Wind and Rainfall Losses from Future Hurricanes

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ABSTRACT: Hurricane is a combination of two extreme events - intense wind and heavy rainfall. The simultaneous occurrence of these two events magnify the overall damage and losses. This could be distinctively observed in residential buildings where high wind speed damages the external structure through which rainfall can enter damaging the interior and content. Further, various studies have shown that future climate could be different from present and the change in climate may affect the hurricane activities. However, the change in climate may have varying degree of impact on hurricane wind and rain and the corresponding losses. Consideration of wind and rainfall losses individually allows a more comprehensive investigation of climate change impact on future hurricane losses and also provides important insights into effective hurricane risk management. Thus, this study evaluates and compares these two types of hurricane losses in residential buildings for climate-dependent future hurricane scenarios.

1. INTRODUCTION

Hurricanes cause catastrophic damages and losses to the communities in the United States. The damage and loss during hurricanes occur due to the presence of two hazardous events - high wind speed and heavy rainfall. These events combinedly result in damage to structures, crop and livestock, tree fall etc. Further, since both these events occur simultaneously, the losses could be much higher compared to if the events had occurred separately. This is especially pronounced in residential building whereby high wind speeds damage the external components, leading to rain ingress which damage the interior and content of the building.

Residential buildings are one of the most vulnerable structures during hurricanes and their damage cause a huge difficulty in people's day-to-day lives. Various post-storm surveys have concluded that rain ingress is the major cause of hurricane damage in residential buildings (Stubbs and Perry 1993, Crandell 1998, Van de Lindt et al. 2007). However, the contribution of rain damage on the overall hurricane loss as well as the dependency of rain ingress to the wind damage is not well understood yet. Understanding the hurricane damage mechanism in residential buildings could be useful not just in assessing the hurricane loss but also in planning for mitigation strategies.

Besides, since hurricane is an atmospheric phenomenon, it could be impacted under climate change scenarios. This could subsequently impact hurricane wind and rain and the corresponding losses. Climate studies have found that the future climate could be very different from present. One of the leading works in this field is done by Intergovernmental Panel on Climate Change (IPCC 2013) which has projected four different climate scenarios based on the anticipated level of natural and anthropogenic processes. In all the scenarios, the average change in future atmospheric and sea surface temperature is found to be higher than the present. Under the climate change, various studies have found an increase in

hurricane wind speed (Emanuel 2008, Knutson et al. 2010). Further, studies have found a positive relationship between hurricane rainfall rate and wind speed (Marks and DeMaria 2003, Tuleya, DeMaria and Kuligowski 2007). As such, both wind and rain losses could increase in the future climate.

Thus, this study aims to investigate in detail the wind and rain losses in residential buildings under climate-dependent hurricane scenarios. For the investigation, Miami-Dade County, FL is selected as the study region. The following sections provide the details of this study.

2. FUTURE CLIMATE SCENARIOS

The earth's mean surface temperature is found to have increased since the nineteenth century and is expected to increase further in the future (IPCC 2013). IPCC has projected four different future climate scenarios - RCP2.6 (lowest change in SST), RCP4.5, RCP6.0, and RCP8.5 (highest change in SST), based on anticipated natural and anthropogenic processes.

In this study, tropical cyclones (TCs) are simulated for present climate corresponding to the year 2005 and future climate corresponding to the year 2100. For the future climate, the best- and the worst-case scenarios, i.e. RCP2.6 and RCP8.5, are considered in this study. The climate parameter considered for the analysis is the sea surface temperature (SST). The SST for present climate is obtained from COBE database (NOAA 2017a) and the SST for the IPCC projected future climate is obtained from NOAA's GFDL (NOAA 2017b).

