Structural performance and fragility assessment of elevated residential buildings during 2017–2018 hurricanes in Texas and Florida

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A B S T R A C T

Elevating coastal houses on columns or piles is recognized as an effective technique for reducing the risks of flooding and storm surges. However, recent hurricanes have exposed a potential vulnerability in this approach, as many elevated residential structures sustained significant wind damage even at wind speeds below the current design level. Elevating a structure increases its exposure to stronger winds and leads to potential changes in the wind effects due to the air gap beneath the floor. However, there has been limited research comparing the performance of actual constructed elevated and slab-on-grade residential structures during realistic wind events. To fill this gap, authors utilized publicly available building performance datasets, collected by the Structural Extreme Events Reconnaissance (StEER) Network and others, to extract data on the performance of 851 elevated and 1536 slab-on-grade residential houses impacted by Hurricanes Irma, Harvey, and Michael. Effects of several key parameters were analyzed in terms of the in- tensity and distribution of the damage experienced by the different components. Furthermore, empirical fragility functions were developed for different roof shapes and cladding materials by combining the estimated wind speed that affected each structure and the assigned damage ratios for the roof and wall claddings. Analysis using the Wilcoxon rank-sum test demonstrated a sta- tistically significant difference in the median wind speeds of various damage states of the com- ponents in both elevated and slab-on-grade houses. Additionally, a significant difference was observed in Texas slab-on-grade houses which experienced either no, minor, moderate, or severe damage, compared to their Florida counterparts. Results showed that elevated houses experience more damage than their slab-on-grade counterparts regardless of the roof shape, cladding ma- terials, and construction age. Additionally, results showed that the elevated houses built in Texas exhibit the highest level of vulnerability among the various housing groups studied. Specifically, the percentage of elevated houses in Texas that experienced destroyed damage state surpassed those of slab-on-grade houses in Texas and elevated houses in Florida by 343 % and 166 %, respectively. The paper identified several knowledge gaps, and it emphasized the need for further experimental tests of building components and different building geometries to improve existing risk models.

1. Introduction

The United States is annually subjected to severe weather-related hazards leading to considerable human losses and high financial toll. Fig. 1 illustrates the number of floods, severe storms (i.e., tornadoes, hail storms, severe weather, etc.) and tropical cyclone (i.e., hurricanes and tropical storms) events that have impacted the US since 1980 and resulted in damages exceeding one billion dollars per event [1]. Fig. 1 presents the total costs (both insured and uninsured) per year from all three events. The frequency of billion-dollar damage events has increased over the years, with 2020 being the year with the highest number of disaster events (20 events). As presented in Fig. 1, the estimated combined losses in 2005 and 2017 exceeded $235 and $315 billion, respectively. In 2005, Category 3 Hurricane Katrina alone cost the US approximately $178 billion, while in 2017, the US was impacted by three Category 4 hurricanes: Harvey, Maria, and Irma, with Hurricane Harvey being one of the costliest with an estimated cost of $125 billion [1]. The increasing damage in recent years can be attributed to, among other factors, the age of existing houses, the growing population in coastal areas, and the increasing number of disaster events [2].

During recent hurricanes, many single-family non-engineered residential units experienced widespread damage even at events with estimated wind speed below the design wind speed for the region ([3], FEMA P-2022 [4], FEMA P-2023 [5]). It is, therefore, essential to determine the reasons that caused such poor performance and to develop new techniques to reduce damage from future hurricanes. Elevating coastal houses on columns or piles is a well-known technique to mitigate flooding and storm surge hazards. The free-of-obstruction area below the floor of an elevated house minimizes the damage by reducing the surface area subjected to wave impact and protecting the interior contents from flooding. Thus, it is essential to select the elevation height to avoid damage from floods appropriately. Fig. 2 shows a schematic of a typical coastal elevated house. According to the Flood Resistant Design and Construction standard (ASCE 24-14) [6], the distance from the ground to the bottom of the lowest horizontal member of the floor should be equal to or exceed the summation of the base flood elevation level (BFE) and a freeboard depth of 1.0 ft. According to (ASCE 24-14) [6], the BFE level is defined as "*elevation of flooding, including wave height, having a 1 % chance of being equaled or exceeded in any given year*". The International Residential Code (IRC) recommends similar provisions for determining the appropriate elevation [7]. In the Fortified Home Program of the Insurance Institute for Business and Home Safety (IBHS), the freeboard depth is recommended to be at least 3.0 ft.

Although residential houses, in coastal areas near the shoreline, with enough elevation height performed well against floods and storm surge hazards, they experienced severe wind-induced damage. Compared to conventional slab-on-grade structures, wind effects on elevated structures could be different for several reasons. First, elevated structures are exposed to stronger winds because of the higher elevation leading to higher wind forces and overturning moment. Second, elevated structures experience flow separation at the edges of the elevated floor leading to high wind suction on the floor underside. Damage to the floor panels, floor framing, or the floor-to-pile/beam connection may affect the lateral stability of the main wind-force resisting system. Third, the majority of elevated houses have partially enclosed regions below the elevated floor, which alter the wind flow below and around them [9]. These not yet well-understood wind effects on elevated structures could lead to different performance compared to slab-on-grade structures.

Therefore, to understand the vulnerabilities of elevated structures, a quantitative assessment of their performance compared to slab-on-grade structures is needed.

Although wind-induced damage to the floor underside of elevated houses was reported for a long time [10], there is still a lack of provisions to determine wind loadings on floors of elevated houses accurately. For example, in the US, the American Society of Civil Engineers (ASCE) 7 Standard is widely adopted to provide provisions for the minimum design loads for buildings and other structures. Provisions to determine wind loading for low-rise buildings have been included in ASCE 7 standard since the first edition which was published in 1988 (ASCE 7–88) [11]. Although these provisions have been developed further in the following editions, provisions for wind loadings on elevated houses were included only in the most recent edition of the ASCE 7, which was published in 2022 (ASCE 7–22) [12]. Nevertheless, the existing provisions to determine the wind loading on the underside of elevated houses do not consider the effect of important parameters such as columns' size, location, and spacing. This lack of provisions may be attributed to the limited experimental studies on the aerodynamic performance of elevated houses.

Holmes [13] investigated the effect of elevation height, wind angles, and shielding effect on the wind pressure acting on roofs and walls of elevated gable-roof houses using a combination of 1:50 and 1:100 scaled models. Results indicated that the mean wind pressures acting on the walls and roofs of elevated houses are expected to be 40 %–80 % higher than those of their slab-on-grade counterparts because of the higher wind speeds at the mean roof height of elevated houses. It should be noted that the study did not consider the wind pressure distribution on the underside of the elevated houses models. Recently, at the Natural Hazards Engineering Research Infrastructure (NHERI) Wall of Wind (WOW) Experimental Facility (EF) at Florida International University (FIU), a series of large-scale wind tests have been carried out to investigate the aerodynamics of elevated houses and the effect of elevation height and number of stories on the wind pressures acting on the underside floor, walls, and roof surfaces [14–17]. The results showed that the underside of elevated houses is subjected to high suctions, especially near the columns and the floor edges due to the flow separation at these regions. The localized peak negative pressure coefficient values at the floor underside were found to be comparable to the roof pressure coefficients. Moreover, increasing the elevation height led to an increase in values of the negative peak pressure coefficients and the size of critical suction zones of the floor. On the other hand, except for the higher values of the negative peak pressure coefficients at the lower part of the elevated walls, no significant change was observed for the pressure coefficient distribution of the roof and walls of elevated and slab-on-grade houses. Recently, the authors carried out large-scale testing to assess the aerodynamics of elevated houses with partially enclosed regions below the elevated floors. Results indicated that the enclosed regions and their location could significantly alter the peak pressure coefficients in all surfaces (i.e., walls, roofs, and floor) [9]. These results and the past damage observations highlight the need for evaluating the performance of elevated structures and quantitatively assessing their vulnerability during extreme wind events.

This study focuses on analyzing and comparing the structural performance of elevated and slab-on-grade residential houses affected by hurricane winds and assessing their vulnerability during hurricanes. For that purpose, authors utilized building performance data, collected by others, for 851 elevated and 1536 slab-on-grade houses surveyed following three hurricanes: Hurricane Irma (2017) and Hurricane Michael (2018) in Florida, and Hurricane Harvey (2017) in Texas.

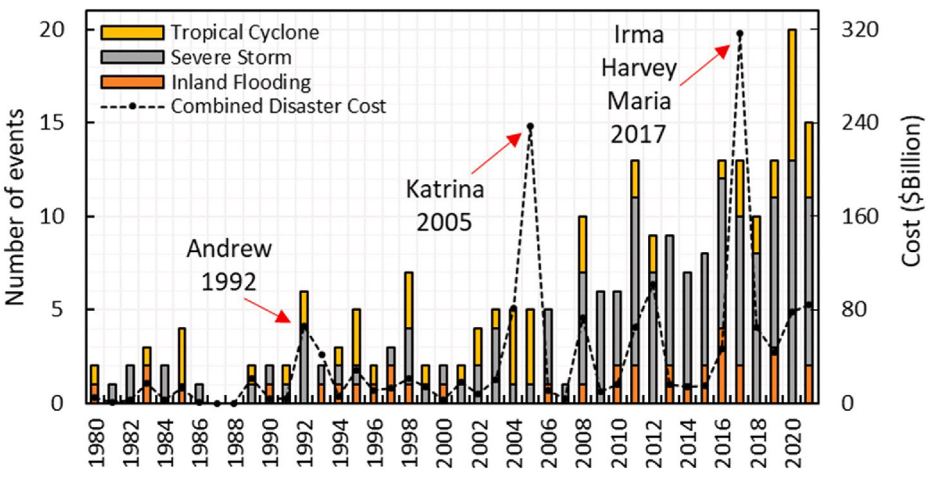

Fig. 1. Annual number of events and their associated costs since 1980 [1].

