JOURNAL OF
EMERGING INVESTIGATORS

Article

An accessible experiment to assess the impact of shapes of buildings and roofs on wind resistance

Lee Tao[1], **Wei Wu**[2]

[1] Benjamin Franklin High School, New Orleans, Louisiana

[2] School of Ocean Science and Engineering, The University of Southern Mississippi, Ocean Springs, Mississippi

SUMMARY

Hurricanes cause extensive amounts of damage in coastal communities each year. Rebuilding is costly, and the impact of hurricanes can be alleviated by mitigating the destruction to buildings. As such, buildings that are resistant to high winds are the key to increasing the resilience of communities to hurricanes. Here, we designed an accessible experiment to evaluate the effects of house and roof shape on wind resistance. We built four types of house models: box-shaped houses with pyramid hip roofs, box-shaped houses with flat roofs, round houses with pyramid hip roofs, and round houses with flat roofs. To evaluate the stability of these house models, we applied strong winds using a leaf blower. We determined stability by measuring the distance between the leaf blower and the house models when they were blown away, and the time it took for the houses to be blown away if the distance was 0 cm. The smaller the distance and the longer the time, the more resistant the houses are to strong winds. We found round houses were more resistant to strong winds than box-shaped houses, and houses with pyramid hip roofs were more resistant to strong winds than houses with flat roofs if other attributes of the houses were kept the same. Furthermore, we found roof shape was more important than house shape among the different combinations of house shapes and roof shapes we studied. Our study provides scientific data to facilitate policy making in improving coastal resilience, particularly through updating building codes that account for house and roof shape.

INTRODUCTION

Half of the U.S. population lives within 50 miles of coastlines (1,2) that are prone to hurricanes, which are one of the world's costliest natural disasters (3). The total monetary damages each decade from 1906 to 2005 in the U.S. due to hurricanes range from $24 billion (1916-1925) to $224 billion (1926–1935) with an individual hurricane's damage costing up to $157 billion (The Great Miami Hurricane of 1926) (4). These values are adjusted for inflation, wealth, and population, updated to 2005 (4). The damages were mostly due to wind, followed by flooding from storm surge and/or heavy rain. Given the rapid growth of coastal populations with more intense hurricanes projected because of climate change, these damages will likely increase further (5-7). Dealing with the aftermath of hurricanes is a very costly and long process. To make coastal communities more resilient to hurricanes, it is important to minimize damages, especially to buildings, as they are critical infrastructure for a community. To do this, we need to find what types of house design (e.g., shapes and materials) can withstand strong winds and minimize damages the most.

The important factors that affect magnitude and distribution of external wind pressures, and therefore the resilience of buildings to high winds, include upstream terrain, wind direction, presence of surrounding buildings (8). They also include house characteristics such as roof shape, roof pitch, eave shape, building geometry, and presence of canopy and parapet (8). Among them, roof shape and terrain are the most important elements to external wind pressures acting on the roof structures (8). Focusing on the building characteristics, researchers have found that the gable roof experiences higher pressure than the hip roof with other factors staying the same for a giving storm and therefore is less resistant to hurricane-force winds (8-15). The slope of a roof also plays an important role in wind resistance. Low-sloped roofs have significantly higher wind uplift forces than steeper sloped ones; therefore, steeper roofs are more resistant to high winds than flatter roofs. The shapes of houses also affect their resistance during hurricanes (16,17). For example, houses with a hexagonal or octagonal floor plans reduce wind loads more than square plans (18).

Different models have been developed to predict hurricane damages for residential structures (19). In fact, the shape of buildings and roofs are so important that HAZUS, the multi-hazard loss estimation methodology and software developed at the Federal Emergency Management Agency (FEMA), has the options to change roof shapes (hip, gable, or flat) and building shapes (square or rectangle) to more accurately evaluate the damages due to hurricanes (14). Despite the importance of shapes of buildings and roofs, they are not required to be considered in building codes in hurricane-prone areas (20). Roof regulation focuses on the material instead of the shape (21). Additionally, limited research exists on evaluating the interaction of house and roof shape in wind resistance.

