Impact of risk mitigation strategies on future hurricane risk of residential buildings in changing climate

Bowei Song
Graduate Student, Dept. of Civil & Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA

Yihan Jiang
Graduate Student, Dept. of Civil & Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA

Eun Jeong Cha
Associate Professor, Dept. of Civil & Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA

ABSTRACT: Hurricanes are one of the biggest natural hazards to residential buildings under the worsening climate change. As the effect of climate change on hurricane risks has been suggested by many studies, the urge to protect residential buildings from hurricane damage has been rising. This study investigates the hurricane risk mitigation benefits of installing add-on structural components (accordion windows, perforated parapets, and hurricane clips) in terms of to what extent they can reduce the hurricane losses to 8 southeastern states in the U.S. The result shows the average loss reduction ranges from 12% to 15% among the current, short-term (2020-2030), and long-term (2090-2100) RCP 8,5 climate conditions, while the reduction rate would double if five percent of the maintenance rate is assumed.

1. INTRODUCTION

The extreme hurricane events are one of the most devastating natural hazard threats to cause severe loss of properties and human lives. Nine out of top ten costliest catastrophes in the United States till 2021 are caused by hurricane events (Institude 2022). As global climate changes, the prediction indicates that the severity and frequency of hurricane events would have an increasing trend due to global warming (Mudd et al. 2014). The Climate Science Special Report (CSSR) announced that in future decades until 2050, an increment of 2.5°F relative to the recent past average temperature (1976-2015) is expected (Wuebbles et al. 2018). The warmer climate could lead to higher sea surface temperature and the rise in sea level, which are related to severer hurricanes that can bring unforeseeable damage and loss (Center for Climate and Energy Solutions 2022). Hence, it is imperative to properly assess the future hurricane risks considering climate change and develop adaptation strategies for physical infrastructure to climate change.

With such expectation that more hurricanes and larger hurricane loss are foreseen in the future, prevention strategies to lower the risk have been investigated from two perspectives in existing literature. Some studies suggested a direct building code change focusing on wind load-related parameters. Noting the increases in the future extreme wind speeds, some studies suggested modifying corresponding coefficients in the national building code to resist hurricanes under changing climate conditions (Hong et al. 2021). Other researchers investigated specific mitigation strategies, aiming at strengthening the buildings' components. Masoomi et al. (2018) investigated different combinations of roof coverings, roof sheathing nailing patterns, and roof-to-wall connection types to show which combo would improve the wind resistance ability the most. While it is effective to implement new building code which considers the impact of climate change, there is still a long-time gap lasting for years before building code changes are taken into actions. During this gap period, maintaining and installing essential structural components could offer a practical way to protect residential buildings from hurricane damages. Furthermore, modification on building code only benefits future construction while implementing risk mitigation strategies strengthens the capacity of both new and retrofitting buildings. Therefore, this paper will focus on the mitigation strategies for critical building components and their impacts on future hurricane risk mitigation.

Specifically, this paper investigates the effect of adopting hurricane risk mitigation strategies to residential buildings to study to what extent they can reduce the hurricane losses to 8 southeastern states in the U.S. From a literature review on existing hurricane risk mitigation strategies for residential buildings, three mitigation strategies are selected first and used to model new building prototypes and the corresponding building inventory. A mathematical model for new building prototype compositions is developed, incorporating the construction rate, demolition rate, and maintenance rate. For efficient regional hurricane risk assessment, an ANN-based hurricane regional loss assessment model is developed to use the new building prototypes and the corresponding building composition as input. The hurricane risk assessment is then performed based on simulations under RCP8.5 climate change scenario to forecast the hurricane risk in selected regions for near-term (2020-2030) and long-term (2090-2300) conditions.

