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# Risk and Fragility Assessment of Residential Elevated Buildings Using an Empirical Approach

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**SUMMARY:**
This study describes the development of fragility functions for elevated and slab-on-grade (SOG) low-rise residential houses using an empirical approach. For this purpose, post-hurricane damage assessment data for 635 elevated and 1156 SOG single-family residential houses surveyed after Hurricanes Irma and Harvey were coupled with the estimated 3-sec gust wind speed for each house. The results showed that elevated houses are more vulnerable than SOG houses which put the integrity of elevated houses during extreme wind events at risk. Furthermore, the results revealed that, at the range of design wind speed in Texas and Florida, elevated and SOG residential houses in these states have 30% to 60% probability of experiencing the highest damage state (i.e., destruction). These results indicate that existing elevated and SOG houses may not perform as targeted in future extreme wind events.

*Keywords: Fragility, Empirical, Residential Buildings.*

## 1. INTRODUCTION

Coastal houses can be either slab-on-grade (i.e., at ground) or elevated houses with the latter representing houses with first floor elevated on piles or columns to mitigate the damage from hurricane-induced surge and flooding. Although previous hurricanes proved the efficiency of this mitigation technique in the case of floods and storm surge, they highlighted the vulnerability of these structures when subjected to hurricane-induced winds: field observations showed that elevated houses' envelope experienced sever wind damage. This widespread damage from hurricanes leads to severe social and economic impacts on the affected societies. Therefore, studying the hurricane-induced risk on residential houses is a decisive step in mitigating hurricane hazards. Herein, this study assesses the fragility and hurricane-imposed risk of elevated and slab-on-grade (SOG) residential houses using empirical methods.

## 2. METHODOLOGY

Details of 2084 elevated and SOG houses that were affected by Hurricanes Irma and Harvey were obtained from the open-access damage assessment data on Fulcrum and DesignSafe platforms (Kijewski-Correa et al., 2018; Roueche et al., 2018). The collected data include information about age, elevation height, roof and wall cover material, hazard type, damage level for both building and components, and building type. Moreover, Risk Management Solutions (RMS) provided the wind field footprints for the hurricanes which have been used to estimate the 3-sec gust speed at the location of each house. In the current study, 635 elevated single-family residential houses with elevation heights ranges between 7.0 and 14 ft were used to develop the empirical fragility curves. Furthermore, 1156 SOG single-family residential houses were used for comparison. For each house, the building damage level was classified by the reconnaissance teams into five damage states: DS0 (No Damage), DS1 (Minor Damage), DS2 (Moderate Damage), DS3 (Severe Damage) and, DS4 (Destroyed Damage) (Kijewski-Correa et al., 2018; Roueche et al., 2018). Herein, the same classification was used to define the limit states for the developed fragility functions. Figure 1 illustrates the damage distribution for the elevated and the SOG houses. Although the number of SOG houses is 1.82 times that of the elevated houses, the number of SOG houses that experienced no damage is 5.25 times that of the elevated houses. Moreover, the number of elevated houses that experienced destroyed damage states (i.e., DS4) is higher than that of the SOG by 90%.

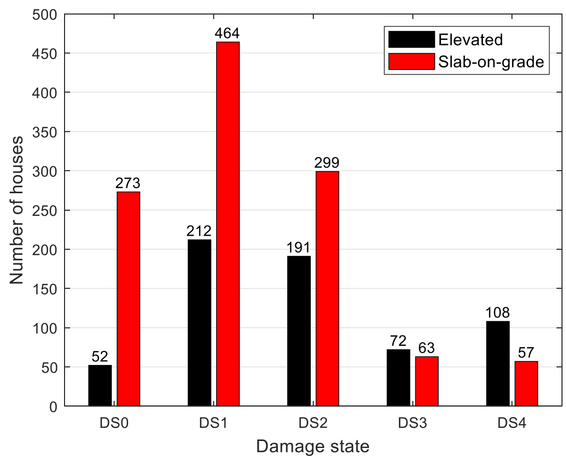


**Figure 1.** Damage distribution of the elevated and slab-on-grade houses.

Developing fragility curves for buildings and components is essential to quantitively determine the expected losses during extreme wind events (Lindt & Dao, 2009). Fragility curves describe the probability of the structure to experience or exceed a damage state of interest (i.e., DS1, DS2, DS3, and DS4) as a function of the 3-sec gust wind speed. Considering the characteristics of the collected data, the bounding Engineering Demand Parameter method was used to develop the fragility curves (Porter et al., 2007). In this method, every structure was assigned a binary value of 0 or 1 where 1 means that the structure experienced or exceeded the damage state of interest. For example, for a fragility curve with DS3 as the damage state of interest, houses with reported damage state < DS3 would be considered as non-damaged structures (i.e., probability of failure is 0) while structures with damage state ≥ DS3 will be assigned a value of 1 (i.e., probability of failure is 1). Previous studies show that fragility curves can be appropriately modelled using the lognormal cumulative distribution function (CDF) shown in Eq. (1). Moreover, the maximum likelihood estimation method was used to determine the CDF parameters that best fit the fragility curves with the observed damage data (Roueche et al., 2017).

$$F(V) = \Phi\left[\frac{\ln(V) - \mu}{\sigma}\right] \quad (1)$$

where $\Phi$ = normal CDF; $\mu$ and $\sigma$ = logarithmic median and standard deviation of wind speed (V).