Our research objectives were to provide quantitative information on the resistance to high winds for buildings with different combinations of house and roof shapes through an accessible experiment. Accordingly, we had two research hypotheses. The first hypothesis is that round houses are more resistant to strong winds than box-shaped houses with the same shapes of roofs. The second hypothesis is that houses with pyramid hip roofs are more resistant to strong winds than with flat roofs with the same shapes of houses. Our study provided scientific evidence on which shapes of houses and roofs could resist strong wind and therefore should be encouraged to build in the hurricane-prone areas to mitigate house damages and improve communities' resilience to natural disasters.

RESULTS

We tested the wind resistance of four types of house models (house or houses thereafter) that vary in shape by subjecting them to strong wind from a leaf blower (**Figure 1**). We measured the distances between the houses and the blower when it blew away the houses. If the blower reached a house without blowing it away (distance of 0 cm), we started to record time until the house was blown away. Houses with shorter distances showed that they were more resistant to winds. If the distance reached 0 cm, the house that could sustain the wind for a longer time was more resistant.

Our results showed that different types of houses had different capabilities to resist strong winds. Houses with flat roofs, no matter the house shape, were blown away before the leaf blower reached them. The distances were shorter for round houses than for box-shaped houses, indicating higher resistance to strong winds for round houses with flat roofs (**Figure 2**). None of the houses with pyramid hip roofs were blown away until the leaf blower reached them, showing pyramid hip roofed houses were more resistant to strong winds than flat-roofed houses (**Figure 2**). In addition, it took longer for the round houses with pyramid hip roofs to be blown away than the box-shaped houses with pyramid hip roofs, again showing higher wind resistance for round houses with the same shapes of roofs, whether the shape was pyramid hip or flat (**Figures 2-3**). There is a statistically significant difference between wind resistance, measured by the blower distance to house, amongst the four different types of houses (one-way ANOVA, $p < 0.001$). All pairwise comparisons were significantly different (Tukey's post-hoc test, $p < 0.05$) except for the round houses with pyramid hip roofs versus box-shaped houses with pyramid hip roofs, as their distances were all 0 cm ($p > 0.05$, **Figure 4**).

Figure 1: Overview of House Models. All house models had the same wall height and base area. (A) Round house models with flat roof, (B) Box-shaped house models with flat roof, (C) Box-shaped house models with pyramid hip roof, and (D) Round house models with pyramid hip roof.

When the shape of the house remained constant, the pyramid hip roofs showed larger resistance to strong winds than the flat roofs. However, it seemed that the pyramid hip roof made a larger difference for box-shaped houses ($p < 0.001$ with a mean difference of 25.19 cm and 95% confidence interval of 14.17 to 36.21 cm), and a smaller difference for round houses ($p < 0.05$ with a mean difference of 14.72 cm and 95% confidence interval of 0.45 to 22.49 cm). Comparing the houses with different shapes and different roofs, round houses with pyramid hip roofs were significantly more resistant to strong winds than box-shaped houses with flat roofs ($p < 0.001$). In fact, the pyramid hip roof was so influential that it made the box-shaped houses more resistant to winds compared to round houses with flat roofs ($p < 0.05$). We used a t-test to compare the time it took for the two different shapes of houses with pyramid hip roofs to be blown away as that cannot be differentiated based on distance. Round houses were more resistant to strong winds than box-shaped houses ($p < 0.05$).

