Probabilistic Treatment of Storm Rotation and Wind-Driven Rain Deposition in a Hurricane Model

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ABSTRACT: Hurricane catastrophe vulnerability models aim to capture the average building exterior and interior damages under extreme uncertainty. Interior damages, which may represent the majority of the repair bill are primarily due to wind driven rain intrusion. Rain intrusion is highly dependent on the storm direction with respect to the building. This paper presents a methodology to capture the effects of storm rotation on the wind driven rain that an "average" building would be exposed to during a hurricane. Two statistical methods are investigated and compared to best capture these effects with the goal of combining a time dependent rain model with a non-time dependent physical damage model.

1. BACKGROUND

The Florida Public Hurricane Loss Model (FPHLM) is the only public hurricane catastrophe model utilized in the insurance industry as a tool to aid in the rate making process. The FPHLM is a state funded, multi-disciplinary research initiative whose methods are open to public scrutiny, unlike proprietary commercial models (Hamid et al., 2011). The FPHLM has been successfully accredited by the Florida Commission on Hurricane Loss Methodology (FCHLPM) since 2005.

The model comprises of a meteorological component, a vulnerability component, and an actuarial component integrated in a computer platform. Aspects of the vulnerability component will be the focus of this paper.

The goal of the vulnerability model is to estimate both the external and internal damage of a portfolio of buildings due to hurricane effects (wind pressure, debris impact, and rain penetration).

2. INTRODUCTION

Catastrophe modelers are tasked with the responsibility of estimating and predicting expected physical and monetary losses under extreme uncertainty. Practically, it is impossible to model every building configuration and combination, so generalizations are made to predict the "average" loss response of a generic structure given a particular hazard. In the case of hurricanes, interior damage might represent the majority of the repair bill so accurate estimates of the interior damage are paramount to a reliable predictive model. Recent studies have shown that wind driven rain (WDR) is the predominant source of interior related losses even in the absence of visible exterior physical damage (Chowdhury et al., 2012; Mullens et al., 2006; Masters et al., 2009). Consequently, the authors investigated two main issues:

1) How much WDR can a building be exposed to during a hurricane?
2) How much of that WDR actually enters the building envelope?

In response to the first question, the FPHLM team implemented a horizontal rain model which samples a statistical distribution of probable free stream accumulated horizontal rain (HR) for the duration of a storm as a function of max wind speed at a particular location (Pita et al., 2012).

Since the storm rotates as it passes over a building, the volume of HR is distributed over different local wind directions. The total number of changes in wind direction and the quantity of HR associated with each direction are important to know since the rain deposition and run-off characteristics on the building envelope are a function of the wind direction with respect to the building geometry (Baheru et al., 2014).

The FPHLM estimates physical envelope damage due to wind pressures and debris impact through the use of Monte Carlo simulations (Weekes, 2014). The output of the damage model represents simulations of the expected damage to each modeled building component as a function of peak 3 sec gust (from 22.4 m/s (50mph) to 111.8m/s (250mph) in 2.2 m/s (5mph) increments) and eight wind directions (in 45° increments, i.e. 8 octants). The damage output of each simulation only indicates the expected envelope damage for a given peak wind speed and associated wind direction but does not have an explicit time component. Up to 2000 simulations are generally done for each combination of wind speed and wind direction.

Previous versions of the FPHLM rain penetration model utilized a factor based on engineering judgment to account for the probability of a modeled breach being exposed to windward rain. This factor however, did not adequately capture the influence of the rotation of the storm.

This paper describes how the rain model, which yields the variation in time and direction of the HR was merged with the external damage model (which does not have an explicit time component), with the goal of estimating the volume of water ingress into a structure and subsequent interior damage.

3. HORIZONTAL RAIN SIMULATION

The rain simulation model exposes 91 uniformly distributed stations to 100,000 synthetic hurricanes. Each hurricane is generated by sampling distributions of key storm characteristics including translational velocity (V_T), radius of max wind, central pressure difference, storm decay etc. See (Pita et al., 2012) for a full model description.

For a given storm, at each station the model computes the total volume of horizontal rain (HR) at a particular location, which can be expressed as the sum of: 1) the horizontal rain HR_1 accumulated from the start of the storm t_0 up to the maximum wind speed time t_{Vmax}; and, 2) the horizontal rain HR_2 accumulated between t_{Vmax} and the end of the storm t_{max} (see Figure 2). The model previously only recorded the value of HR_1, HR_2, and peak 3-sec gust wind speed at each station but was modified to also record the wind direction at each station for each time step (6 min).