2. Post hurricane building performance data

This study uses publicly available building performance data from post-hurricane reports of three recent hurricanes affecting coastal areas in Texas and Florida. The hurricane tracks for these events are illustrated in Fig. 3. For more comprehensive information about these hurricanes, readers are referred to Refs. [18–20]. Below is a concise summary of each hurricane along with the associated building performance dataset on.

- **Hurricane Harvey** made its landfall on San Jose Island, Texas, US on August 25th, 2017, as a Category 4 hurricane with a sustained wind speed of 130 mph (58.1 m/s) (FEMA P-2022) [4]. Through support by the National Science Foundation, Roueche et al. [21] assessed Hurricane Harvey impact on total of 1177 individual buildings.
- **Hurricane Irma** impacted the Florida Keys, Florida, US, as a Category 4 hurricane with an estimated sustained wind speed of 130 mph (58.1 m/s) [20]. Hurricane Irma made its second landfall in the US on Marco Island as a Category 3 hurricane with maximum sustained winds of 115 mph (51.4 m/s). Kijewski-Correa et al. [22] collected data and assessed Irma's impact on 1121 individual buildings.
- **Hurricane Michael** struck the US on October 10th, 2018, near Mexico Beach in Florida as a strong Category 5 hurricane with a maximum sustained wind speed of 161 mph (72 m/s). Hurricane Michael resulted in widespread damage to residential buildings due to its high-speed winds and inundation levels, (FEMA P-2077) [23]. The Structural Extreme Events Reconnaissance (StEER) Network initiated and executed a virtual and field assessment studies following the landfall of Hurricane Irma [24]. The reconnaissance teams collected data about 736 different buildings.

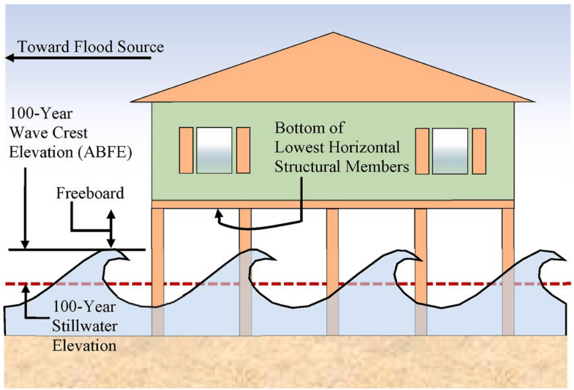

Fig. 2. Typical coastal house elevated on piles (reproduced from (FEMA P-499) [8]).

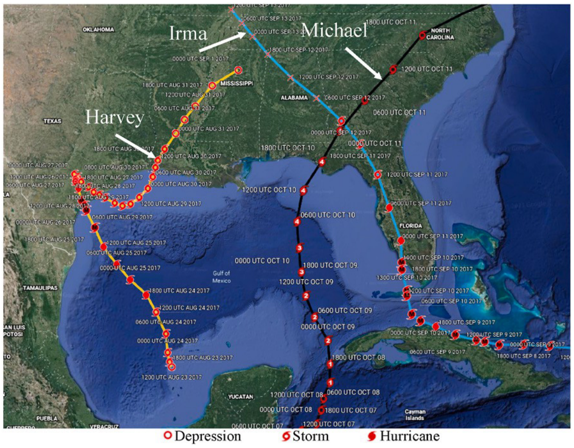

Fig. 3. Hurricanes Irma, Michael, and Harvey best track with Hurricane Irma represented by the light blue line, Hurricane Michael by the black line, and Hurricane Harvey by the yellow line. (Data from NOAA). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The reconnaissance teams used the proprietary data collection platform Fulcrum [25] to record and document the data which are publicly accessible in the Natural Hazard Engineering Research Infrastructure (NHERI) platform (DesignSafe-CI) [26]. The methodology, workflow, quality control, and data curation of StEER are reported in detail by Ref. [27]. For the current study, metadata such as buildings and components' damage level, elevation height, year built, location, damage modes, and damage images for 851 elevated and 1536 slab-on-grade residential houses have been extracted from the curated datasets which include a total of 3034 structures. Damage modes here refer to the types of hazards that affected the surveyed buildings, such as wind, surge, combined wind and surge, etc. Given that the current study specifically examines the wind performance of elevated and slab-on-grade houses, buildings affected only by surge hazards were excluded from our analysis. Buildings impacted solely by wind were included in the analysis. For buildings with combined wind and surge, those with severe or destroyed surge damage were excluded, and only those with no damage, minor, or moderate damage were included. However, buildings with minor or moderate surge damage and lower wind damage were excluded. In total, out of the 2387 houses considered in this study, 2290 houses were exposed only to wind hazards, and 64 buildings experienced minor surge damage while experiencing higher wind damage.

Moody's RMS [28] provided the wind field footprints for the three hurricanes which have been used to estimate the 3-sec gust speed at the location of each house. It should be noted that Moody's RMS employs a land mask to distinguish between water and land bodies, adjusting over-land wind speeds accordingly to account for surface roughness conditions. Figs. 4 and 5 show the geospatial depiction of the surveyed elevated and slab-on-grade structures in Texas and Florida, respectively. Different colors are used to describe the assigned damage state, provided by reconnaissance teams, for each structure.

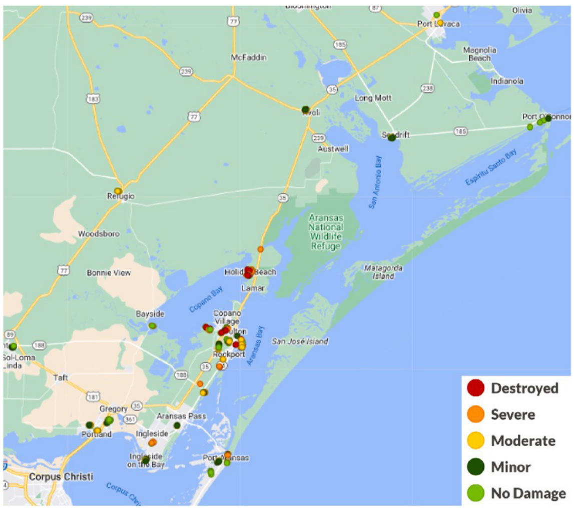

Fig. 4. Location of 295 elevated and 813 slab-on-grade houses surveyed in Texas during Hurricane Harvey (Source: NSF STEER on Fulcrum).

