Performance of Manufactured Housing during Hurricanes Irma and Michael

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Abstract: Manufactured homes historically have been some of the most vulnerable structures to earthquakes, tornadoes, and hurricanes. More than 20 million people reside in manufactured homes in the US, leaving many at considerable risk across the country. Approximately 10% of the nation's manufactured home stock is in Florida, where they were subjected to 2 consecutive years of intense hurricanes, including 2017 Hurricane Irma and 2018 Hurricane Michael. This paper presents posthurricane imagery and damage assessment of 279 manufactured homes assessed after each of these hurricanes in Florida. Predicted and mapped peak and sustained wind speed data were coupled with public database information of manufactured homes and parks in order to identify site locations with particular ranges of wind speeds in the impacted areas. Damage observations at the component- and system-level were presented based on post-Michael reconnaissance imagery. It generally was observed that manufactured home performance was consistent with historical observations, including 20% of surveyed homes classified as completely destroyed. These findings are intended to highlight the physical vulnerabilities of manufactured housing and to provide impetus for further research and updated standards for safer, affordable housing. **DOI: 10.1061/(ASCE)CF.1943-5509.0001486.** *© 2020 American Society of Civil Engineers.*

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Introduction

Manufactured homes are the quintessential example of the intersection between high physical and social vulnerability. In the US, over 20 million people reside in manufactured homes, the majority of which are built to outdated standards (Geoghegan 2013). However, despite their susceptibility to natural hazards, limited studies to date have systematically measured structural performance, whether in the laboratory, through numerical simulations, or in the field after disasters. This work builds upon the lack of observations through the reporting of RAPID reconnaissance findings after Hurricanes Irma (2017) and Michael (2018) regarding the wind performance of manufactured housing. The objective of this paper was to process wind damage data on manufactured homes in Florida so that it can be used by the research and design code development communities to improve the performance of manufactured homes when subjected to long-duration and strong wind loading.

Previous studies observed that there are three major locations of critical damage to manufactured homes: (1) to the trailer itself, through building envelope damage, roof sheathing damage, failure of roof-to-truss connections, or failure of roof-to-wall connections (which often leads to the collapse of walls); (2) to the foundation, including the trailer sliding off the foundation and overturning failure; and (3) to attached structures, including carport and porch attachments, which typically are connected poorly and easily ripped off, ultimately creating vulnerabilities in the trailer leading to cascading failure (Longinow 2004; IBTS 2005; FEMA 2005, 2006; Hebert and Levitan 2009). However, it is not clear whether the damage to manufactured housing is due to peak wind loads or to fatigue from sustained wind loads, because the previously observed damage to manufactured homes occurred in areas where only the peak wind load was measured or published.

This work considered both peak wind speed and sustained wind speed, when possible, to investigate both total damage and whether catastrophic damage cascades from the initiation of fatigue failure of connections and components. Damage data were captured for 119 manufactured homes after Hurricane Irma and 160 manufactured homes after Hurricane Michael. This paper first provides an overview of the history of hurricane damage and building code regulations for manufactured housing, and then presents observations from the data acquisition and processing.

History of Hurricane Damage to Manufactured Housing

In 1980, Congress formally renamed mobile homes as manufactured homes, recognizing that although positioned on a chassis system, these dwellings typically never are moved after initial installation. The US Department of Housing and Urban Development (HUD) took responsibility for standardizing the construction quality of manufactured homes in 1976. In 1988 the ASCE-sponsored Task Committee on Mitigation of Severe Wind Damage

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recommended that improvements be made to manufactured homes by adding redundancy and ductility to the structure, as well as anchorage of the unit to a permanent foundation (McDonald and Mehnert 1988). However, these recommendations were not enacted, and in 1992 Hurricane Andrew damaged or destroyed over 10,000 manufactured homes. These disastrous results, combined with legal actions that followed, fortunately were enough motivation to use existing research, promote new research, and improve design standards for manufactured homes (Marshall 1993). Finally, in 1994, HUD provisions incorporated new standards (Longinow 2004). Henceforth designs are categorized as pre-1976, 1976–1994 and post-1994 designs.

2004 Hurricane Charley and 2005 Hurricanes Katrina and Rita provided the real-world environments in which observe improvements in post-1994 manufactured home performance. Field investigations were performed after Hurricanes Charley, Katrina, and Rita, and although they provided some insight, these insights were limited because these storms did not reach design-level wind speeds at the observed manufactured home sites (IBTS 2005; FEMA 2005, 2006; Hebert and Levitan 2009). Regardless, although the winds during Hurricane Charley reached between only 50% and 75% of the design loads for post-1994 manufactured homes, they still caused damage to approximately 40% of observed manufactured homes (IBTS 2005). Corroded and rusted tie-down straps were observed, and no manufactured homes were found sited on permanent foundations designed in accordance with HUD permanent foundation guidelines for manufactured homes. After Hurricanes Katrina and Rita, Hebert and Levitan (2009) observed a sample of 251 units in which 62% of post-1994 manufactured homes and 61% of the pre-1994 manufactured homes were damaged. In both field studies, pre-1994 manufactured homes performed worse (reached higher extents of damage on average) than post-1994 manufactured homes, as expected.

Although damage assessment reports exist for more-recent hurricanes, e.g., Hurricanes Ike (2008), Sandy (2012), Matthew (2016), Harvey (2017), and so forth, the focus and mention of manufactured housing is limited. Of the available reports, the FEMA Mitigation Assessment Team (MAT) report for Hurricane Ike (FEMA 2009) most thoroughly addressed the damage withstood by manufactured homes; however, this storm is noted for its combined hazards of storm surge, waves, floodborne debris, and wind, all of which impacted manufactured homes. Many of the manufactured homes were installed below the effective base flood elevation (BFE) established after Hurricane Rita, resulting in either destruction or excessive damage. Furthermore, many of those homes that were compliant with the BFE and with the foundation and anchoring requirements put forth by HUD, performed well overall (FEMA 2009). The MAT concluded that the houses that were sufficiently tied down and rested on strong foundations were able to survive Hurricane Ike if the flood levels did not surpass the chassis frames and the wind speeds remained relatively low (FEMA 2009).