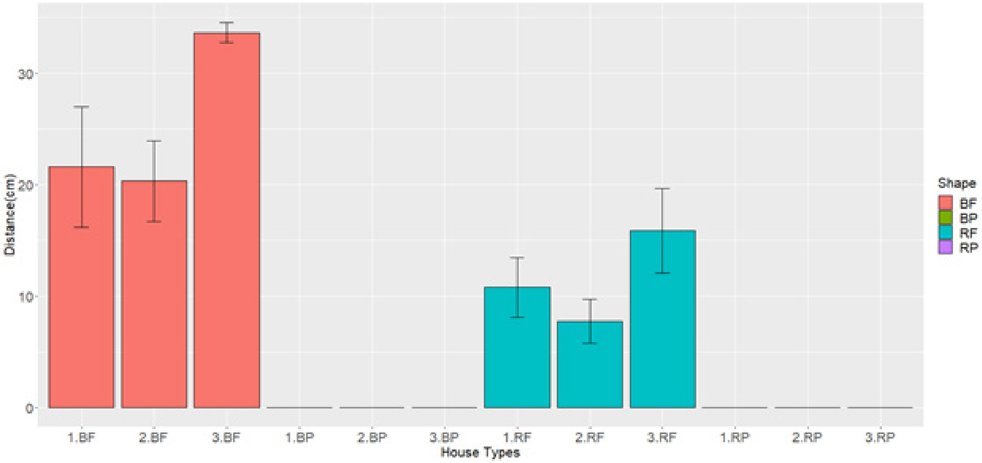

Figure 2: Distance between the leaf blower and the house models when the house models were blown away. The shorter the distance, the more resistant the house models are to strong winds. As the distances for BP and FP were 0 cm, there were no error bars for these two types of houses in the figure. Error bars show standard deviation for two trials for each house model. The most wind-resistance houses had pyramid hip roof. With the flat roofs, the round houses were more wind resistant than the box-shaped houses. BF = Box-shaped house with flat roof, BP = Box-shaped house with pyramid hip roof, RF = Round house with flat roof, RP = Round house with pyramid hip roof. 1, 2, and 3 on the x-axis denote replicate number of house models.

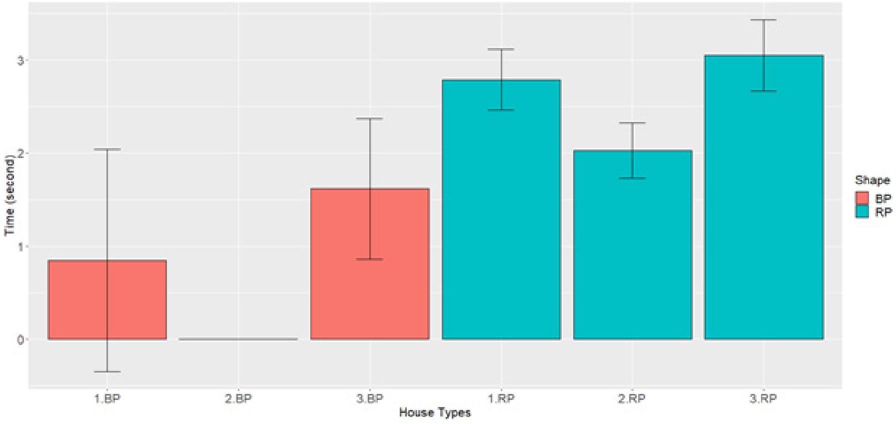

Figure 3: Time it took for the house models to be blown away after the leaf blower reached the house models. The longer the time, the more resistant the houses to strong wind. Error bars show standard deviation for two trials for each house model. Round houses were more wind resistant than the box-shaped houses with the same pyramid hip roofs. BP = Box-shaped house with pyramid hip roof, RP = Round house with pyramid hip roof. 1, 2, and 3 on the x-axis denote replicate number.