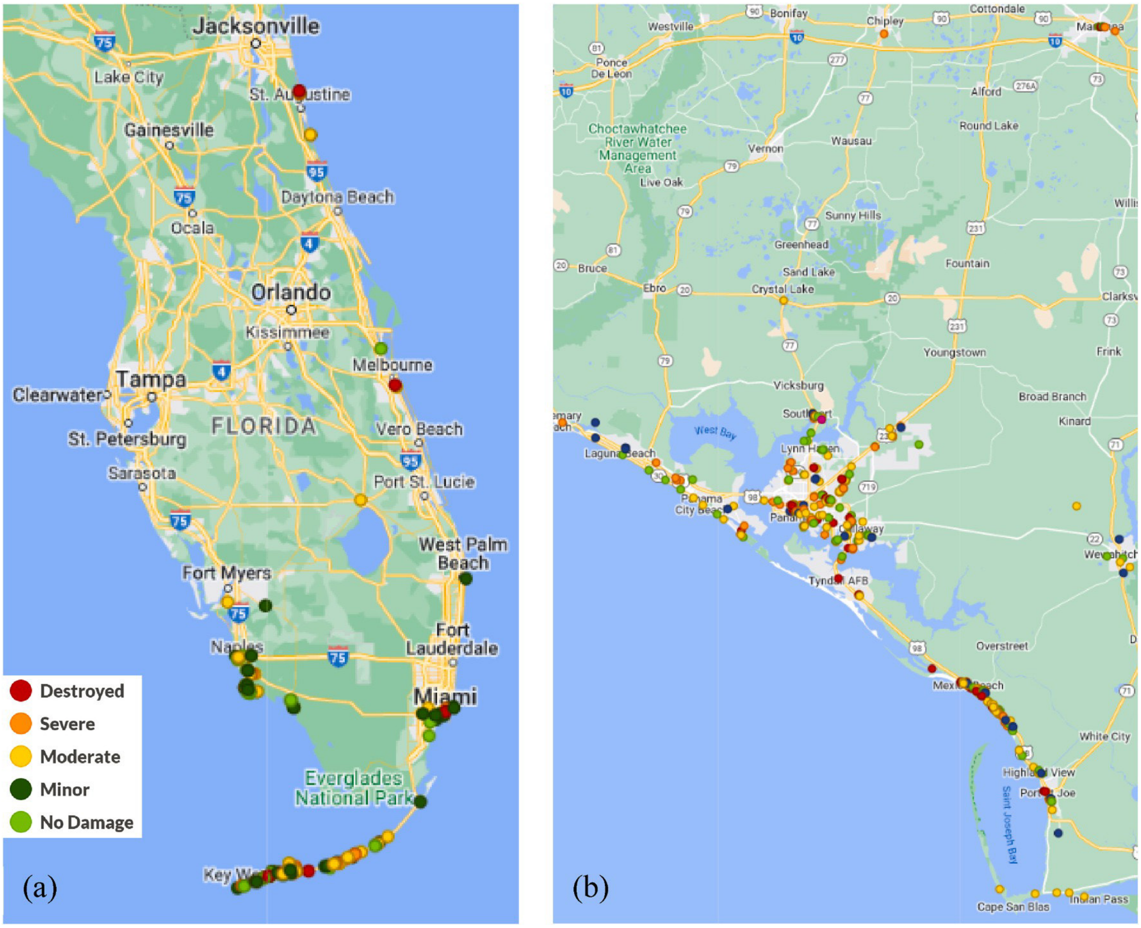

Fig. 5. Location of 557 elevated and 723 slab-on-grade houses surveyed in Florida during (a) Hurricane Irma and (b) Hurricane Michael (Source: NSF STEER on Fulcrum).

3. Damage classification

Assessment teams categorized the level of damage of each structure into five distinctive states, namely: DS0 (state of no damage), DS1 (state of minor damage), DS2 (state of moderate damage), DS3 (state of severe damage), and DS4 (destroyed damage state). Each

Table 1
Quantitative guidelines for assigning overall damage rating.

Damage State	Description*
DS0 (No damage)	Maximum of 2% damage in roof and wall cover
DS1 (Minor damage)	Roof/wall cover failure between 2 and 15%; a maximum of 1 window, door, or garage door failure; no roof sheathing failure; no roof structural failure
DS2 (Moderate damage)	Roof/wall cover failure between 15 and 50%; between 1 and 3 window, door, or garage door failures; and between 1 and 3 sheathing failures; no roof structure failure.
DS3 (Severe damage)	Roof/wall cover failure more than 50%; from 3 or 20% to 50% of the windows, doors, or garage door failures; between 3 and 25% sheathing failures; maximum of 15% roof structure failure
DS4 (Destroyed)	Roof/wall cover failure more than 50%; more than 50% of the windows, doors, or garage door failures; more than 25% sheathing failures; more than 15% roof structure failure; wall structure failure occurs

* Reproduced from [29].

component (roof cover, roof sheathing, roof structure, wall cladding, wall sheathing, wall structures, and doors and windows) was assigned a damage ratio ranging from 0 % to 100 % in 10 % increments. Table 1 illustrates the quantitative guidelines for assigning an overall damage rating for houses based on the damage experienced by each component [29]. It is crucial to note that this study assesses damage for both buildings and their components separately. For buildings, we used the overall damage rating assigned by assessment teams, which was revised by the authors. Concerning individual components, the component damage ratios from each damage state in Table 1 were applied. For example, the roof cover is assigned DS0 or DS3 states if the observed component damage is less than 3 % or more than 50 %, respectively. Similarly, the wall structure is designated as a DS0 state in the absence of damage and as DS4 if any wall structural damage was reported. Using these metrics, Tables 2 and 3 illustrate the damage distribution across elevated and slab-on-grade houses surveyed in Florida and Texas, respectively.

4. Damage observations

Damage to residential houses can be classified into two types: damage to the structural system and damage to the building envelope. A structural system includes the roof, walls, and underneath floor structure, whereas a building's envelope consists of the roof cover, wall cladding, sheathing, doors, and windows. Based on the considered surveyed damage data, the distribution of the structural and envelope damage for roofs and walls of elevated and slab-on-grade houses is illustrated in Fig. 6. As can be seen, roof cover damage is the most widespread type of damage evidenced by almost 76 % and 71 % of the surveyed elevated and slab-on-grade houses, respectively. Roof and wall structural damage were the least observed damages with about 22 % and 14 % of the elevated structures experienced structural damage, respectively. Moreover, it can be seen from Fig. 6 that the percentages of cover, sheathing, and structural damage of roofs are higher than their wall counterparts which reiterates their higher vulnerability to wind damage.

As can be seen in Fig. 6(b), slab-on-grade houses have similar damage trends to that of the elevated houses. However, for all the considered components, elevated houses experienced more damage frequency than slab-on-grade houses. A significant difference can be seen in the wall cladding damage of elevated and slab-on-grade houses. About 56 % of the elevated structures experienced wall cladding damage which is almost 2.7 times the percentage (i.e., 20.8 %) in the case of slab-on-grade houses. That could be attributed to the change in the values and distribution of the pressure coefficients of the walls of elevated houses as previously mentioned.

The Wilcoxon rank-sum (WRS) test was used to determine whether the 3-sec wind speed experienced by each structural and envelope component in the different damage states is significantly different between elevated and slab-on-grade houses. The null hypothesis of the WRS test is that the two types of houses are samples from continuous distributions with equal medians, using a two-tailed 95 % confidence interval. The results, shown in Table 4, reveal that there is statistically significant difference in several damage states of the components. This implies a significant difference in the median wind speed experienced by these components between elevated and slab-on-grade houses.

The difference between slab-on-grade and elevated structures is the existence of the underneath floor and the airgap between the floor surface and the ground. Fig. 7 shows typical damage observed on the underside of some of the surveyed structures during Hurricane Irma and Hurricane Michael. For each building, a record ID is provided to enable readers to access the source data and further investigate that specific case. According to the assessment teams, buildings in Fig. 7(a–b) were affected by wind damage only while buildings shown in Fig. 7(c–e) were subjected to combined wind and surge hazards. Damage to the underneath floor varies from a few panels at the edges [Fig. 7(a-b)] to damage concentrated around the corner column [Fig. 7(c-d)], then to complete loss of the underside panels, as shown in Fig. 7(e). The wind-induced damage to the underneath floor can be attributed to the high wind suction developed around the corners and edges of the floor of elevated structures as reported by Ref. [14]. Wind-induced damage to the floor is complex and progressive in nature because the failure of one cladding element leads to excessive changes in the net pressure on the remaining floor claddings and supporting structure. Damage can be even amplified if combined wind and surge hazards exist. Unfortunately, assessment teams did not report the number of elevated houses with damaged undersides which limited the authors of the current study from quantifying their wind performance. However, Kim et al. [16] reported that 28 out of 50 surveyed elevated structures (i.e., 56 %), impacted by Hurricane Michael, experienced floor cladding damage. To better assess the structural performance of underneath floors and facilitate evaluating their vulnerability, future reconnaissance efforts should consider documenting the floor damage of coastal elevated houses. Additionally, conducting computational fluid dynamic simulations for the combined impact of wind and surge hazards could be crucial for a comprehensive understanding of floor damage. The next sections provide more insights on the damage observations based on several controlling factors.

Table 2
Damage distribution across elevated houses.

Damage State[a]	Hurricane			Total
	Irma	Harvey	Michael	
DS0	64	10	1	75
DS1	196	89	22	307
DS2	131	77	26	234
DS3	50	43	14	107
DS4	44	76	9	129
Total	485	295	72	852

[a] DS0: No Damage; DS1: Minor; DS2: Moderate; DS3: Severe; DS4: Destroyed.

Table 3
Damage distribution across slab-on-grade houses.

Damage State[a]	Hurricane			Total
	Irma	Harvey	Michael	
DS0	88	193	27	308
DS1	172	301	135	608
DS2	75	224	129	425
DS3	23	48	46	117
DS4	17	47	11	75
Total	375	813	348	1536

[a] DS0: No Damage; DS1: Minor; DS2: Moderate; DS3: Severe; DS4: Destroyed.

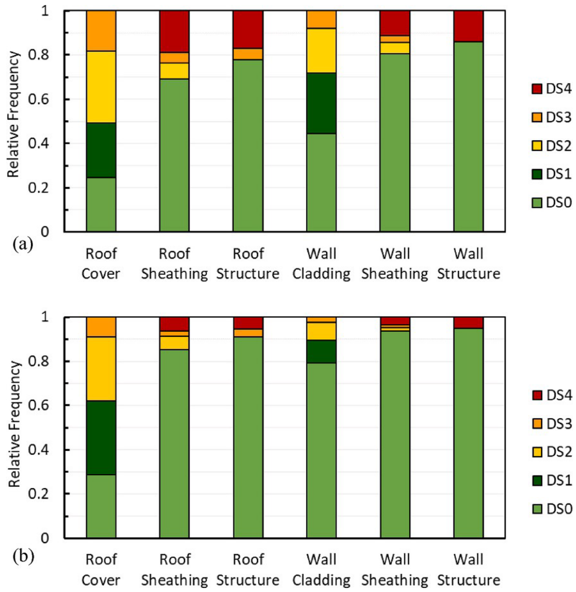

Fig. 6. Distribution of structural and envelope damage to the roof and walls of (a) elevated and (b) slab-on-grade houses.

Table 4
Wilcoxon rank-sum test results.