In the wake of 2016 Hurricane Matthew, Florida's Manufactured Housing section conducted a study of the damage due to high winds (FLHSMV 2016). Much of the damage they noted was sustained by additions to older homes. In some instances, a carport or screen room was pulled off the structure by wind and took with it the roof over, i.e., a secondary roof to which it was attached. Although newer homes with carports and screen rooms also lost these additions, damage to the post-Hurricane Andrew manufactured homes was markedly less or entirely nonexistent according to the report (FLHSMV 2016). Available reports on Hurricanes Sandy and Harvey largely were devoid of detailed analyses of the performance of manufactured homes. The FEMA MAT report for Hurricane Sandy made no mention of manufactured homes (FEMA 2013). Brief comments such as "Manufactured homes were hit especially hard, and some did not survive the storm," generally were the extent to which this issue was discussed (FEMA 2013). Similarly, little information exists in regard to 2017 Hurricane Harvey's effects on manufactured homes aside from anecdotal accounts of inundation in which homes experienced flood levels that markedly exceeded home elevation (NOAA 2018a). Although understanding flood, surge, and tornado damage to manufactured homes is important, this paper focuses on wind damage to manufactured homes.

Wind Load Standards for Manufactured Housing

HUD standards for wind loads on manufactured homes vary based on geographical location. The US is subdivided into three zones: Zone 1, Zone 2, and Zone 3. Zones 2 and 3 are designed for 161- and 177-km/h(100- and 110-mi/h) 50-year storms, respectively. Zone 1 requires design for 0.72 kPa (15 psf) of horizontal load and 0.43 kPa (9 psf) of uplift. Zone 2 requires design for a 161-km/h (100-mi/h) 50-year storm with net horizontal drag of 1.87 kPa (39 psf) and uplift of 1.29 kPa (27 psf) on anchoring components. Zone 3 requires design for a 177-km/h (110-mi/h) 50-year storm with a net horizontal drag of 2.25 kPa (47 psf) and uplift of 1.53 kPa (32 psf) on anchoring components [24 C.F.R. 3280 (2018)]. For site-built housing and other building structures, ASCE Standard 7 (ASCE 2016) uses 3-s-gust peak wind speeds. The wind speeds [161 and 177 km/h (100 and 110 mi/h)] for Zones 2 and 3) in HUD standards are the fastest-mile wind speeds based on 1988 maps from ASCE 7. Whereas wind speeds in ASCE 7 have been updated several times to account for a lower risk of exceedance from recent hurricane data for all other buildings, wind speeds in HUD standards have not changed for decades. Notably, manufactured homes also are designed for 121-km/h (75-mi/h) (fastest-mile) sustained wind for transportation on highway purposes.

During 2017 Hurricane Irma, all 67 Florida counties were placed under a state of emergency, 14 of which were located in Zone 3. Of the 35 Florida counties that were placed under states of emergency following 2018 Hurricane Michael, only 4 (Franklin, Gulf, Lee, and Pinellas) were located in Zone 3 [24 C.F.R. 3280 (2018)]. The fastest-mile wind speed first must be converted to 3-s-gust wind speed, resulting in values of 185 and 203 km/h (115 and 126 mi/h) for Zones 2 and 3, respectively. Then, to be comparable to standards for site-built housing, these values must be converted to an equivalent ultimate strength 3-s-gust design wind speed. Using the conversion provided in ASCE 7 Table C26.5-7 (ASCE 2016) produces equivalent ultimate strength 3-s-gust peak wind speeds of 235 and 256 km/h (146 and 159 mi/h) in Zones 2 and 3, respectively, and 182 km/h (113 mi/h) sustained wind speed for highway transportation purposes. For Risk Category 2 buildings, current wind maps for Florida in ASCE 7 (ASCE 2016) set peak design wind speeds between 185 and 290 km/h (115–180 mi/h) for different parts of the state. The portion of Florida impacted by Hurricane Irma has design wind speed ranges from 209 to 290 km/h (130–180 mi/h); the portion of Florida impacted by Hurricane Michael has design wind speed ranges from 185 to 209 km/h (115–130 mi/h).

Overview of Hurricanes Irma and Michael

According to the National Oceanic and Atmospheric Administration (NOAA 2018b), Hurricane Irma was the most powerful Atlantic

Hurricane on record, sustaining 298-km/h (185-mi/h) winds and Category 5 status longer than any prior storm and generating the third highest recorded accumulated cyclone energy in the history of tropical Atlantic storms. The storm's track left a path of destruction across the Caribbean, impacting both the US Virgin Islands and Puerto Rico during its Category 5 period. Hurricane Irma eventually made its first landfall in the continental US on Cudjoe Key in southern Florida early on Sunday, September 10, 2017, passing just 31 km (20 mi) from Key West with Category 4 winds that reached 209 km/h (130 mi/h). The National Hurricane Center downgraded Irma to a Category 3 storm as it made its second landfall later that afternoon on Marco Island, just south of Naples in Florida's Gulf Coast, with sustained winds near 193 km/h (120 mi/h). Irma continued to move northward along Florida's Gulf Coast, weakening to a Category 1 storm and eventually to a Tropical Storm as it moved through the northern portions of the state.

Hurricane Michael made landfall on the afternoon of October 10, 2018 near Mexico Beach, Florida as a strong Category 4 hurricane; the strongest to hit the continental US since Hurricane Andrew in 1992. It is considered the most powerful storm to impact the Florida Panhandle in recorded history. At the time of this writing, the death toll had reached 43 fatalities with expectations that numbers could increase as the long recovery continues. Although final numbers still are not known, economic loss estimates have been reported between $4.5 billion and $53 billion (O'Connor 2018; Sullivan 2018; Barrabi 2018; Perryman Group 2018). Fig. 1 presents the best trajectories of Hurricane Irma and Hurricane Michael as they approached Florida.

Hurricane Michael's rapid intensification was particularly noteworthy and attributed to higher than average sea surface temperatures in the Gulf of Mexico (NOAA 2018c). Weather instruments captured Hurricane Michael's most powerful gusts and highest surges as it made landfall. At the time of landfall, the Category 4 hurricane was moving forward at approximately 22.5 km/h (14 mi/h), with maximum sustained wind speeds of 250 km/h (155 mi/h) (NOAA 2018c). The maximum surge observed was 2.7 m (9 ft) in Mexico Beach, Florida (Berke 2018).

