Assessing wind speeds in tornadoes using a fragility framework

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Fujita Scale

- Developed by Ted Fujita at Univ. of Chicago in the 1960s
- Explicit correlation of damage states is a strength
- Limited number of damage indicators
- Residential home primary damage indicator – ‘engineered structure’
- Implemented by NWS in 1970s

<table>
<thead>
<tr>
<th>F-scale Category</th>
<th>Estimated Wind Speed Range (mph)</th>
<th>Typical Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>40 - 72</td>
<td><em>Light damage.</em> Some damage to chimneys; branches broken off trees; shallow-rooted trees pushed over; sign boards damaged.</td>
</tr>
<tr>
<td>F1</td>
<td>73 - 112</td>
<td><em>Moderate damage.</em> Peels surface off roofs; mobile homes pushed off foundations or overturned; moving autos blown off roads.</td>
</tr>
<tr>
<td>F2</td>
<td>113 - 157</td>
<td><em>Considerable damage.</em> Roofs torn off frame houses; mobile homes demolished; boxcars overturned; large trees snapped or uprooted; light-object missiles generated; cars lifted off ground.</td>
</tr>
<tr>
<td>F3</td>
<td>158 - 206</td>
<td><em>Severe damage.</em> Roofs and some walls torn off well-constructed houses; trains overturned; most trees in forest uprooted; heavy cars lifted off the ground and thrown.</td>
</tr>
<tr>
<td>F4</td>
<td>207 - 260</td>
<td><em>Devastating damage.</em> Well-constructed houses leveled; structures with weak foundations blown away some distance; cars thrown and large missiles generated.</td>
</tr>
<tr>
<td>F5</td>
<td>261 - 318</td>
<td><em>Incredible damage.</em> Strong frame houses leveled off foundations and swept away; automobile-sized missiles fly through the air in excess of 100 meters (109 yds); trees debarked; incredible phenomena will occur.</td>
</tr>
</tbody>
</table>

From Fujita (1981)
### Enhanced-Fujita (EF) Scale

- Developed by Texas Tech University in 2006
- Lowered the speeds at the high end of the scale
- Brought in many more (i.e., 28) Damage Indicators (DI)

<table>
<thead>
<tr>
<th>Fujita Scale</th>
<th>Fastest 1/4/-mile Wind Speeds, mph</th>
<th>3-Second Gust Speed, mph</th>
<th>EF Scale</th>
<th>3-Second Gust Speed, mph</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>40 - 72</td>
<td>45 - 78</td>
<td>EF0</td>
<td>65 - 85</td>
</tr>
<tr>
<td>F1</td>
<td>73 - 112</td>
<td>79 - 117</td>
<td>EF1</td>
<td>86 - 109</td>
</tr>
<tr>
<td>F2</td>
<td>113 - 157</td>
<td>118 - 161</td>
<td>EF2</td>
<td>110 - 137</td>
</tr>
<tr>
<td>F3</td>
<td>158 - 207</td>
<td>162 - 209</td>
<td>EF3</td>
<td>138 - 167</td>
</tr>
<tr>
<td>F4</td>
<td>208 - 260</td>
<td>210 - 261</td>
<td>EF4</td>
<td>168 - 199</td>
</tr>
<tr>
<td>F5</td>
<td>261 - 318</td>
<td>262 - 317</td>
<td>EF5</td>
<td>200 - 234</td>
</tr>
</tbody>
</table>
Degrees-of-Damage for Wood-Frame Houses

2. ONE-AND TWO-FAMILY RESIDENCES (FR12)
   (1000 – 5000 sq. ft.)

Typical Construction

- Asphalt shingles, tile, slate or metal roof covering
- Flat, gable, hip, mansard or mono-sloped roof or combinations thereof
- Plywood/OSB or wood plank roof deck
- Prefabricated wood trusses or wood joist and rafter construction
- Brick veneer, wood panels, stucco, EIFS, vinyl or metal siding
- Wood or metal stud walls, concrete blocks or insulating-concrete panels
- Attached single or double garage
### Degrees-of-Damage for Wood-Frame Houses