2. FUTURE BUILDING INVENTORY MODEL

2.1. Hurricane risk mitigation strategies

To model future building inventory change under hurricane risk assessment, existing studies on hurricane risk mitigation strategies with add-on structural components have been reviewed. From the review, three strategies with outstanding wind-resisting performance were selected, including hurricane clips, perforated parapets, and accordion windows. These strategies are known to help buildings withstand extreme winds by diminishing water intake, detracting strong wind uplift forces, and boosting component capacity. Specific risk mitigation benefits adopted in this study for each strategy are shown in Table 1.

Water intrusion is one of the main hurricane damage mechanisms. Strong winds of hurricanes break the building envelope system, which leads to water invasion. Thus, reinforcing the envelope system components can be a strategy to reduce the volume of water intrusion by hurricanes and the associated damage. Accordion shutters are a popular approach adopted to strengthen windows in the latest houses. Vutukuru et al. (2019) reported 77-87% reduction in the volume of water intrusion through the windows with the use of accordion shutters compared to non-impact-resistant windows with no shutters based on an experiment conducted by the Wind Driven Rain intrusion model. In addition, the existence of an accordion window system decreased the pressure difference across the interior and exterior surfaces of the window by 6-14%. To be conservative, a 6% reduction in external wind pressure and a 77% decrease in water intrusion are adopted in this study. The cost of installing accordion windows is approximately $14.86 per square feet. (Alibaba 2023)

The perforated parapets are another common hurricane risk mitigation strategy that is known to effectively reduce high wind uplift forces. Azzi et al. (2020) performed a wind pressure test and found a 40% reduction in area-averaged peak external pressure coefficients for roofs added with perforated parapets compared to those without the parapets. The installation of perforated parapets costs $25 per square foot (Lyon Construction 2022). Also, the convenience of construction makes perforated parapets a popular hurricane mitigation strategy.

The physical connections between wood frames in different planes could prominently enhance the strength of buildings as well. Ahmed et al. (2011) tried different amount of hurricane clips installed at one connection and proved that 2 hurricane clips utilized together contributes to a great promotion in uplift load carrying capacity and help reducing the risk of failures due to plane weakness. In the study, the increase in the uplift load carrying capacity is reported in terms of the mean and COV. The expense of hurricane clips is neglected in this study.

2.2. Future building prototype composition model

To assess the hurricane risks, a new building prototype composition model is introduced considering the three new hurricane risk mitigation strategies building upon Pant and Cha (2018). The building prototypes used in this study are summarized in Table 2. The original model classifies buildings by the type of wall, type of roof, type of roof cover, number of roof nailing, and number of stories, which forms 32 baseline prototypes and cover 86% of all residential house types in Miami-Dade county (Hazus). In this study, existence of accordion windows, existence of perforated parapets, and number of hurricane clips are considered additionally to model potential changes in building compositions in the future under climate change. Every category contains two options, and thus, total of 8 different building features composite total of 256 building prototypes.

A future building prototype composition model is developed by considering the change in the building inventory due to the potential adoption of the three hurricane risk mitigation strategies. For the model, construction of new buildings, and demolition and maintenance of existing buildings are considered. The number of buildings with the new hurricane mitigation strategies is estimated by considering the current number of buildings and building construction and maintenance rates (MR). The new and retrofitted buildings are assigned to new building prototypes with the hurricane risk mitigation strategies by using distribution function. The number of future buildings in each baseline building prototype with

Table 1: Risk mitigation effects and implementation cost of the add-on structural components considered in this study.

	Mitigation effects and cost
HC (Masooni et al. 2018)*	*Wind resistance:* *COV = 0.12; Mean = 2625.77lbs*
*PP** (Azzi et al. 2020)*	*Wind pressure: 40% reduction* *Cost: $25/sf*
*AW*** (Vutukuru et al. 2019)*	*Wind pressure: 40% reduction* *Water intrusion: 77% reduction* *Cost: $14.86 /sf*
HC & PP	*Wind resistance: same as HC* *Wind pressure: 40% reduction* *Cost: $25 /sf*
HC & AW	*Wind resistance: same as HC* *Wind pressure: 40% reduction* *Water intrusion: 77% reduction* *Cost: $14.86 /sf*
PP & AW	*Wind pressure: 43.6% reduction* *Water intrusion: 77% reduction* *Cost: $39.86 /sf*
ALL	*Wind resistance: same as HC* *Wind pressure: 43.6% reduction* *Water intrusion: 77% reduction* *Cost: $39.86 /sf*

* HC = Hurricane clips, ** PP = Perforated parapets, and *** AW = Accordion windows.

