# Overview of Damage Observed in Regional Construction During the Passage of Hurricane Irma over the State of Florida

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## ABSTRACT

Hurricane Irma made its first landfall in the continental US at Cudjoe Key in southern Florida on September 10, 2017, with Category 4 winds. Irma made its second landfall later that afternoon on Marco Island on Florida's Gulf Coast, as a Category 3 storm, weakening further as it moved north. Reconnaissance teams respectively dedicated to the Gulf Coast, Atlantic Coast and Miami/Florida Keys carried on a first wave of rapid reconnaissance from September 15-20, 2017. A second more exhaustive campaign was then conducted in the Florida Keys on September 22-25, 2017. These investigations employed primarily door-to-door damage assessments to classify buildings and evaluate component damage levels using a Fulcrum mobile smartphone application for data collection in a unified assessment framework feeding into a quality assurance/quality control process. At select locations, unmanned aerial surveys generated aerial imagery, 3D point clouds and 3D textured meshes. This study presents the geospatial distribution of observed damage, correlated by age of construction, typology, construction materials, and estimated wind speed. Specific case studies highlight common failure modes observed in different construction classes and editions of the Florida Building Code.

## INTRODUCTION

Hurricane Irma provided a unique opportunity to assess the relative performance of the built environment in Florida and to confirm lessons learned after hurricane Charley [Gurley et al., 2011]. This paper presents the observed damage, correlated by age of construction, typology, construction materials, and wind speed. It presents specific case studies to highlight common failure modes in different construction classes and editions of the Florida Building Code (FBC).

## HURRICANE IRMA

Hurricane Irma made its first landfall in the continental US at Cudjoe Key in southern Florida on September 10, 2017, with Category 4 winds reaching 58 m/s (130 mph). The National Hurricane Center (NHC) downgraded Irma to a Category 3 storm as it made its second landfall later that afternoon on Marco Island, just south of Naples on the Florida's Gulf Coast, with sustained winds near 54 m/s (120 mph). It weakened further to a Category 2 once inland .

The storm's large wind field resulted in strong winds across much of Florida. The highest reported sustained wind speed was 50 m/s (112 mph) on Marco Island, while the strongest observed wind gust was 64 m/s (142 mph), recorded near Naples, though wind gusts of 67 to 72 m/s (150 to 160 mph) likely occurred in the Middle Florida Keys. Generally, heavy amounts of rainfall were recorded to the east of the Irma's path, including a peak total of 550 mm (21.66 in) in Fort Pierce. Heavy precipitation – and storm surge, in some instances – overflowed at least 32 rivers and creeks, causing in significant flooding, particularly along the St. Johns River and its tributaries. The highest recorded storm surge was 2.3 m (7.6 ft) NAVD near the Matanzas Inlet, though there were no observations from the Ten Thousand Islands, where the highest storm surge likely occurred (FDEP, 2017).

## RECONNAISSANCE EFFORT

### Design

As part of a larger, multi-storm reconnaissance effort managed by the third author's coordination node at the University of Notre Dame (Kijewski-Correa et al. 2018, Prevatt et al. 2018), regional nodes were established at the University of Florida (UF, led by Kurt Gurley), Florida Institute of Technology (FIT, led by Jean-Paul Pinelli), and Florida International University (FIU, led by Ioannis Zisis), from which local reconnaissance was organized to respectively document damage along the Gulf Coast, Atlantic Coast and Southern Tip of the state. The second author served as Data Standards Lead to ensure uniformity in data collection, processing and curation standards. Each regional node engaged faculty and affiliated partners to assemble a team to assess their assigned geography, with the objective of swiftly deploying the initial wave of teams within a week of the storm's landfall. A total of 1142 structures were surveyed across Florida.