3. TROPICAL CYCLONE SIMULATION

This study adopts the methodology provided in Vickery et al. (2000) to simulate tropical cyclones. Vickery's methodology simulates TCs based on a statistical model which also includes a temperature term making it suitable to perform climate-dependent analysis. In this study, 40,000 years of TCs are simulated for present as well as each of the future climate scenarios

To simulate TCs, the North Atlantic Ocean is divided into a 5° latitude x5° longitude grids and TCs are initiated at each grid based on a Poisson distribution. In this study, the impact of climate change on frequency has not been considered since the existing studies do not have a clear agreement on how climate change could impact frequency (Mann et al. 2007, Knutson et al. 2010, Emanuel et al. 2008) and many suggests no change in frequency (Landsea et al. 2010, Knutson et al. 2010). Thus, the mean frequency of the Poisson distribution is assumed to be constant for all climate change scenarios and is evaluated based on the past hurricane data from 1944. The year 1944 is selected for the evaluation since various studies have suggested that the hurricane records before this year might be incomplete owing to deficiencies in observational techniques. The TCs are then simulated over time and the central pressure difference, translation velocity and approach angle are recorded at each time step.

The central pressure difference is measured in terms of relative intensity as given below.

$$ln(I_{i+1}) = c_0 + c_1 \cdot ln(I_i) + c_2 \cdot ln(I_{i-1}) + c_3 \cdot ln(I_{i-2}) + c_4 \cdot T_s + c_5 \cdot \left(T_{s_{i+1}} - T_{s_i}\right) + \varepsilon \quad (1)$$

where I represents relative intensity, T_s represents sea surface temperature and ε represents random error term. The subscript i represents the time step. The time step for this study is assumed to be 6-hour.

Similarly, the approach angle is evaluated as

$$\Delta\theta = b_1 + b_2 \cdot \psi + b_3 \cdot \lambda + b_4 \cdot ln(V_{t_i}) + b_5 \cdot \theta_i + b_6 \cdot \theta_{i-1} + \varepsilon \quad (2)$$

where ψ and λ are latitude and longitude of the storm center, θ is the approach angle and V_t is the translation velocity. This equation is slightly different from the equation provided in Vickery's model in that $ln(V_{t_i})$ is used instead of V_{t_i}. This modification is because it was found that $\Delta\theta$ has a higher correlation with $ln(V_{t_i})$ compared to V_{t_i}.

The translation velocity is evaluated as

$$ln\left(V_{t_{i+1}}\right) = a_1 + a_2 \cdot \psi + a_3 \cdot \lambda + a_4 \cdot$$
$$ln\left(V_{t_i}\right) + a_5 \cdot \theta_i + a_5 \cdot T_{s_i} + \varepsilon \qquad (3)$$

The coefficients a_1, b_1, c_1, a_2, b_2, etc. in the Eqs. (1) – (3), are obtained by analyzing past hurricanes from HURDAT. Further, the above TC parameters are bounded based on the past observed data to ensure realistic limits. The simulated TCs were found to compare well with the past observed TCs.

The TCs are simulated using the Eqs. (1) – (3) until the TCs makes a landfall after which the relative intensity is converted back to central pressure. The central pressure is then decayed using the equation provided in Vickery et al. (2005). After landfall, the translation velocity and approach angle are still evaluated using Eq. (2) and (3), however without the SST terms.

The wind speed is evaluated at the selected locations using the empirical equation provided in Georgiou (1984) which relates wind speed to the above hurricane parameters evaluated using Eqs. (1) – (3). Similarly, the rainfall rate is evaluated based on the R-Cliper model (Marks and DeMaria 2003, Tuleya, DeMaria and Kuligowski 2007). Since the R-Cliper model provides vertical rainfall rate, it is converted to horizontal rainfall rate using the physics-based equation provided in Straube and Burnett (2000).

4. REGIONAL HURRICANE LOSS ASSESSMENT MODEL FOR MIAMI-DADE COUNTY

For the loss assessment, Miami-Dade is divided into sub-regions and the damage is assessed for each prototype building in each of the sub-region. Based on existing studies, the following prototypes buildings are selected for this study.