Damage State	Roof Cover	Roof Sheathing	Roof Structure	Wall Cladding	Wall Sheathing	Wall Structure
DS0	✓	✓	✓		✓	✓
DS1				✓		
DS2						
DS3	✓					
DS4						

✓ : There is statistically significant difference.

4.1. Influence of elevation height

To investigate the effect of elevation height on the level of damage that a house may experience during a hurricane event, the collected data is divided into six groups of elevation heights as shown in Fig. 8. Overall, the slab-on-grade houses experienced less damage compared to all groups of elevated houses. To some extent, the percentage of houses that experience DS0 and DS1 (i.e., no damage and minor damage states) is inversely related to the increase in elevation height. For example, 60 % of slab-on-grade structures showed no or minor damage. However, this percentage decreases to 28 % for structures with 1.2–2.4 m (4.0–8.0 ft) elevation height and decreases to 40 % (on average) in case of elevation height ≥2.4 m (8.0 ft).

From the results shown graphically in Fig. 8 it can be seen that more than a quarter of the houses elevated 2.4 m (8.0 ft) and higher experienced at least Damage State DS3 (i.e., DS3 and DS4). For comparison, less than 12.5 % of slab-on-grade houses in this study suffered at least DS3 damage levels. Precisely, percentage of houses with elevation ≥2.4 m (8.0 ft) that experienced DS3 or DS4 are 65 % and 181 % higher than those of slab-on-grade houses, respectively. Remarkably, 44 % of houses with elevation height between 1.2 and 2.4 m (4.0–8.0 ft) experienced DS4 which is 3–4 times the percentage of the other elevated groups. It should be noted that 78 % of

(a) Hurricane Irma
Record ID: 7acb1c1a-13ec-4308-a926-e5132ce6954b
Damage mode: Wind
Location: Little Torch Key, FL, 33042
Elevation Height: 2.7 m
Estimated 3-sec WS: 115.5 mph (51.6 m/s)
Storm surge: 1.2-2.4 m

(b) Hurricane Irma
Record ID: 4a69021f-6544-44c1-96a6-682b2e7ef296
Damage mode: Wind
Location: Ramrod Key, FL, 33042
Elevation Height: 2.4 m
Estimated 3-sec WS: 112.3 mph (50.2 m/s)
Storm surge: 1.2-2.4 m

(c-d) Hurricane Michael
Record ID: 5707c2e0-471e-4a27-9e9e-4600fd6ade30
Damage mode: Surge, Wind, Wind-borne debris
Location: Mexico Beach, FL, 32456
Elevation Height: 3.2 m
Estimated 3-sec WS: 149.7 mph (66.9 m/s)

(e) Hurricane Michael
Record ID: 25261fab-e23f-4f19-b672-cbc7044c5868
Damage mode: Surge, Wind
Location: Mexico Beach, FL, 32456
Elevation Height: 3.14 m
Estimated 3-sec WS: 150.5 mph (67.3 m/s)

Fig. 7. Cladding damage of the underside of elevated structures [22,24] (Source: NSF StEER on Fulcrum).

the destroyed houses in this group (i.e., with elevation height between 1.2 and 2.4 m) were constructed in Texas. Notably, the houses that experienced DS4 were originally constructed at or before the year of 2000. However, based on the windstorm Certificates of Compliance maintained by the Texas Department of Insurance (TDI), it is observed that 77 % of the houses underwent improvements in construction following either the 2000, 2003, or 2006 edition of the International Residential Code (IRC). These observations call for more investigations for the effect of building code adoption, age, and construction techniques of different states on the wind performance of elevated residential houses.

To explore the impact of elevation height and location on damage levels, we categorized the dataset into four groups. Groups 1 and

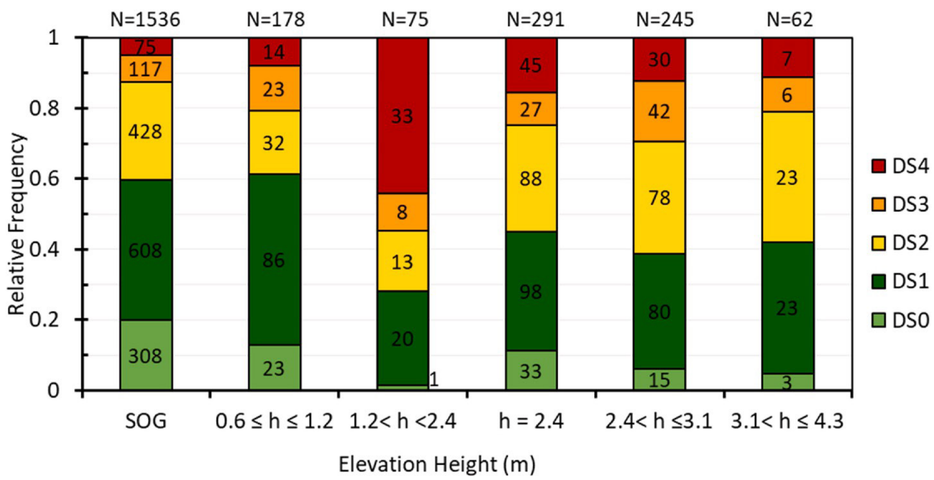

Fig. 8. Effect of elevation height on the damage distribution of elevated houses.

2 represent elevated and slab-on-grade houses in Texas, while Groups 3 and 4 represent elevated and slab-on-grade houses in Florida, respectively. The Wilcoxon rank-sum test was conducted to examine the hypothesis that elevation and location are linked to the damage levels experienced by houses, aiming to discern any statistically significant differences in the associated peak gust wind speed. For the elevation effect, we conducted separate comparisons between elevated and slab-on-grade houses in each state, taking into account the distinct construction techniques employed in the two states. Regarding the location effect, we first compared slab-on-grade houses in both Texas and Florida and subsequently compared the elevated ones. The summarized results are presented in Table 5.

The outcomes outlined in Table 5 reveal a statistically significant difference in the median peak gust wind speed associated with all damage states between elevated and slab-on-grade houses in Texas. In Florida, a similar observation holds true for DS1, DS2, and DS3. In terms of the location effect, the results indicate a statistically significant difference in the median peak wind speeds associated with DS0 to DS3 experienced by slab-on-grade houses in both Texas and Florida. Notably, the groups of elevated houses in both states did not exhibit a significant difference, except for DS4. These findings suggest that the location and elevation of houses exert a significant effect on the damage experienced by residential buildings. The results presented in Tables 4 and 5 and Figs. 6 and 8 warrant further analysis to explore the implications of these findings for the wind resilience of elevated and slab-on-grade houses. Moreover, further experimental tests are needed to quantify the effect of elevation height on the wind loadings acting on elevated structures.

4.2. Influence of roof shape and cover material

As previously mentioned, damage to roof coverings is the most widespread damage observed in the surveyed elevated and slab-on-grade houses. Poor wind uplift performance of roof covers may lead to a breach in the building envelope that causes (or creates) a path for wind-driven rain to enter the building interior, damaging finishes and building contents. Furthermore, the failed roof covers may become windborne debris that can produce damage to surrounding houses. Thus, it is important to evaluate the performance of the different roof cover materials.

Fig. 9(a) illustrates the results of the damage distribution observed for each roof cover material in elevated houses. Asphalt shingles (both 3-tab and laminated) were found to be the most vulnerable covering material with less than 10 % of these houses did not experience roof cover damage. This percentage increases to more than 46 % in houses with metal roof covering. Furthermore, more than 60 % of the elevated houses with asphalt shingles lost more than 15 % of their roof cover (i.e., DS2 and DS3). However, only 35 % of roofs with metal coverings experienced the same damage level. This high percentage of damage could be attributed to, among other factors, the underestimation of the ASCE 7 provisions for wind loads on shingled roofs, installing issues, and loss of sealant before

Table 5
Wilcoxon rank-sum test results.

Damage State	Elevation effect (SOG vs Elevated)		Location Effect (Texas vs Florida)	
	Texas	Florida	SOG	Elevated
DS0	✓		✓	
DS1	✓	✓	✓	
DS2	✓	✓	✓	
DS3	✓	✓	✓	
DS4	✓			✓

✓: There is statistically significant difference.
SOG: Slab-on-grade.

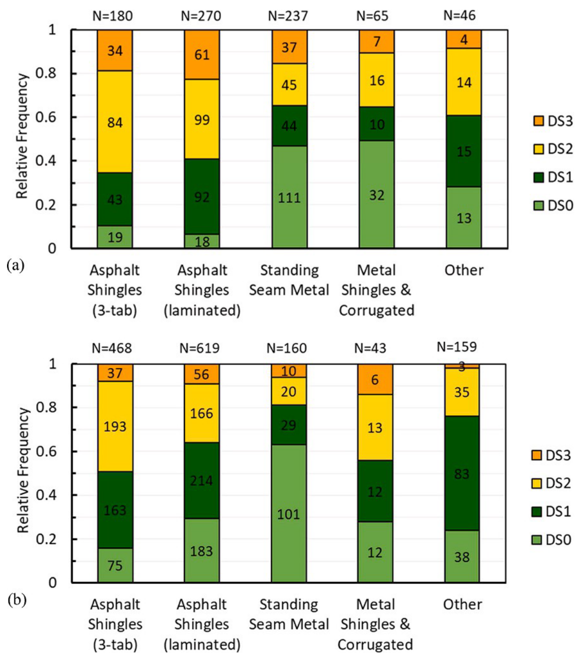

Fig. 9. Frequency of damage to roof covering of (a) elevated and (b) slab-on-grade houses' roofs.

hurricanes [30–33]. Fig. 9(b) indicates that the same pattern can be seen in slab-on-grade houses. However, roofs of slab-on-grade houses with asphalt shingles or standing seam metal experienced less damage than their counterparts of the elevated houses. These observations agree well with FEMA recommendations for using metal roofs in high wind speed zones(FEMA P-499) [8].