Hurricanes Irma and Michael presented important opportunities to investigate wind performance of manufactured homes given the range of wind speeds recorded, including wind speeds reaching and exceeding design winds at the coast and further inland.

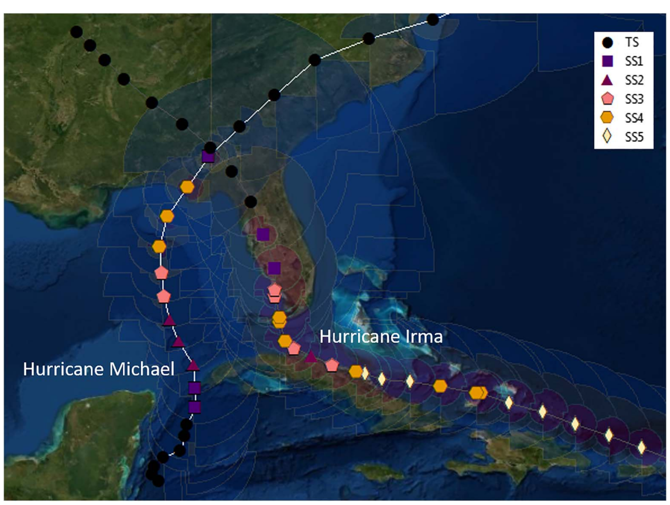

Fig. 1. Hurricanes Irma and Michael best track and radii of hurricane- and tropical-force winds. Legend entries indicate storm classification on Saffir–Simpson Hurricane Wind Scale: TS = tropical storm; SS1 = Category 1; SS2 = Category 2; SS3 = Category 3; SS4 = Category 4; and SS5 = Category 5. (Data from NOAA 2019.)

Hurricane Irma Data Sources

For the purposes of this study, data were acquired from several different sources. Physical damage to manufactured housing units after Hurricane Irma was gained from a National Science Foundation (NSF) RAPID-reconnaissance study performed September 15–25, 2017. The authors were permitted early access to the data, which included photographs, location tags, and building type classification in some cases. These data now are publicly available on DesignSafe-CI (Kijewski-Correa et al. 2018). More than 300 photos were taken of 119 manufactured homes in Florida during the post-Irma RAPID field study. Additionally, the authors acquired pre-event photos from Google Maps imagery where available. Parcel-level tax data and permit data were obtained from each county; these data are publicly available, and included address; photos of the unit; fabrication year; effective year built; tax assessed property, land, and improvement values for 2016, 2017, and 2018; and information about attachments and the installation date of those attachments. Lastly, mapped predicted wind speed data from Applied Research Associates (ARA) were used to gain information about the hazard.

This study focused on manufactured housing, a small subset of the RAPID data available on DesignSafe-CI (Kijewski-Correa et al. 2018). In total, 119 manufactured homes were identified in the data; all were located in either Monroe or Collier Counties.

Hurricane Michael Field Study Methodology and Data Sources

Immediately following Hurricane Michael, the NSF-funded Structural Engineering Extreme Event Reconnaissance (StEER) network initiated a virtual reconnaissance study, and shortly thereafter sent a team to perform a preliminary survey of the areas that were hit the hardest. Their data consisted of geocoded imagery and contextual information, and were used to help identify study locations for the present study. In addition to the information provided in the aforementioned StEER reports, mapped wind field data from ARA were used to determine site locations for collecting perishable data on wind-damaged manufactured housing. Prior to entering the field, wind field data were overlaid with storm surge data from NOAA to identify cities in which hurricane winds were the primary hazard to reduce hazard uncertainty in damage classification. These individual maps were included in Alipour et al. (2018).

The post-Hurricane Michael RAPID field investigation was performed by the authors on October 20–22, 2018. Data acquisition was performed in inland areas that experienced lower wind speeds, but not a surge, to assess failure of nonstructural components. These locations of failures were no longer evident in areas that experienced very high wind speeds due to more-significant system-level damage. Inland and coastal areas experiencing a range of wind speeds were visited for analyzing overall system-level performance. To identify specific field study sites, Florida public records of mapped mobile home park locations were checked against Google Maps, and leads were followed in the field. There are more than 5,000 registered mobile home parks in Florida, more than 200 of which were in the area of interest after removing recreational vehicle parks from the list. Table 1 provides the city, peak and sustained wind speeds (from ARA), and the number of units surveyed in each city during the field investigation. In total, 164 manufactured housing units were surveyed. The peak wind speeds in Table 1

Table 1. Hurricane Michael reconnaissance summary

Florida city	ARA peak wind speed [km/h (mi/h)]	ARA sustained wind speed [km/h (mi/h)]	Number of units surveyed
Mexico Beach	225 (140)	161 (100)	4
Port St. Joe	209 (130)	137 (85)	11
Panama City	193 (120)	121 (75)	43
Marianna	177 (110)	116 (72)	54
Cottondale	161 (100)	N/A	38
Vernon	129 (80)	80 (50)	14

are 3-s-gust basic wind speeds assuming open terrain and 10-m height. The peak wind speed in Table 1 is 225 km/h (140 mi/h), reflecting the predicted contours from ARA, which is much less than the peak wind speed of 249 km/h (155 mi/h) reported by the National Hurricane Center. Sustained wind speeds were based on time-series data recorded from sensors located near the city listed in Table 1. The time-series data were provided by ARA (Alipour et al. 2018).

Data collected included photographs of all sides of the structure and close-up images of any specific damaged component. An Environmental Systems Research Institute (ESRI) smartphone application, Survey123 version 3.9.149, was used to collect additional information, including location coordinates, type of foundation, type of roof, a list of all visibly damaged elements, and a systematic classification of the overall physical damage level. Two specific approaches were used to confirm that the structure damage was caused primarily by wind loading: (1) the presence of water marks on each building exterior was checked, and (2) the damage path was examined. Wind damage typically creates a path that initiates from the top of a structure through the roof and to the roof-to-wall connections, leading eventually to wall collapse. Damage due to storm and flood water often starts from the lower levels through the foundation and floor structure. These understandings were used to examine the damage path and to identify whether the damage was caused primarily by wind or water.

