Wind Engineering Research at UIUC

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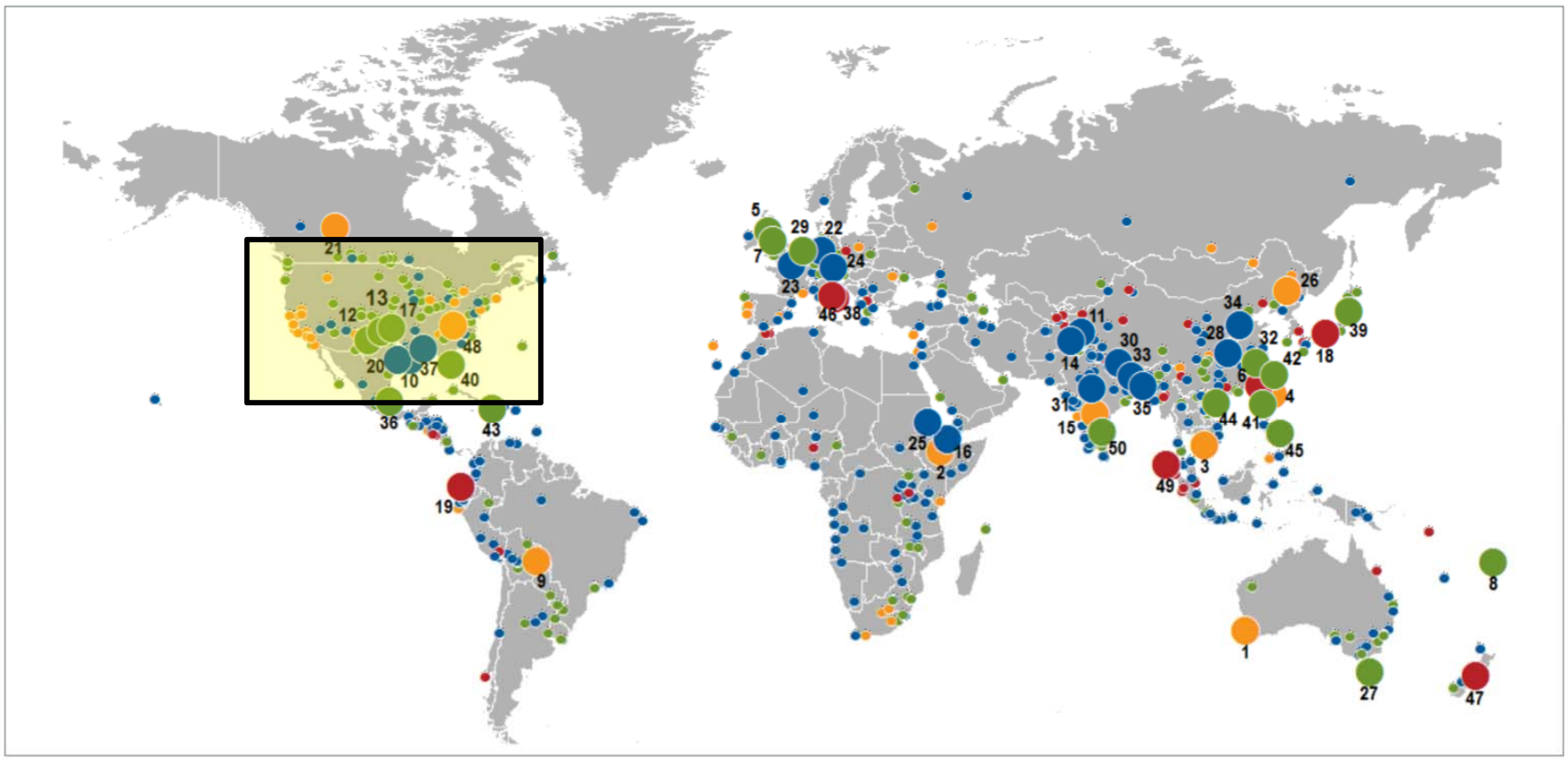
THE Conference
Illini Union
February 28, 2018

WIND-RELATED LOSSES

- 60% of losses in N. America

Topics Geo – World map of the 50 major loss events 2016

Munich RE



1,060 natural hazard events, thereof

○ 50 major events (details overleaf)

- **Geophysical events:** Earthquake, tsunami, volcanic activity
- **Meteorological events:** Tropical storm, extratropical storm, convective storm, local storm
- **Hydrological events:** Flooding, mass movement
- **Climatological events:** Extreme temperatures, drought, wildfire

WIND-RELATED LOSSES

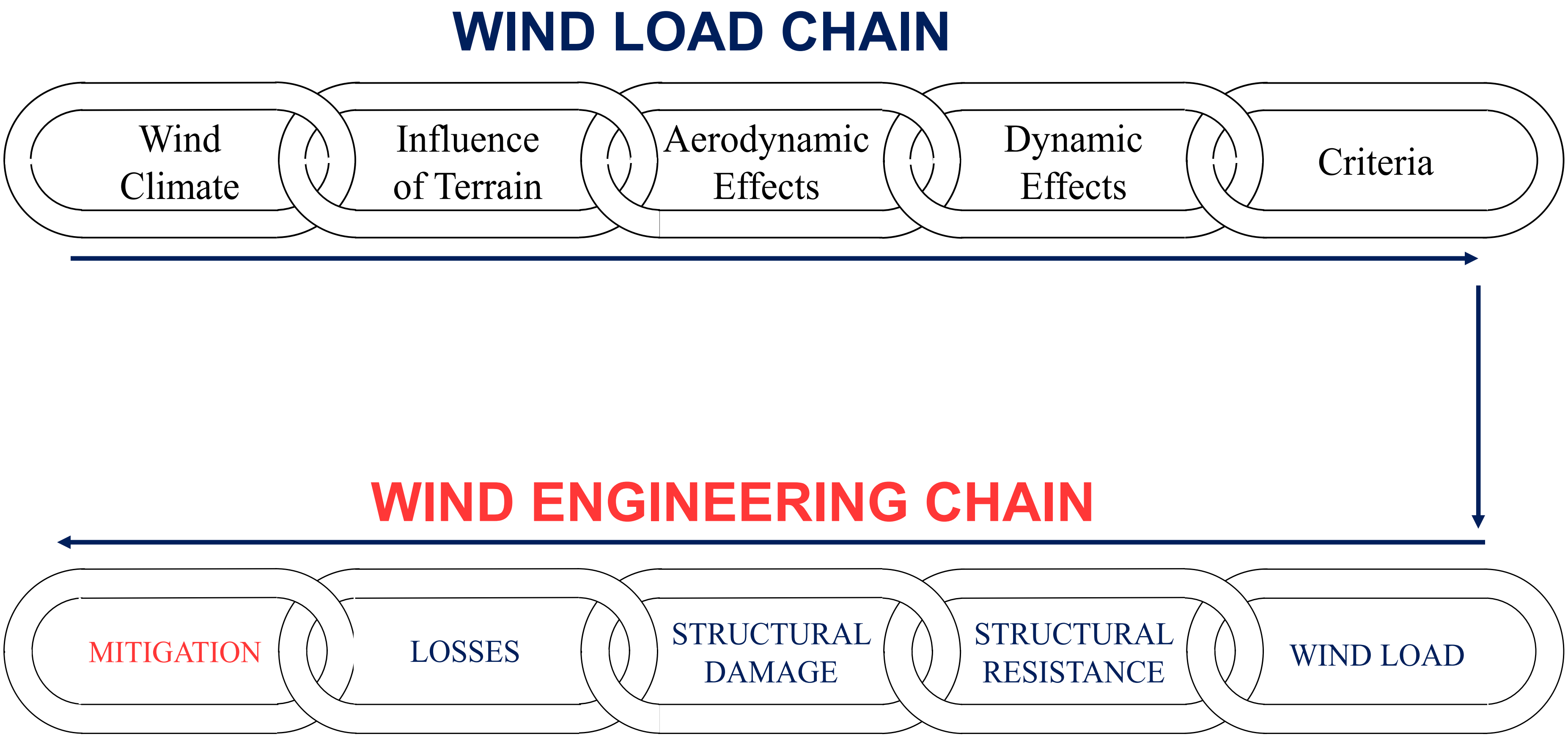
- Tornadoes and thunderstorms account for nearly 1/3rd of total natural hazard losses in the U.S. over the last 10 years (NOAA)
- Relatively little is known about these types of events from a structural engineering perspective – not considered in design – “Grand Challenge” in wind engineering (NIST, 2014)

MOTIVATION: JOPLIN, MO TORNADO

- 161 fatalities – deadliest tornado in the official record
- ~8,000 structures damaged (7,000 residential); 3M yd^3 of debris (urban area)
- $2B in insured losses ($700M – St. Johns Hospital)
- Detailed investigation of environment, buildings and human response

RESEARCH FRAMEWORK

- HOW DO WE SOLVE THESE PROBLEMS?