- Roof type: hip or gable
- Roof cover: shingle or tile
- Roof nailing: 6d with 6/12" nailing pattern, 8d with 6/12" nailing pattern or 8d with 6/6" nailing pattern
- Wall type: concrete-masonry or wood-framed

- Number of stories: one-story or two-story

4.1. Evaluation of individual building damage
In this study, the building damage is evaluated by assessing the damage in each individual component, which can be broadly categorized into external structure, interior and content. The damages in each component are then used to evaluate individual building losses, the details of which are provided in the following sections.

4.1.1. Structural damage
As stated above, high wind speed during hurricane causes damages in structural components. In this study, damage is recorded for each vulnerable sub-component of the external structure. Based on the existing studies (FEMA 2013, Cope 2004), the vulnerable external sub-components during wind loading are found to be – roof cover, roof sheathing, window, door, wall and roof-to-wall connections. The loadings for the components are evaluated based on Eqs. (4) and (5) (ASCE 7-16 2016).

$$q_h = 0.00256 K_z \cdot K_{zt} \cdot K_d \cdot V^2 \qquad (4)$$
$$p = RF \cdot q_h \cdot GCp - P_i \qquad (5)$$

where K_z represents velocity exposure coefficient and K_{zt} represents topographic factor and is assumed to be 1. RF represents the reduction factor whose value is taken to be 0.8. The RF is introduced to negate the inherent safety factor present in the pressure coefficients of the ASCE 7 wind load equation (Cope 2004). V represents 3-sec gust wind speed, GCp represents product of external pressure coefficient and the gust effect factor. The uncertainty is considered by assuming that the pressure coefficients (GCp) for roof and wall follow a normal distribution with mean equal to the nominal value given in the code and COV of 0.1. P_i represents the internal pressure and is calculated based on the external damage to the structure.

The capacities of the components are taken directly from HAZUS manual as well as Cope (2004). Thus, for each of the components, the capacity is compared with the loading and if the

loading is found to be lower than the capacity, damage is recorded. The final damage for each component is recorded in terms of damage ratio which indicates the proportion of damage of similar sub-components to the total area of the sub-component.

4.1.2. Interior and content damage

As stated above, various post-storm studies have conceded that rain ingress is the primary cause of damage to interior and content. Thus, this study evaluates damage to interior and content based solely on the amount of rain ingress.

Based on the horizontal rainfall rate evaluated above, the rain ingress through the openings in a building is evaluated as given below.

$$Vol_t = (RAF \cdot A_o \cdot RR_v + SRC \cdot A_{SR} \cdot RR_v) \cdot t \quad (6)$$

where RR_v is the horizontal rain rate i.e. rain rate passing through a vertical plane, A_o is the area of opening, A_{SR} is the area for surface runoff and Vol_t is the total volume of water accumulated due to the opening during time interval t. The coefficient RAF and SRC correspond to the rain ingress due to impinging rain and surface runoff, respectively. These coefficients are obtained from Baheru (2014). The volume of rain ingress is divided by the floor area to obtain the depth of rain ingress.

The depth of rain ingress is then related to interior damage based on Eq. (7) (Pita et al. 2014).

$$IDR = \begin{cases} \frac{1}{t_d} \cdot d_r & d_w < t_d \\ 1 & d_w \geq t_d \end{cases} \quad (7)$$

where IDR is interior damage ratio, d_r is the depth of rain ingress and t_d is the threshold depth of water which represents complete interior damage. The content damage is then calculated as percentage of interior damage as provided in Gurley et al. (2005).

4.2. Individual building loss

The damage in individual buildings are evaluated in terms of loss ratio (LR) as given below.

$$LR = \sum_{s=1}^{n}(DR_s \cdot RCR_s) \quad (8)$$

where DR_s represents damage ratio in the sth component, RCR_s represents replacement cost ratio for the sth component, and n is the number of all the considered individual components. The replacement costs provided in Gurley et al. (2005) are used for this study.