Upon completion of the field study, secondary data were gathered, including prestorm imagery from Google Maps where possible, and year built and effective year data from Florida public records. After cleaning the data, four samples were dropped from the survey due to insufficient details, reducing the Hurricane Michael sample size to 160 homes. Details of the secondary data collection, and cleaning process of the full dataset were reported by Sutley et al. (2019).

Physical Damage Classification

A new quantitative guideline was developed for classifying damage into five distinct categories for the purposes of this work. The quantitative guideline is presented in Table 2. For measurement consistency across field studies, events, and field study teams, the guideline is based largely on the guideline presented and used by Roueche et al. (2018) after Hurricane Harvey, but has been extended to incorporate features specific to manufactured homes, including damage to skirting, floor underside, and foundation.

More than 300 photos were taken of 119 manufactured homes in Florida during the post-Irma RAPID field study (Kijewski-Correa et al. 2018), along with more than 700 photos taken of 160 manufactured housing units during the post-Michael RAPID study (Sutley et al. 2019). The guideline in Table 2 was used to classify damage to manufactured homes after Hurricanes Irma and Michael. In the case of Hurricane Irma, only images were used in the classification. A combination of in-person observations and follow-up imagery assessment was performed for the damage classification

Table 2. Quantitative guidelines for assigning overall damage ratings to manufactured homes

Damage state	Damage description	Roof/wall cover failure (%)	Window/door failure	Roof/deck failure	Skirt failure (%)	Underside floor failure	Roof structure failure	Wall structure failure[a]	Foundation failure	Interior water damage
0	No damage or very minor damage	≤2	No	No	≤2	No	No	No	No	None
1	Minor damage	>2 and ≤15	1	No	>2 and ≤15	No	No	No	No	Minor rainwater ingress, no evidence of flooding
2	Moderate damage	>15 and ≤50	>1 and less than or eqaul to the larger of 3% or 20%	1–3 panels	>15 and ≤50	Yes	No	No	Structure partially shifted on supports	Water marks 0–0.61 m (0–2 ft) above first floor; significant rainwater ingress; interior damage ≤30%
3	Severe damage	>50	greater than the larger of 3% or 20%, and ≤50%	>3% and ≤25%	>50	Yes	≤15%	No	Structure partially fallen off supports	Water marks 0.61–1.2 m (2–4 ft) above first floor; interior damage >60%
4	Destruction	>50	>50%	>25%	>50	Yes	>15%	Yes	Structure completely fallen off supports	Water marks >1.2 m (4 ft) above first floor; interior damage >60%

Source: Data from Roueche et al. (2018).
[a]Wall structure refers to walls in living areas only. The ground floor of elevated structures often has breakaway walls that can be easily damaged by storm surge.

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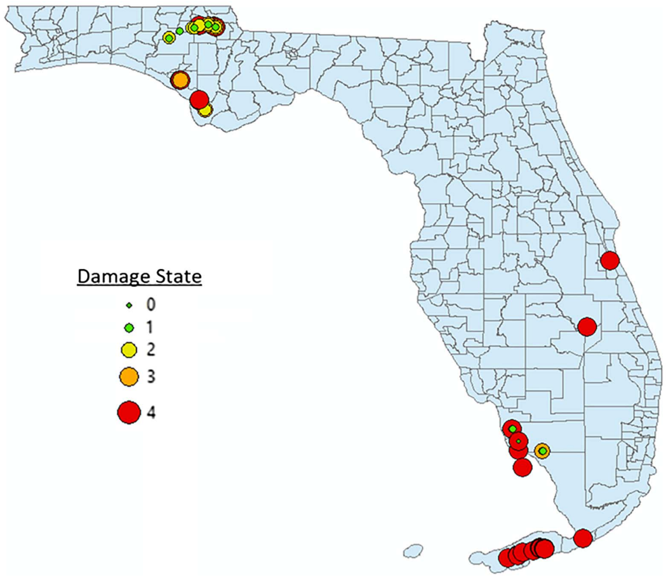


Fig. 2. Geospatial depiction of posthurricane damage to manufactured homes in Florida.

Table 3. Damage distribution across manufactured homes surveyed in Florida

Damage state	Hurricane Irma	Hurricane Michael	Total
0	17	15	32
1	48	52	100
2	12	51	63
3	3	26	29
4	39	16	55
Total	119	160	279

post-Hurricane Michael. In some cases, particularly with the Hurricane Irma data, minor levels of damage were distinguished by comparing post-Irma photos with pre-Irma imagery to determine as best as possible what was different because of the hurricane. Fig. 2 provides a geospatial damage distribution of the sampled manufactured homes across both hurricane events in Florida; varying marker sizes are used to show damage distribution across the survey sites. Table 3 tabulates the distribution of damage assessed after Hurricanes Irma and Michael. The following sections provide imagery comparisons exemplifying each damage state; damage to different portions of the structure, including the foundation, trailer, and attachments; and a closer look at how manufactured homes constructed across the three fabrication periods performed during both events and in different geographic areas.

Physical Damage Observations of Manufactured Housing

Damage state 0 was classified for 11% of the homes, in which no damage was visible from the post-Irma imagery and no damage was observed during the post-Michael reconnaissance. In many cases, debris was visible on the ground surrounding the home, and portions of the landscape were damaged. It was not clear that this debris came from the home, and generally, multiple angles of the unit were photographed to confirm this presumption.

Fig. 3. Damage state 1 classification example. (Image by authors.)

Fig. 4. Damage state 2 classification example. (Image by authors.)

Fig. 5. Damage state 3 classification example. (Image by authors.)

Damage state 1 was classified for 36% of the homes surveyed. Fig. 3 is a post-Michael photo of a manufactured housing unit classified as Damage state 1. The damage visible in Fig. 3 is to the skirting, which is common across all damage state classifications. The siding, door, windows, and attachment all are unharmed.

Fig. 4 is an image of a manufactured home classified as Damage state 2. In total, 23% of all surveyed homes were classified as Damage state 2. Noticeably in Fig. 4, there is between 15% and 50% skirting and siding loss. The foundation, windows, and attachment all are unharmed.

