Performance and Fragility of Elevated Structures During Hurricane Events

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ABSTRACT:
Elevating coastal houses that are close to the shoreline has been found to be an effective technique to mitigate flooding and storm surge hazards. However, elevated structures are exposed to stronger winds and unique aerodynamics characteristics due to the presence of air gap beneath the floor. This leads to wind loads on roof, floor, walls, and piles that are different from those on a slab on grade counterpart and not yet defined in building codes. Thus, it is of critical importance to assess the vulnerability of elevated structures to wind hazards. Utilizing available data from post-hurricane damage reconnaissance, this paper analyses the wind resistance performance observed for 900 elevated structures, located in Florida and Texas, United States, which were impacted by Hurricanes Irma, Michael, and Harvey. We report on observed damage to structural and non-structural components and relate these to the estimated failure wind speeds. Furthermore, the data is used to empirically develop fragility curves for elevated structures subjected to strong winds. Results showed that besides wind speed, building age, location, and elevation height may affect the damage level of elevated structures.

Keywords: Elevated structures, Fragility, Empirical, Wind effects

1. INTRODUCTION

The United States suffers from landfalling hurricanes that impose multi-hazards on coastal communities on an annual basis. Coastal structures experience severe damage due to flooding, storm surge, and strong winds(Amini & Memari, 2020). To mitigate flooding and storm surge hazards, the Federal Emergency Management Agency recommends elevating coastal structures to a safe level known as Base Flood Elevation level (FEMA P-550). Of the several benefits of such a mitigation technique on the resiliency of such structures, elevating buildings may increase their vulnerability to wind hazards since they would be exposed to higher wind speeds (Kim et al., 2020). Yet, there are unknown changes in the wind loading acting on an elevated structure due to the changes in the aerodynamics created by air gap under the floor. To fill this gap, Abdelfatah et al. (2020) carried out large-scale aerodynamic tests on four models which represent low rise gable roof single story elevated structure with four different elevation heights. Results showed that, for elevated structure, the floor surface experiences suction pressure. Moreover, increasing the elevation height leads to increasing the critical suction zones' area.

Although hurricanes are multi-hazard events, the current research considers only the effect of strong winds and their induced damage. Precisely, this paper analyses the performance and fragility of coastal elevated structures. First, Data sources and damage classification method for the damaged elevated structures, located in Texas and Florida, are briefly introduced. Second,

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effect of elevation height on the observed damage level is examined. Finally, fragility functions are developed for elevated structures using empirical approach.

2. METHODOLOGY

Following the landfall of Hurricanes Irma, Harvey, and Michael, several reconnaissance efforts have been organized to collect data about damaged structures. For example, the Structural Extreme Events Reconnaissance (StEER) Network initiated and executed virtual and field assessment study following Hurricane Michael which impacted the state of Florida (Kijewski-Correa et al., 2020). Also, RAPID-reconnaissance studies were executed following the landfall of Hurricanes Irma and Harvey which impacted Florida and Texas, respectively (Kijewski-Correa et al., 2018; Roueche et al., 2018). It should be noted that the collected metadata for the damaged elevated structures is published on the Natural Hazard Engineering Research Infrastructure (NHERI) DesignSafe-CI platform. Assessment teams have categorized the level of damage of each structure into five distinctive states, namely: DS0 (no damage), DS1 (minor damage), DS2 (moderate damage), DS3 (severe damage), and DS4 (destroyed damage state). Readers are referred to (Roueche et al., 2018) for more information about the quantitative guidelines used for assigning an overall damage rating for each structure.

2. DAMAGE OBSERVATIONS

Following these criteria and to investigate the effect of elevation height on the damage level that a house may experience during a hurricane event, the damage data used in the current study is divided into 5 groups of elevation heights as shown in Figure 1(a). Obviously, percentage of houses that experiences DS0 and DS1 is inversely proportional to the increase in elevation height. For example, almost 60% of structures with elevation height of 2.0 – 4.0 ft showed no or minor damage. However, this percentage decreases to 26% for structures with 4.0 to 8.0 ft elevation height and decreases to 40% (on average) in case of elevation height ≥ 8.0 ft. With respect to DS4 (i.e., destroyed damage), groups with elevation height >4.0 ft have higher percentage than that of the group with elevation height of 2.0 – 4.0 ft. Remarkably, 45% of houses with elevation height between 4.0 and 8.0 ft experienced DS4. This percentage is 3-4 times that of the other groups. It should be noted that 75% of the damaged houses in this group (i.e., with elevation height between 4.0 and 8.0 ft) were constructed in State of Texas.