In addition to using different roof cover materials, several roof shapes, such as gable, hip, and flat roofs, have been observed in the surveyed houses. While most of the buildings have a unique roof shape (i.e., hip, gable, or flat), some buildings have mixed shapes. Fig. 10 illustrates the damage distribution observed for gable and hip roofs of elevated and slab-on-grade houses with laminated

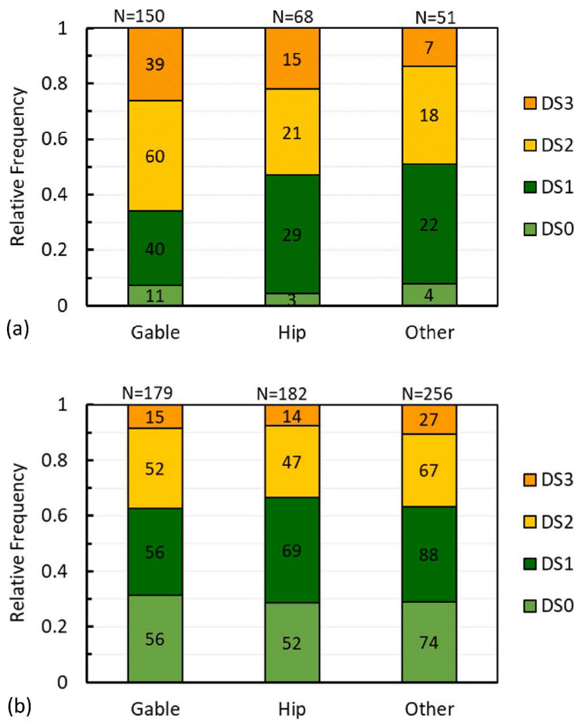

Fig. 10. Effect of roof shape on the damage distribution of (a) elevated and (b) slab-on-grade houses' roofs with laminated shingles.

shingles as roof cover material. The mixed roofs are included in the group "Other". It can be seen from the damage distribution shown in Fig. 10 (a) that hip roofs of elevated houses performed better than gable roofs. For example, the percentages of gabled roofs with DS2 and DS3 damage levels are 40.0 % and 26.0 %, respectively, which are higher than those of the hip roofs (30.8 % and 22.0 %). That can be attributed to the different aerodynamic behavior of both shapes. For example, Meecham et al. [34] found that local peak negative pressure on hip roofs can be 33 % less than those of gable roofs. Houses with mixed roof shapes behaved almost the same as those with hip roofs. Fig. 10 (b) shows that, for the same roof shape and cover material, slab-on-grade houses outperformed the elevated houses. Accordingly, hip and mixed roofs are recommended as a mitigation technique for elevated houses in zones with high wind speeds.

4.3. Influence of wall cladding material

Several types of wall cladding, such as vinyl siding, stucco, wood panel, and wood plank siding, have been used on the surveyed houses. Fig. 11 shows representative samples of the induced damage for walls with different cladding materials. At estimated wind speed of 123 mph (55 m/s), the elevated house with stucco claddings shown in Fig. 11(a) experienced minimal wall damage. On the other hand, two houses with wood panels and plank siding experienced more damage at estimated wind speed of 110 mph (49.17 m/s) and 123 mph (55 m/s) [see Fig. 11(b-c)], respectively. The elevated house shown in Fig. 11(b) lost almost 50 % of its wall claddings. Fig. 11(d) shows an elevated house with vinyl siding that lost almost 80 % of its wall cladding at an estimated wind speed of 102 mph (45.6 m/s). The distribution of wall cladding failures by cladding type is shown in Fig. 12 for both elevated and slab-on-grade houses. 63.0 % of elevated houses with vinyl siding experienced cladding failures. This percentage decreased to about 56 % for elevated houses with wood panels and plank siding. As can be seen in Fig. 12(a), the best performance for wall cladding is observed for elevated houses

(a) **Record ID**: e6fed13c-dbe3-423b-8b62-737e453d935d

(b) **Record ID**: 543ca2ba-5d7c-4e6a-a038-9a6c7e3c0c23

(c) **Record ID**: 828abaac-7f03-4cfd-bb42-f2113eb60a86

(d) **Record ID**: 53130e37-f266-4242-b6cb-b4394263277d

Fig. 11. Observed damage to walls with (a) Stucco claddings (estimated wind speed = 55 m/s), (b) Wood panel siding (estimated wind speed = 49.17 m/s), (c) Wood plank siding (estimated wind speed = 55 m/s), and (d) Vinyl siding (estimated wind speed: 45.6 m/s) [22].

with stucco cladding, as 67.0 % of these houses did not experience cladding failures. Thus, the percentage of undamaged houses with stucco cladding is 1.8 times that with vinyl siding. Remarkably, 91.0 % and 97.0 % of slab-on-grade houses with stucco and brick veneer claddings did not experience damage, respectively. Similar to roof cover materials, wall claddings of elevated houses experienced greater damage than slab-on-grade houses, regardless of the material type. This serves as another proof of the higher vulnerability of elevated houses compared to slab-on-grade [Fig. 12(b)].

4.4. Influence of age, location, and building code

Fig. 13(a) presents the damage distribution of the elevated houses for each hurricane event considered in this study. The most notable observation in Fig. 13(a) is the percentage of houses that have a DS4 rating. In Florida, the percentage of elevated houses with DS4 that were impacted by Hurricane Michael is 38 % higher than that of houses impacted by Hurricane Irma. This may be attributed to the different wind intensities for both events. At the landfall of Hurricane Michael, the wind speeds reached Category 5 hurricane with estimated sustained winds of 161 mph (72 m/s), while Hurricane Irma was a Category 4 hurricane with estimated sustained winds of 130 mph (58.1 m/s) (FEMA P-2023, FEMA P-2077) [5,23]. Since Hurricane Harvey made landfall in Texas as a Category 4 hurricane with estimated sustained winds of 130 mph(58.1 m/s) (FEMA P-2022) [4], comparing the wind damage resulted from Hurricanes Irma and Harvey can explain how elevated and slab-on-grade houses perform in Florida versus Texas. 25.8 % of the elevated houses in Texas were assigned DS4. This percentage is higher than that of the houses with DS4 in Florida by 184 % at the same intensity level. Unlike elevated houses, slab-on-grade residential houses in Florida and Texas performed almost the same in these two hurricanes, as can be seen in Fig. 13(b). These results necessitate further investigations to identify the potential reasons for the high vulnerability of elevated houses in Texas, particularly with the lack of enforcement for code requirements in the State of Texas (FEMA P-2022) [4].

By scrutinizing the data, it was found that the level of damage may vary significantly for houses in the same area that are exposed almost to the same wind speed with the same exposure and elevation height. For example, Fig. 14 shows an aerial image of the damage in Little Torch Key, Florida, during Hurricane Irma for five houses with the same elevation height. It should be noted that Fig. 14 is provided with the estimated wind speed from Hurricane Irma and the current design wind speed for this region, in addition to a black arrow indicating the wind direction. Moreover, for each house, a colored box is provided to show in which year the house was built, the first-floor elevation in ft, and the damage state based on the color. It should be noted that the year of re-roofing, whenever available, was used instead of the built year of the house. The houses in Fig. 14 experienced an estimated wind speed of 115 mph (51.4 m/s) which is lower than the current design wind speed for this region (i.e., 180 mph or 80.46 m/s). However, since these building were built in different years, such comparison may not be valid except for the house built in 2017. The design wind speed according to the South Florida Building Code [35] was at least 120 mph (53.64 m/s). Furthermore, the 3-sec design wind speed for the same region according to the (ASCE 7-05) is 150 mph (67.0 m/s). That is, these houses experienced estimated wind speed less than the design level corresponding to the construction year. While no damage was observed for the 2017 house, the 1987 and 1983 houses experienced complete structural failure for both roofs and walls. On the other hand, the 2010 house experienced mainly roof cover damage with limited sheathing damage, soffit damage, and no structural failure.