Fig. 5 is a post-Michael image of a home categorized as Damage state 3. In total, 10% of all surveyed homes were classified as Damage state 3. The damage observed in Fig. 5 includes significant wall

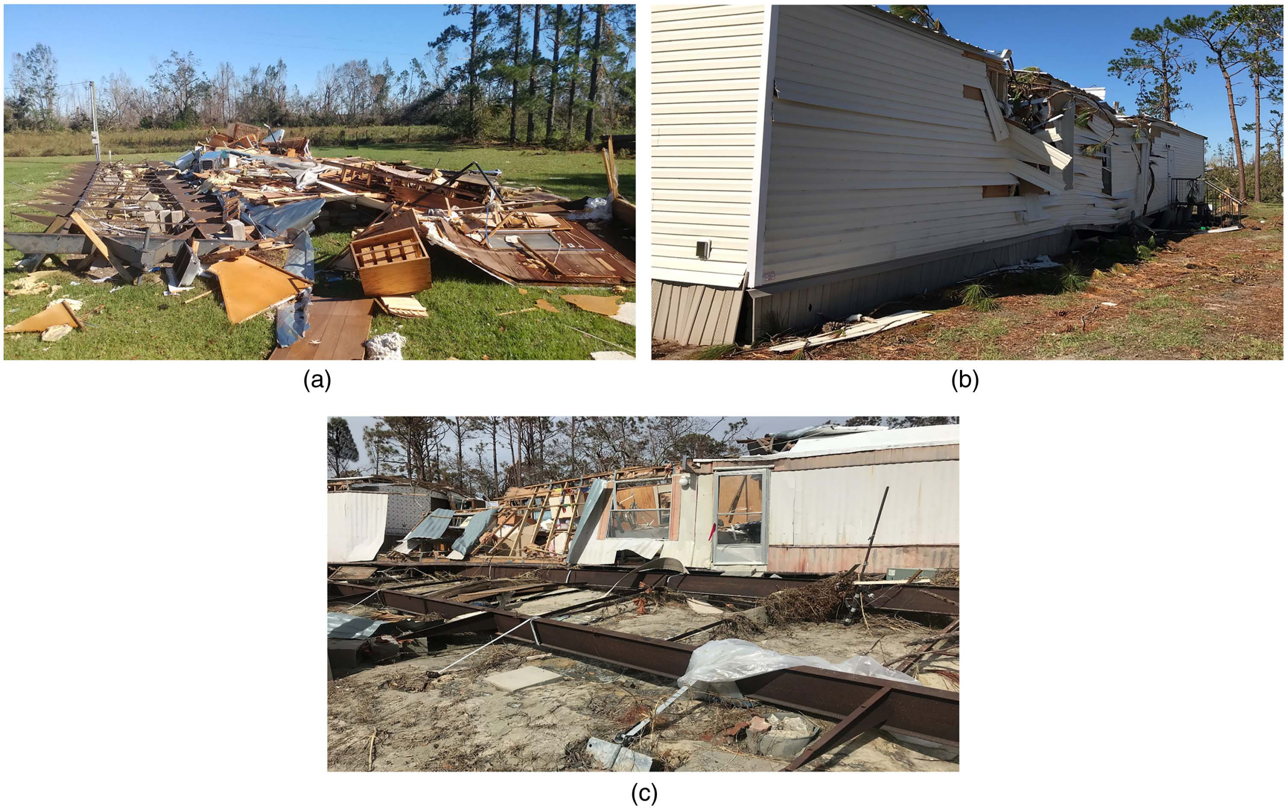


Fig. 6. Damage state 4 classification example: (a) exploded home; (b) tree-destroyed home; and (c) surge-dislocated and partially collapsed home. (Images by authors.)

cover loss and some skirt loss. The structural integrity of the home appears to remain in good shape.

Fig. 6 provides three examples of manufactured homes classified as Damage state 4, representing 20% of the total sample. These were the three most common catastrophic failures observed. Fig. 6(a) shows an exploded home, which was quite common for older homes due to their poor connections and lack of wood sheathing used in the walls and roofs. Fig. 6(b) shows a home with the middle third collapsed due to tree-fall. Fig. 6(c) shows a home that was picked up and dislocated from its foundation. This latter case was due to the surge and flooding experienced by homes on the coast, which in total represented a small portion of the sample. The majority of damage observed and classified in the sample was caused by wind, including some of the damage shown in Fig. 6(c). In Fig. 6(c), sections of the wall and roof structure have collapsed, exposing the structural system, which again lacks sheathing. Also notable in Fig. 6(c) are the anchor straps which kept the chassis system in place; the trailer itself was not well-attached to the chassis system, and thus was easily picked up and relocated with the surge.

Influence of Wind Speed and Fabrication Period on Damage

The distribution of damage across the samples from both Hurricanes Irma and Michael is provided in Fig. 7 with reported maximum wind speed, using the wind speeds from the ARA wind fields representing basic wind speeds measured at 10 m above the ground over open, flat terrain; ARA wind field maps are provided in ARA (2017) for Hurricane Irma and in Alipour et al. (2018) for Hurricane Michael. Based on these wind fields, predicted wind speeds peaked during Hurricane Irma at 185 km/h (115 mi/h) and at 209 km/h (130 mi/h) during Hurricane Michael. The 3-s-gust wind speed conversion from the HUD design values are 185 and 203 km/h (115 and 126 mi/h) for Zones 2 and 3, respectively, which are very close to the peak wind speeds predicted in the surveyed areas. Therefore, a distribution of damage ratings was anticipated and is reflected in Fig. 7. The highest proportion

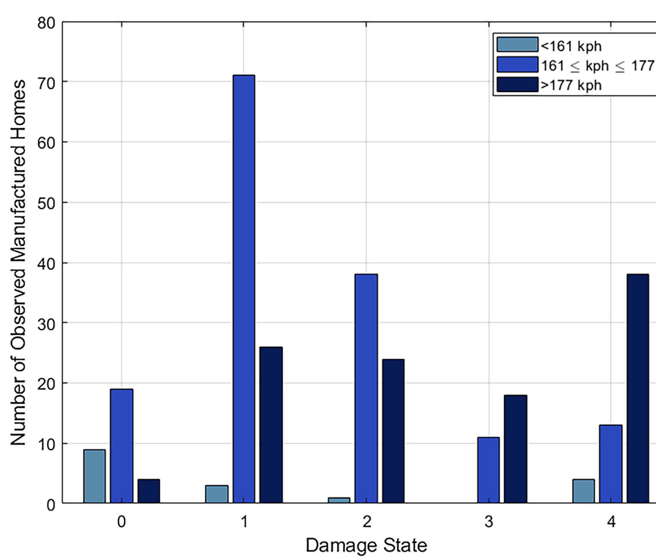


Fig. 7. Manufactured housing damage distribution across wind speed ranges ($n = 279$).