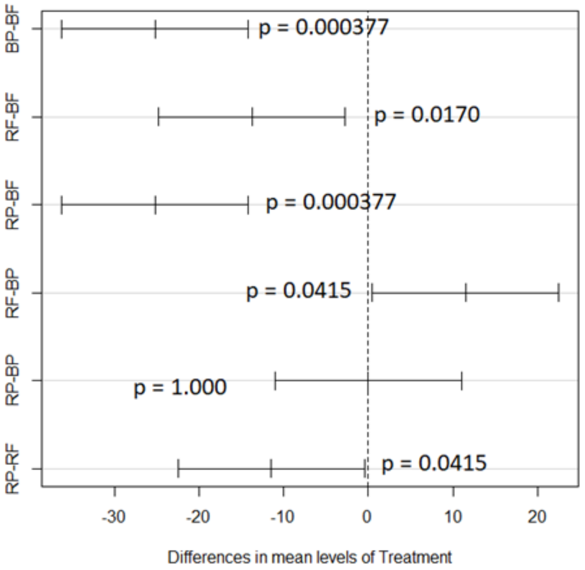

Figure 4: 95% of confidence intervals of Tukey's multiple comparisons (indicated by horizontal lines). Mean values of leaf blower distance (in cm) between different types of house models (treatment) were compared. BF = Box-shaped house with flat roof, BP = Box-shaped house with pyramid hip roof, RF = Round house with flat roof, RP = Round house with pyramid hip roof.

DISCUSSION

Wind effects are influenced by the shapes and sizes of buildings, their fundamental period of vibration, stiffness of surfaces, and strength of connections (8,18). In our research, we focused on the effect of shapes, including shapes of buildings and shapes of roofs. Our finding that the round houses or pyramid hip roofs were more resistant to strong winds than box-shaped houses or flat roofs can be explained by fluid dynamics. The round house has a more aerodynamic shape than the box-shaped house as the round shapes have less drag (22). When the wind hits the round house, it goes around the house, dissipating the force. When the wind hits the box-shaped house, the force is not dissipated as well. Similarly, the hip roof has a more aerodynamic structure than the flat roof. A flat roof experiences outward pressure (18). The overhang on the flat roof can cause the wind to pick the house up by its roof, which is much less likely to happen to the hip roof.

Engineers understand the importance of aerodynamic structures. They apply a well-established technique, the wind tunnel, to test reduced scale home models in an atmospheric boundary layer to evaluate the effect of house shapes on wind loads (10,16,23,24). Prior research conducted at the Department of Aerodynamics and Climatic Engineering at Center for Building Science and Technology in France showed that a home with a hexagonal or octagonal floor plan with multiple panels reduced wind loads, and roofs with multiple slopes, such as hip roofs, could reduce more wind loads than gable roofs (18). Though our experiment did not compare the same types of house shapes or roof shapes, and our research did not involve expensive equipment like a wind tunnel, our finding that a multi-slope roof (hip) was more resistant to winds than a flat roof (no slopes) is consistent with the finding of this previous work (18). Additionally, we took a further step to test different combinations of house and roof shapes and found that the shape of the roof was more important than the house shape through our two-factorial design. A previous study also showed that the shape of the roof for light-frame and low rising buildings a more important house characteristic to affect wind force loading and houses' resistance to high wind compared to roof pitch, eave shape, building height, overhang ration and aspect ratio (8). Therefore, to build more resilient houses, we need to start by building roofs that are more resilient.

On the other hand, applying the appropriate engineering knowledge into the construction of houses that could withstand strong winds in cyclone-prone areas is lagging behind (25). In some regions, like the Caribbean islands, engineers have rarely been involved in the design of houses (16). To facilitate the application, the results of our experiment and other experiments using wind tunnels and modeling must be extrapolated to explain different resistances of the houses to high winds or building performance in the real world. This endeavor requires further studies that link the reduced-scale house experiments with the empirical analysis related to hurricane damage assessments. Scaling these houses up is not linear and involves many uncertainties related to simplified spatial-temporal varying wind loads in the experiments, resolution of numerical models, and building component capacity (8). Full-scale or large-scale wind tests are needed to fill in the knowledge gap and should be promoted in future research, but will be challenging due to social, economic, and institutional barriers (8,26).