Fig. 15 shows an aerial image of the damage in Rockport, Texas, during Hurricane Harvey where the 3-sec peak wind speed is estimated to be 125 mph (55.88 m/s). For each house, whenever possible, the adopted code according to the windstorm certificates of

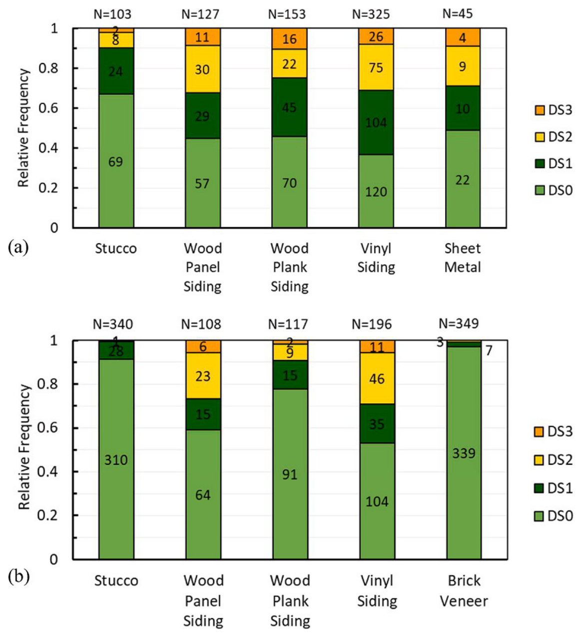

Fig. 12. Frequency of damage to wall cladding of (a) elevated and (b) slab-on-grade houses' walls.

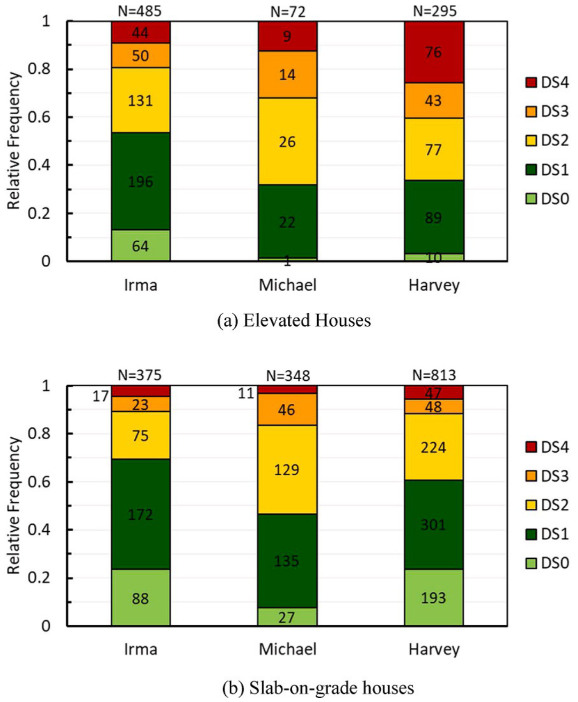

Fig. 13. Frequency of damage across elevated and slab-on-grade houses surveyed in Florida and Texas.

Fig. 14. Levels of wind-induced damage to construction in Little Torch Key, Florida, during Hurricane Irma with estimated wind speed (EWS) ≈115 mph (51.4 m/s) and current design wind speed (DWS) = 180 mph (80.46 m/s) [22] (Source: NSF STEER on Fulcrum).

compliance is added. The observations from Fig. 15 can be summarized as follow.

- Various editions of codes were adopted such as the 2000, 2003, and 2006 editions of the IRC, ASCE7-95(1995) [36], and the Southern Standard Building Code (SSBC).
- Out of nine buildings constructed in or before 2000, seven were completely destroyed (i.e., DS4) and the remaining two experienced severe damage (i.e., DS3).
- While some of the recently constructed buildings that adopted the 2003 and 2006 editions of IRC experienced non or minor damage, there are still some houses constructed between 2009 and 2012 that got destroyed.

With respect to the design wind speed, the 2003 and 2006 editions of IRC referenced the wind speed suggested by ASCE 7-02 (2002) [37] and ASCE 7-05 (2005) [38] which is 126 mph (56.33 m/s) for the shown region. It should be noted that the wind speed maps in ASCE 7-05 and ASCE 7-02 reflect the allowable stress design (ASD) values. By using appropriate conversion factors, this wind speed is almost 160 mph (71.52 m/s) at the design-level values. That indicates that these buildings were damaged at estimated wind speed much lower than the design wind speed. This finding suggests that construction age, among other factors, could significantly affect the level of wind-induced damage to elevated houses. Furthermore, the trend may not be the same in Texas and Florida for newly constructed elevated houses.

To further explore this point and account for variations in building codes and construction provisions between the states of Florida and Texas, the surveyed houses were categorized into two groups for each state. Group 1 represents houses constructed before the adoption of the main building codes in the state, and Group 2 represents houses constructed after the state adopted a building code. In Florida, the two groups are labeled Pre Florida Building Code (Pre FBC) and Post FBC houses. To illustrate the impact of adopting the first edition of the FBC, the year 2001 was chosen to demarcate the two groups.

Due to the lack of building code enforcement in the state of Texas, a specific year cannot be selected to reflect changes in house performance based on the adopted building codes. To address this, the authors examined windstorm certificates of compliance maintained by the TDI, finding that surveyed houses followed provisions from various editions of codes such as the 2000, 2003, and 2006 International Residential Code (IRC) editions, ASCE7-95, and the Southern Standard Building Code (SSBC). Some houses did not adhere to any of these standards. Consequently, the Texas elevated and slab-on-grade houses were divided into Pre IRC and Post IRC groups. The Post IRC group includes buildings adopting one of the three mentioned IRC editions, while the remainder, adopting older editions of other standards or not adopting at all, were included in the other group (i.e., Pre IRC).

Fig. 16(a) shows the frequency of damaged elevated houses in Florida and Texas with respect to code adoption. Elevated houses that embraced modern codes in both states demonstrated superior performance compared to their counterparts, as evident in the

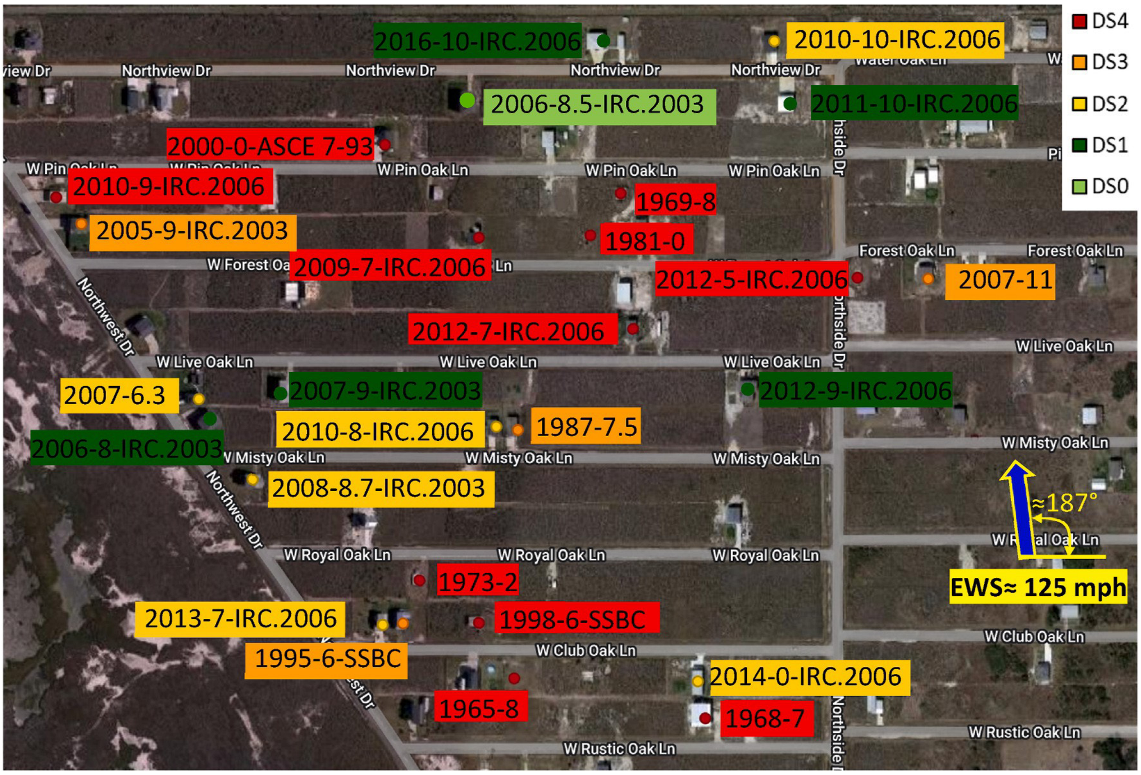

Fig. 15. Levels of wind-induced damage to construction in Rockport, Texas, during Hurricane Harvey with estimated wind speed ≈125 mph (55.88 m/s) [21] (Source: NSF STEER on Fulcrum).

percentages of houses with DS4 and DS3. Specifically, the percentages of Post FBC and Post IRC elevated houses with DS3 and DS4 in Florida and Texas are 13.0 % and 33.9 %, respectively. These percentages rise to 26.3 % and 50.5 % for Pre FBC and Pre IRC houses in the two states, respectively. Similar trends are observed for slab-on-grade houses in both states. In essence, elevated and slab-on-grade houses constructed after adopting building code provisions exhibit significantly improved performance. The favorable performance of Post IRC houses in Texas may also be attributed to lessons learned from damage caused by extreme wind events before the first IRC edition, such as Hurricane Allen (1980), Hurricane Alicia (1983), and Tropical Storm Allison (2001).