Table 2: Building prototype classification

Wind-resistant characteristics	*Ranges*	*Number*
Types of Walls	*Masonry; Wood-frame*	*2*
Types of Roofs	*Hip; Gable*	*2*
Roof Cover	*Shingle; Tile*	*2*
Roof Nailing	*6d; 8d*	*2*
Number of Stories	*One-story; Two-story*	*2*
Existence of Accordion Windows	*Yes; No*	*2*
Existence of Perforated Parapets	*Yes; No*	*2*
Number of Hurricane Clips	*0; 2*	*2*
	Total building prototypes	*2^8=256*

each hurricane risk mitigation strategy combination is estimated by

$$n_{future_{i,j}} = n_i \cdot (r_B + r_M \cdot (1 - r_D)) \cdot f(j) \quad (2)$$

where $n_{future_{i,j}}$ is the number of future buildings in the i^{th} baseline prototype with the j^{th} hurricane risk mitigation strategy combination, $i = 1,2,\ldots,32$, $j = 1,2,\ldots,7$, n_i is the number of buildings in the i^{th} baseline prototype in present, r_B is the building construction rate, r_M is the building MR , r_D is the demolition rate and $f(j)$ is the distribution function. It is assumed that the adoption of a hurricane strategy is mandatory for construction and regular maintenance of buildings. The current number of buildings is collected from the Building Construction Database on Statista website (US Census Bureau 2022). For simplicity, an equal distribution function is used for this study.

Many buildings will remain in their current baseline building prototypes without any hurricane risk mitigation strategies. The number of those future buildings is calculated by

$$n_{future_{i,0}} = n_i \cdot (1 - r_M) \cdot (1 - r_D) \quad (3)$$

where $n_{future_{i,0}}$ is the number of future buildings in the i th baseline prototype without any hurricane risk mitigation strategies. Two cases for the MR are considered, which are 5% and 0%. The demolition rate of every state in the U.S. is calculated by the sum of product of the probability of buildings' being demolished in different ages (U.S. Census Bureau 2018) and the frequency of buildings at corresponding ages (Infutor 2021). The construction rate is estimated by the net increase in building count among the total after gathering the number of housing units in the U.S. (U.S. Census Bureau 2022) and calculating the number of demolished buildings. The ratio of new buildings established every year is 6.29%.

3. REGIONAL HURRICANE WIND LOSS ASSESSMENT MODEL

Hurricane risk is assessed by using hurricanes simulated for 5 study regions (Region 1: Texas (TX) state; Region 2: Louisiana (LA), Mississippi (MS), and Alabama (AL) states; Region 3a: Florida state by the coast of the Gulf of Mexico (FL_G); Region 3b: Florida state by the coast of the Atlantic Ocean (FL_A); Region 4: Georgia (GA), South Carolina (SC), and North Carolina (NC) states.). The losses by all simulated hurricanes for study regions are aggregated.

Extensive regional hurricane risk assessment is conducted, by utilizing an artificial neural network (ANN)-based hurricane wind loss assessment model. A similar approach to Lin and Cha (2020) is adopted, which takes hurricane parameters and building vulnerability as input and aggregated regional loss as output. The hurricane parameters include the maximum surface wind speed and the maximum rainfall intensity. The building vulnerability parameters include the topographic information of the census tract and building prototype composition. For the aggregated regional loss, building and content loss are calculated, in which building loss consists of structure and interior loss.