Observations through post-hurricane assessment have confirmed the importance of aerodynamic structure design to mitigate damages. For example, most houses with hip roofs in Puerto Rico after Hurricane Maria appeared to be undamaged (27). Researchers also found that hip roofs performed better than gable roofs after Hurricane Hugo (18). However, the post-hurricane damage assessments do not always relate the damages to the shapes or other properties of houses, though this information is important to understand empirically how the house properties affect wind resistance. High-resolution remote sensing images (aero-photographs, Unmanned Aerial System images, or high-resolution satellite images) can provide a useful tool for us to evaluate sustainability of different shapes and sizes of houses/roofs efficiently at a broad spatial scale.

To build more wind resistant houses, we also need to consider socio-economic factors. Previous research shows that single family damage after Hurricane Ike in 2008 can be predicted by hazard exposure, structural characteristics, and socioeconomic characteristics (28). Social vulnerability can turn hurricane hazards into hurricane disasters (29). Addressing social vulnerability is important to increasing coastal resilience, but it is beyond our study. We did not consider cost either, so the feasibility of building pyramid hip roofs should be further evaluated. In general, building pyramid hip roofs is more expensive than building flat roofs because there are more materials needed, and it is a much more difficult design (30).

Though our experiment was simple and used common household items, it clearly supported the findings from the research that is generally not accessible to high school students (like the wind tunnel experiment), and it demonstrated the importance of house and roof shape in determining houses' wind resistance. The experiment can be repeated by anyone, and it provides key information to policy makers to facilitate the design of mitigation plans to build more resilient communities. The study particularly urges city planners in coastal regions to consider accounting for shapes of roofs in the building codes. The information can also help insurance companies, as they can play an important role in setting policy guidelines and providing incentives in premiums to encourage more aerodynamic designs in new houses to mitigate hurricane damages (25).

In conclusion, we designed a low-cost and accessible experiment to evaluate how different combinations of shapes of houses and roofs affected resistance of houses to high winds. We found round houses were more resistant to strong winds with the same shapes of roofs (flat or pyramid hip), and houses with pyramid hip roofs were more resistant to strong winds with the same shapes of houses (box-shape or round) given other factors stayed the same (height, base area, wind power, terrain, etc.). In addition, the shape of the roof was more important than the shape of the house in affecting wind resistance of houses. These findings suggest some feasible ways to make communities more resilient to hurricanes, like accounting for the shape of roof in building codes or providing incentives from federal programs in FEMA or insurance companies that can make expensive pyramid hip roofs more affordable.

MATERIALS AND METHODS

Construction of house models

We first built house models that had two different shapes: round/cylinder and square/box using cardboard and two different shapes of roofs: pyramid hip and flat using magazine paper. We built three replicates for each house and roof combination: box with flat roof, box with pyramid hip roof, round with flat roof, and round with pyramid hip roof (**Figure 1**). All twelve house models had the same materials, same wall heights (10 cm) and same base areas (100 cm^2).

Wind resistance trials

For each trial, we glued one house model to the floor at one time using Elmer's white school glue. After two minutes, the leaf blower was turned on 3 meters away from the house. The wind speed of the leaf blower was 150 miles per hour (mph), very close to sustained wind speed in Category 5 hurricane (157 mph or higher) based on the Saffir-Simpson Hurricane Wind Scale (31). We steadily walked closer to the house at a straight line until the house was blown away or the blower reached the house. We measured the distances between the house models and the blower when it blew away the house models. If the blower reached the house (distance of 0 cm), we started to record time until the house got blown away. For each of the 12 houses, we conducted 2 trials. We averaged the distances or time of the two trials for each house to conduct statistical analysis.

Statistical Analysis

To evaluate whether there existed significant differences in the distances (resistance to winds) among the four types of house models we tested, we applied Analysis of Variance (ANOVA) in R (32). P-values smaller than 0.05 indicated a significant difference. If we detected significant difference, we further performed post-hoc analysis in R based on Tukey's multiple comparisons of means to derive which two types of house models differed in their resistance to winds. We also conducted a statistical test on time for the house types with distances of 0 cm. As this only applied to two types of houses, we implemented t-test in R. We generated figures using the ggplot2 package in R.