<table>
<thead>
<tr>
<th>DOD*</th>
<th>Damage description</th>
<th>EXP</th>
<th>LB</th>
<th>UB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Threshold of visible damage</td>
<td>65</td>
<td>53</td>
<td>80</td>
</tr>
<tr>
<td>2</td>
<td>Loss of roof covering material (&lt;20%), gutters and/or awning; loss of vinyl or metal siding</td>
<td>79</td>
<td>63</td>
<td>97</td>
</tr>
<tr>
<td>3</td>
<td>Broken glass in doors and windows</td>
<td>96</td>
<td>79</td>
<td>114</td>
</tr>
<tr>
<td>4</td>
<td>Uplift of roof deck and loss of significant roof covering material (&gt;20%); collapse of chimney; garage doors collapse inward; failure of porch or carport</td>
<td>97</td>
<td>81</td>
<td>116</td>
</tr>
<tr>
<td>5</td>
<td>Entire house shifts off foundation</td>
<td>121</td>
<td>103</td>
<td>141</td>
</tr>
<tr>
<td>6</td>
<td>Large sections of roof structure removed; most walls remain standing</td>
<td>122</td>
<td>104</td>
<td>142</td>
</tr>
<tr>
<td>7</td>
<td>Exterior walls collapsed</td>
<td>132</td>
<td>113</td>
<td>153</td>
</tr>
<tr>
<td>8</td>
<td>Most walls collapsed, except small interior rooms</td>
<td>152</td>
<td>127</td>
<td>178</td>
</tr>
<tr>
<td>9</td>
<td>All walls</td>
<td>170</td>
<td>142</td>
<td>198</td>
</tr>
<tr>
<td>10</td>
<td>Destruction of engineered and/or well constructed residence; slab swept clean</td>
<td>200</td>
<td>165</td>
<td>220</td>
</tr>
</tbody>
</table>

* DOD is degree of damage

This provides a realistic sequence of the damage as wind speeds increase (except for DOD-5)
Degree of Damage Indicators for Wood-Frame Houses

• These wind speed – damage relationships were obtained from an expert elicitation process, conditioned on existing knowledge. No calculations were made.

• One motivation of our research program has been to quantify this relationship using full-scale testing, wind tunnel testing and field observations wherever possible.

• This involved the development of a new full-scale testing laboratory in order to better understand the performance of wood-frame houses under extreme conditions.

• We’ve studied many aspects of housing performance, which cover DOD-2 to DOD-7 for wood-frame, single-family houses...here we focus on roof failures (DOD-6).
Why do we need to know wind speeds in tornadoes?

Wind speeds in tornadoes, and the relationship of wind speed to damage, are required for several purposes:

1. For risk & loss analyses – insurance sector
2. For design of critical infrastructure (e.g., nuclear reactors, electrical transmission towers) – engineering
3. For developing warnings for the public – government
4. For assessing basic climatology of tornado occurrence – meteorology
5. For developing a basic scientific understanding of an important natural phenomenon...which we could use to develop mitigation strategies
Objectives for this presentation

Quantify the wind speed – damage relationship for houses in tornadoes using the best available current knowledge.

Our focus in this talk is DOD-6 for wood-frame houses using a fragility-analysis framework
Calculation of Failure Wind Speeds using Fragility Analysis

Failure occurs when the load exceeds the capacity, i.e.,

\[ Z > 0, \text{ where} \]

\[ Z = \text{Wind Load} - \text{Resistance} - \text{Dead Load} \]

We can analyze this equation probabilistically to assess wind speeds...
Primary Parameters Affecting Failures of Wood-frame Houses

- **Terrain and Surroundings** (suburban v. open; surrounding structures, trees, etc.)
- **Openings** in the envelope – internal pressurization (which may be altered in tornadoes)
- **Duration** of high winds (long storms have larger peak loads and failure mechanisms which depends on number of peaks)
- **Tornado wind field** structure (in lower 10m, particularly the vertical wind component)
- **Roof Shape** (hip versus everything else – aerodynamic and structural)
- **Types and Quantity of Fasteners**
- **Quality of construction** (e.g., errors, missing nails, etc.)
  - is difficult to quantify
Houses – our most common type of structure – are complicated to analyze

- Traditional process – evolved from holding roof up not tying it down
- They are not really engineered
- Many elements, closely spaced - very difficult to analyze
- Variable material properties and connection strengths
- Main purpose of houses is to control our environment/climate and provide safety
Wood-Frame Houses – Points of Vulnerability

- Rafter/top plate
- Roof joist/top plate
- Wall stud/bottom plate
- Wall/foundation
Wood-Frame Houses – Points of Vulnerability

Wind Loads are Upwards!