OVERVIEW

1. Extreme Wind Characterization (probabilistic, physical, tree-fall)

2. Extreme Wind Load Characterization (unsteady aerodynamics, mitigation)

3. Damage Analysis (Joplin, Naplate, citizen science)

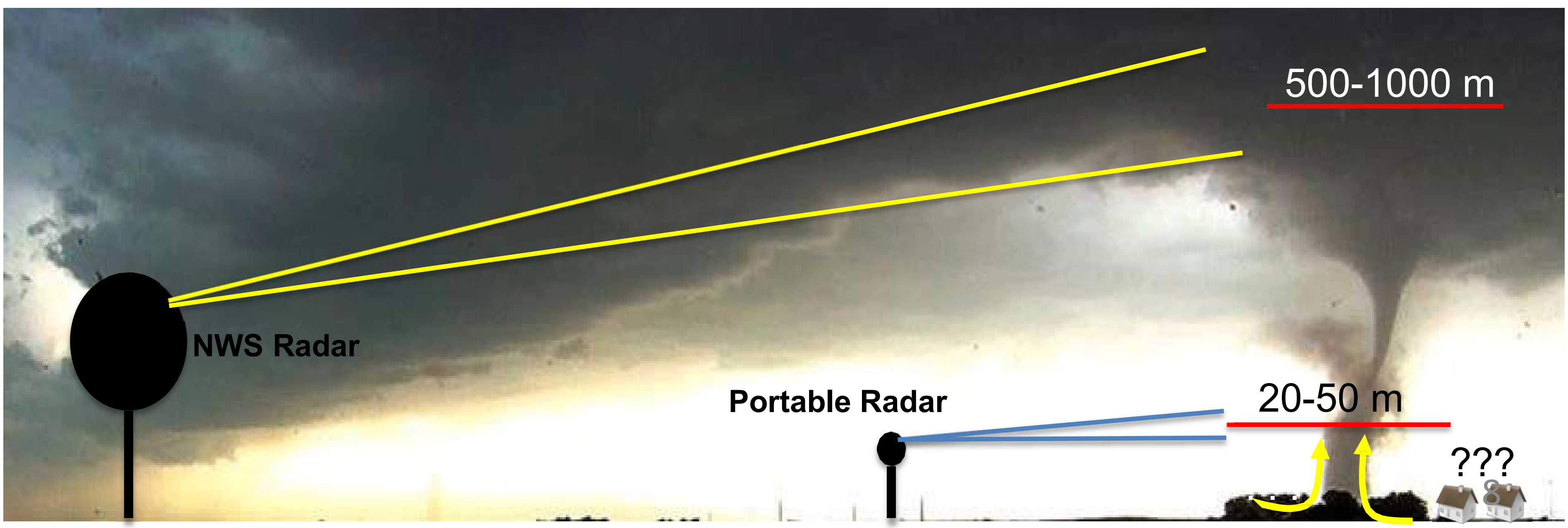
4. Smart Wind Engineering Research Facility (address wind load, engineering chains)

5. Wind and Transportation??

Extreme Wind Characterization

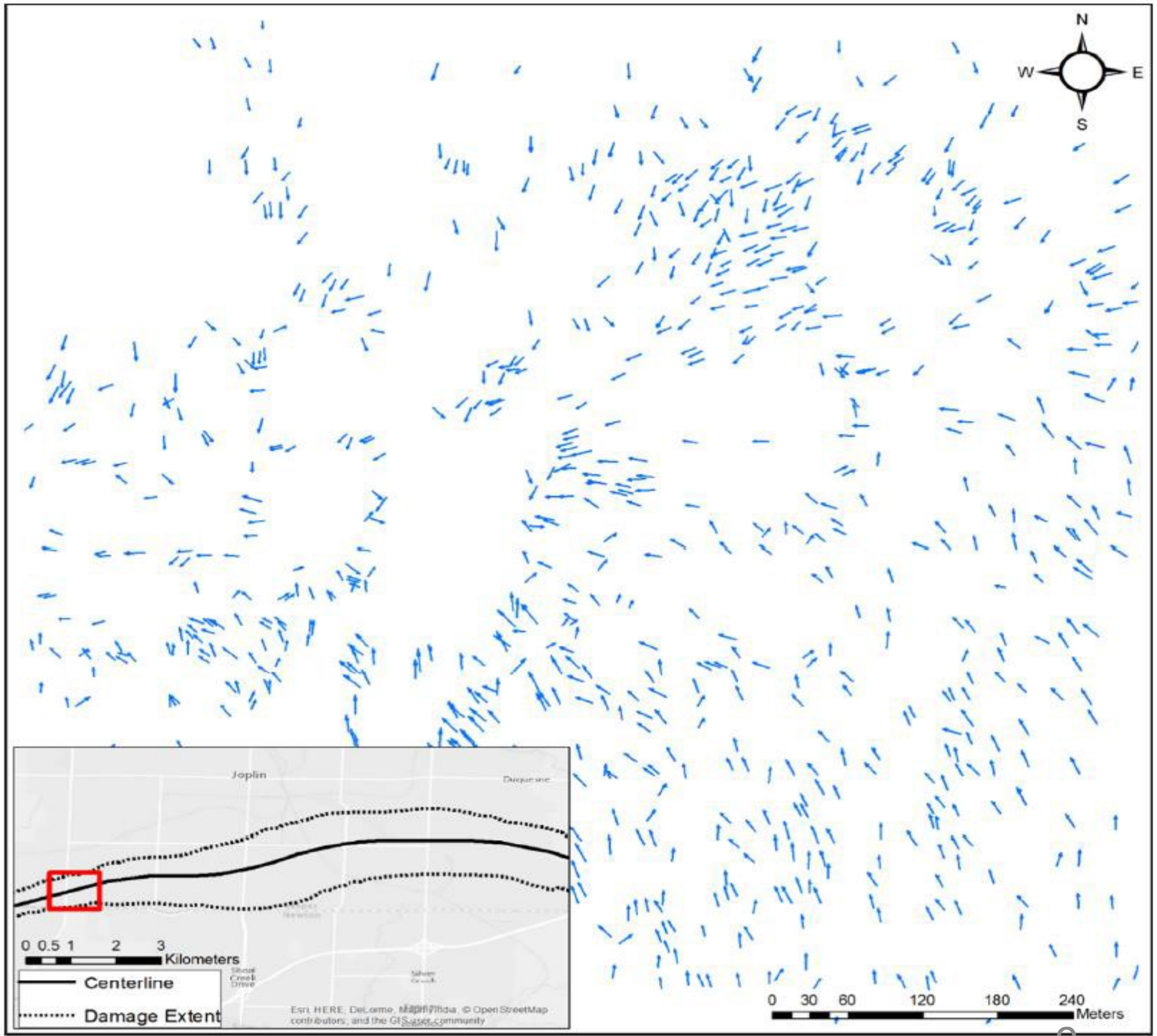
EXTREME WIND CHARACTERIZATION

- Limited full-scale data – much is unknown and uncertainties are large – especially close to the surface – resort to other methods
- **Probabilistic** and **physical** differences than what is prescribed for design – based on ‘stationary’ wind tunnel/full-scale data
- Push for ‘tornado-based’ design (very low probability event) and broader performance-based design for wind engineering (ASCE 7-22)
- Most important quantity in design for wind loading