of homes experiencing no damage experienced the lowest wind speed range, and the highest proportion of homes experiencing complete damage experienced the highest wind speed range. Of the homes located within the highest wind speed range (greater than 177 km/h), 4 homes were recorded after Hurricane Irma as having no damage; 19 were recorded after Hurricane Irma and 6 homes were recorded after Hurricane Michael as having minor damage; and 8 homes were recorded after Hurricane Irma and 16 were recorded after Hurricane Michael as having moderate damage. It was expected that all homes would be severely or completely damaged after experiencing wind speeds greater than the design wind speeds, which vary based on the HUD zone and fabrication year. Thus, this discrepancy in the data can be attributed to (1) fabrication year of the home, and any further enhancements to the structure; and (2) the fact that peak wind speeds are based on predicted contours, and do not perfectly represent the actual peak wind speed recorded at the site, which could have been different from the contour values.

As discussed previously, major changes occurred in the construction standards for manufactured housing at two distinct points in time, creating three categories of structural quality based on design and fabrication provisions: pre-1976 units, units fabricated between 1976 and 1994, and post-1994 units. Fig. 8 presents the distribution of these three periods for each damage state and accounting for the same three wind speed ranges. The year built could be determined for only a portion of surveyed homes; thus the sample size in Fig. 8 is 133, and consists of homes surveyed after both hurricanes. In total, 40 homes (30%) were fabricated before 1976, 65 homes (49%) were fabricated between 1976 and 1994, and 28 homes (21%) were fabricated after 1994.

In total, 58% of pre-1976 homes experienced no or minor damage; 58% of 1976–1994 homes experienced no or minor damage, and 43% of post-1994 homes experienced no or minor damage. Interestingly, large proportions of both of the relatively older (pre-1976) and newer (post-1994) homes were completely damaged, 20% and 19%, respectively, whereas only 11% of the homes built between 1976–1994 experienced similar damage. Notably, the newer post-1994 homes experienced complete damage only when exposed to the highest wind speeds, whereas a pre-1976 home in the lowest wind speed range also was destroyed. Homes fabricated between 1976 and 1994 experienced a range of damage levels, but when exposed to winds slower than 161 km/h, no damage was observed. Overall, when winds exceeded 177 km/h, all three period ranges included homes in every damage category, from no damage to complete damage. Interestingly, post-1994 homes exposed to the highest wind speed range experienced only moderate or worse damage, whereas older homes experienced the full range of damage levels at the highest wind speed range. Both of these facts are attributed to unknown strength variability of the homes, such as older homes having updated foundations, and discrepancies in predicted peak wind speeds and actual peak wind speeds at each site. In general, fewer post-1994 homes were observed, and thus fewer were noticed in each damage category, and none were observed in the lower wind speed range.

Damage Observations to Foundation

Close-up photographs were not taken during the post-Irma investigation; therefore this section, which focuses on foundation damage, and the next two sections, which focus on trailer and attachment damage, use imagery collected only during the post-Michael investigation. Of the 160 manufactured homes surveyed, 16 were completely destroyed. Of the remaining 144 homes, 24 experienced damage to the foundation. Foundation types varied, and most homes utilized a combination of structural systems, which greatly influenced the wind speed range causing failure. In total, 126 homes rested on a chassis system, 140 used stacked block footers, 114 had engineered anchorage devices, 22 had engineered

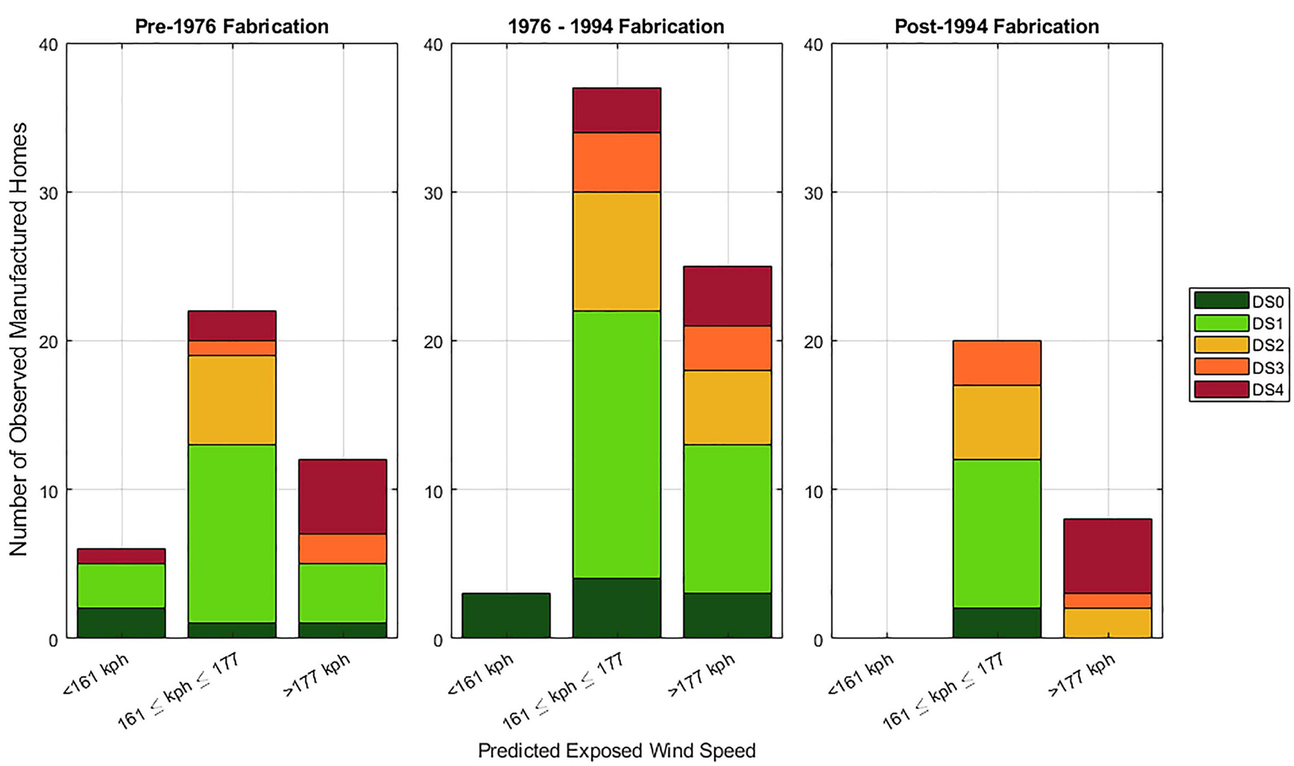


Fig. 8. Observed manufactured housing damage distribution across fabrication periods and wind speed ranges ($n = 133$).

