Performance under Pressure

How Building Performance in Recent Hurricanes Can Inform Tornado-Resistant Design Strategies

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Tornado?
Thunderstorm?
Hurricane?
Outline

➢ Building performance assessments
➢ 2017 hurricane season
➢ Engineering observations of building performance
➢ Relating hurricane and tornado building damage
➢ Lessons learned for tornado design strategies
➢ Summary
Structural Damage Assessments

• Non-biased assessment of structural performance
  ▫ Representative samples across wide hazard intensity gradient
  ▫ Document good and bad performance relative to design
  ▫ Avoid “damage hunting”

• Context matters – collect the metadata
  ▫ Surrounding terrain
  ▫ Building/structure attributes (e.g., year built)
  ▫ Typical construction practices and building code in place

• Document reliable hazard intensity indicators
Complete roof failure

Metal straps at R2W

No evidence of opening protection

50% wall cladding failure

30% Wall Sheathing Failure
Damage Assessments using Fulcrum App

<table>
<thead>
<tr>
<th>Building Info</th>
<th>Overall Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Address</td>
<td>Damage Modes</td>
</tr>
<tr>
<td>495 Augusta Drive</td>
<td>Minor</td>
</tr>
<tr>
<td>Rockport Texas 78382</td>
<td>Damage Description</td>
</tr>
<tr>
<td>United States</td>
<td>n/a</td>
</tr>
<tr>
<td>Building Type</td>
<td>Roof Cover Dmg</td>
</tr>
<tr>
<td>Single Family Residence</td>
<td>10%</td>
</tr>
<tr>
<td>Construction Type</td>
<td>Roof Sheathing Dmg</td>
</tr>
<tr>
<td>Wood</td>
<td>0%</td>
</tr>
<tr>
<td>Roof Type</td>
<td>Roof Structure Dmg</td>
</tr>
<tr>
<td>Asphalt Shingle</td>
<td>0%</td>
</tr>
<tr>
<td>Roof Shape</td>
<td>Wall Cover Dmg</td>
</tr>
<tr>
<td>Gable</td>
<td></td>
</tr>
<tr>
<td>Number of Stories</td>
<td></td>
</tr>
</tbody>
</table>
App Fields (Modified ATC 20)

**Basic Info**
- Surveyor Name*
- Survey Date
- Disaster Type
- General text input
- Geotagged photographs
- Audio recordings

**Building Information**
- Physical address
- Building type*
- Year built
- Number of stories
- Roof shape
- Roof cover
- Wall cladding
- First floor elevation
- General text input

**Building Condition**
- Overall damage rating*
- Damage modes
- # of sides visible
- Roof cover DR**
- Roof sheathing DR
- Roof structure DR
- Wall cover DR
- Wall sheathing DR
- Wall structure DR
- Window DR
- Door DR
- General text input

**Structural Details**
- Structural system
- Roof sheathing nail size and spacing
- Roof-to-wall connection
- Opening protection
- Garage door location
- General text input

* Indicates required field, ** DR = damage ratio (%)
Hurricane Harvey

- Landfall near Corpus Christi, TX on 8/25/2017 as Cat 4 hurricane
- Historical, multi-day flood event in Houston (up to 52 in.)
- Primarily wind event on TX coast – some storm surge, not widespread in populated areas
- Peak 3-sec gust wind speed: 135 mph (F.J. Masters with FCMP towers)
NSF RAPID: Collection of Perishable Data on Wind- and Surge-Induced Residential Building Damage in Texas during 2017 Hurricane Harvey

Deployments:
8/25/17 – 8/31/17: Roueche and Krupar
9/28/17-10/2/17: Lombardo team
10/2/17 – 10/5/17: Roueche, Krupar, Smith, Soto

Assessment Platform:
Fulcrum app with custom assessment form based on ATC-20

Target Locations:
Clusters of single-family homes within each 10 mph contour in ARA maps

Data Summary:
> 1,200 individual assessments logged, > 5,000 geotagged photographs
Hazard Intensity Indicators

Lower bound wind speed and direction

High Water Marks

2.4 m
Observations - Hurricane Harvey

1. Common to see dissimilar damage levels in adjacent homes

Copano Bay, Rockport, TX
Observations - Hurricane Harvey

1. Common to see dissimilar damage levels in close proximity

Key Allegro, Rockport, TX
Observations - Hurricane Harvey

1. Common to see dissimilar damage levels in close proximity

Rockport, TX
Observations - Hurricane Harvey

2. Common to see metal straps at roof-to-wall connections

Rockport, TX
Observations - Hurricane Harvey

3. Clear effects of ground roughness on observed damage

Interior Rockport ($V_{3\text{sec}, 10m, open} \cong 135 \text{ mph}$)
Hurricane Irma