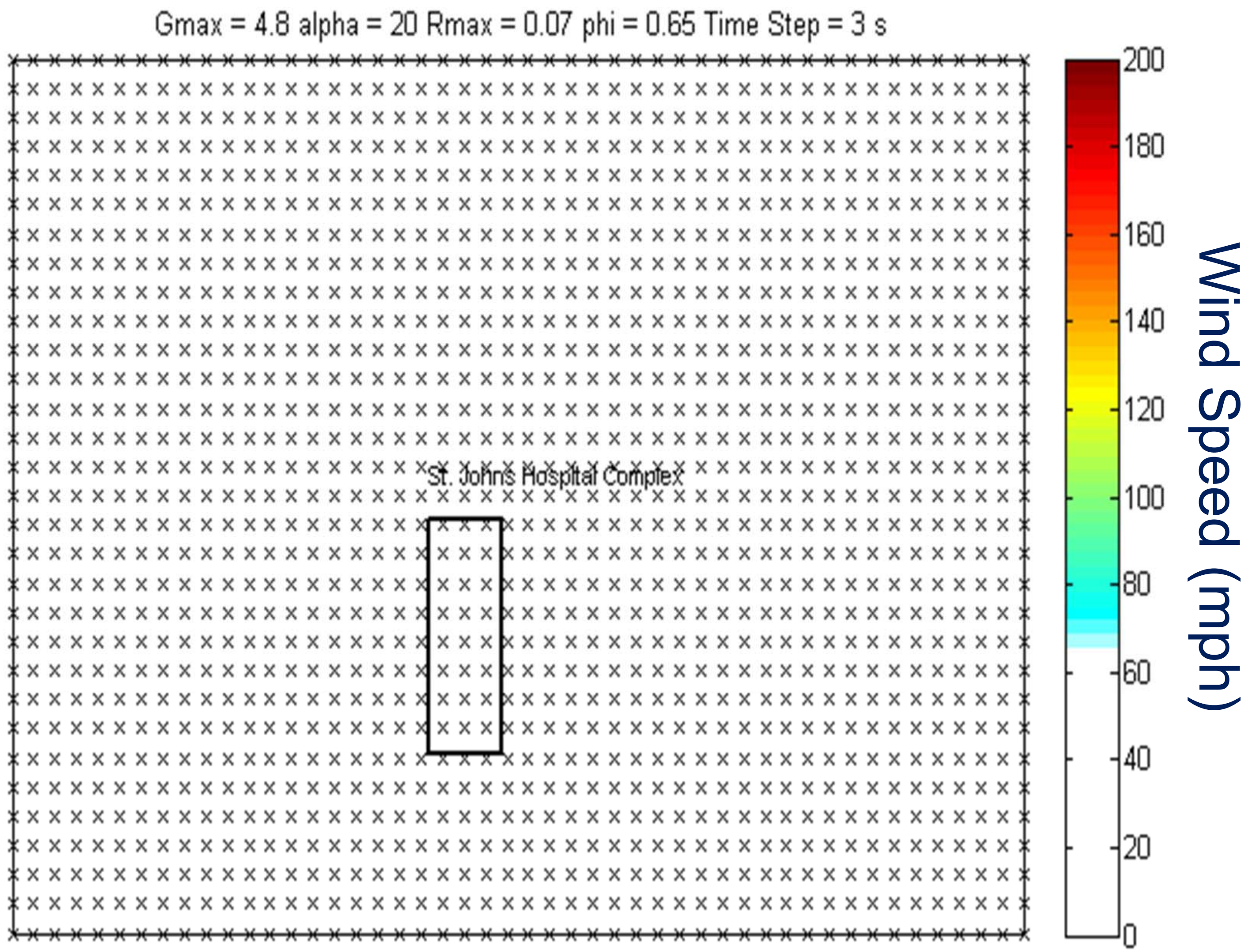


EXTREME WIND CHARACTERIZATION - TORNADO

- Tree-fall pattern analysis

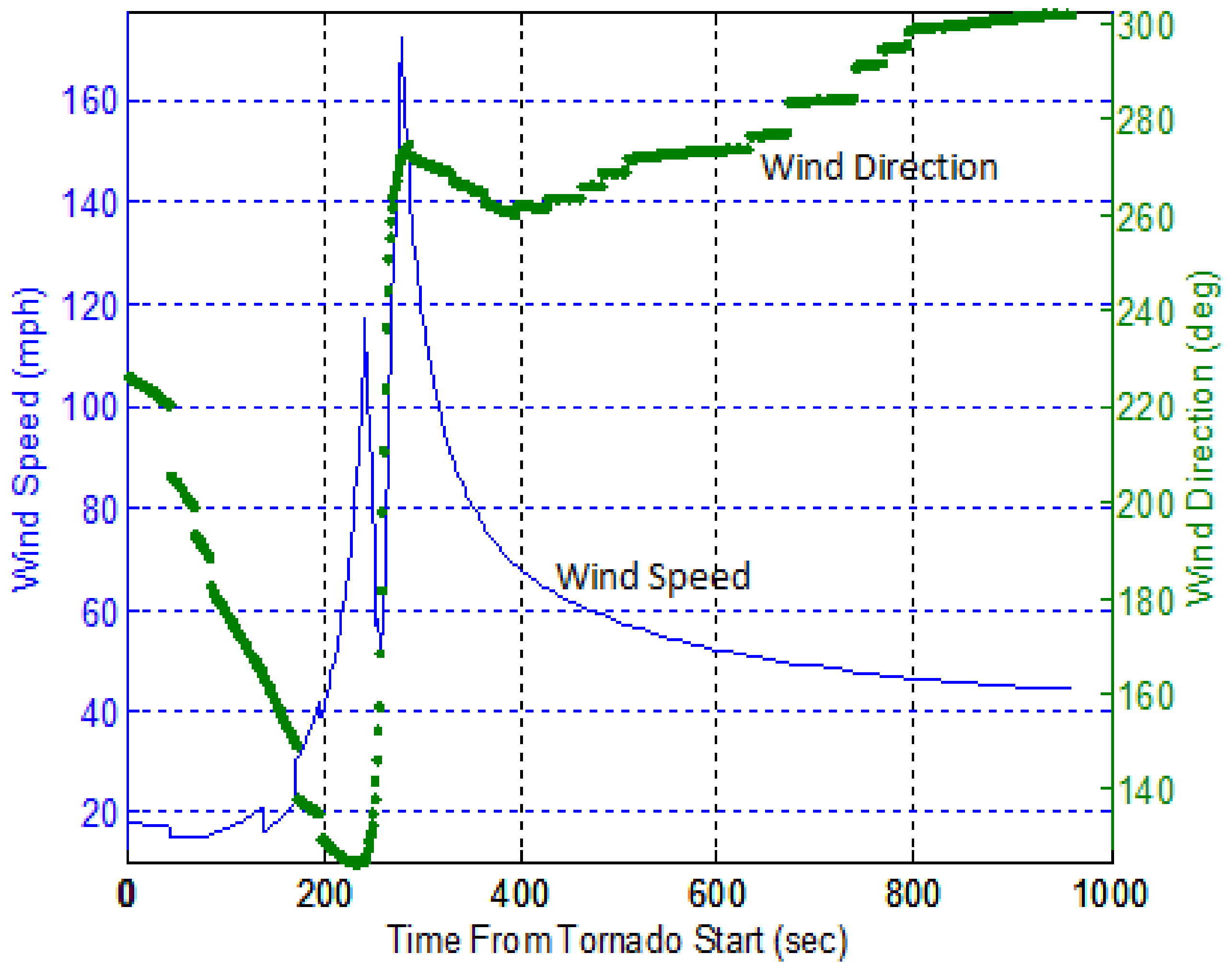


EXTREME WIND CHARACTERIZATION - TORNADO

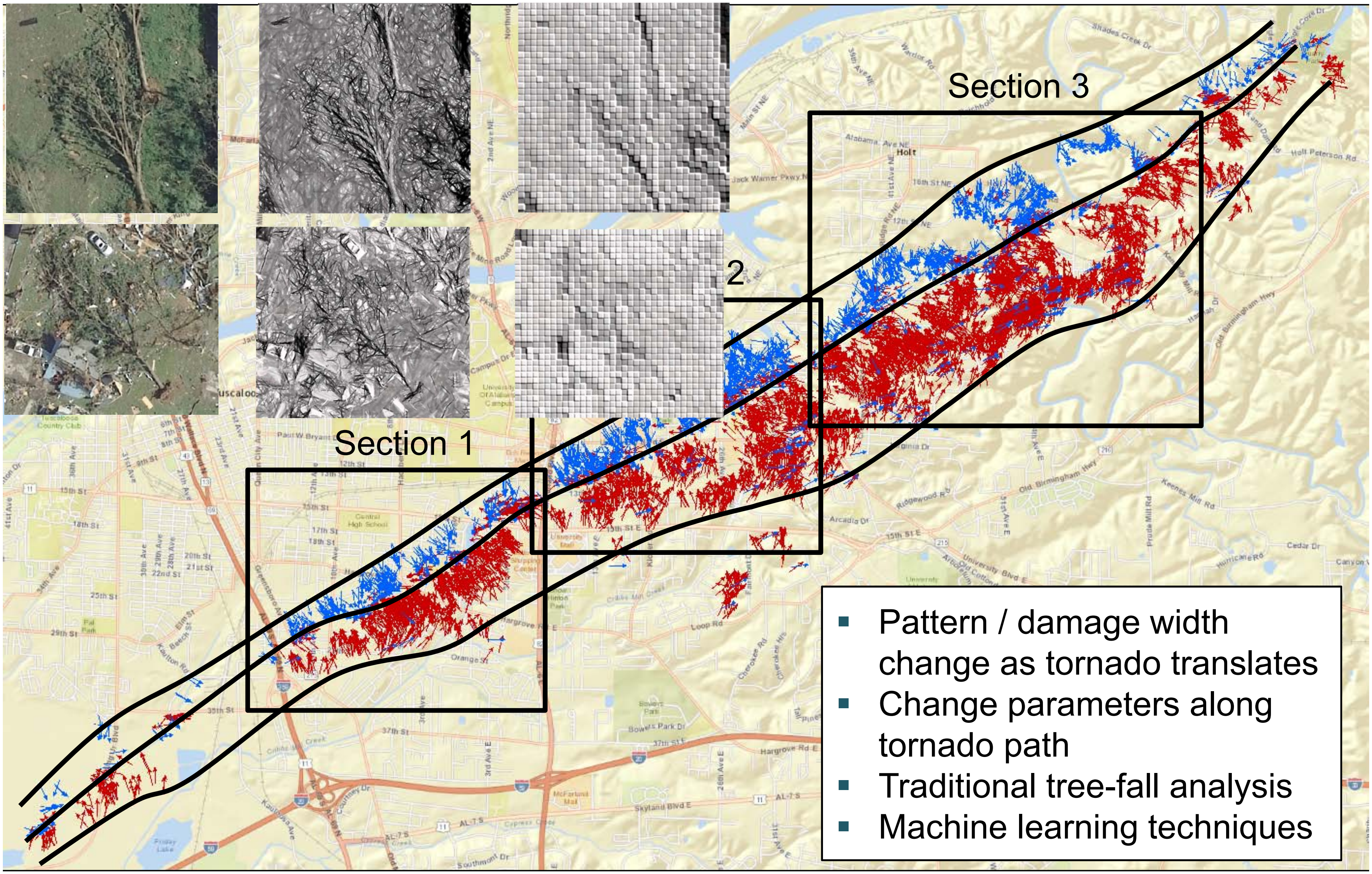


EXTREME WIND CHARACTERIZATION - TORNADO

Figure: Time history (at one location) generated from tornado model



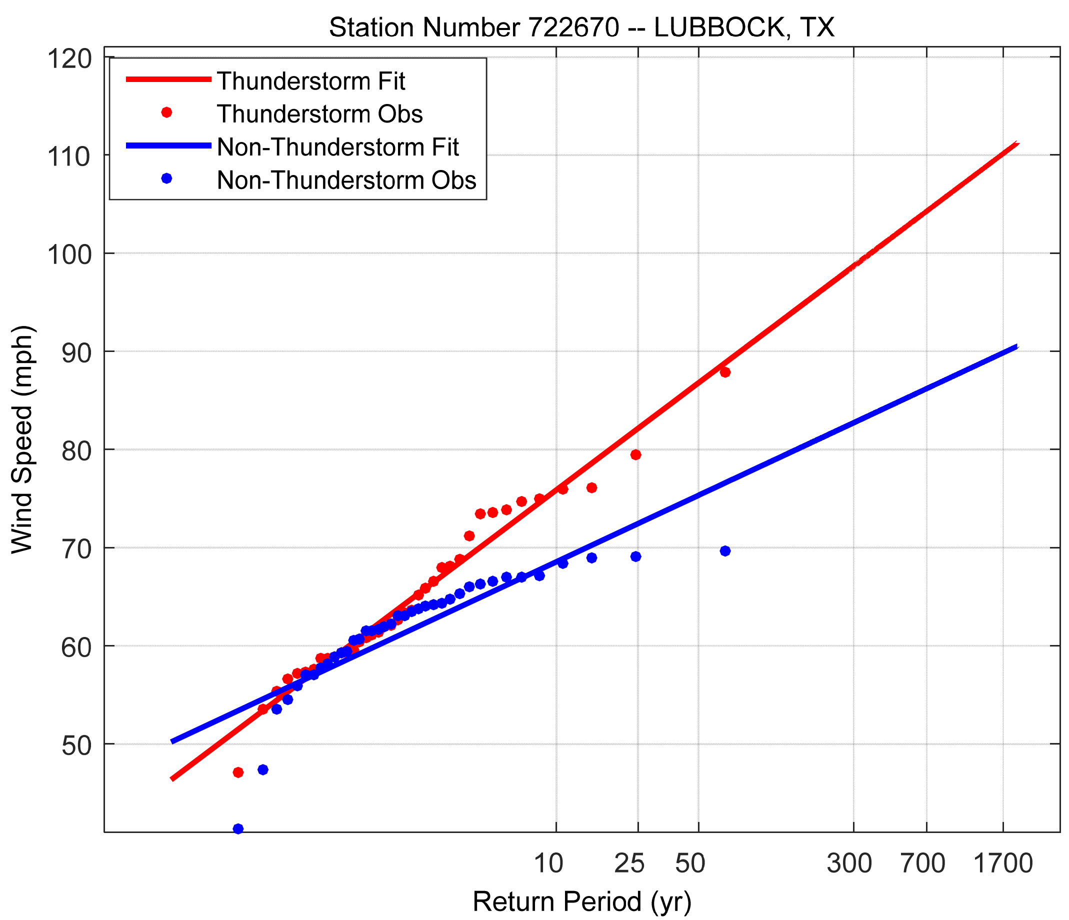
EXTREME WIND CHARACTERIZATION - TORNADO



- Pattern / damage width change as tornado translates
- Change parameters along tornado path
- Traditional tree-fall analysis
- Machine learning techniques