- Rafter/top plate
- Roof joist/top plate

- Wall stud/bottom plate
- Wall/foundation
Wood-Frame Houses – Points of Vulnerability

Nails are very important to how houses perform
Full-scale tests at the “3 Little Pigs” project

Detailed tests on two houses (one with gable roof, the other with a hip roof) have been studied, along with many component tests (like the RTWCs)
Full-Scale Tests Using Simulated Wind Loading

In this approach:

1. A “standard” scale model wind tunnel study is performed to obtain the external pressure coefficients. These are then scaled to full-scale pressure time histories.
2. The pressures are then replicated on a full-scale structure using a multi-pressure-chamber approach, i.e., enough pressure chambers so that we have a reasonable simulation of the overall loads.
The loading concept is simple; we replicate the pressures that the wind induces. Fans are used, NOT TO BLOW WIND, but more like a vacuum cleaner.
Industry-Standard Pressure Tests

Typical product tests apply a single, static, uniform pressure (i.e., a single pressure chamber is used)

Image courtesy of Clemson University
The measured, external pressures are replicated in the full-scale system by the Pressure Loading Actuators.
Wind Induced Pressures on the Roof of a House

Roof Wind Pressure Coefficients on Gable Ended Test House

Wind Direction

Playback is real time for a 25 meters per second Wind
The multi-chamber, pressure test methods developed at the ‘3 Little Pigs’ Project:
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RESPONSE to GUST WIND SPEEDS
The RTWC track the very fast change in uplift, but not the decrease in load following the peak.

Responses are highly correlated across the roof because of load sharing.
Wind tunnel tests of houses
## Wind tunnel study of houses

### Roof Type

<table>
<thead>
<tr>
<th>Roof Type</th>
<th>Roof Slope</th>
<th>Roof Dimension (L x W)</th>
<th>Building Eaves Height</th>
<th>Overhang Length</th>
<th>No. of Pressure Taps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gable</td>
<td>5:12 and 6:12</td>
<td>11.34 m x 10.16 m (37.2’ x 33.3’)</td>
<td>3.6 m, 6.7 m, 9.1 m</td>
<td>0.46 m (1.5’)</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>7:12, 9:12, and 12:12</td>
<td>11.28 m x 10.06 m (37’ x 33’)</td>
<td>(11.7’, 22.1’, 30’)</td>
<td>0.51 m (1.67’)</td>
<td>192</td>
</tr>
<tr>
<td>Hip</td>
<td>4:12</td>
<td>11.28 m x 10.06 m (37’ x 33’)</td>
<td></td>
<td>0.51 m (1.67’)</td>
<td>592</td>
</tr>
<tr>
<td></td>
<td>5:12 and 6:12</td>
<td>11.34 m x 10.16 m (37.2’ x 33.3’)</td>
<td>(One-, Two-, Threestorey)</td>
<td>0.46 m (1.5’)</td>
<td>242</td>
</tr>
<tr>
<td></td>
<td>7:12, 9:12, and 12:12</td>
<td>11.28 m x 10.06 m (37’ x 33’)</td>
<td></td>
<td>0.51 m (1.67’)</td>
<td>158</td>
</tr>
</tbody>
</table>

- Single, isolated houses and houses in 4 neighbourhood patterns
- Open and suburban terrain...
  - 87 configurations in total
Aerodynamics of Gable-roofed houses (suburban terrain)

\(\beta = 5:12\)

\(\beta = 6:12\)

\(\beta = 7:12\)

\(\beta = 9:12\)

\(\beta = 12:12\)
Aerodynamics of Hip-roofed houses (suburban terrain)

\[ \beta = 4:12 \]

\[ \beta = 5:12 \]

\[ \beta = 6:12 \]

\[ \beta = 7:12 \]

\[ \beta = 9:12 \]

\[ \beta = 12:12 \]
Calculation of Failure Wind Speeds using Fragility Analysis

Failure occurs when the load exceeds the capacity, i.e.,

\[ Z > 0, \text{ where} \]

\[ Z = \text{Wind Load} - \text{Resistance} - \text{Dead Load} \]

We can analyze this equation probabilistically to assess wind speeds...
Estimated probability of failure versus wind speed for roof failures using wind-tunnel data and full-scale structural test data.