- Near-miss of US VI (St. Thomas and St. John) as Cat 5
- US landfall in Cudjoe Key, FL on 9/10/2017 as Cat 4 hurricane
- 2\textsuperscript{nd} landfall near Marco Island, FL on 9/10/2017 as Cat 3 hurricane
- Combined wind and surge event in FL Keys
- Heavy flooding/surge in NE FL
Hurricane Irma (NSF-RAPID)

- PI: Kijewski-Correa (ND)
- > 30 contributors from 9 different institutions
- Teams deployed between 9/15/17 – 9/26/17
- > 1050 assessments logged in FL, > 5,000 photographs
Wind Damage, Water Ingress
Florida Keys
Cyclone-induced EF2 Tornado
Hurricane Maria

• Near-miss of US VI (St. Croix) as Cat 4 hurricane
• Landfall on 9/20/2017 in Puerto Rico as Cat 4 hurricane
• Heavy wind/flood impacts in PR
• Official count of 55 direct fatalities in PR (unknown number of indirect fatalities)
• Humanitarian crisis in PR (36% still without power as of 12/11/2017)
US-VI (Hurricanes Irma and Maria)

• PI: Kijweski-Correa (Notre Dame)

• Coordinated reconnaissance with structures team (Prevatt, U. Florida) and coastal team (Kennedy, Notre Dame)

• Deployments between 11/8/17 – 11/14/17

• ~300 assessments logged
Topography Effects (St. John)

Peak Wind Speeds

1

2
Application to Tornadoes
**Hurricane vs Tornado Wind Speeds**

**Peak wind speeds (3-sec gust, 10 m height, open exposure) over land in all three hurricanes were roughly equivalent to a high-end EF2 tornado**

### Table C6.5-2 Approximate Relationship between Wind Speeds in Asce 7 and Saffir/Simpson Hurricane Scale

<table>
<thead>
<tr>
<th>Saffir/Simpson Hurricane Category</th>
<th>Sustained Wind Speed Over Water</th>
<th>Gust Wind Speed Over Water</th>
<th>Gust Wind Speed Over Land</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74–95</td>
<td>90–116</td>
<td>81–105</td>
</tr>
<tr>
<td>2</td>
<td>96–110</td>
<td>117–134</td>
<td>106–121</td>
</tr>
<tr>
<td>3</td>
<td>111–130</td>
<td>135–158</td>
<td>122–143</td>
</tr>
<tr>
<td>4</td>
<td>131–155</td>
<td>159–189</td>
<td>144–171</td>
</tr>
<tr>
<td>5</td>
<td>&gt;155</td>
<td>&gt;190</td>
<td>&gt;171</td>
</tr>
</tbody>
</table>

*1-minute average wind speed at 33 ft (10 m) above open water

*3-second gust wind speed at 33 ft (10 m) above open water

*3-second gust wind speed at 33 ft (10 m) above open ground in Exposure Category C. This column has the same basis (averaging time, height, and exposure) as the basic wind speed from Figure 26.5-1.

### Table 6. Recommended EF-Scale Wind Speed Ranges

<table>
<thead>
<tr>
<th>Derived EF Scale</th>
<th>3-Second Gust Speed, mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF0</td>
<td>65 – 85</td>
</tr>
<tr>
<td>EF1</td>
<td>86 – 109</td>
</tr>
<tr>
<td>EF2</td>
<td>111 – 135</td>
</tr>
<tr>
<td>EF3</td>
<td>136 – 165</td>
</tr>
<tr>
<td>EF4</td>
<td>166 – 200</td>
</tr>
<tr>
<td>EF5</td>
<td>&gt;200</td>
</tr>
</tbody>
</table>

### Comparing Saffir-Simpson and EF-Scale

<table>
<thead>
<tr>
<th>Category</th>
<th>Saffir-Simpson (mph)</th>
<th>EF-Scale (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EF0 / TS</td>
<td>&lt; 81</td>
<td>65 – 85</td>
</tr>
<tr>
<td>EF1/Cat1</td>
<td>81 – 105</td>
<td>86 – 110</td>
</tr>
<tr>
<td>EF2/Cat2</td>
<td>106 – 121</td>
<td>111 – 135</td>
</tr>
<tr>
<td>EF3/Cat3</td>
<td>122 – 143</td>
<td>136 – 165</td>
</tr>
<tr>
<td>EF4/Cat4</td>
<td>144 – 171</td>
<td>166 – 200</td>
</tr>
<tr>
<td>EF5/Cat5</td>
<td>&gt;171</td>
<td>&gt;200</td>
</tr>
</tbody>
</table>
Lesson 1: Continuous load path is more important than any individual link.
EF-2 Tornado (Hurricane Irma)
Crescent Beach, FL
Year Built - 1982
Weak Links in the Load Path