In this study, new ANN models are developed by using the newly generated wind loss dataset based on the hurricane loss assessment model by Pant and Cha (2018; 2019). There exists no real damage data available to date that can be used for the wind loss assessment ANN model development. Thus, loss data simulated by existing and validated wind loss assessment model is used for this purpose. Pant and Cha's model assesses the damage at structural component level to estimate the loss for individual prototypes, which is aggregated for the regional hurricane loss assessment. The simulated loss data has 259 independent variables, including recorded 3-second wind gust, maximum rain rate, surface roughness length, and 256 building prototype composition ratios, and two dependent variables including building and content loss ratios, which corresponds to the input and output for the proposed ANN. 1,000 simulated hurricanes and loss assessment for Miami-Date County generated 58,344 rows of simulated data after filtering out the invalid data to develop ANN.

The ANN training configuration and the network structure with the best performance suggested by Lin and Cha (2020) is used. The simulated loss data is split into training and test datasets with the ratio of 7:3 to develop the ANN. Besides input and output layers, the network has three hidden layers and five hidden neurons per layer. It employs the Levenberg-Marquardt back-propagation as network training algorithm and the hyperbolic tangent sigmoid function as the activation function in hidden neurons.

4. HURRICANE RISK ASSESSMENT CONSIDERING MITIGATION STRATEGIES UNDER FUTURE CLIMATE

4.1. Evaluation methodology of hurricane damage mitigation

This study investigates to what extent the proposed hurricane damage mitigation strategies will effectively protect residential buildings from hurricane damage. For the study, hurricanes are simulated from their landfall at the U.S. southeast coastline defined by the 5 study regions. For each of the simulated hurricanes, estimated loss ratios are generated at census tract level based on the loss prediction model described in section 3.2.

This study analyzes the hurricane risk at the county level (each county consists of several census tracts) for the 8 southeastern states. The effect of hurricane damage mitigation strategies is investigated by comparing the annual average aggregated hurricane loss ratios for the present and the future building inventories. The risk mitigation benefit is investigated with three climate scenarios under the most extreme climate condition, RCP8.5 mean, as proposed by IPCC (2013 and 2014), which is summarized in Table 3.

Table 3: Climate scenarios considered in the research

Scenario	*Description*
CC	*Current climate condition (1986 - 2005)*
NT	*2020-2030 under RCP8.5 mean*
LT	*2090-2100 under RCP8.5 mean*

4.2. Future hurricane risk prediction

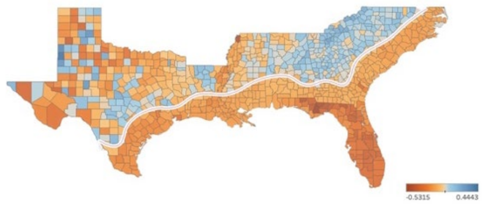
4.2.1. Reduction in regional aggregated loss ratio with new building prototype compositions

The percentage regional risk reduction is calculated by using the disaster impacts by the simulated hurricanes for building inventories with and without hurricane mitigation strategies under each climate scenario. The results are summarized into maps, as shown in Figs. 4 (a) – (f). Each cell in the map represents a county. The value of each cell indicates the change in the annual average regional loss ratio for the building inventory associated with the adoption of hurricane risk mitigation strategies compared to the status quo. Total of six figures were generated (1) for three climate scenarios and (2) with or without 5% MR. On the map, orange represents a decrease (risk reduction), and blue represents an increase (no risk reduction). The darker the color is, the greater the absolute value of risk reduction is. In addition, the white line crossing the map describes a rough boundary between orange and blue areas. The general patterns are found to be similar between the maps with or without MR for a same climate scenario. Adoption of new hurricane risk mitigation strategies for existing buildings with 5% MR shows darker colors for all counties.