Received: April 28, 2022
Accepted: September 26, 2022
Published: February 6, 2023

REFERENCES

1. Crowell, Mark, *et al*. "An Estimate of the U.S. Population Living in 100-Year Coastal Flood Hazard Areas." *Journal of Coastal Research*, vol. 26, no. 2, 2010, pp. 201–11, doi.org/10.2112/JCOASTRES-D-09-00076.1.
2. Mooney, C. "Storm World: Hurricanes, Warming, and Scientific Uncertainty." *Skeptical Inquirer*, vol. September, 2007, pp. 38–43.
3. Berardelli, Jeff. "How climate change is making

hurricanes more dangerous." yaleclimateconnections.org/2019/07/how-climate-change-is-making-hurricanes-more-dangerous/. Accessed 21 November 2022.

4. Pielke, Roger A., *et al*. "Normalized Hurricane Damage in the United States: 1900–2005." *Natural Hazards Review*, vol. 9, no. 1, 2008, pp. 29–42, doi.org/10.1061/(asce)1527-6988(2008)9:1(29).
5. Hauer, Mathew E., *et al*. "Millions Projected to Be at Risk from Sea-Level Rise in the Continental United States." *Nature Climate Change*, vol. 6, no. 7, 2016, pp. 691–95, doi.org/10.1038/nclimate2961.
6. Crossett, K., *et al*. *National Coastal Population Report, Population Trends from 1970 to 2020*. 2014, oceanservice.noaa.gov/facts/coastal-population-report.pdf. Accessed 21 November 2022.
7. Holland, Greg, and Cindy L. Bruyère. "Recent Intense Hurricane Response to Global Climate Change." *Climate Dynamics*, vol. 42, no. 3–4, 2014, pp. 617–27, doi.org/10.1007/s00382-013-1713-0.
8. He, J., *et al*. "A Review of Wood-Frame Low-Rise Building Performance Study under Hurricane Winds." *Engineering Structures*, vol. 141, 2017, pp. 512–29, doi.org/10.1016/j.engstruct.2017.03.036.
9. "Hip vs. Gable Roof". www.tulsaprotech.com/hip-vs-gable-roof/. Accessed 21 November 2022.
10. Meecham, D., *et al*. "The Magnitude and Distribution of Wind-Induced Pressures on Hip and Gable Roofs." *Journal of Wind Engineering & Industrial Aerydynamics*, vol. 38, no. 2–3, 1991, pp. 257–72.
11. Xu, Y. I., and C. F. Reardon. "Variations of Wind Pressure on Hip Roofs with Roof Pitch." *Journal of Wind Engineering & Industrial Aerodynamics*, vol. 73, no. 3, 1998, pp. 267–84.
12. Gavanski, E., *et al*. "Wind Loads on Roof Sheathing of House." *Journal of Wind Engineering & Industrial Aerodynamics*, vol. 114, 2013, pp. 106–21.
13. Vickery, Peter J., *et al*. "HAZUS-MH Hurricane Model Methodology. II: Damage and Loss Estimation." *Natural Hazards Review*, vol. 7, no. 2, 2006, pp. 94–103, doi.org/10.1061/(asce)1527-6988(2006)7:2(94).
14. Liao, Dezhi. *Physically-Based Visualization of Residential Building*. PhD Dissertation, University of Central Florida, Orlando, Florida. 2007. stars.library.ucf.edu/cgi/viewcontent.cgi?article=4241&context=etd. Accessed 21 November 2022.
15. Meecham D. *Wind action on low-rise buildings.* PhD Dissertation, The University of Western Ontario, London, ON, Canada. 1988.
16. Prevatt, D. O., *et al*. "Engineering Perspectives on Reducing Hurricane Damage to Housing in CARICOM Caribbean Islands." *Natural Hazards Review*, vol. 11, no. 4, 2010, pp. 140–50, doi.org/10.1061/(asce)nh.1527-6996.0000017.