Figure 1 illustrates a typical hurricane making landfall. The rotational wind direction is counterclockwise. At each building location the initial local wind direction is reported at the "start" of the storm. As the storm passes, the local wind direction changes depending on the buildings' relation to the eye. The red arrow indicates the local wind direction at the time of maximum wind speed. As the storm continues to pass over land and eventually move over the building stock, the last wind direction is recorded at each location.

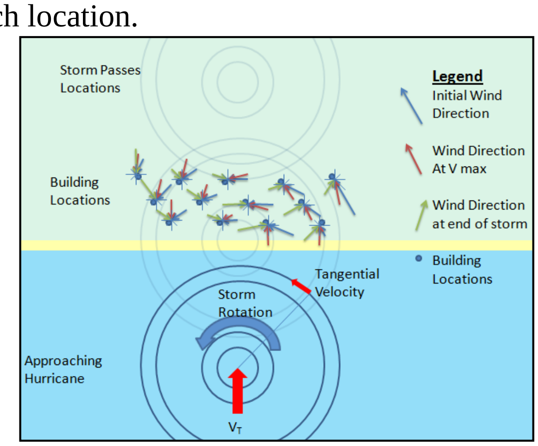

Figure 1: Simulated storm event with local wind direction changes

3.1. Directionality scheme.

Since HR_1 and HR_2 are not uniformly distributed throughout time, not all surfaces of a building will be subject to equal shares of horizontal rain. Consequently, estimating the probable contribution of impinging rain on a particular breach or building defect requires further refinement. To account for this, the authors developed a directionality scheme where, during the rain simulation process, the model records and calculates the HR_1 and HR_2 values while the wind direction falls into a certain 45° octant.

The distribution of the horizontal rain at a particular location as a function of time is illustrated in Figure 2. The vulnerability model assumes the peak wind to occur at the center of its wind direction sector or octant (at time t_{Vmax} in Figure 2). For the sake of consistency, in the rain model, the sectors are defined so that the peak wind occurs at the center of the sector which contains the max wind.

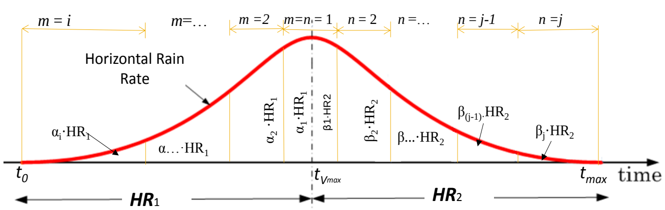

Figure 2: Horizontal rain rate as a function of storm duration

The overall volume of HR expected at a particular location can be expressed by the following equation:

$$HR = \sum_{m=1}^{i} \alpha_m * HR_1 + \sum_{n=1}^{j} \beta_n * HR_2 \quad (1)$$

Where α_m is the fraction of HR_1 for a given wind direction octant and i is the total number of wind direction changes between the initial start of the storm (t_0) and the time of max wind speed (t_{Vmax}). Consequently, $\sum_{m=1}^{i} \alpha_m = 1$ and m = 1 represents the wind direction half octant at t_{Vmax}, and m=i represents the wind direction at the beginning of the storm, t_0. If i=1 it means that the wind has blown in the same octant from t_0 to t_{Vmax} .

Similarly, β_n is the fraction of HR_2 for a given wind direction octant and j is the total number of wind direction changes from the time of max wind speed to the end of the storm. Consequently, $\sum_{n=1}^{j} \beta_n = 1$ and n = 1 represents the wind direction half octant at the time of maximum wind velocity (V_{max}), while n= j represents the wind direction at the end of the storm t_{max}.

3.2. Rain Model Assumptions.

The following assumptions are made.

- Each station in the rain model is treated as a point in space but in reality, the point represents a 4 sided structure in the damage model, with each side exposed to a portion of the total volume of horizontal rain, as the storm rotates. For any given damage simulation, the link between the rain model and the vulnerability model is the peak 3 sec gust wind speed V_{max}: i.e. the wind direction being evaluated in the physical damage model is the reference angle at V_{max} in the rain model.
- The wind directions or angles at which the tangential wind hit each station are split into eight 45° octants such that a registered "change in direction" only occurs if the wind direction changes from one octant to the next one.
- In the damage simulation model, the authors assume that all physical damage occurs at the time and direction of max wind speed.