EXTREME WIND CHARACTERIZATION – THUNDERSTORM

- **Probabilistic** description
- Thunderstorms produce highest *recorded* wind speeds at many U.S. locations
- Important for low annual probability events (high return periods)
- Basis for ASCE 7-16 wind maps



EXTREME WIND CHARACTERIZATION - TORNADO

- **Physical** description
- October 2010 Arizona Tornado
- Large accelerations and significant vertical component
- How do these events “load” a structure? – likely different

Figure: Tornado wind speed time history from Arizona. 83 m/s peak wind speed at 2.5 m height.

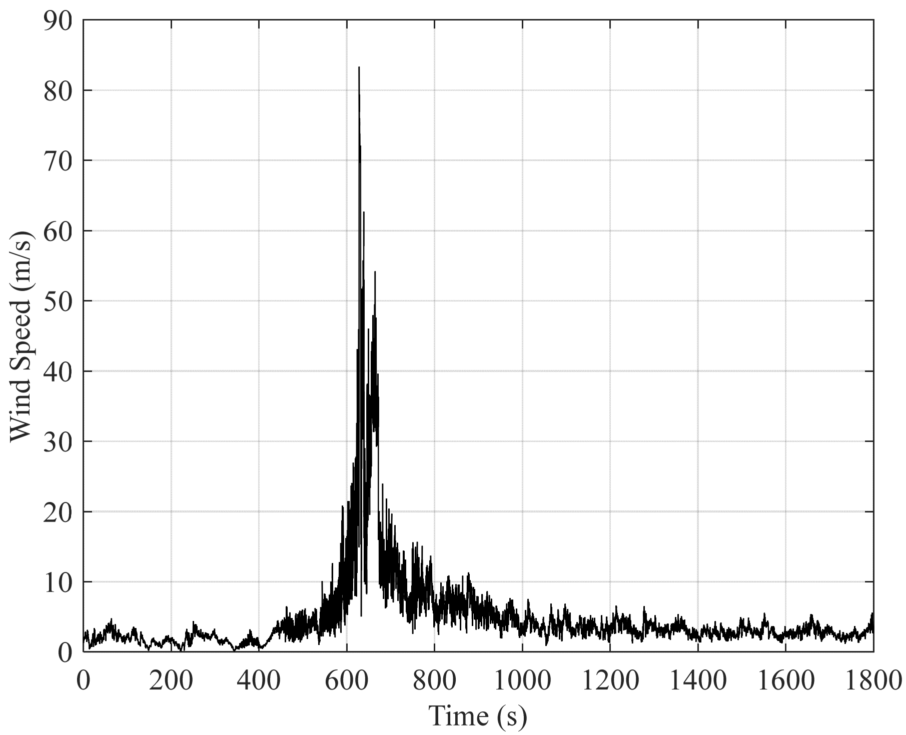
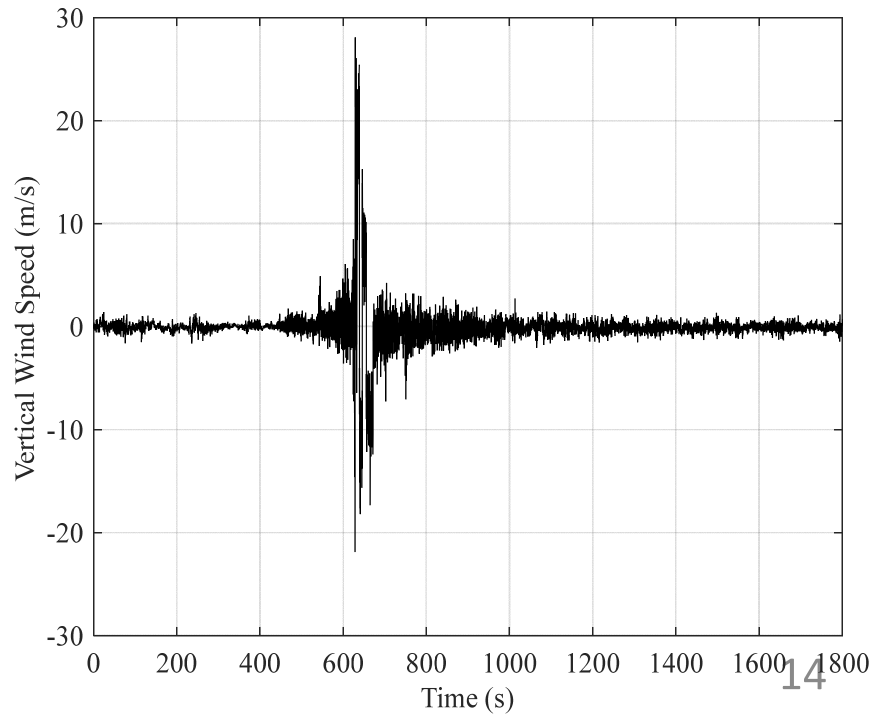
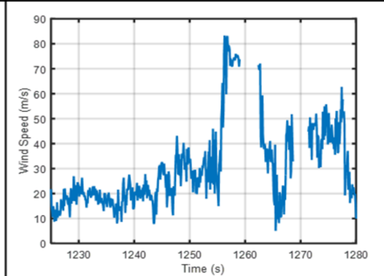
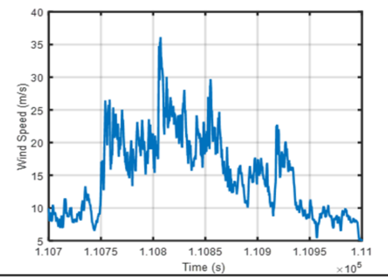
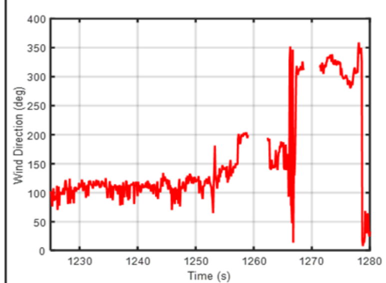
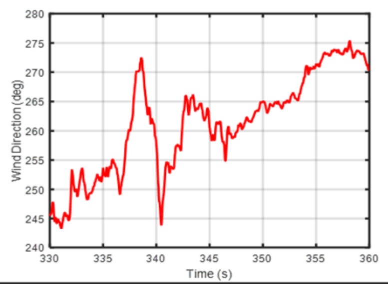
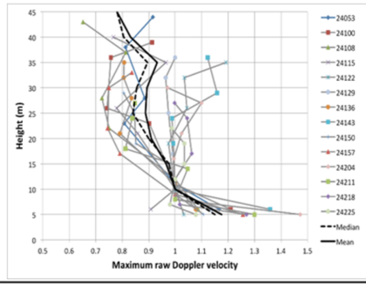
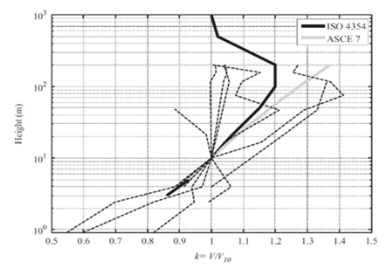
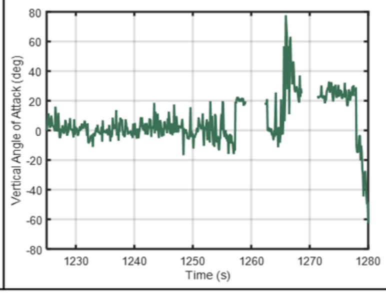
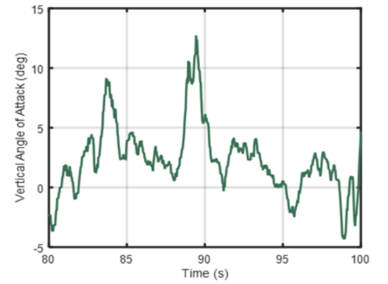


Figure: Peak 25 m/s vertical (upward) component at 2.5 m height.