### Tools

Teams documented damage to structures, delineating the effects of wind and coastal hazards with a standardized damage assessment instrument created and programmed using the Fulcrum mobile smartphone application (Spatial Networks, 2017) for door-to-door implementation, modeled upon the efforts of Lombardo et al. (2017) with modifications based on the experience of team members in Hurricane Harvey. Fulcrum supports in-line capture of geotagged photos directly from the user's mobile device, extracts all device-supplied metadata (date, time, etc.), and automatically geocodes local addresses based on GPS coordinates. The customized App then steps through major assessment categories, beginning with classification of the structure including number of stories, occupancy and typology (roof shape, etc.). Any visible mitigation measures are also noted. Assessment teams assign an overall damage rating, attribute damage cause (wind, surge/wave, rain damage/water penetration, freshwater flooding, tree fall) and post-event functionality, followed by component-level damage ratings. Table 1 defines the total damage rating scale for low-rise (less than 3 stories), single- and multi-family residential structures. Assessments relied on direct exterior observations accompanied by geotagged photos and statements from eyewitnesses to establish failure sequences, high water marks and interior damage. At select locations, professional Unmanned Aerial Surveys (UAS) generated additional geolocated aerial imagery for subsequent creation of photogrammetric products like point clouds, 3D models, digital elevation models, and orthomosaics. A deliberate pre-programmed flight plan captured all data to achieve a targeted ground sample distance (resolution) of 3 centimeters or less.

### Data Processing

Damage assessments underwent a rigorous quality assurance/quality control (QA/QC) process, developed by the second author and led by a team of Data Librarians. This process was divided into stages, each with a detailed procedure. Most critical were Stage 1 -- verifying basic building attributes, geolocation details, and overall damage state; and Stage 2 -- adding or updating relevant property details and verifying or adding overall/component damage ratings, respectively using public sources such as county property appraiser websites and post-event aerial imagery (NOAA, 2018). Once the dataset completed its QA/QC process it was curated in NHERI DesignSafe (Rathje et al., 2017) along with any derived data products, including analysis of damage mapped against observation-based data products from ARA (supplied by NIST).

## RECONNAISSANCE ALONG THE FLORIDA GULF COAST

### Itinerary and survey data set demographics

The damage survey team consisted of UF's faculty and students, faculty from Auburn University and James Cook University, Australia and two doctoral students from the University of Western

Ontario, Canada. The team deployed to various regions along Florida's northeastern and southwestern coasts between Tuesday, September 12 2017 and Sunday, September 17 2017.

Between September 12 and September 17, the ground team covered the communities of Marco Island, Goodland, Chokoloskee, Everglades City, Port Charlotte, Fort Myers, and Naples.

Table 1. Total Damage Rating Scale

| | |
|---|---|
| Destroyed/Collapsed | Complete roof failure and/or failure of wall frame. Loss of more than 50% of roof sheathing. |
| Severe damage (major impacts to structural load path) | Major window damage or roof sheathing loss. Major roof cover loss. Some roof structure failure. |
| Moderate damage (load path preserved, but significant repairs required) | A few roof sheathing panels damaged. Roof cover loss < 50%. |
| Minor damage (damage confined to envelope) | Up to one door or window failure. Some wall cladding and soffit failure noted. Up to 15% roof cover loss. |
| Undamaged | No visible damage. |

### Observations

In several areas (Chocolosee, Everglades City) the team observed storm surge damage to buildings (Fig. 1b). There was extensive flooding in a few neighborhoods in Naples, but the water was too high during the survey there to observe damage. It did not appear that wave impact loading accompanied the storm surge. In some areas, the team found little evidence of the damaging water, except in some places where a high-water mark remained on walls (Fig. 1a). Many newer homes that remained showed little signs of external damage from the water.

Light to moderate wind damage was observed. UAV's proved to be valuable in properly assessing the extent of roof damage to buildings. High resolution cameras enables UAV to capture incredible details of damage, at the ideal vantage points inaccessible to researchers on the ground, for example damage to clay tile roof covering on a 10-story condominium building.

## RECONNAISSANCE ALONG THE FLORIDA ATLANTIC COAST FROM MIAMI TO JACKSONVILLE

### Itinerary and survey data set demographics

An initial scouting survey was conducted on September 13 in Ponte Vedra (near St. Augustine), followed by surveys of Palm Beach and the Miami metro area on September 16. The following day, the FIT team documented a few additional properties in Rockledge (near Melbourne). On September 14 2017, members of the UF led team surveyed regions in northeastern Florida, including the area with the worst reported wind damage caused by a tornado in Crescent Beach, and the coastal surge damage north of Vilano Beach along Florida A1A.

Figure 1a: Interior Damage

Figure 1b: Storm surge damaged house toppled off its piers in Everglades City, FL.