17. Amini, Mehrshad, and Ali M. Memari. "Review of Literature on Performance of Coastal Residential Buildings under Hurricane Conditions and Lessons Learned." *Journal of Performance of Constructed Facilities*, vol. 34, no. 6, 2020, p. 04020102, doi.org/10.1061/(asce)cf.1943-5509.0001509.
18. Taher, Rima. "Design of Low-Rise Buildings for Extreme Wind Events." *Journal of Architectural Engineering*, vol. 13, no. 1, 2007, pp. 54–62, doi.org/10.1061/(asce)1076-0431(2007)13:1(54).
19. Pinelli, Jean-paul, *et al*. *Hurricane Damage Prediction Model for Residential Structures*. no. November, 2004, doi.org/10.1061/(ASCE)0733-9445(2004)130.
20. 2021 International Building Code, 2020. Available at https://codes.iccsafe.org/content/IBC2021P2. Last accessed on 1/12/2023.
21. Chapter 15, Roof assemblies and rooftop structures. In 2021 International Building Code, 2020. Available at https://codes.iccsafe.org/content/IBC2021P2/chapter-15-roof-assemblies-and-rooftop-structures. Last accessed on 1/12/2023.
22. What is aerodynamics? Available at www.nasa.gov/audience/forstudents/k-4/stories/nasa-knows/what-is-aerodynamics-k4.html. Last accessed on 1/12/2023.
23. Holmes J. D., Best R.J. *An approach to the determination of wind load effects*. 1981, pp. 273–87. www.aivc.org/sites/default/files/members_area/medias/pdf/Airbase/airbase_00777.pdf. Accessed 20 November 2022.
24. Liu, Z., *et al*. "Field Measurement and Wind Tunnel Simulation of Hurricane Wind Loads on a Single Family Dwelling." *Engineering Structures*, vol. 31, no. 10, 2009, pp. 2265–74, doi.org/10.1016/j.engstruct.2009.04.009.
25. Prevatt, D. O. "Improving the Cyclone-Resistance of Traditional Caribbean House Construction through Rational Structural Design Criteria." *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 52, no. C, 1994, pp. 305–19, doi.org/10.1016/0167-6105(94)90056-6.
26. National Research Council. *Review of the Need for a Large-Scale Test Facilitaty for Research on the Effects of Extreme Winds on Structures*. Washington DC.1999.
27. Prevatt, D.O., *et al*. "Performance of Structures under Successive Hurricanes: Observations from Puerto Rico and the US Virgin Islands after Hurricane Maria." *Proceedings of Forensic Engineering 8th Congress*, 2018.
28. Highfield, Wesley E., *et al*. "Mitigation Planning: Why Hazard Exposure, Structural Vulnerability, and Social Vulnerability Matter." *Journal of Planning Education and Research*, vol. 34, no. 3, 2014, pp. 287–300, doi.org/10.1177/0739456X14531828.
29. Crowley, Julia. "Social Vulnerability Factors and Reported Post-Disaster Needs in the Aftermath of Hurricane Florence." *International Journal of Disaster Risk Science*, vol. 12, no. 1, 2021, pp. 13–23, doi.org/10.1007/s13753-020-00315-5.
30. Maghiar, Marcel, *et al*. "Roof Design Efficiency for Energy Consumption in Residential Units". *EPiC Series in Built Environment Volume* 3, 2022, pp. 767–75. ASC2022. 58th Annual Associated Schools of Construction International Conference.
31. "Saffir-Simpson Hurricane Wind Scale". ww.nhc.noaa.gov/aboutsshws.php. Accessed 21 November 2022.
32. R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, 2015, www.R-project.org/. Accessed 21 November 2022.

JOURNAL OF
EMERGING INVESTIGATORS