3.3. Rain Model Output.

From the rain simulation output, 2 data sets were produced that capture the α_m and β_n values along with their corresponding V_{max}. (see sample of the alpha data set in Table 1)

Table 1: sample of α_m dataset with corresponding Vmax.

Vmax (m/s)	α_1	α_2	α_3	α_4
23.2	0.41	0.58	0.01	0.00
24.6	0.40	0.59	0.01	0.00
25.9	0.38	0.61	0.01	0.00
27.3	0.36	0.61	0.03	0.00
…	…	…	…	…

It should be noted that stations caught in the storm's eye capture jumps in local wind direction with no rain deposition for octants between β_1 and β_5 i.e. β_2 or β_3 = 0 even when values of β_4 or β_5 are present. (See Table 2 for example)

Table 2: sample of β_n dataset with corresponding Vmax.

Vmax (m/s)	β_1	β_2	β_3	β_4	β_5
23.2	0.38	0.60	0.02	0.00	0.00
24.6	0.36	0.60	0.04	0.00	0.00
25.9	0.34	0.61	0.05	0.00	0.00
45.6	0.26	0.00	0.00	0.21	0.53
46.5	0.26	0.00	0.00	0.00	0.74
…	…	…	…	…	…

The distributions of $\alpha_{m=1\text{-}4}$ and $\beta_{n=1\text{-}5}$ are shown in Figure 3 and Figure 4 respectively.

4. ANALYSIS OF RAIN MODEL OUTPUT

The objective is to best represent the typical exposure of a "generic" building to hurricane induced WDR including the effect of storm rotation. Both the orientation and location of a typical building with respect to the eye, and the number of changes in wind direction are unknown. The vulnerability model essentially needs to define a sequence of α_m and β_n for each realization of the damage model, i.e. the 2000 or so simulations for each combination of wind speed and wind direction. There were two methodologies investigated and compared: 1) using the mean α_m and β_n as a function of wind speed, which appears to best represent the "expected" rotation and deposition characteristics; alternatively, 2) a sampling method. Both methods have some benefits as well as some draw backs, and will be discussed in the forthcoming sections.

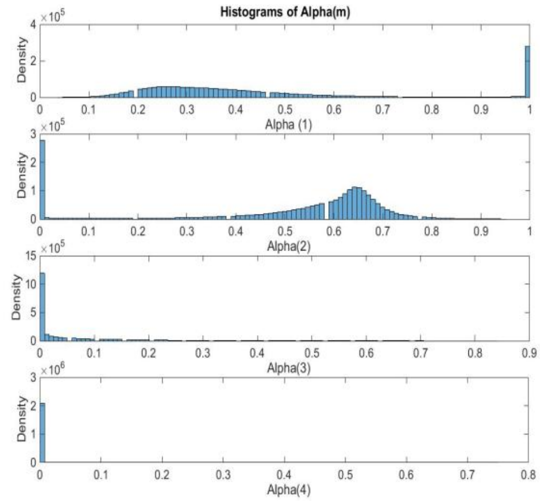

Figure 3: Histograms of α_m

There are only a few cases where α_4 and $\beta_{4 or 5}$ are captured which is typically at higher wind speeds.

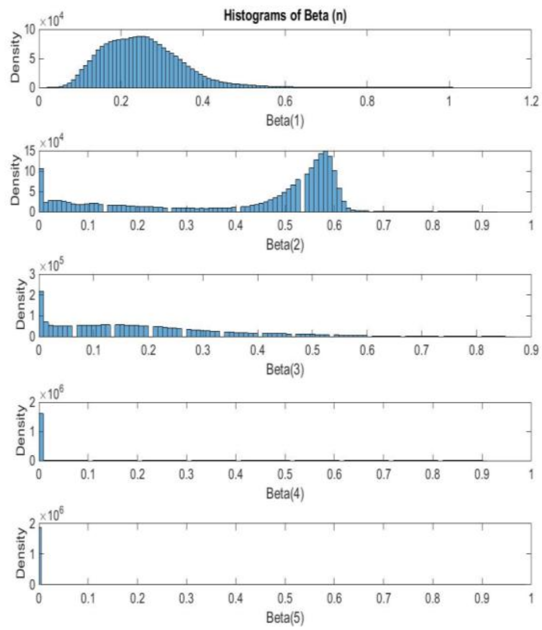

Figure 4: Histograms of β_n

4.1. Regression Fit

The first method was to fit a regression function to each of the α_m and β_n as a function of wind speed. Figure 5 shows a box plot of the data as a function of wind speed for β1. The mean appears to decrease as a function of wind speed. This is reasonable since higher wind speeds generally indicate more rotation and less contribution from the initial angle of attack at the time of the breach.