By comparing the damaged Pre FBC elevated and slab-on-grade houses in Florida [22], it was observed that the percentage of elevated houses with DS4 (12.7 %) is almost 2.44 times that of the slab-on-grade houses (5.2 %) [see Fig. 16(b)]. Interestingly, the situation in Texas is worse, as the percentage of Pre IRC elevated houses with DS4 (27.9 %) is 3.2 times the percentage of Pre IRC slab-on-grade houses (8.7 %). In other words, Pre-code-constructed elevated houses are more vulnerable to wind hazards than their slab-on-grade houses counterparts, and the situation is more critical in Texas, where their Pre IRC houses are more vulnerable than Pre FBC houses in Florida. Remarkably, the performance of slab-on-grade houses is comparable in both Texas and Florida with almost 50 %–66 % experienced either non or minor damage. However, the same observation is not applicable for the case of elevated houses. Both Pre and Post IRC elevated houses exhibited the worst performance among the different groups, with 24.6 %–27.9 % of the houses experiencing DS4 (i.e., destroyed damage state).

The data was analyzed to evaluate the performance of the structural systems of the walls and roofs. Overall, a significant decrease in the frequency of damage was observed in the roof and wall structural systems of Post FBC elevated and slab-on-grade houses in Florida, as well as Post IRC slab-on-grade houses in Texas, compared to their Pre FBC and Pre IRC counterparts. The damage percentage decreased from 16.7 % to 6.2 %. Notably, the analysis revealed that 31 % of the Post IRC elevated houses in Texas experienced damage to their wall and roof structures, whereas this percentage increased to 37 % in Pre IRC elevated houses. Although these findings indicate that structural damage is not a common issue in Post FBC slab-on-grade and elevated houses in Florida, as well as Post IRC slab-on-grade houses in Texas, concerns arise about excessive damage to wall and roof structures in the other groups. Particularly, in the Pre and Post IRC elevated buildings in Texas, which show the highest vulnerability for structural systems. Finally, while elevating coastal houses may reduce their damage from flooding, the findings of this study indicate that elevated houses become more vulnerable to wind hazards than slab-on-grade houses particularly in Texas. Therefore, there is a pressing need to investigate the wind actions on elevated houses further.

5. Empirical fragility functions for roof and wall coverings

The previous results did not consider the wind speed level that caused the damage to the components. Therefore, fragility curves, which describe the probability of a component experiencing or exceeding a damage state of interest as a function of the 3-sec gust wind speed, are very important to compare the performance of both elevated and slab-on-grade residential houses during extreme wind events [39,40]. Considering the characteristics of the data used in this study, the bounding Engineering Demand Parameter (EDP) method was used to develop the fragility curves for the failure initiation of wall claddings and roof covers [41]. In this method, every structure was assigned a binary value of 0 or 1, with the latter meaning that the component of interest experienced or exceeded the damage state of interest (i.e., failure initiation). Previous studies show that fragility curves can be appropriately modeled using the lognormal cumulative distribution function (CDF) shown in Eq. (1) [42,43]. Moreover, the maximum likelihood estimation method was used to determine the CDF parameters that best fit the fragility curves with the observed damage data [44].

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

where Φ = standard normal CDF; μ = logarithmic median of wind speed, given by V; and σ = logarithmic standard deviation of V.

Since roof and wall coverings are the most vulnerable components, fragility curves for the failure initiation of these components were developed using the same procedure explained above. Fig. 17 shows the developed fragility for elevated and slab-on-grade houses in both Texas and Florida. As expected, the roof covering of elevated houses in Texas and Florida are the most vulnerable component with a median failure wind speed of 21.4 m/s (47.9 mph) and 28.4 m/s (63.5 mph), respectively. These values are 36 % and 11 % less than that of the slab-on-grade houses in Texas and Florida, respectively. A similar trend can be seen in the case of wall claddings. However, the median failure wind speed of wall claddings of elevated houses in Florida (47.4 m/s) and Texas (45.6 m/s) is 49.5 % and 43.6 % less than that of the slab-on-grade houses, respectively. This difference shows that wall claddings become significantly more vulnerable when houses are elevated. Furthermore, the higher median failure wind speed of the wall claddings compared to that of the roof coverings explains the wide damage observations for the roof covers compared to the wall claddings.

The fragility curves depicted in Fig. 17 did not account for the impact of material type on the failure of roof coverings. To address this, fragility curves were developed for the failure of roofs in both elevated and slab-on-grade buildings, considering three types of coverings: 3-tab shingles, laminated shingles, and standing seam metal coverings [see Fig. 18]. It is important to note that these curves describe the probability of reaching or exceeding damage to 15 % of the roof area (i.e., Damage ≥ DS2). DS2 is chosen due to the limited number of cases with DS0.

While Fig. 9 did not reveal a significant difference in damage distribution between 3-tab and laminated shingles, a notable distinction emerges in Fig. 18 when incorporating the effect of the estimated wind speed that impacted each house. For instance, damage exceeding 15 % for roofs with laminated asphalt shingles has a 50 % probability of occurrence at 44.5 m/s and 63.4 m/s for elevated and slab-on-grade houses, respectively. These values are 11 % and 33 % higher than the wind speed at a 50 % probability of failure for 3-tab shingles in elevated and slab-on-grade houses, respectively. The median failure wind speed of elevated houses with 3-

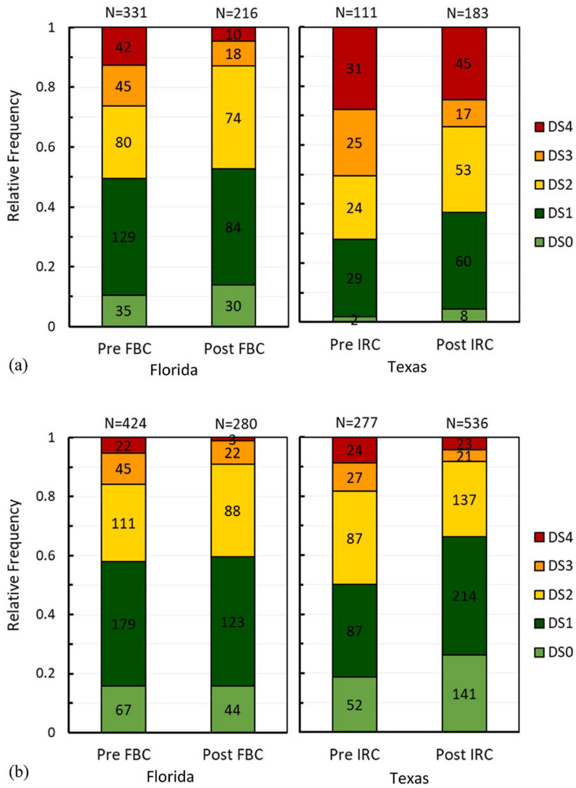

Fig. 16. Frequency of damaged (a) elevated and (b) slab-on-grade houses in Florida and Texas with respect to code adoption.

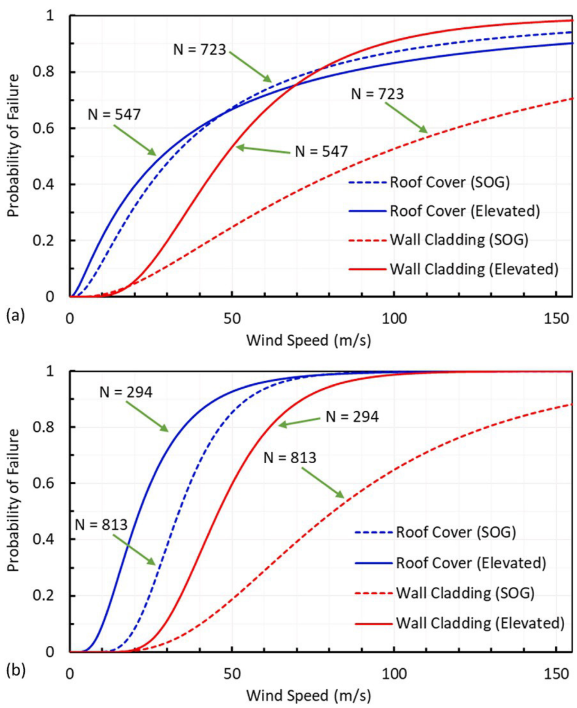

Fig. 17. Empirical fragility curves for failure initiation in the roof and wall coverings of elevated and slab-on-grade (SOG) houses in (a) Florida and (b) Texas.

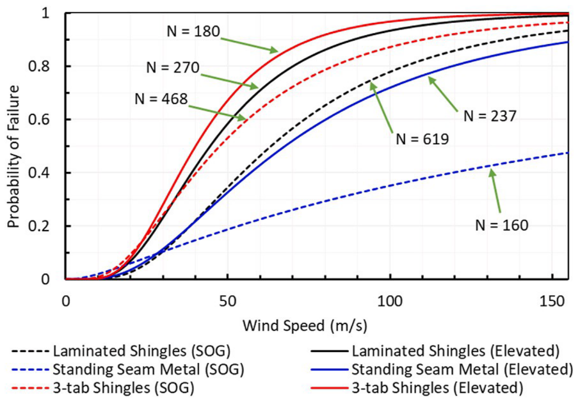

Fig. 18. Empirical fragility curves for different roof coverings in elevated and slab-on-grade (SOG) residential houses.

tab or laminated shingles is 15.5 % and 29.7 % less than that of slab-on-grade houses, confirming the higher vulnerability of elevated houses. According to (ASCE 7–16) [45], the design 3-sec gust wind speeds for the state of Florida exceed 44.7 m/s (100 mph). Therefore, even if the house is designed according to the recommended wind speed by ASCE 7–16, damage to more than 15 % of roof shingles in elevated houses is expected with high probability (>50 %) given the current properties, strength, and installation methods. On the other hand, standing seam metal covers outperform both types of asphalt shingles. For elevated houses, standing seam metal has a median failure wind speed of 67.5 m/s, which is 1.52 and 1.68 times that of laminated and 3-tab shingles, respectively. Furthermore, at 80.5 m/s (180 mph), the highest design wind speed in Florida for buildings with risk category II, it has a 30 % and 60 % probability of occurrence for slab-on-grade and elevated houses, respectively. These results align well with the full-scale failure assessment tests conducted by Ref. [46], which indicated failure initiation of standing-seam metal roofs at wind speeds of64.8 m/s (145 mph).