Hurricane Harvey
Rockport, TX
Failure Sequence

1. Debris impact collapses garage door on windward wall
2. Wind pressurizes interior of building, increasing loads
3. Failure initiates at weak link (ridge board)
4. Failure propagates – entire roof fails
Lesson 2: Preventing large openings in the building envelope is critical to maintaining structural integrity of the building.
Effect of Internal Pressure on Roof Pressures

Enclosed Building

\[ V_{ult} = 140 \text{ mph} \]

Exposure B (suburban)

30 ft height

Partially Enclosed Building

Garage Door Breached

\[ GC_{pi} = \pm 0.18 \text{ (Internal Pressure)} \]

\[ GC_{pi} = \pm 0.55 \text{ (Internal Pressure)} \]

**Used in IRC 2015**

<table>
<thead>
<tr>
<th>ASCE 7 Roof Zone</th>
<th>Roof ( Cp_e )</th>
<th>( \rho_{design, ASD} ) (Enclosed)</th>
<th>( \rho_{design, ASD} ) (Part. Enclosed)</th>
<th>( \frac{\rho_{design (Part. Enc.)}}{\rho_{design (Enc)}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1 (Field)</td>
<td>-0.9</td>
<td>-19.3</td>
<td>-26.0</td>
<td>1.35</td>
</tr>
<tr>
<td>Zone 2 (Edge)</td>
<td>-1.7</td>
<td>-33.7</td>
<td>-40.3</td>
<td>1.20</td>
</tr>
<tr>
<td>Zone 3 (Corner)</td>
<td>-2.6</td>
<td>-49.8</td>
<td>-56.4</td>
<td>1.13</td>
</tr>
</tbody>
</table>

\[ \rho_{design, ASD} = 0.00256 \cdot K_z \cdot K_{zt} \cdot K_d \cdot V_{ult}^2 \cdot \left(V_{ASD}/V_{ult}\right) \cdot (Cp_e - Cp_i) \]
Finding #7: Structural failures strongly correlate with breached building envelope.

Sliding Glass Door
Correlation between Roof Failure and Breached Envelope

- Analyzed damage patterns in the 2011 tornadoes in Joplin, MO and Tuscaloosa, AL
- Found that ~80% of homes with partial or full roof structure failure also experienced breached envelope (window or door failure)
- May be significant driver of the randomness often observed in wind damage (wind-borne debris impact is a stochastic process)

Lesson 3: Performance expectations for code-compliant and non-code compliant buildings are not clearly defined.
ASCE 7-10 Design Wind Speeds (Category II Buildings)

- Hurricane Harvey
  \[ \left( \frac{V_{ASCE,II}}{V_{obs,max}} \right)^2 \approx 1.24 \]
- Hurricane Irma
  \[ \left( \frac{V_{ASCE,II}}{V_{obs,max}} \right)^2 \approx 1.92 \]
- Hurricane Maria
  \[ \left( \frac{V_{ASCE,II}}{V_{obs}} \right)^2 \approx 1.37 \]
A home is built in Moore, OK to the wind-resistant building code (design wind speed 135 mph). A 135 mph wind event occurs. What does construction to the building code guarantee at a minimum?

- No loss of life
- No catastrophic collapse
- Building remains usable
- Building is undamaged
100 homes in Moore, OK are built to the wind-resistant building code (design wind speed 135 mph). A 135 mph wind event occurs. How many homes are not livable?
City councils and mayors “absolutely do not know” about the life-safety objective & how damaged a code-compliant building stock will be in the aggregate, and (they) are unsatisfied when they do learn of (the expected damage.)

Need for Clear Performance Expectations

• Every step forward with stronger building codes is beneficial for reducing damage

• However, without clearly defining performance expectations, it is difficult to define success

• Without a clear criteria for success, it is difficult to accelerate the adoption of stronger building designs in other communities
Closing Thoughts

- All extreme wind events are not created equal, but common lessons can be learned from any event.
- The 2017 hurricanes provided a case study as to how a variety of buildings, constructed to different design requirements, performed in ~EF2 wind speeds.
- Key lessons thus far (much more to come):
  - Hurricane straps alone are not the answer – continuous load path is needed.
  - Protecting the building envelope is critical.
  - Clear performance expectations are needed for future building code changes in order to clearly demonstrate success.
Acknowledgements

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Thank You!

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