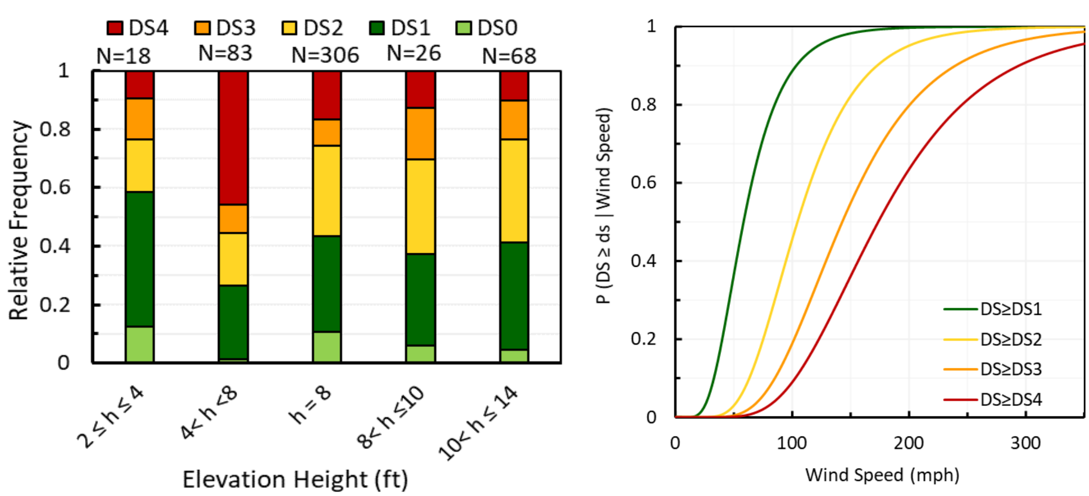

Figure 1. (a) Elevation height effect on the damage distribution and (b) fragility curves for elevated structures.

3. FRAGILITY FUNCTIONS OF ELEVATED STRUCTURES

Following the procedures proposed by (Roueche et al., 2017), empirical fragility curves for elevated structures are developed as shown in Figure 1 (b). As can be seen, the median wind speed increases while moving from DS1 (lowest) towards DS4 (i.e., highest median wind speed). Precisely, the median wind speeds to be in or exceeding DS1, DS2, DS3, or DS4 are 58.3, 104.4, 142.72, and 173.5 mph, respectively. Interestingly, difference between each two damage measures is not constant and decreases as damage level increases. For example, the difference in median failure wind speed between DS1 to DS2 (46.1 mph) is 50% higher than that between DS3 to DS4 (30.8 mph). That can be attributed to the progressive nature of the wind induced damage at higher damage states (Amini & Memari, 2020). For example, at DS3, if an elevated structure experiences damage to roof/wall sheathing panels, windows, doors, and slight roof structure failure, this can quickly lead to DS4 damage level if pressurization, loss of loading path, or loss of lateral supports to walls occur.

4. CONCLUSIONS

Based on this preliminary investigation, it can be concluded that elevation height is a key parameter in determining the damage level that an elevated structure may experience. Furthermore, work is ongoing to develop fragility functions at building and component level for both elevated and slab-on-grade structures.

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REFERENCES

Abdelfatah, N., Elawady, A., Irwin, P., & Chowdhury, A. (2020). A study of aerodynamic pressures on elevated houses. *Wind and Structures, 31*(4), 335-350.

Amini, M., & Memari, A. M. (2020). Review of Literature on Performance of Coastal Residential Buildings under Hurricane Conditions and Lessons Learned. *Journal of Performance of Constructed Facilities, 34*(6), 04020102. doi: 10.1061/(asce)cf.1943-5509.0001509

FEMA P-550. (2009). Recommended Residential Construction for Coastal Areas: Building on Strong and Safe Foundations. *Washington, DC*(Second Edition).

Kijewski-Correa, T., Prevatt, D., Roueche, D., Robertson, I., Berman, J., Mosalam, K., & Grilliot, M. (2020). PRJ-2113 | StEER - Hurricane Michael. *DesignSafe-CI [publisher]*, Dataset, doi: 10.17603/ds17602-17605aej-e17227

Kijewski-Correa, T., Roueche, D., Pinelli, J.-P., Zisis, I., Gurley, K., Haan Jr, F., . . . Rhode-Barbarigos, L. (2018). RAPID: A Coordinated Structural Engineering Response to Hurricane Irma (in Florida). *DesignSafe-CI [publisher]*, Dataset. doi: 10.17603/DS2TX0C

Kim, J. H., Moravej, M., Sutley, E. J., Chowdhury, A., & Dao, T. N. (2020). Observations and analysis of wind pressures on the floor underside of elevated buildings. *Engineering Structures, 221*, 111101.

Roueche, D. B., Krupar III, R. J., Lombardo, F. T., & Smith, D. J. (2018). Collection of Perishable Data on Wind-and Surge-Induced Residential Building Damage During Hurricane Harvey (TX). *DesignSafe-CI [publisher]*, Dataset, doi:10.17603/DS17602DX17622

Roueche, D. B., Lombardo, F. T., & Prevatt, D. O. (2017). Empirical Approach to Evaluating the Tornado Fragility of Residential Structures. *Journal of Structural Engineering, 143*(9), 04017123. doi: 10.1061/(asce)st.1943-541x.0001854