EXTREME WIND CHARACTERIZATION

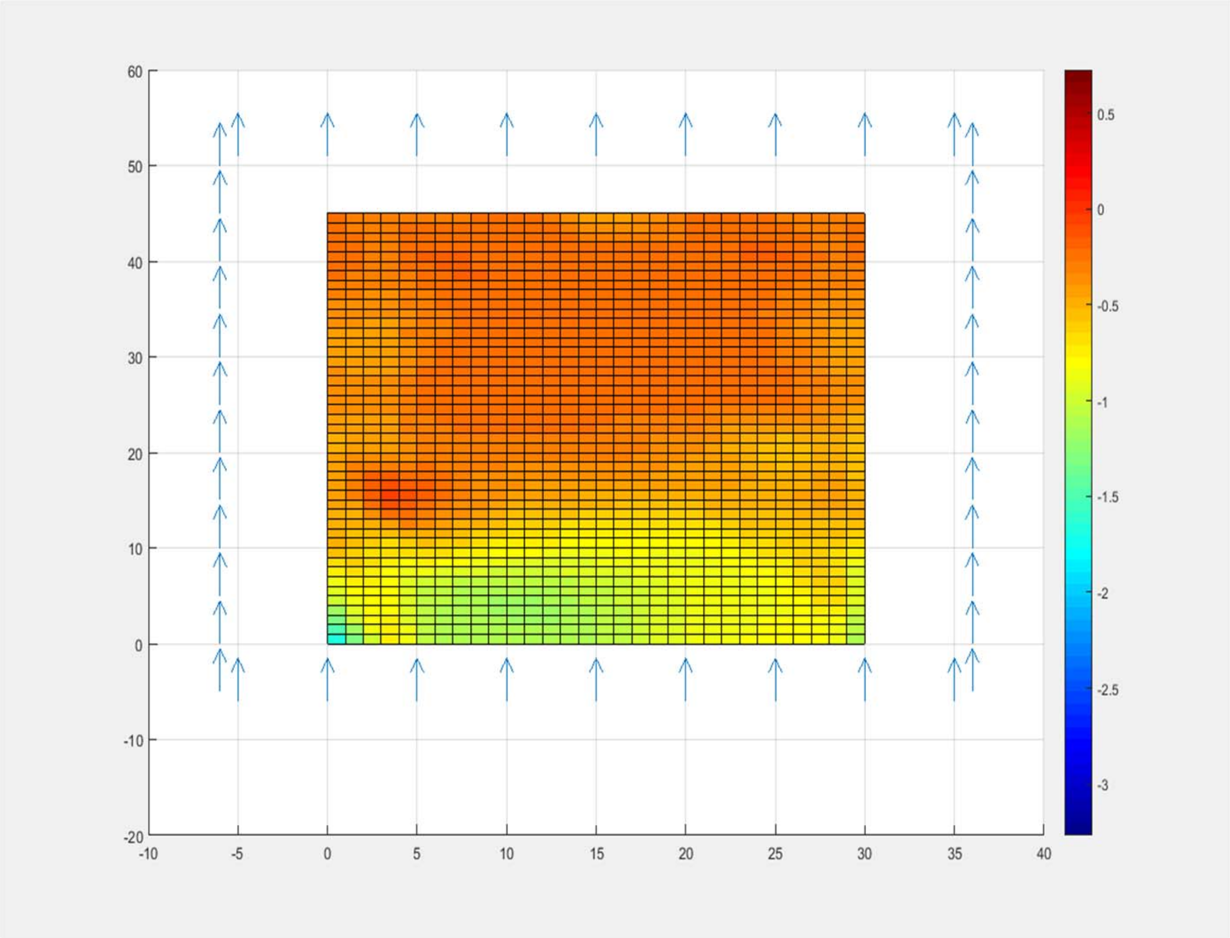
TRANSIENT/NON-STATIONARY CHARACTERISTICS	TORNADO	THUNDERSTORM
WIND SPEED		
WIND DIRECTION		
VERTICAL PROFILES		
VERTICAL ANGLE OF ATTACK		

- Physical characteristics of extreme winds likely of importance

Extreme Load Characterization

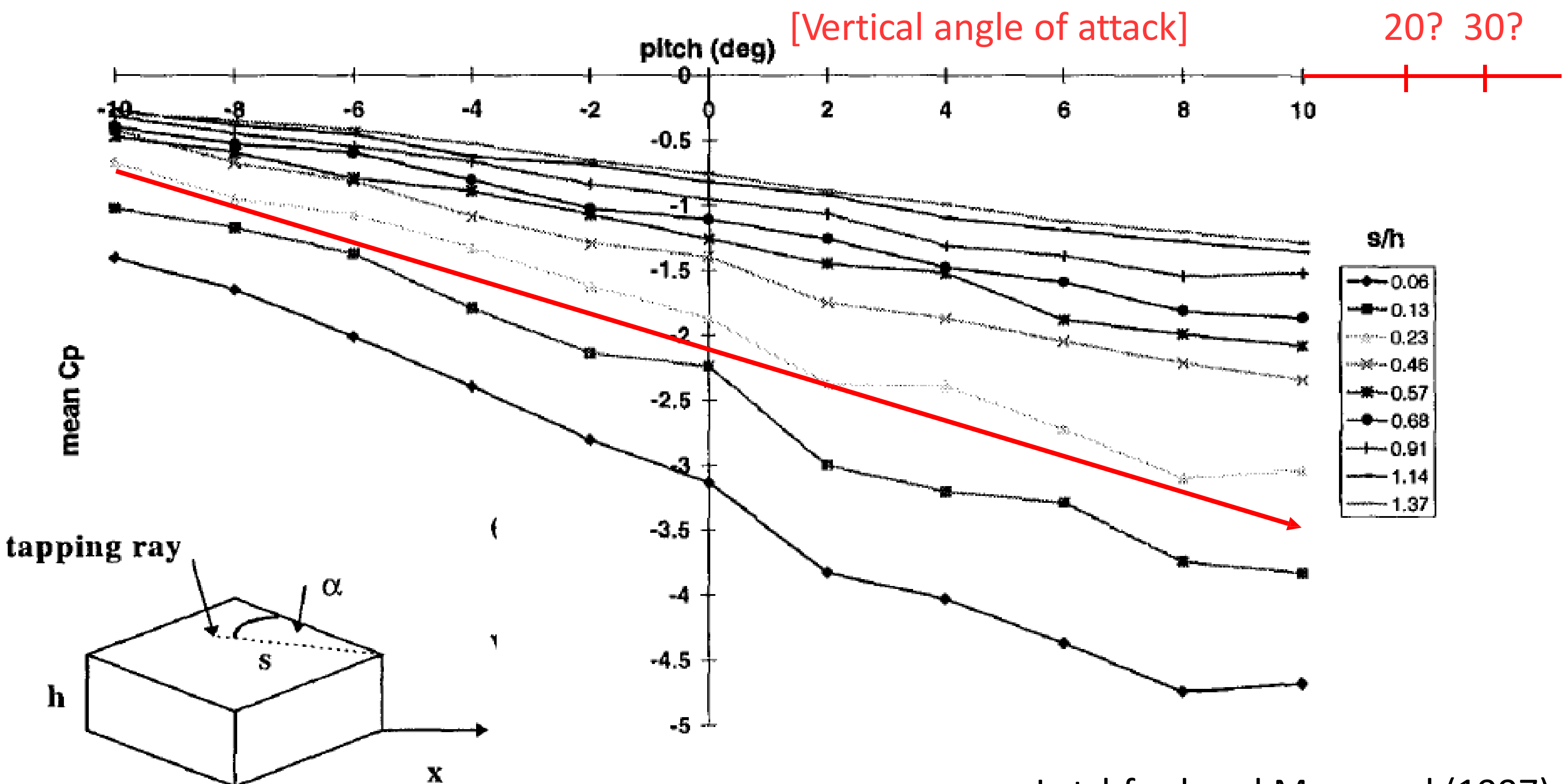
EXTREME LOAD CHARACTERIZATION

- **Unsteady bluff body aerodynamics**
  - Codes and standards based on 'straight' flow in the wind tunnel
  - Properties change rapidly in extreme events and have been shown to affect loading



EXTREME LOAD CHARACTERIZATION

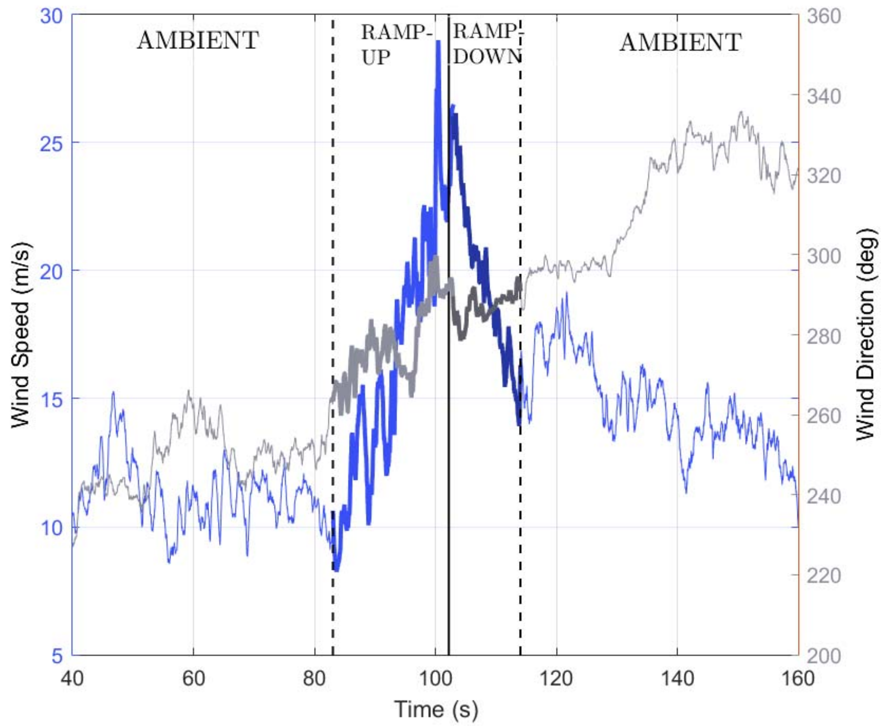
- Tornado wind field – vertical angle of attack (β) ≠ 0°
- Average suction on roof increases by factor of 1.5 (or more)



Letchford and Marwood (1997)