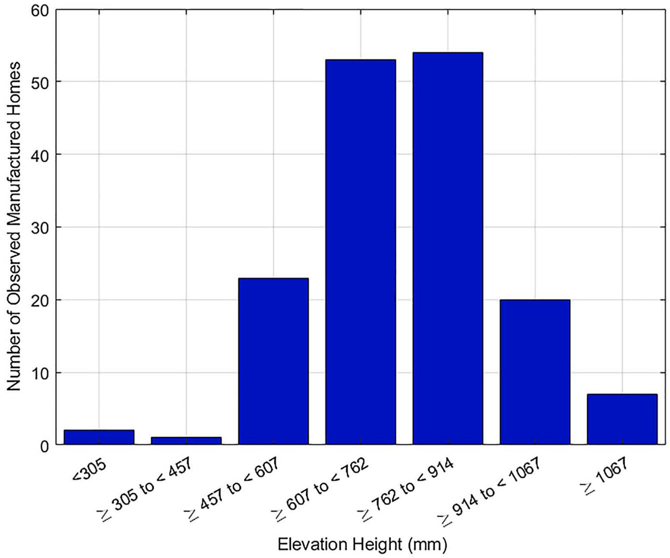


Fig. 9. Histogram of manufactured home elevation heights.

bracing, 7 were recorded as having other foundation types, and 5 were recorded as having permanent foundations. Homes also were elevated to different heights, which can influence the amount of airflow and thereby uplift or suction pressure on the floor underside. Fig. 9 provides a histogram of the range of elevation heights measured in the field, in which the first bin captures heights up to 305 mm (1 ft) in elevation and the last bin captures heights more than 1,067 mm (42 in.) in elevation. Most homes were elevated between 457 and 914 mm (18 and 36 in.); recent wind tunnel tests showed that buildings raised to these lower heights experience high suction pressure coefficients on their floor underside (based on forthcoming work by the authors). Fig. 10 provides examples of the types of damage observed to the foundation, including anchorage devices becoming detached from the ground or the unit, and wood or concrete blocks being displaced and even collapsing. The images in Fig. 10 are in addition to complete failures related to the foundations of manufactured homes, in which common failure modes included the trailer rolling off of the foundation or experiencing a pancake-like collapse onto the foundation.

Damage Observations to Trailer

Of the 160 manufactured homes surveyed after Hurricane Michael, 90% were single-wide, and 10% were double-wide. The trailers had a variety of roof shapes: 143 had gable roofs (which had much lower slopes than site-built gables), 3 had hip roofs, 2 had monoslope roofs, and 12 were categorized as other; surveyor notes documented these as mostly being arched or rounded roof structures. Due to a lack of visibility, roof damage often was difficult to observe and precisely document; aerial photography of each home was unavailable during either survey.

Fig. 10. Damage to foundation: (a) anchorage device detached from ground; (b) wood block slipped off concrete block footing; (c) collapsed concrete block footing; and (d) permanently tilted concrete block footing. (Images by authors.)

The most common damage to the trailers was damage to the skirting; of the 144 homes that were not completely destroyed, 122 experienced damage to the skirting. Skirt damage consists of partial or complete removal of the skirting, which cascades into two new vulnerabilities. First, removed portions of the skirt become debris missiles that can cause damage and risk of injury. Second, the missing skirting changes the aerodynamics beneath the unit, potentially inducing high suction pressures on the floor underside during high winds (Based on forthcoming work by the authors).

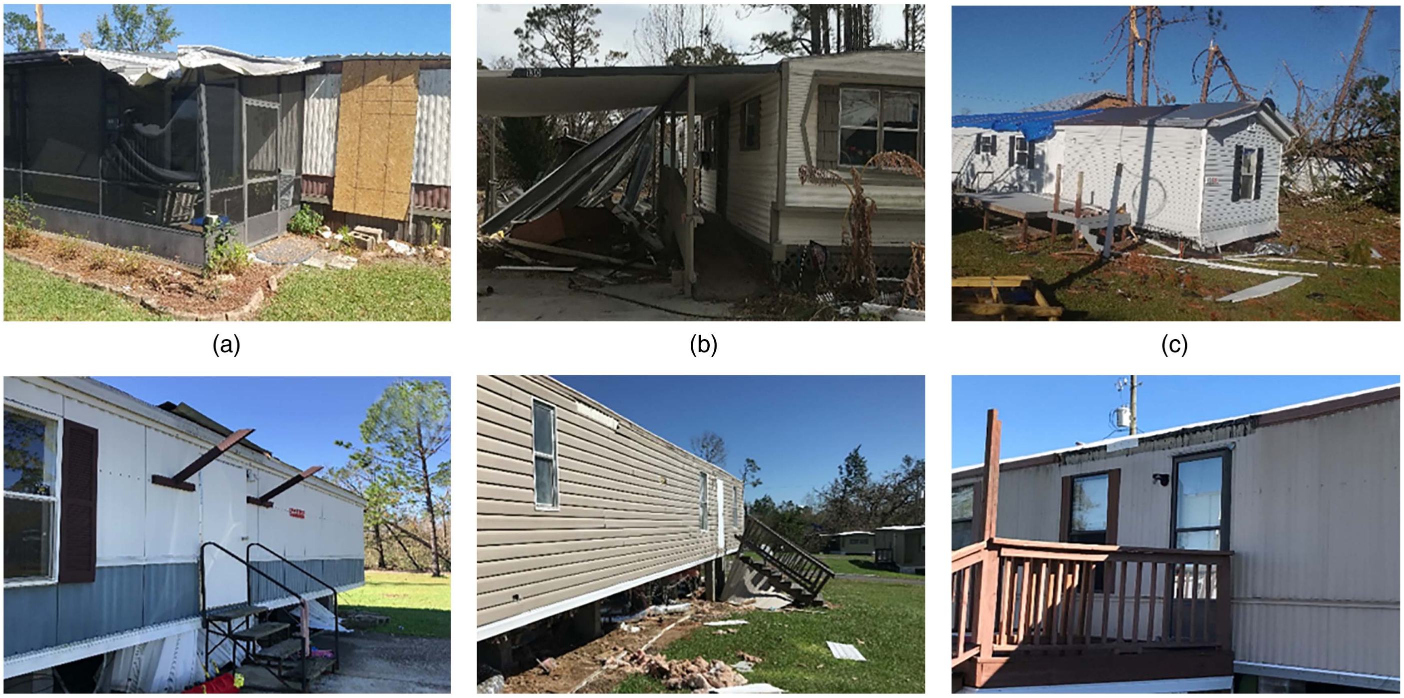
Excluding skirt damage, 99 homes experienced other types of damage to the body of the trailer (e.g., roof, walls, floor, windows, and doors). Fig. 11 provides images of different types and locations of damage to the body of the trailer, including the floor underside, with insulation components ripped out; removed siding; out-of-plane wall siding indentations; damage to the wall structure, exposing the interior; debris missile impacts; tarped portions of the trailer; roof structure loss exposing the interior; tree impact to the roof structure; and shingle loss on the roof. Figs. 11(b and f) show differences in wall structures. Stud spacing without exterior sheathing, which is common in older homes, can lead to the out-of-plane deformation observed in Fig. 11(c). As before, these damages were in addition to the complete destruction of the trailer for homes that were marked as Damage state 4.