## Observations

Light wind damage was observed in northeast and central regions of Florida, primarily consisting of asphalt shingle removal and displaced gutters, flashing and similar cladding material. However, a few single-family residential structures near Ponte Vedra, FL suffered severe structural damage with uplift of portions of the wood roof structure. In each case, the failures occurred to structures built prior to the adoption of the FBC in 2002. The heaviest structural wind damage occurred to a group of condominiums near Crescent Beach, FL that a cyclone-induced tornado rated EF2 impacted. Large sections of the roof structure were removed and several upper story walls collapsed in three of the three-story condominium buildings within the 0.27 km wide by 1.9 km long damage path (NOAA, 2017). In addition to the wind damage, storm surge washed out large sections of the coast near Ponte Vedra, FL, causing at least ten single-family homes to partially or completely collapse.

On the Florida Space coast, widespread light wind damage was observed, with pockets of more intense damage, including five damaged houses in the Rockledge area, all built before the enactment of the FBC. According to the homeowners, a wind vortex or tornado might have hit the area, which explains the alignment of the damaged houses, while other houses in the neighborhood suffered no damage. The damage included substantial roof damage and soffit damage.

In Palm Beach, the team identified only one condominium structure with damage to its balcony sliders. Otherwise, the damage was limited to a large amount of yard debris.

Structures in Miami area suffered minimal damage, predominantly related to barrel tile roofs. Although the structural damage was not significant it is noteworthy that several areas in Miami were impacted by power failures, attributed to fallen trees. Moreover, large amount of debris caused road closures that made the power restoring efforts even more challenging.

## RECONNAISSANCE IN THE FLORIDA KEYS

### Itinerary and survey data set demographics

Team 1 (led by FIU) began to work along Overseas Highway (US 1) from September 18 to September 20. A second targeted campaign (Team 2, led by FIT) initiated on September 22 till

September 25. Team 2 also collected aerial imagery. A total of 16 areas were surveyed through 17 flights where two flights included overlapping image grids usable for 3D mapping.

Fig. 2 shows the location of the Keys in relation to the hurricane track (provided by NHC) as well as the estimated 3-second gust wind speeds (mph) at 10 m above ground over open terrain from ARA model (1mph = 0.45m/s). The Florida Keys were classified into 3 main zones of wind speeds: Zone 1 where wind speeds reached below 49 m/s (110 mph); Zone 2 between 49 m/s and 54 m/s (110 mph to 120 mph); finally, Zone 3 above 54 m/s (120 mph).

The teams surveyed 537 structures in the Florida Keys. They consisted of low- and mid-rise buildings, manufactured homes and RV resorts, gas stations, marinas and utility poles. Table 3 gives the distribution of the building by wind zones. Table 4 shows the distribution of roof shape, roof cover and structural framing system for the single-family homes.

The single-family residence were classified by eras of construction. These eras are pre-1960; 1960 to 1993; 1994-2001; 2002-onward, according to the evolution of the building code. Table 5 shows the distribution by year-built and effective year-built, corresponding to a retrofit (not identified). Almost 80% of structures belong to the 1994-2001 era after being retrofitted.