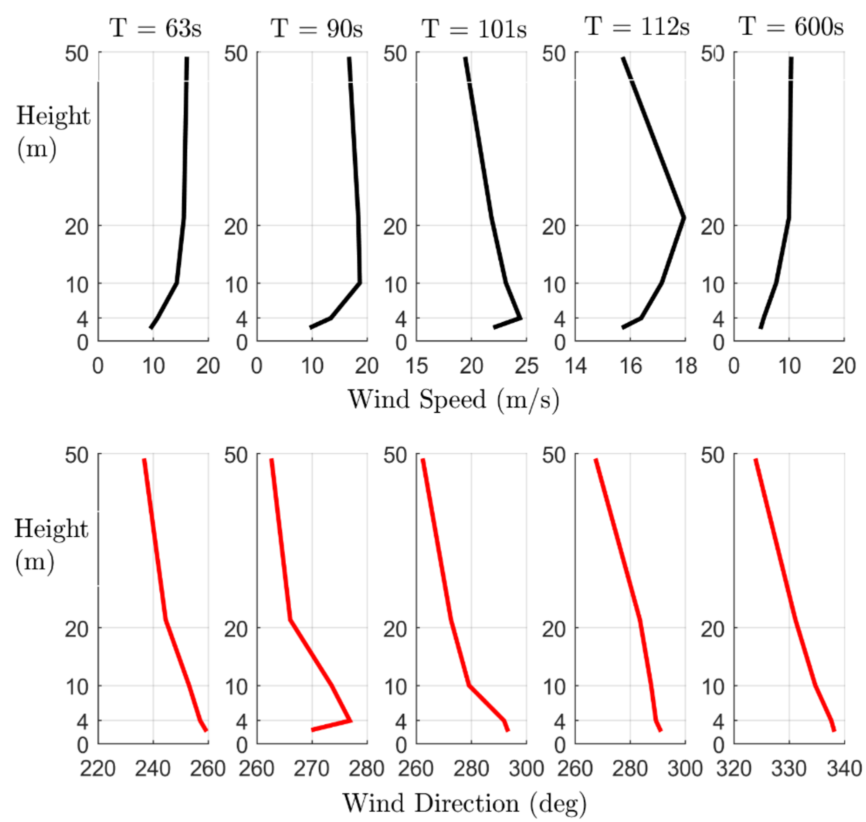
EXTREME LOAD CHARACTERIZATION

- Thunderstorm downburst event (full-scale)



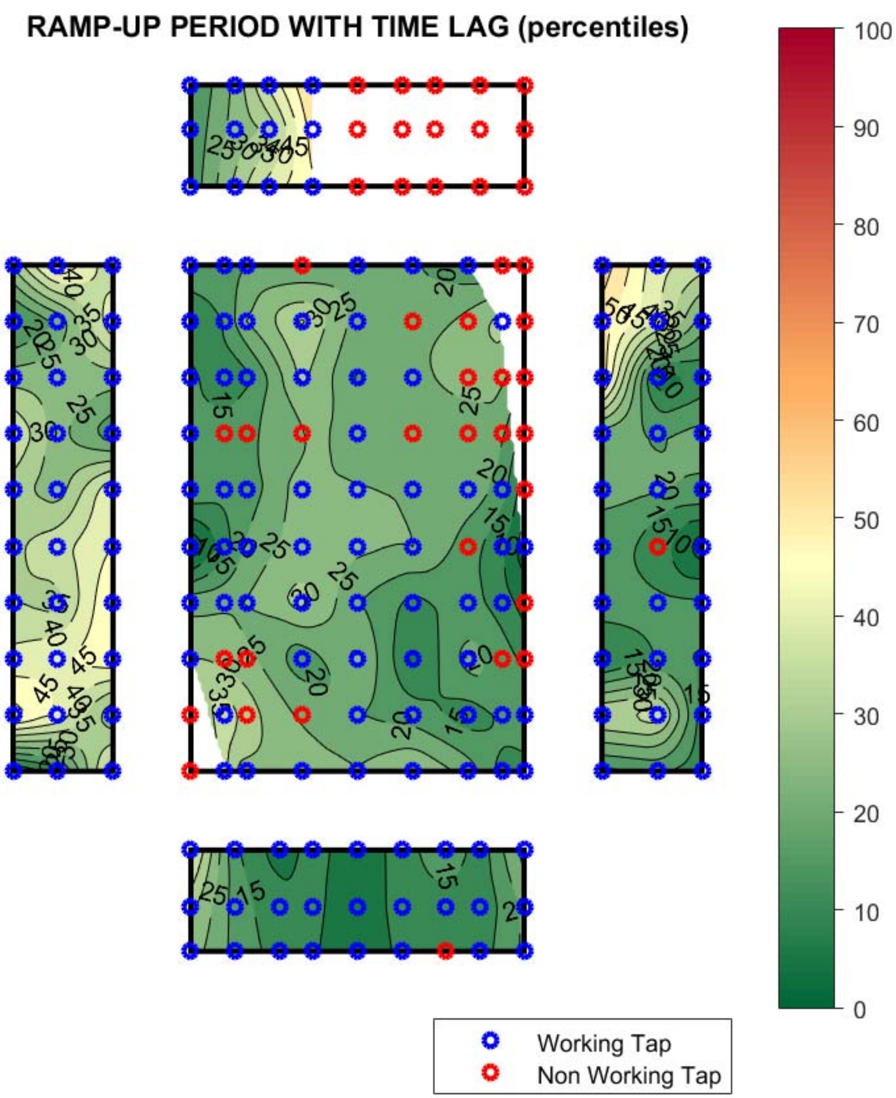
Above: Time history at 4 m showing 'ramp-up' (acceleration) and 'ramp-down' (deceleration)

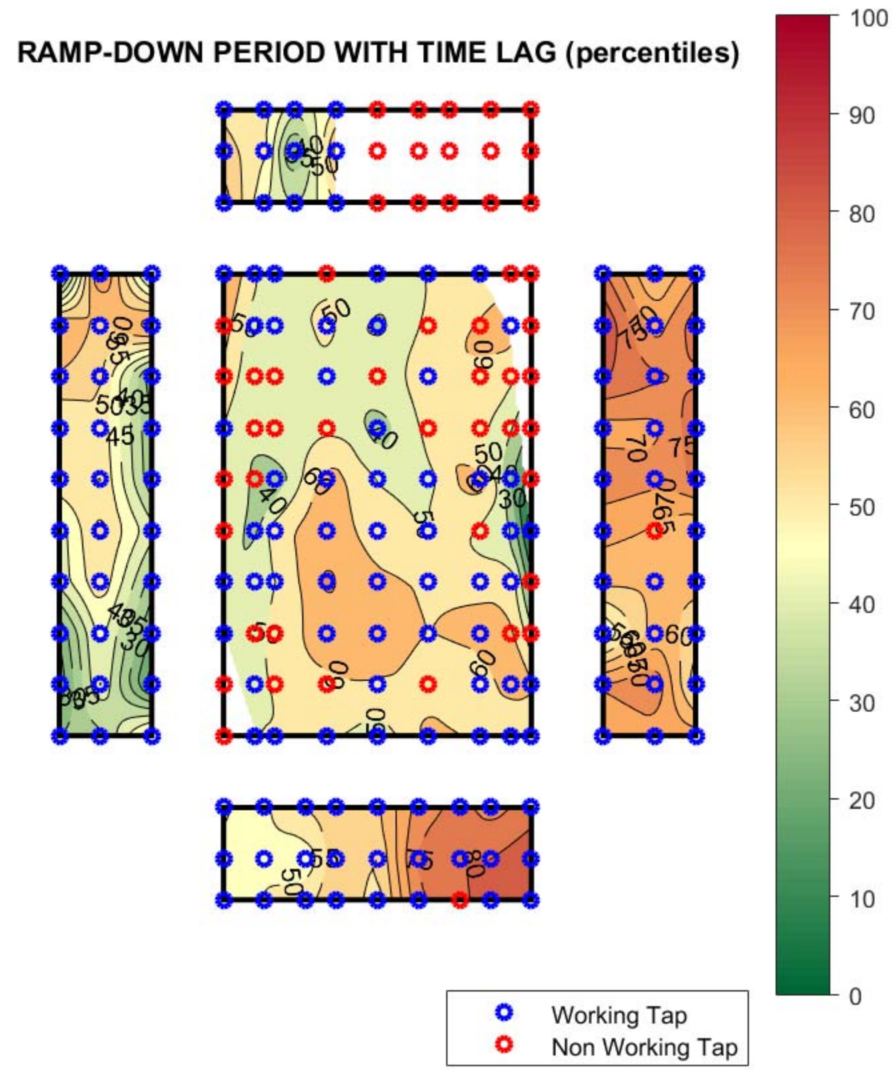
Below: Wind speed and direction profiles



EXTREME LOAD CHARACTERIZATION

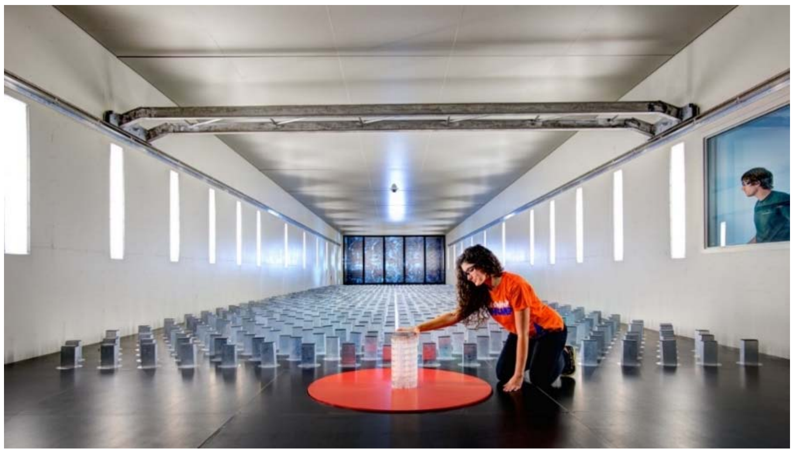
- Acceleration and deceleration differences