Two different areas are considered here, for two different roof shapes.
DOD-6 has wind speeds of 104 – 142 mph (i.e., 47 – 64 m/s).
Variation in these plots accounts for all possible wind directions and the fastener variability (but assumes perfectly built). This does not account for missing nails in the connections or for engineered connections (hurricane clips).
Assumes an opening in the building envelope.
The gable roof (5/12 slope) has the same variation as for DOD-6. Hip roofs perform much better than gable roofs and have much higher failure wind speeds, into EF-3 range.
For hip roofs, this result suggests that complete roof failure is less probable than other failures.
Differences between hip and gable roof performance:

Calculated differences seem to be supported by damage surveys, but research is needed, particularly with the failure sequence.

Barrie Tornado, 1985
Failure Sequences for Gable and Hip Roofs

Complete Roof Failure versus first sheathing panel failure.

Gable

Hip

sheathing

Complete roof

(c) Sheathing panel with 8d spiral, 150/300

(c) Sheathing panel with 8d spiral, 150/300
Degrees-of-Damage for Wood-Frame Houses

EF-Scale should likely be interpreted as representing median (or average) values.

<table>
<thead>
<tr>
<th>Degree</th>
<th>Description</th>
<th>EF-Scale Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Large sections of roof structure removed; most walls remain standing</td>
<td>122, 104, 142</td>
</tr>
</tbody>
</table>

From the WSEC (2006) EF-Scale report:
“…if only the roof structure of the two-story residence is uplifted by a storm and the exterior walls remain in place (DOD-6), the expected wind speed of the storm at that location is estimated to be 122 mph. The reported value could vary from 104 to 142 mph depending on circumstances...
Large overhangs (greater than 2 ft), improper toe-nailing (two nails instead of three) ... would suggest a wind speed less than 122 mph but not less than 104 mph. Use of hurricane clips...suggest a wind speed higher than 122 mph, but not greater than 142 mph.”
Effects of Neighbourhood Patterns

Different neighbourhood patterns have little effect on roof failure wind speeds

(a) RTWC (L1+L2+L3)

(c) Sheathing panel with 8d spiral, 150/300
Errors in construction will alter all of these results. These effects can be estimated, but they are hard to identify in damage surveys (especially in massive events). This is a significant short-coming.
What remains to be done (for houses)?

We need a more explicit handling of building aerodynamics in tornadic wind fields.

Specific open questions include determining:
1. the role of the vertical component of the wind in tornadoes
2. Failure sequence for wood-frame houses with hip roofs, versus gable roofs.
3. The role of the tornado vortex structure on wind loads
4. the details of the tornado boundary layer, and the effects of terrain on it
5. the role of the low core pressure on failures (internal pressures)
Uplift coefficient for a flat roof as function of wind direction and vertical component
Effects of vertical component of the wind

Relative change in the uplift coefficient as a function of elevation angle is about 20% increase - that’s about a 10% decrease in the wind speeds I’ve shown.
Final Comments

• Fragility analysis is a more reliable way for us to estimate wind speeds for DIs with high levels of variability over a wide range of parameters.
• Analysis of detailed damage surveys is important in combination with fragility calculations. The two can aid each other.
• The current results suggest that the DOD wind speeds for the various DIs should be considered as median (average) values (this would seem to be the intent of the current scale). We need further correlation analyses between DIs using detailed damage surveys. This will better establish wind speed bounds.
• The DOD sequence and wind speeds do not seem to be well-suited for hip roofs on wood-frame houses.
• The effects of neighbourhoods on roof failures is insignificant.
• There could be significant bias in results caused by construction variability and errors because these may not be (or cannot be) identified in damage surveys.
• We need wind speed measurements close to the ground (lower 5 m) to better understand the tornado boundary layer.
Questions?

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