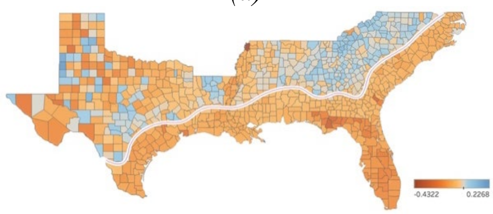
Finally, the maps tend to be redder as a more severe climate condition is considered, implying that the number of counties that have no risk reduction benefit is significantly less. In other words, the considered hurricane risk mitigation strategies are beneficial for most regions especially considering long-term climate change.

Table 4: Average loss ratio reduction rate in combined cases

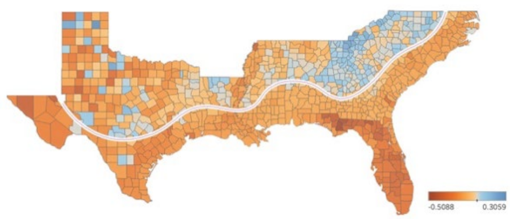
Case		*Loss Ratio Reduction*
CC	*5% MR*	*-29.18%*
	0% MR	*-15.35%*
NT	*5% MR*	*-26.58%*
	0% MR	*-13.83%*
LT	*5% MR*	*-23.75%*
	0% MR	*-12.21%*



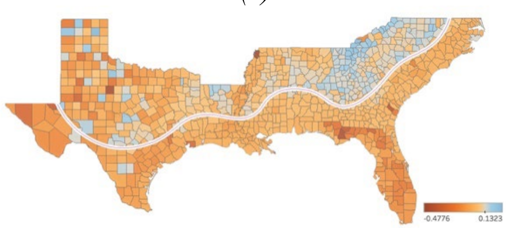
(a)



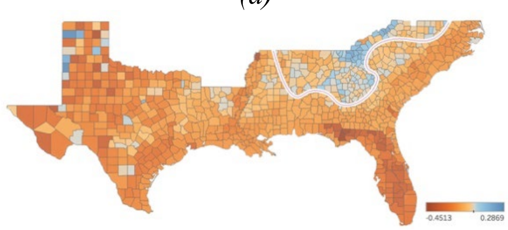
(b)



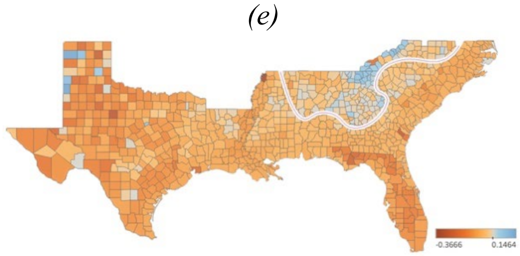
(c)



(d)



(e)



(f)

Figure 4. Risk mitigation map: (a) with 5% MR (CC), (b) 0% MR (CC), (c) with 5% MR (NT), (d) 0% MR (NT), (e) with 5% MR (LT), and (f) 0% MR (LT)

Average risk reduction rates are calculated for each climate scenario, which is summarized in Table 4. It is revealed that the proposed mitigation strategy proves to be effective in reducing the loss ratio by more than 20% and 10% with and without 5% MR, respectively, for all scenarios. It is observed that the adoption of the proposed mitigation strategies is effective even when no climate change occurs. It is also noticeable that the percentage risk reduction decreases as more severe climate scenarios are considered. This implies the considered mitigation strategies may not provide sufficient risk mitigation benefits in severe climate scenarios. As observed in the previous section, the retrofitting of existing buildings (with a 5% MR) increases risk mitigation benefits significantly and the case with 0% MR (adoption of risk mitigation strategies only for the new buildings) has a lower reduction value. This result implies that the existing buildings should be integral part of climate adaptation planning for effective hurricane risk management.