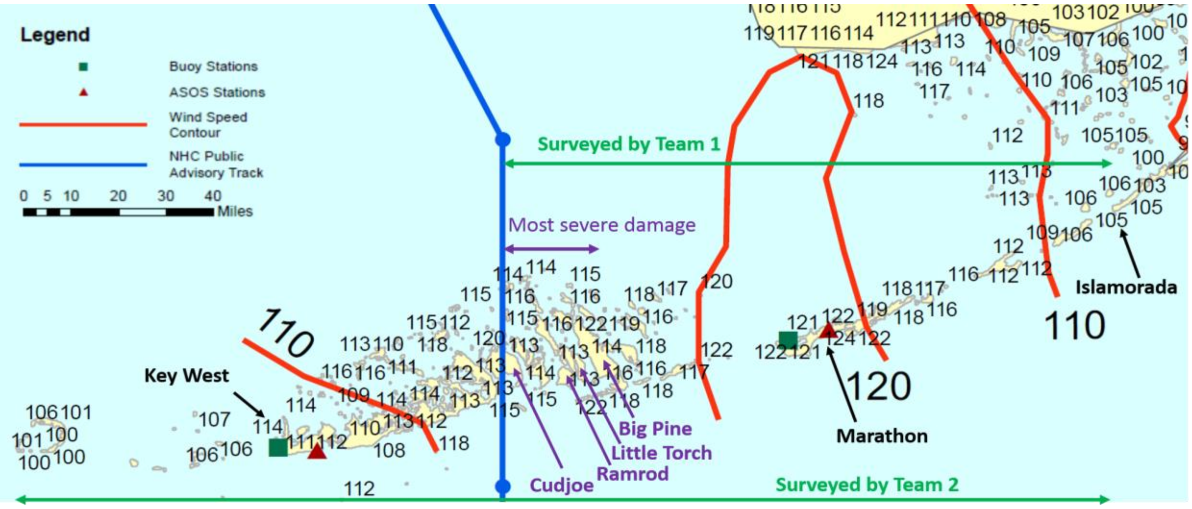

Figure 2: estimated 3-s gust wind speeds (mph) at 10 m above ground over open terrain from ARA model fit to surface level observations using NHC storm track and central pressure data through Forecast/Advisory 52 at 0300UTC on 9/12/2017. Map created on: 9/18/2017. Source: ARA

## Observations

The wind damage in the Keys ranged from light to total structural failure. Fig. 3a shows the distribution of damages to single family homes. Wind damage to various structures was observed from Islamorada all the way to Key West. Although the highest wind gusts are estimated for Marathon, the most severe damage was observed between Big Pine Key and Cudjoe Key. Also, the wind damage on the ocean side of the Keys appeared to be more significant compared to the Gulf side. Clearly, newer constructions or retrofitted buildings performed better under extreme wind conditions when compared to older buildings that are not built to the updated code standards.

Fig. 3b illustrates that trend for single-family homes in the wind zone 2. Table 6 results further confirm this, for single-family homes in the year range 1980 to 1989.

Table 2: Distribution of buildings surveyed by wind zones

| Wind speed zone | Single Family Homes | | Manufactured Homes | Apartment and Condominium |
|---|---|---|---|---|
| | On grade | Elevated | | |
| Zone 1 | 11 | 17 | 16 | 0 |
| Zone 2 | 76 | 253 | 63 | 2 |
| Zone 3 | 22 | 17 | 6 | 8 |
| Total | 109 | 287 | 85 | 10 |

Table 3. Single family homes components in the Florida Keys

| Roof Type | | Roof Cover | | Structural Framing System | |
|---|---|---|---|---|---|
| Gable | 256 | Asphalt Shingles | 160 | Wood Frame | 186 |
| Hip | 80 | Metal | 185 | Masonry | 106 |
| Flat | 18 | Tiles | 18 | Unknown | 99 |
| Complex | 39 | Tar and Gravel | 9 | Reinforced Concrete | 3 |
| Other | 3 | Others | 5 | Metal | 2 |
| | | Unknown | 19 | | |

Table 4: Eras of construction

| Building mix by year built | | Building mix after retrofitting | |
|---|---|---|---|
| Year built | Total | Effective year built | Total |
| Pre 1960 | 16 | Pre 1960 | 0 |
| 1960 - 1993 | 242 | 1960 - 1993 | 82 |
| 1994 - 2001 | 55 | 1994 - 2001 | 135 |
| 2002 - Current | 83 | 2002 - Current | 179 |

Other observations include overturned gravestones from a cemetery on the north side of Big Coppitt Key, which were used to estimate 3-sec gust wind speeds (at 10m) of between 49 and 67 m/s (110 and 150 mph).

Finally, surge damage was widespread and generated an extraordinary amount of waste from discarded interior, contents, and appliances.

**Case studies**

Fig. 4 shows a 2017 construction, two houses to the west of an older house in Ramrod Key. While the new building experienced no damage after the hurricane, the older building has lost its roof and 3/4 of the second floor walls. A similar trend was observed at other neighborhoods.

A number of elevated buildings had wind damage on the ceiling of the open ground level. The wind pressures are responsible for the damage (Chowdhury et al., 2017).

Table 5: Impact of retrofitting for 1980-1989 single-family homes

| Mitigation | Number of houses | Severe or total damage |
|---|---|---|
| Non retrofitted | 12 | 75% |
| Retrofitted | 98 | 24% |

A five-story hotel building in Key West, in zone 1, experienced severe damage to its pre-FBC 2002 roof. The roof truss was uplifted and airborne for more than 100m.

