Insurance Regulation (FOIR). The opinions, results, discussion, and conclusions are not necessarily those of the FOIR.

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