4.2.2. Spatial variation in risk reduction

The results from the previous sections reveal that the proposed hurricane mitigation strategies can effectively reduce future hurricane loss ratio in most counties considered in this study. It would be also meaningful to figure out which region will benefit the most, which could be an important question to government and insurance companies for their region-level policy development. Table 5 shows the annual average risk reduction by study region for each climate condition. The reduction values for eastern coastal states (Florida, Georgia, South Carolina, and North Carolina) are notably higher than those of southern coastal states (Texas, Louisiana, Mississippi, and Alabama). Florida is found to have the highest average risk reduction among the four study regions. The overall loss ratio decreases by 31.81% in the current climate condition, 29.56% in the near-term scenario (2020-2030), and 26.36% in the long-term scenario (2090-2100).

Table 5: Regional Reduction under Current climate, near-term and long-term climate change scenario

Case			Reduction
Texas	CC	5% MR	-18.89%
		0% MR	-11.53%
	NT	5% MR	-18.37%
		0% MR	-11.21%
	LT	5% MR	-17.47%
		0% MR	-10.64%
Louisiana, Mississippi & Alabama	CC	5% MR	-18.61%
		0% MR	-10.79%
	NT	5% MR	-18.72%
		0% MR	-10.69%
	LT	5% MR	-17.21%
		0% MR	-9.91%
Florida	CC	5% MR	-31.81%
		0% MR	-16.95%
	NT	5% MR	-29.56%
		0% MR	-15.59%
	LT	5% MR	-26.36%
		0% MR	-13.74%
Georgia, South Carolina & North Carolina	CC	5% MR	-26.95%
		0% MR	-14.18%
	NT	5% MR	-25.01%
		0% MR	-13.06%
	LT	5% MR	-22.79%
		0% MR	-11.89%

5. CONCLUSION AND DISCUSSION

Hurricanes are one of the biggest natural hazard concerns to residential buildings under the worsening climate change year by year. This paper investigates the effect of installing essential building components which have hurricane risk mitigation characteristics to study to what extent they can reduce the hurricane losses of 8 southeastern states in the U.S.

From the investigation, it is found that the new building prototypes with three additive components (accordion windows, perforated parapets, and hurricane clips) can effectively decrease the average hurricane loss ratio over most of the studied locations under current climate situation, near-term (2020-2030), and long-term (2090-2100) climate change scenarios (RCP 8.5). When ignoring the maintenance rate, the average loss reduction ranges from 12% to 15% among the three climate scenarios, while the reduction rate would double if 5% of maintenance rate is assumed, i.e., 5% of existing buildings are also retrofitted. Furthermore, the average ratio lowers over time, which may be triggered by several reasons. For example, the impact of climate change on hurricanes may be greater than the positive impact of efforts to reduce their impact, suggesting the use of more effective measures. However, the number of counties that benefits from the new building code in the long-term is greater than that in the near-term and current condition.

This paper also discovers that if all the studied regions implement the same building prototype composition as proposed, Florida residential houses, compared to other states, would benefit the most from the new building prototypes with hurricane damage mitigation characteristics under all three climate scenarios. The maximum reduction value reaches 31.81% in region 3 (Florida) under the current situation and the minimum is 9.91% in region 2 (Louisiana, Mississippi, and Alabama) in the long-term (2090-2100).

It should be noted that the intent of this research is to evaluate the effect of applying new building prototypes with hurricane damage mitigation strategies on the hurricane loss reduction. The building prototypes employed in this study is modeled only from residential buildings of Miami-Dade County and consists of more than 86% percent of the overall housing inventory of that county. Therefore, a more comprehensive building inventory that can represent all southeastern states counties is expected in future study. In addition, when considering mitigation strategies, a constant maintenance rate of 5% or 0% is used based on assumption. The true value is not yet discovered and may change the assessment result as well. Consequently, subsequent research might improve the accuracy of the study by employing more representative and generalized building prototypes and using maintenance rate closer to reality.