The survey identified significant damage on gas stations, starting from Marathon and up to Sugarloaf Key. Damage was severe on the free standing canopies as well as the gas pumps. Gas station canopy failure mode was predominantly due to failure on columns at ground level. The majority of the inspections showed severe corrosion that resulted in brittle failure (see Fig. 5). The brittle failure mode at the pump base due to wind-induced overturning moment was consistent in all recorded cases, (see Fig. 5).

Wooden and concrete power poles experienced severe damage because of high wind speeds and fallen trees. The majority of failures occurred predominantly due to excessive flexural stresses in the pole body at mid-height and/or low-height level. Moreover, progressive failure of a number of poles in a single line was also observed in some cases.

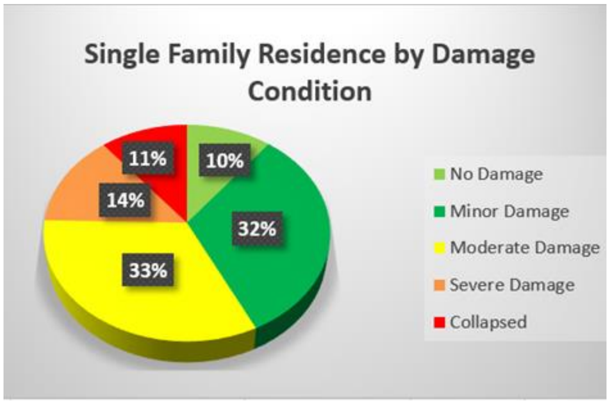

Figure 3a: Damage distribution of single-family homes in the Keys

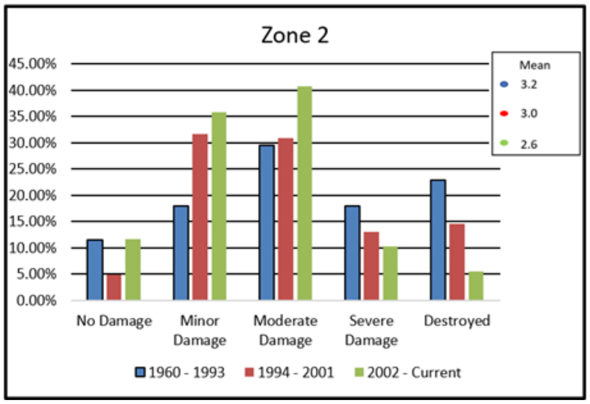

Figure 3b: Distribution of damage by year built or last retrofitted for single-family homes

*Surge damage.* In Marathon, between 80th St. and 90th St., out of 15 properties surveyed, 10 of them were slab on grade houses damaged by surge. Walls, sliders, windows and doors were the components with more damages. Also, the interior of the houses was damaged. Measurements in three homes showed that the water height inside the houses reached between 30 to 36 inches. (See Fig. 6). Also in Marathon, at a 3 story elevated building the surge destroyed ground level masonry walls and the pool, and buried the ground floor with 37 inches of sand. Sand deposition occurred in many areas affected by surge.

## CONCLUSIONS

These are preliminary findings, pending further curating of the data. Nevertheless, in most mainland areas, the observations catalogued minor to moderate property damage, consistent with the moderate wind speeds of the hurricane during its passage across mainland Florida. While in the Keys, subjected to higher winds, 25% of the observed damage was severe or collapse. All things being equal, the actual peak 3-s gust wind speeds recorded in Hurricane Irma produced wind loads ranging from 24% to 97% of prescribed design wind loads of the specific FL areas. Although most, if not all, structures built or retrofitted to the current FBC performed well, older non-retrofitted structures exhibited substantial wind damage, especially in the roof cover. Wind damaged also gas stations and utility poles, as well as other type of structures.

Surge was a significant source of damage in the Keys, in the Naples area, and in the Jacksonville area.

Figure 4: UAV image shows damage to low-rise houses along two streets of Ramrod Key. The green circle marks a new construction while the red circle shows an older construction.

Figure 5: Damage to gas stations

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Figure 6a: surge damage to walls

Figure 6b: surge interior damage

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