As shown in Fig. 18, the fragility curves of different roof coverings of slab-on-grade houses are shifted to the right of their counterparts of elevated houses. That is, regardless of the roof covering material, roofs of elevated houses have a higher probability of failure than that of slab-on-grade houses at the same wind speed.

In addition to the covering material, the shape of the roof also influences the damage level of the roof. Fragility curves for DS2 of gable and hip roofs of elevated and slab-on-grade structures with laminated asphalt shingles are shown in Fig. 19. Elevated houses with gable roofs are more susceptible to damage than houses with hip roofs at wind speeds ≤80 m/s. The damage of laminated shingles installed on gable and hip roofs is initiated at a wind speed of almost 9.0 m/s and 20 m/s, respectively. It reaches a 50 % probability of failure at 37.1 m/s and 51.2 m/s, respectively. Thus, it is recommended to use hip roofs for elevated houses to reduce the potential wind-induced damage. Similar behavior can be seen for the gable and hip roofs of slab-on-grade buildings. Compared to slab-on-grade houses, the gable and hip roofs of elevated houses with laminated shingles have a higher probability of failure. The median wind speed for gable and hip roofs of slab-on-grade houses is 1.78 and 1.2 times that of the elevated houses. Figs. 17–19 confirm the increase in roof damage due to elevating residential houses regardless of the roof shape and covering material.

Fig. 20 presents the developed empirical fragility curves for failure initiation of different wall claddings in elevated houses. Vinyl siding is the most vulnerable cladding type with failure initiated at a wind speed of 10 m/s and a median failure wind speed of 41.7 m/s. This finding matches the reported observations by the FEMA Mitigations Assessment Team following the 2008 Hurricane Ike in Texas and Louisiana (FEMA P-757 [47], FEMA P-2022 [4]). Panel and plank sidings have comparable fragility curves with median failure wind speed of 47.5 m/s, respectively. Wall cladding stucco has the lowest probability of failure occurrence compared to the other types which agrees well with the results presented in Fig. 12. Therefore, this study recommends using stucco or brick veneer for

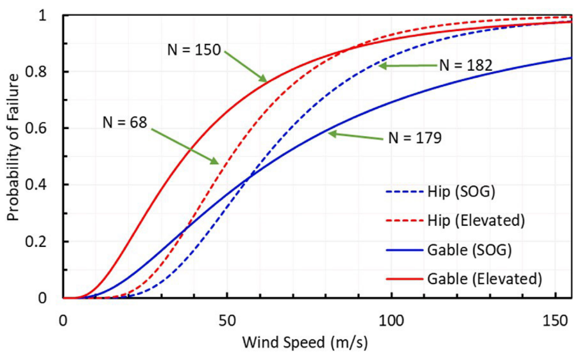

Fig. 19. Empirical fragility curves of gable and hip roofs of elevated and slab-on-grade houses with laminated asphalt shingles covering.

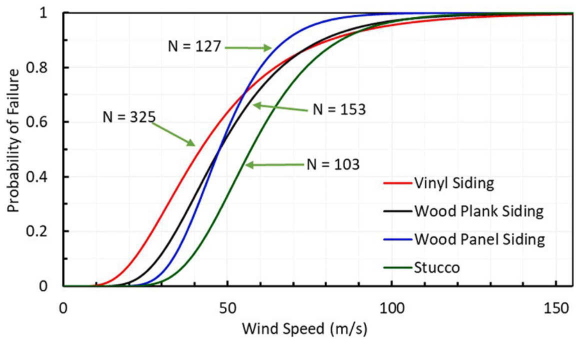

Fig. 20. Empirical fragility curves for failure initiation of different wall claddings in elevated structures.

walls of elevated houses to reduce the damage from future wind events.

6. Conclusions and recommendations for future work

This study analyzed the building performance of 851 elevated and 1536 slab-on-grade single-family residential houses that were impacted by Hurricanes Irma, Harvey, and Michael. The building performance data were extracted from curated and publicly available datasets collected by StEER and others. By combining the performance data with wind field footprints of the three hurricanes, empirical fragility functions were developed to assess the failure initiations of roof and wall claddings. The analysis revealed several key observations, including.

- There is a statistically significant difference in the performance of components installed on elevated and slab-on-grade houses.
- Elevated houses are more vulnerable to wind damage than slab-on-grade houses regardless of the roof covering material, wall claddings, age, and location.
- Elevated houses constructed after adopting the first edition of the FBC and IRC suffered less damage than the other houses. These results corroborate the findings previously reported by Refs. [48–50]. Interestingly, results showed that Pre IRC elevated houses in Texas are the most vulnerable group of houses.
- More than 90 % of elevated houses have experienced damage to their shingled roofs, with damage occurring to more than 15 % of the laminated and 3-tab shingled roof areas at median wind speeds of 99.6 mph (44.5 m/s) and 89.6 mph (40.05 m/s), respectively. Considering that these wind speeds are significantly lower than the design 3-sec wind speed required by the FBC code, this study strongly recommends the implementation of several measures. These include periodic inspections for existing shingled roofs, repairing existing deficient shingles, and the installation of novel shingles with enhanced performance for new roofs. Prevatt et al. [51] and Tolera et al. [52] have proposed two potential solutions for repairing and performance enhancement of shingles.
- A significant improvement was observed in the roof and wall structural systems of Post FBC elevated and slab-on-grade houses and slab-on-grade houses adopting IRC editions, resulting in a decrease in damage percentages from 16.7 % to 6.2 %. While this notable reduction underscores the effectiveness of the current provisions for the design and construction of roofs and walls' structural systems, it is crucial to note that the majority of the damage still occurred at wind speeds below the design level wind speed.
- The findings of this study indicate that elevated and slab-on-grade houses will experience minimal wind-induced damage to the roof covering if constructed as hip roofs with standing seam metal covering. Similarly, utilizing stucco or brick veneer leads to minimal damage to the wall claddings.

The findings of this study also raise several key points that require further investigation, including.

- Homeowners who have taken steps to protect their homes from flooding and storm surges by elevating their houses should be aware of the potential trade-off: while elevation reduces the risk of water damage, it also increases vulnerability to wind which necessitates reinforcing or replacing vulnerable components of their homes, particularly if buildings are elevated to or more than 2.4 m (8.0 ft) as the results showed a 65 % and 181 % increase in percentage of DS3 and DS4 compared to slab-on-grade houses, respectively.
- Although the occurrence of elevated floor damage in the aftermath of hurricanes is common, its documentation remains insufficient, possibly due to restricted access to the damaged structures. This dearth of recorded information impeded our ability to fully analyze the failure mechanisms associated with elevated floors. To fill this gap, the authors recently completed a comprehensive large-scale aerodynamic test to investigate and mitigate the wind effects on elevated floors.
- It is necessary to investigate the impact of increased wind forces on the fatigue life of the envelope components of elevated houses. This is particularly important given the dynamic nature of wind, the prolonged duration of hurricanes, and the higher ratio of loading cycles (i.e., actual loading range to the component capacity) involved in elevated structures, which may significantly reduce the number of cycles required to cause damage.
- The developed fragility functions in this study represent a significant advancement in distinguishing between low-rise elevated and slab-on-grade residential buildings within risk assessment models. To further enhance these advancements, empirical fragility functions are needed for the various damage limit states of components and overall damage states of both elevated and slab-on-

grade houses. These functions will provide a realistic representation of their performance under hurricane wind conditions. Moreover, they will play a crucial role in validating future analytical fragility models for elevated buildings, ultimately facilitating their integration into risk assessment models. Following the procedures proposed by Refs. [43,53], the authors are currently working on developing these functions and assessing their uncertainties.

- The collected data has shown that elevated houses have a wide range of geometry in the field, with a significant proportion featuring partially enclosed spaces beneath the elevated floor. These spaces may alter the wind effects on the external surfaces, as reported by Ibrahim et al. [9]. To deepen our understanding of the wind-induced failure modes of elevated houses and inform the design of more resilient structures, a comprehensive experimental campaign is needed to investigate the aerodynamics of rectangular and nonrectangular elevated houses, including those with open and partially enclosed spaces beneath the floor.
- With the availability of new data collected from future hurricanes, multivariate analysis and/or advanced machine learning techniques are recommended to investigate the interaction between the various factors considered in the current study and their effect on the final damage of the buildings.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2024.109393.

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