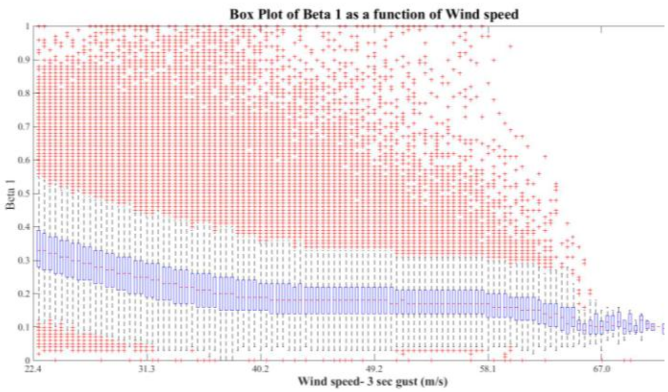

Figure 5: Box Plot showing mean (red bar), standard deviation (blue trace), 75th and 25th percentile (black dashed lines) and outliers (red crosses) for β_1 as a function of Vmax.

The means for each of the α_m and β_n are illustrated in Figure 6 Figure 7 respectively. The trends are smooth and appear logical up until around 60m/s. The rain model does not capture too many instances of high wind speed events and maxes out at 76.5 m/s. This leads to large variations in mean after 54 m/s at each subsequent wind increment.

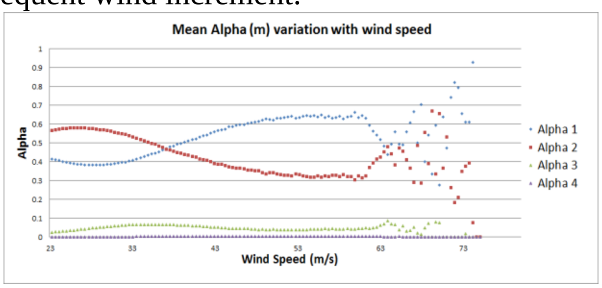

Figure 6: Mean of Alpha(m) ($\bar{\alpha}_m$) as f(wind speed)

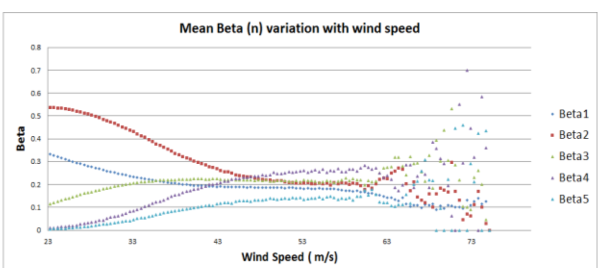

Figure 7: Mean of Beta(n) $(\bar{\beta}_n)$ as f(wind speed)

To adequately capture the storm behavior at lower wind speeds a polynomial regression function was fitted to each of the data sets up to 54m/s and kept constant from 54m/s to 112m/s. The constant value is assumed due to the limitations in the data set and to preserve continuity in the vulnerability functions.

4.1.1. *Advantages*

The main advantage of this method is its simple implementation. The mean is a valid representation of the behavior of the storms rotation characteristics for a building given that the building model could be anywhere in the storm system. Since the contributions of α_m and β_n are modeled as a function of wind speed, their means capture the probability of increased storm rotation (and hence, proximity to the eye, since wind speeds are inversely correlated to distance from the eye). The means capture proximity as well as the influence of rain deposition on the building surfaces that may fail under leeward pressure. Since the final vulnerability model output is a "mean" of all simulations across all wind directions, the regression function adequately represents the overall influence of storm rotation.

4.1.2. *Disadvantages*

The primary disadvantage of using the mean value is that we lose the co-dependency between *m* and *n* over the life of the storm. Assigning an average for all instances essentially implies that all octants could have contributions, even if those contributions are negligible.

The simplification of keeping the α_m and β_n constant after 54m/s ignores the rain model results for higher wind speeds that have limited data sets. This is of minimal consequence though, since these higher wind speeds occur rarely, and when they do occur, the physical external damage is such that it trumps any damage due to rain penetration.