4.3. Regional hurricane loss

The regional hurricane loss is then evaluated using Eq. (9).

$$AAL = \sum_{j=1}^{m} \sum_{i=1}^{nb} \left(\sum_{k=1}^{nh}(LR_{ijk}) \cdot n_{ij} \right) \cdot IV_j \quad (9)$$

where AAL is the annual aggregated loss, IV_j is the insured value of the buildings in the jth sub-region, n_{ij} is the number of the ith building type in the jth sub-region and nb is the number of building prototypes, nh is the total number of hurricane per year, and LR is the loss ratio. The insured value of building's external structure and interior is taken to be 50% of the median value of building in census 2005 (Davis and Palumbo 2008). The content insured value is assumed to be 50% of insured value of external structure and interior (Bhinderwala 1995).

5. WIND AND RAINFALL LOSSES FOR CLIMATE-DEPENDENT HURRICANE SCENARIOS

Using the methodology described above, hurricane loss is evaluated for individual building prototypes. The losses in the individual buildings are assessed in terms of loss ratio. Figure 1 shows the mean loss ratio due to both wind and rain ingress for a 1-story wooden building. In the figure, the loss ratios are averaged for each 10-mph wind speed.
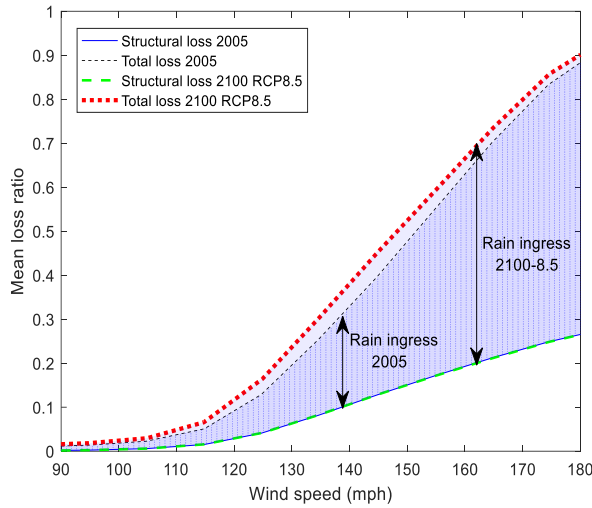
Figure 1: Mean loss ratio for a 1-story wooden building with gable roof and 8d nails.

It is found that the loss due to rain ingress is also positively dependent on wind speed as observed from the figure. This could be because rain ingress in a building depends upon the occurrence of two factors - rainfall rate and breaches in the building. Both these factors increase with increasing wind speed, thus causing the rain ingress to increase with the increasing wind speed.

From Figure 1, it is observed that rain ingress causes much higher damage than wind alone for residential buildings during hurricane events. Further, it is also noted that even though the structural damage for a given wind speed is same in all climate scenarios, the total loss is found to be higher in future climate scenario. This could be because rainfall rate during hurricane not only depends on the wind speed at the considered location but also depends on the maximum wind speed. Since wind speed is found to be higher in future climate, rainfall rate and the corresponding loss are found to be higher in future climate scenario even for the same wind speed in the location under consideration. This highlights the importance of considering climate change in evaluation of hurricane losses.

Figure 2 shows the mean ratio of interior and content loss to structural loss for all the building prototypes. It is noted that at low wind speed, the