Regarding Fig. 11(e), the reconnaissance team entered the field just 1–2 weeks after Hurricane Michael. In the coastal cities, such as Port St. Joe and Mexico City Beach, this sometimes seemed too soon, because some homeowners were returning to their damaged homes at the same time the reconnaissance team reached the site, although utmost efforts were made to never interfere with emergency response operations. However, further inland, the timing sometimes seemed late, because many structures with apparent roof damage and major wall damage already were covered with tarps, making detailed observations impossible.

Damage Observations to Attachments

All post-Michael samples were identified as having attachments, which, at a minimum, included steps leading up to the front door.

Fig. 11. Damage to trailer: (a) floor underside damage; (b) skirting and siding loss; (c) siding indentation; (d) debris missile; (e) tarping covering portions of the roof and wall structure; (f) siding and skirting removed with a full-height hole in the wall structure; (g) hole in the roof; (h) tree fall onto roof; and (i) roof shingle loss. (Images by authors.)



(a) (b) (c) (d) (e) (f)

Fig. 12. Damage to attachments: (a) roof crumpling; (b) carport collapse; (c) railing removal; (d) awning loss; (e) stair collapse; and (f) awning loss with removal of trailer roof edging. (Images by authors.)

Attachments also included awnings, carports, screened porches, and elevated decks; as is the case for damage to trailer components, detached attachments can become additional hazards in the form of windborne debris. Of the 144 manufactured homes surveyed that were not completely destroyed, only 19% were recorded as having damage to attachments. Fig. 12 provides images of several types of attachment failures, including damage to porch roofing, carport collapse, damage to stairs and stair railing, and damage to awnings. Figs. 12(d and f) show instances of roof awning loss; the latter also shows that a portion of the trailer's roof edging was ripped off with the awning. This type of failure is particularly important to capture because it can lead to cascading failures of homes by creating new vulnerabilities to the trailer.

Conclusions

This paper presents the empirical findings of wind damage to manufactured housing recorded during two posthurricane investigations. A quantitative guideline was developed for classifying damage into five distinct categories with guidance specific to manufactured homes, including underside floor, skirt, and foundation failures. Prehurricane imagery was used when possible to assist in identifying damage caused by the hurricanes as opposed to damage caused by deferred maintenance. Of the 279 homes surveyed after Hurricanes Irma and Michael, 11% were not damaged and 20% were completely destroyed. Furthermore, 59% experienced nonstructural damage (Damage states 1 and 2), and 30% experienced structural damage (Damage states 3 and 4). Damage varied as a function of wind speed and fabrication year. Although common failures of the foundation, trailer, and attachments were observed and reported here, trends identifying which type(s) or elevation(s) of foundations, roof shapes, or attachments caused the most or least damage were not possible given the size of the data set. Such information will be critical for making major improvements to the performance of manufactured homes, and is suggested for future studies on this topic.

Based on ARA estimates, wind speeds peaked very near the design wind speeds for these homes, considering any fabrication year. The results in Fig. 8 are consistent with the well-documented findings that homes built prior to 1976 experience more damage and more severe damage at lower wind speeds. Pre-1994 fabricated homes also tended to have more damage and more severe damage overall and in the medium to high wind ranges, although both had considerable variability. Similarly, detailed images were provided of the failure modes of the foundation, trailer, and attachments, which were consistent with past findings despite the fact that most homes utilized engineered foundation systems.

The results of the damage investigation are alarming. The unwarranted losses caused by the physical vulnerability of manufactured homes are exacerbated by the overlying high social vulnerability of manufactured home residents, who typically represent low-income groups with minimal insurance. Manufactured home residents experience disasters from hazards more often, have the hardest time recovering from such disasters, and mostly are dependent on private charities or other disaster assistance programs for postdisaster repairs and reconstruction. This disparity hinders the community's recovery as a whole, including prolonging the need for temporary housing. These empirically based facts should be taken into consideration along with the presented posthurricane findings to improve the quality of manufactured homes for safer affordable housing and more resilient communities.

Data Availability Statement

The data sets of wind damage ratings and photographs of manufactured homes following Hurricane Michael used for this study are available in the DesignSafe-CI data repository at https://doi.org/10.17603/ds2-85fv-n684. Photographs of damaged manufactured homes following Hurricane Irma used for this study are available in the DesignSafe-CI data repository at http://doi:10.17603/DS2TX0C.

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