6. REFERENCES

Alibaba "Superhouse accordion windows cost aluminum folding window" Accessed January 31, 2023. https://www.alibaba.com/product-detail/Superhouse-accordion-windows-cost-aluminum-folding_1600351230005.html

Azzi, Z., Habte, F., Elawady, A., Gan Chowdhury, A., and Moravej, M. (2020). "Aerodynamic mitigation of wind uplift on low-rise building roof using large-scale testing." *Frontiers in Built Environment*, 5, 149.

Center for Climate and Energy Solutions. 2022. "Hurricanes and climate change." Accessed January 31, 2023. https://www.c2es.org/content/hurricanes-and-climate-change/

FEMA. (2013). *Hazus—MH 2.1 Technical manual: Hurricane Model*. https://www.fema.gov/sites/default/files/2020-09/fema_hazus_hurricane-model_technical-manual_2.1.pdf

Hong, H., Tang, Q., Yang, S., Cui, X., Cannon, A., Lounis, Z., and Irwin, P. (2021). "Calibration of the design wind load and snow load considering the historical climate statistics and climate change effects." *Structural Safety*, 93, 102135.

Infutor, & Statista. 2021. "Number of homes in the United States as of October 2021, by age (in millions) [Graph]". Accessed January 31, 2023.https://www.statista.com/statistics/1042458/home-age-usa/

Institude, I. I. 2022. "Facts + Statistics: U.S. catastrophes." Accessed Jan 26, 2023 https://www.iii.org/fact-statistic/facts-statistics-us-catastrophes.

Lin, C.-Y., and Cha, E. J. (2020). "Hurricane risk assessment for residential buildings in the southeastern US coastal region in changing climate conditions using artificial neural networks." *Natural Hazards Review*, 21(3), 04020024.

Lyon Construction. 2022. "Tulsa Construction Estimating and Renovation Cost." Accessed February 7, 2023. https://lyonconstruct.com/construction-estimating-and-renovation-cost/

Masoomi, H., Ameri, M. R., and van de Lindt, J. W. (2018). "Wind performance enhancement strategies for residential wood-frame buildings." *Journal of Performance of Constructed Facilities*, 32(3), 04018024.

Mudd, L., Wang, Y., Letchford, C., and Rosowsky, D. (2014). "Assessing climate change impact on the US East Coast hurricane hazard: temperature, frequency, and track." *Natural Hazards Review*, 15(3), 04014001.

Pant, S., and Cha, E. J. (2018). "Effect of climate change on hurricane damage and loss for residential buildings in Miami-Dade County." *Journal of Structural Engineering*, 144(6), 04018057.

Pant, S., and Cha, E. J. (2019). "Wind and rainfall loss assessment for residential buildings under climate-dependent hurricane scenarios." *Structure and Infrastructure Engineering*, 15(6), 771-782.

Sheikh Saad Ahmed, Ivan Canino, Arindam Gan Chowdhury, AmirMirmiran, and Nakin Suksawang. "Study of the capability of multiplemechanical fasteners in roof-to-wall connections of timber residentialbuildings." *Practice Periodical on Structural Design and Construction,*16(1):2–9, 2011

U.S. Census Bureau. 2018. Methodology for State and County Total Housing Unit Estimates (Vintage 2017): April 1, 2010 to July 1, 2017

US Census Bureau. 2022. "Number of housing units in the United States from 1975 to 2021 (in millions) [Graph]." Accessed January 31, 2023.https://www.statista.com/statistics/240267/number-of-housing-units-in-the-united-states/

Vutukuru, K. S., Moravej, M., and Gan Chowhdury, A. "Wind Driven Rain Intrusion Reduction for Shuttered Windows." *Proc., Proceedings of 15th International Conference on Wind Engineering, Beijing, China*.

Wuebbles, D., Fahey, D. W., and Hibbard, K. A. (2018). "How will climate change affect the United States in decades to come?" *Eos*, 99(1), 18-23.