4.2. *Data sampling*

The second methodology was to directly sample a data vector for each wind speed from both the alpha and beta data sets. This method essentially creates subsets of the data base for each modeled wind speed and uniformly samples a row of the data set which represents the alpha and beta values of any given storm with the corresponding maximum wind speed. The data set for the highest recorded wind speed is assumed to represent the distribution of α_m and β_n to wind speeds not modeled in the rain simulation but within the scope of the damage model

4.2.1. Advantages

The primary advantage in a sampling method is that the co-dependencies of m and n are preserved. Secondly, variations and outliers are captured for the same wind speed over the 2000 simulations even though they are averaged out when computing the final vulnerability.

4.2.2. Disadvantages

Since the data subsets are a function of wind speed, low wind speeds have very large data subsets, and the sampling generally converges towards the mean over the 2000 simulation points. However, at higher wind speeds there are far smaller sample sizes to sample from with large variations. This method is therefore susceptible to the sporadic changes from wind speed to wind speed illustrated in the tail end of Figure 6 and Figure 7. In addition, this method adds additional computational demands by requiring drawing the samples from the large α and β databases.

It should be noted that both methods provide a way for a continuous transition and smooth extrapolation of rain accumulation beyond the values of the wind speeds captured in the rain model.

5. WATER PENETRATION ESTIMATION

The FPHLM interior damage model performs Monte Carlo simulations to estimate the total volume of water that penetrates through a building envelope on a component by component basis, through either defects in the component or breaches. Defects are defined as cracks, gaps or small openings that allow water ingress when subject to WDR. Breaches are component failures such as broken windows, missing sheathing, etc.

Two sources of WDR are considered in estimating the total volume namely; direct impinging rain (DI) or surface runoff rain (SR). The following section aims to briefly show how the directionality scheme is used in estimating water intrusion. For the sake of brevity, only the DI rain effect will be explained here but the directionality methodology extends to both DI and SR.

5.1. General Interior damage equation

To answer the question of "How much of the WDR actually enters the building envelope" we need to define a relationship that relates the HR to the building envelope. The issue of impinging rain and the building vs. driving rain interaction has been studied by Straube and Burnett (2000), Blocken et al. (2007) and others (Choi, 1994), although not under tropical storm conditions. Recent efforts by (Baheru et al., 2014) are the first to quantify the fraction of direct impinging rain. A rain admittance factor (RAF) is used to quantify the fraction of HR that directly deposits on a building surface. And is defined as the following

$$RAF = \frac{RR_{b,DI}}{RR_v} \qquad (2)$$

where $RR_{b,DI}$ is the rate of WDR deposition at a given location on the building façade due to direct impinging raindrops. RR_v is the rain rate in an unobstructed free stream wind profile at the mean roof height. RAF is independent of the wind speed but varies with the wind direction.

This relationship is used to quantify the volume of HR that directly impinges on a building component. For a given damage state (breach or defect), the volume of penetrating impinging rain can be expressed as the following equation:

$$Vol_{C,DI} = \left(RAF \cdot HR \cdot A_{o\_comp}\right) \qquad (3)$$

Where $Vol_{C,DI}$ = the volume of water through a component (C) through either breach or defect area (A_{o_comp}) .

For any given simulation, the link between the rain model and the vulnerability model is the maximum wind speed. A given defect or breach on a particular surface is subject to all the fractions of impinging rain corresponding to the different wind directions (or octants) the defect or breach is subjected to as the storm rotates before and after the occurrence of the maximum wind speed. Consequently, before t_{Vmax} (i.e. before the occurrence of V_{max} and the occurrence of any breach in the model for that simulation), as the storm rotates, the total value of impinging rain penetrating through a defect area $A_{d_{comp}}$ is the following sum:

$$RAF \cdot HR \cdot A_{o_{comp}} = [\sum_{m=1}^{4} RAF_{\theta m} * \overline{\alpha_m}(V_{max})\,] * HR_1 * A_{d_{comp}} \quad (4)$$

Where $RAF_{\theta m}$ is the RAF value for a wind direction θ_m. For each damage simulation, θ_1 is the wind direction or octant at t_{Vmax}, θ_2 is the previous octant in the rotation (45 degrees), and so on.