## 4. FRAGILITY ASSESSMENT

Figure 2 shows the developed fragility curves for both elevated and SOG houses. Moreover, the 3-sec gust wind speed limits for the different categories of hurricanes based on Saffir-Simpson scale is provided in Figure 2. In general, up to the 3-sec gust wind speed limit of category 5 hurricane, elevated houses have higher probability of exceedance for the four damage states than the slab-on-grade houses. In elevated houses, the median failure wind speeds for DS1, DS2, DS3, DS4 are 25 m/s, 45.6 m/s, 65.6 m/s, and 71 m/s. These values increased to 31.6 m/s, 51.4 m/s, 70.8 m/s, and 73.4 m/s in case of slab-on-grade houses. That is, the median failure wind speeds in slab-on-grade houses for DS1, DS2, DS3, DS4 are higher than that of the elevated houses by 26%, 12.7%, 7.8%, and 3.2%, respectively. Since damage states DS1 and DS2 mainly depend on the roof/wall claddings, the high percentage of increase for these two states indicates the higher vulnerability of the building envelope components after being elevated. According to the results in Figure 2, serious decisions about enhancing the wind resistance of coastal elevated and slab-on-grade residential houses in Texas and Florida are needed as the probability of reaching and exceeding DS4 is 30% to 60% at the range of the design wind speeds, respectively.

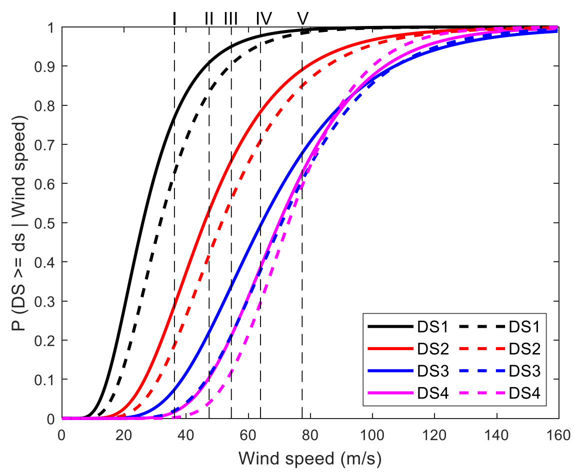


**Figure 2.** Comparison of empirically derived building fragility functions for elevated (solid lines) and slab-on-grade (dash lines) residential structures.

## 6. RISK ANALYSIS

Annual probability of failure ($P_f$) or exceeding a certain damage state is another metric that can be used to quantify the hurricane-imposed risk on elevated and SOG houses. This metric combines the structural response of the houses conditioned on the 3-sec wind speed with hurricane hazard data for a specific site. Thus, the main advantage of this metric is that it considers the entire range of intensities that contribute to failure in addition to the effect of the site location. To calculate $P_f$, the previously developed building fragilities were convoluted with the probability density function of the annual maximum hurricane wind speed in Miami. Figure 3 illustrates the $P_f$ of elevated houses normalized by the $P_f$ of SOG houses. For DS1 and DS2, elevated houses have higher $P_f$ than SOG houses by 34% and 42%, respectively. Interestingly, these percentages of increase reached 97% and 82%, for DS3 and DS4, respectively.

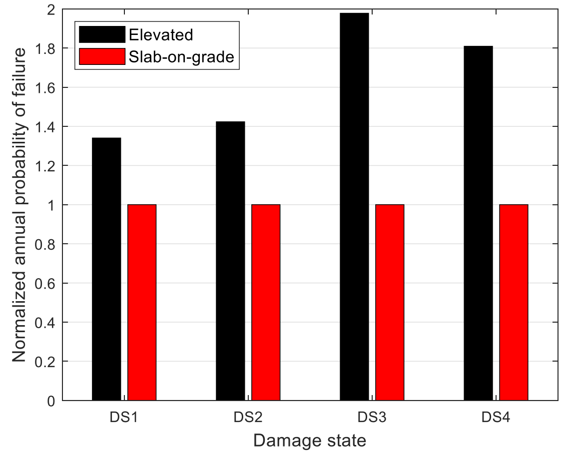


**Figure 3.** Normalized annual probability of failure for the elevated and the SOG residential houses.

## 7. CONCLUSIONS

This study assessed the fragility and hurricane-imposed risk of elevated and SOG residential houses using empirical methods. The developed fragility functions showed that elevated houses have higher probability of failure at the same wind speed. Furthermore, results showed that elevated and SOG houses have 30% to 60% probability of reaching and exceeding destroyed damage state at the range of the design wind speeds in Texas and Florida, respectively. Therefore, future research should focus on providing designers with accurate estimation for the wind loads on elevated houses in addition to further investigate the strength capacity of the different components in order to design houses that can safely resist winds at the design wind speed level.

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