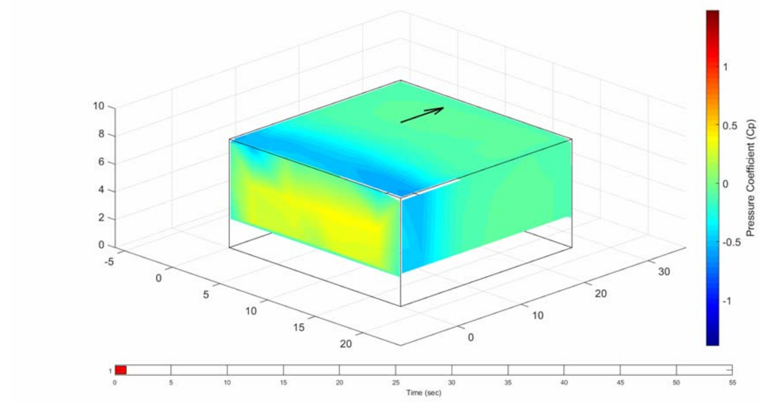


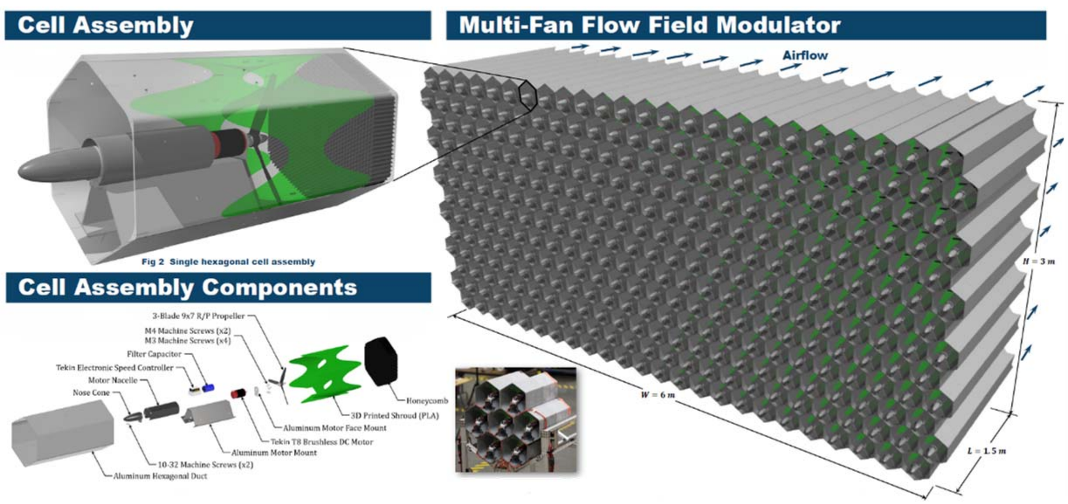
EXTREME LOAD CHARACTERIZATION

- Wind tunnel testing
- Preliminary experiments run at U. Florida boundary layer tunnel in May 2017

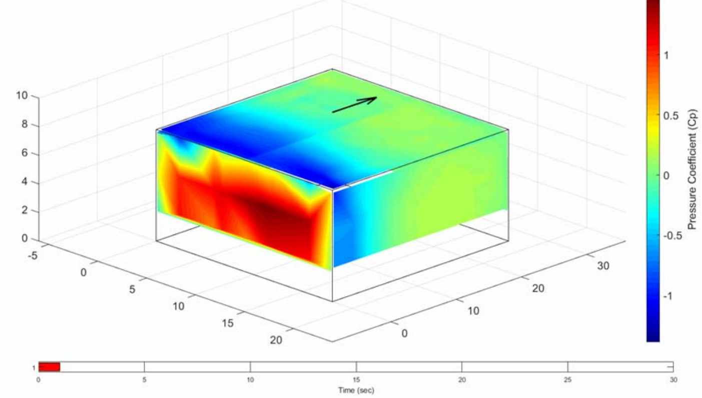


NO 'RAMP'





RAMP



Damage Analysis

DAMAGE ANALYSIS

- Damage surveys focused on individual structures
- Need new paradigm to understand totality of event
- Technology helping to push boundaries
- Group has performed tornado, thunderstorm and hurricane surveys and analyzed archived data

DAMAGE ANALYSIS – JOPLIN, MO

- Damage to commercial, critical facilities ("engineered structures") surveyed

Finding: Although structure itself undamaged, total loss of envelope led to complete loss of functionality (e.g., St. Johns Hospital)

Finding: Relied on a less robust roof system (such as box–type system (BTS) buildings with light steel roof decks) were prone to structural collapse.

DAMAGE ANALYSIS – JOPLIN, MO

- Damage to nearly 7,500 residential structures

Finding: Nearly half of all damaged residential structures suffered EF-2+ damage

Finding: Failure of connections (roof-wall, wall-foundation); Lack of vertical load path

Finding: Envelope breached by impacts from flying debris

DAMAGE ANALYSIS – JOPLIN, MO

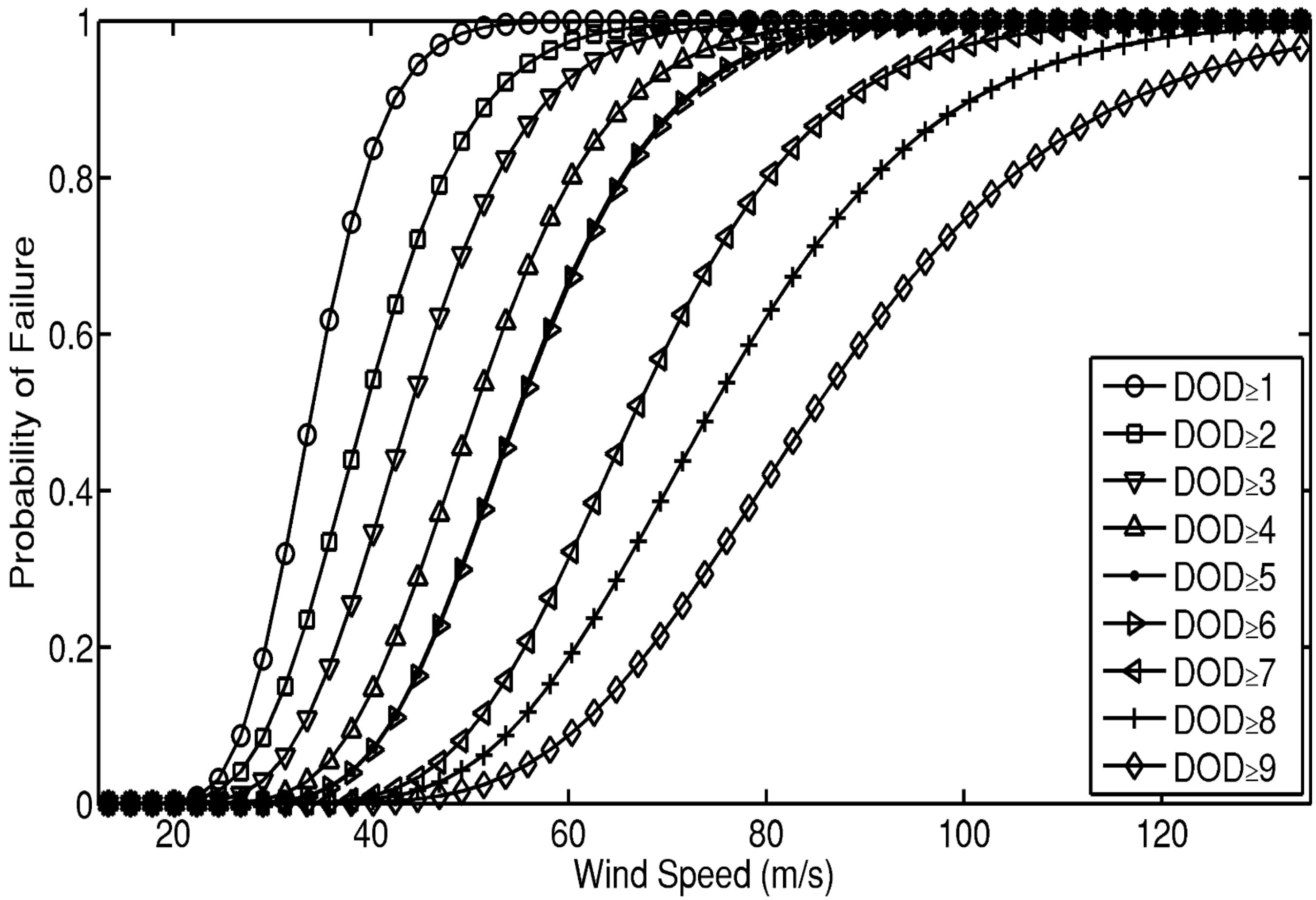
- ~1200 residential structures surveyed and damage rated using EF-Scale by U. Florida and others → then converted to wind speed
- Comparison to tree-fall estimated wind speeds (Lombardo, Roueche and Prevatt, 2015)

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	65	53	80
2	Loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding	79	63	97
3	Broken glass in doors and windows	96	79	114
4	Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward or outward; failure of porch or carport	97	81	116
5	Entire house shifts off foundation	121	103	141
6	Large sections of roof structure removed; most walls remain standing	122	104	142
7	Top floor exterior walls collapsed	132	113	153
8	Most interior walls of top story collapsed	148	128	173
9	Most walls collapsed in bottom floor, except small interior rooms	152	127	178
10	Total destruction of entire building	170	142	198

* DOD is degree of damage

DAMAGE ANALYSIS – JOPLIN, MO

- Derive fragility curves for residential construction (Roueche et al., *J. Struct. Eng.*, 2017) using tree-fall wind speeds
- Empirical curves for tornadoes have not been developed
- Will perform for other survey cases (damage analysis)