After t_{Vmax} (i.e. after the occurrence of V_{max} and the occurrence of some breaches in the model for that simulation), as the storm continues to rotate, the total value of rain impinging on the breach is the following sum:

$$RAF \cdot HR \cdot A_{o\_comp} = [\sum_{n=1}^{5} RAF_{\theta n} * \overline{\beta_n}(V_{max})\,] * HR_2 * A_{Breach\_comp} \quad (5)$$

Where the $RAF_{\theta n}$ is the RAF value for a wind direction θ_n. For each damage simulation, θ_1 is the wind direction or octant at t_{Vmax}, θ_2 is the next octant in the rotation (45 degrees), and so on.

5.2. Influence of Directionality on Vulnerability Model

A 1 story timber frame model is selected to illustrate the influence of the aforementioned methodologies. Models of three different strengths (weak, medium and strong), which represent various configurations of building component capacities and historical building practices, (FPHLM, 2011), are evaluated using both directionality schemes from 1) the mean regression function and 2) the sampling method. Figure 8 compares the corresponding vulnerability curves (which represent the expected damage ratio as a function of wind speed). There appears to be very little difference between the two methods (max absolute difference is 5.7% for the medium strength case at 71.5m/s). Method 2 does however fluctuate about the results from method 1, and tends to produce slightly lower damage ratios at higher wind speeds.

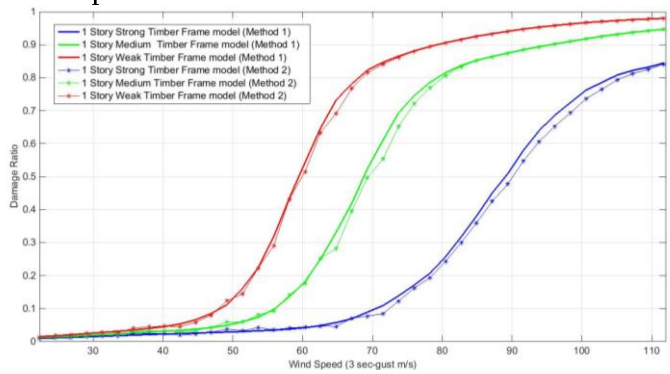

Figure 8: Vulnerability curves for a weak (red), medium (green) and strong (blue) 1 story timber frame model (method 1 vs. method 2)

The influence of directionality on the model was investigated. A test run was conducted whereby setting $\alpha_1 = 1$ and $\beta_1 = 1$ while all other values are zero, i.e. no storm rotation is considered and therefore only one building face is subject to all HR (Figure 9). What is important to note is that although the full contribution of HR is applied to the breaches or defects of one surface only, many of the modeled building components fail due to negative pressure on leeward surfaces. Therefore, these components do not record any water intrusion if storm rotation is not included and subsequently the expected damage ratio is under predicted.

6. DISCUSSION AND CONCLUSIONS

This paper showed how two independent simulation models were combined to capture the rain-induced interior damage mechanisms of a residential building during a hurricane. One model simulates the time history of accumulated rain for different wind speed events, taking into account storm rotation. The other model simulates external damage to the envelope of a building for different combinations of peak wind speed and wind direction. The challenge lies in the fact that the damage model does not carry on any explicit time analysis, and that for any instance of external damage, there are numerous possible combinations of rain and storm rotation.

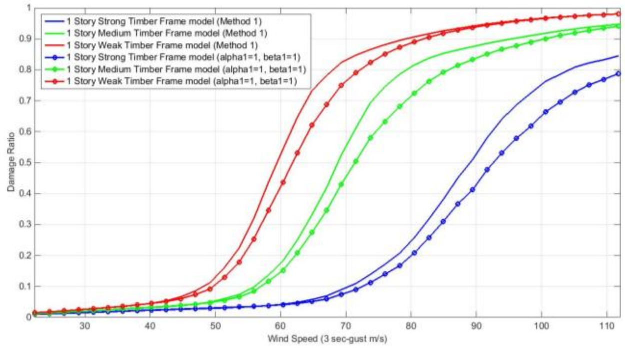

Figure 9: Influence of directionality scheme

To solve the problem, a directionality scheme was developed, which statistically quantifies the hurricane rain deposition and local storm rotation that a typical building can be exposed to. Two methods highlighted how the resulting data sets could be used differently to achieve the same goal.

The first method (based on regression analyses) uses mean values of directional rain deposition, while the second method uses random sampling of directional rain deposition. Both methods yield similar results, however the first one is recommended since the overall output adequately captures the physical problem at hand without increasing computational demands. Although data sampling retains some important correlations, the benefits are not justified given the additional computational demands and limitations in the data sets.

7. ACKNOWLEDGMENT

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