ratio is very high. This is because at low wind speeds rain could have already ingressed inside a building through the vents causing damage to interior and content, though the structural damage is minimum. However, once appreciable damage is done (example after 120 mph), the ratio somewhat stabilizes. For the present climate scenario, the ratio is found to be between 3 to 3.2 and for future RCP 8.5 scenario, the ratio is between 3.2 to 4.1. It is also to be noted that for all the building prototypes, the ratio of interior and content losses to structure losses is found to be greater than 1 i.e. rain ingress is found to be the dominating factor for hurricane losses in all the considered residential building prototypes.
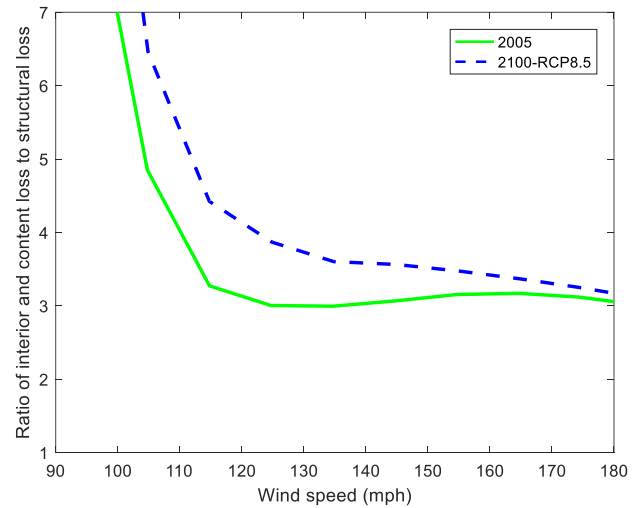

Figure 2: Average ratio of interior and content loss to structural loss of all building prototypes.

The loss ratios in the building prototypes are then combined using Eq. (9) to evaluate the overall regional loss for Miami-Dade County for present and future climate scenarios. To distinguish between loss due to wind alone and loss due to rain ingress, annual aggregated structural loss (AASL) and annual aggregated structural loss (AATL) is evaluated separately. For AASL, the loss ratio in Eq. (9) considers only structural loss ratio and for AATL the loss ratio considers the total loss ratio. Further, other factors like exposure, fragility, building density, building types etc. have been taken the same as present climate since the intention of this study is only to

study the impact of climate change on hurricane losses.

Figure 1 shows the value of AASL and AATL for the county. For Miami-Dade County, AASL is found to be 0.31, 0.36 and 1.18 US billion dollars and AATL is found to be 1.2, 1.4 and 4.8 US billion dollars for present, RCP2.6 and RCP8.5 scenario respectively. The difference in the huge amount of losses between the two future climate scenarios show the importance of climate mitigation on reducing hurricane losses. Further, the ratio of average annual loss due to rain ingress to structural damage is found to be 2.83 for present climate, 2.92 for RCP2.6 scenario in the year 2100 and 3.08 for RCP8.5 scenario in the year 2100, thus highlighting that rain ingress is the dominating factor for hurricane losses.
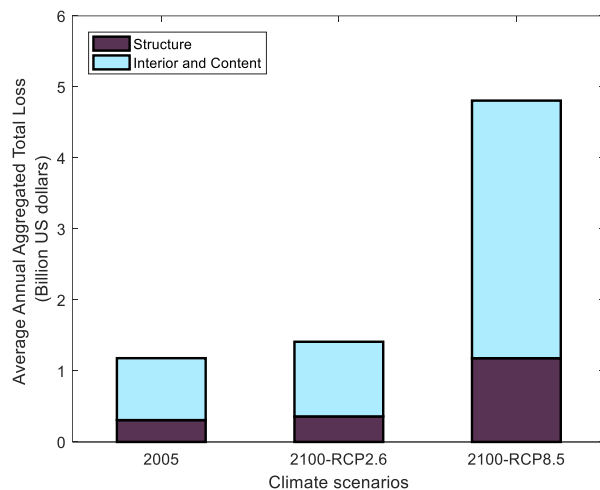

Figure 3: Average annual aggregated loss for Miami-Dade County for present and future climate scenarios.

6. CONCLUSION

In residential buildings, hurricane losses can be primarily attributed to damage due to high wind speed as well as rain ingress. This study investigated the mechanism of hurricane losses due to both these factors under climate-dependent hurricane scenarios. It is found that the losses due to rain ingress are much higher compared to wind losses in residential buildings for all the considered climate scenarios.

It is to be noted that this study does not consider other forms of hurricane damage in residential buildings including flooding, storm surge etc. Further, the climate change impact on hurricane frequency is not considered. Besides, any possible changes in future building inventory, exposure, fragility is not considered, since the study is intended to focus only on the changes in hurricane losses due to climate change.

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