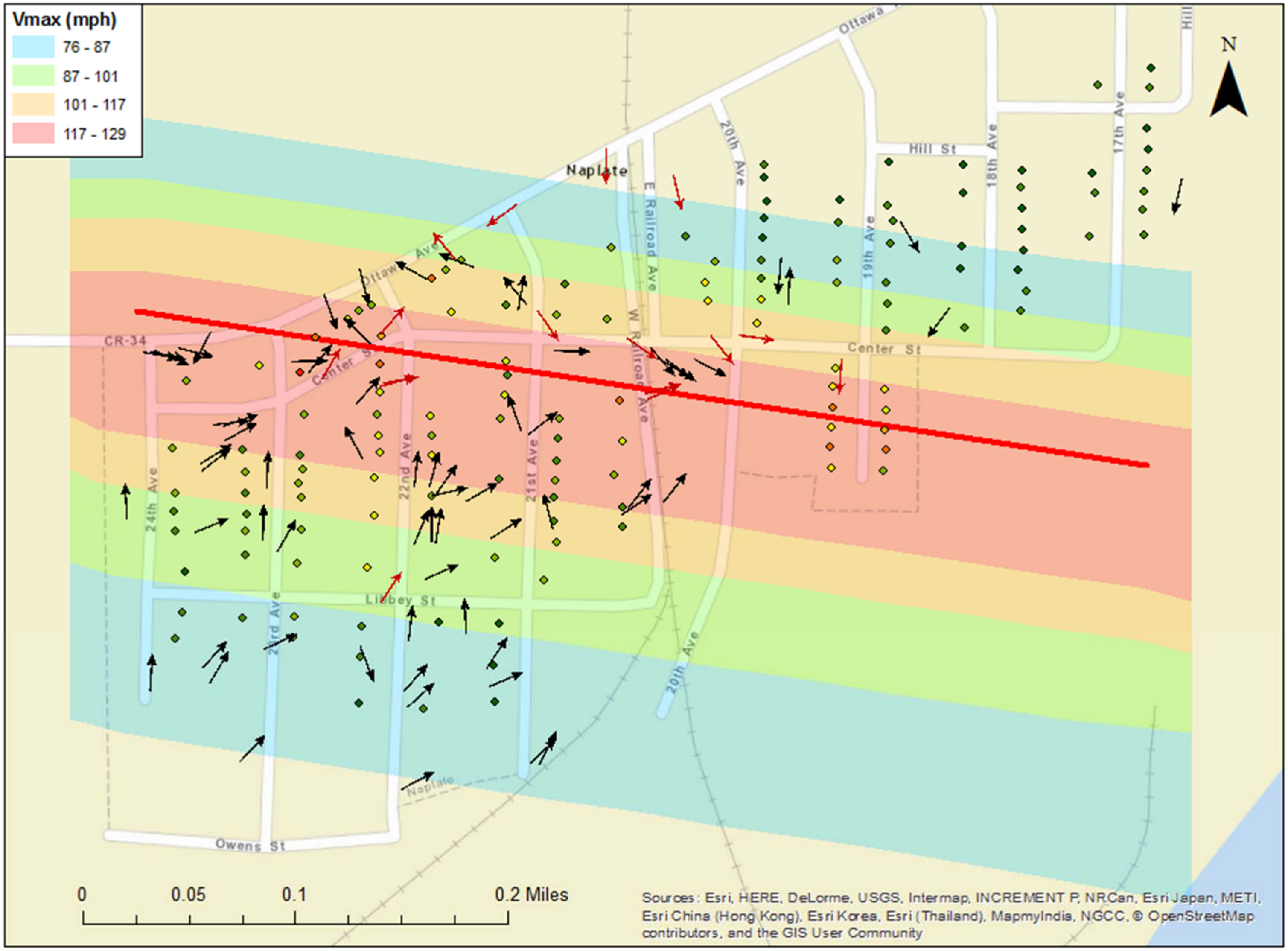


DAMAGE ANALYSIS – NAPLATE, IL

- EF-3 rated tornado on February 28, 2017
- Ground survey – Residential houses (DOD), trees, street signs, distribution poles (Location and direction)

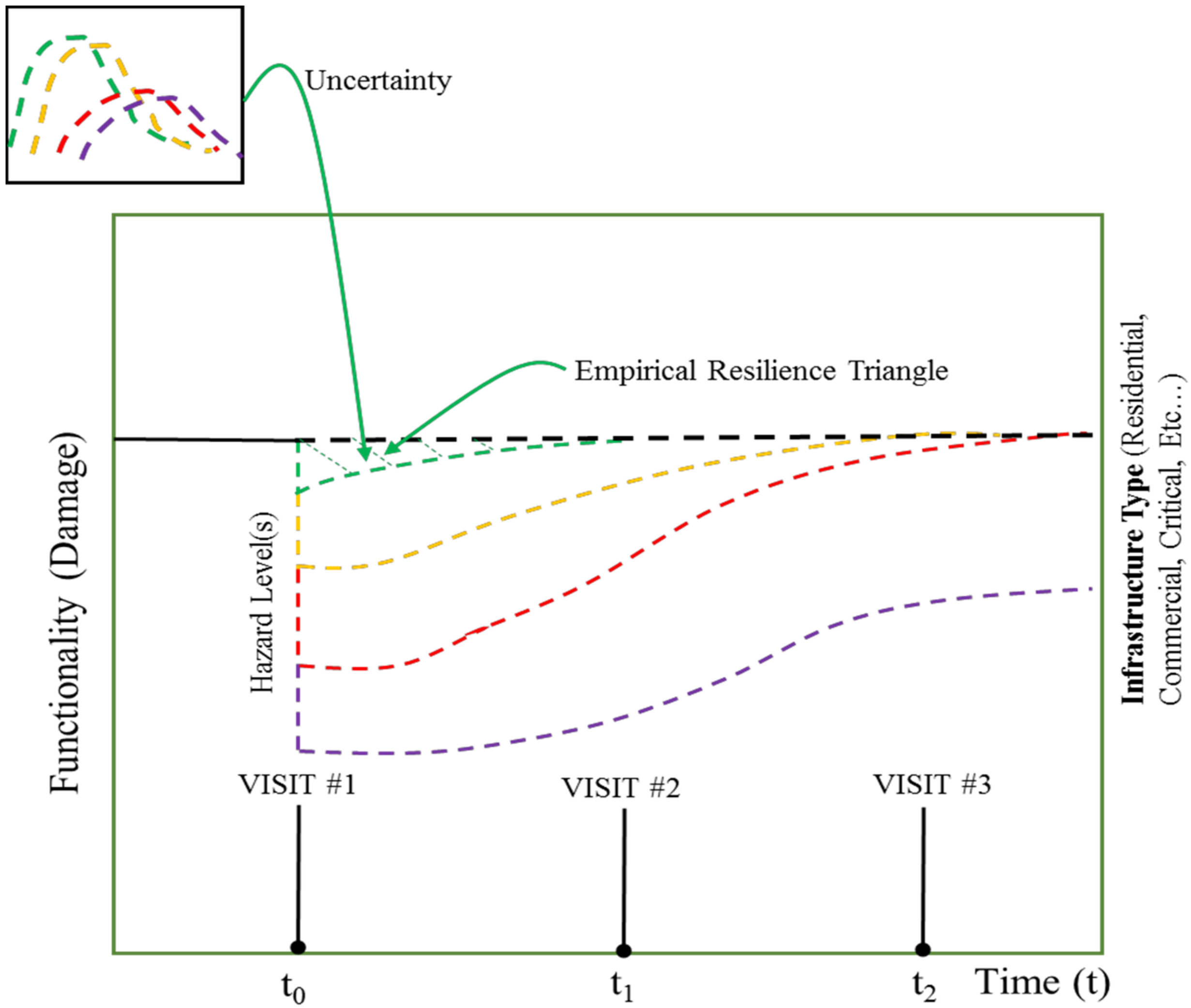
DAMAGE ANALYSIS – NAPLATE, IL

- Tree-fall estimated wind speeds



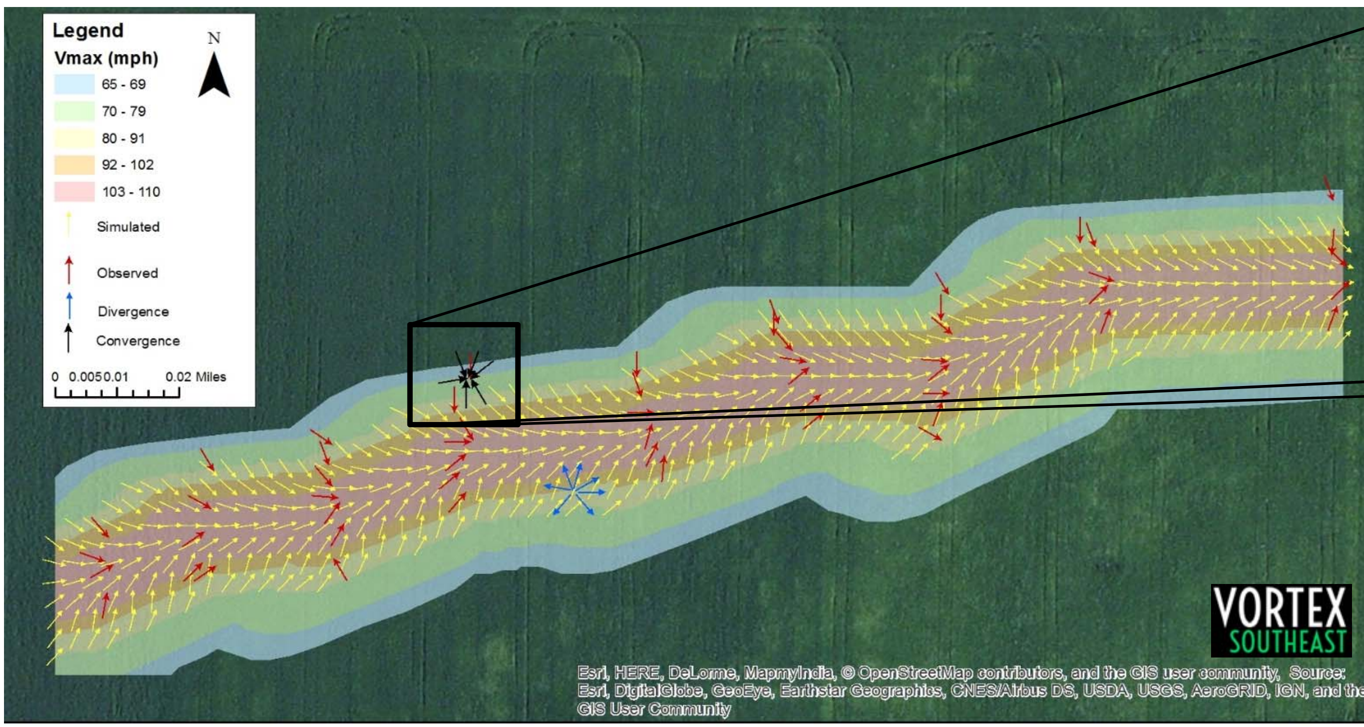
DAMAGE ANALYSIS – NAPLATE, IL

- Fourth visit to Naplate on March 12, 2018
- Measure ‘resilience’ of buildings to tornado



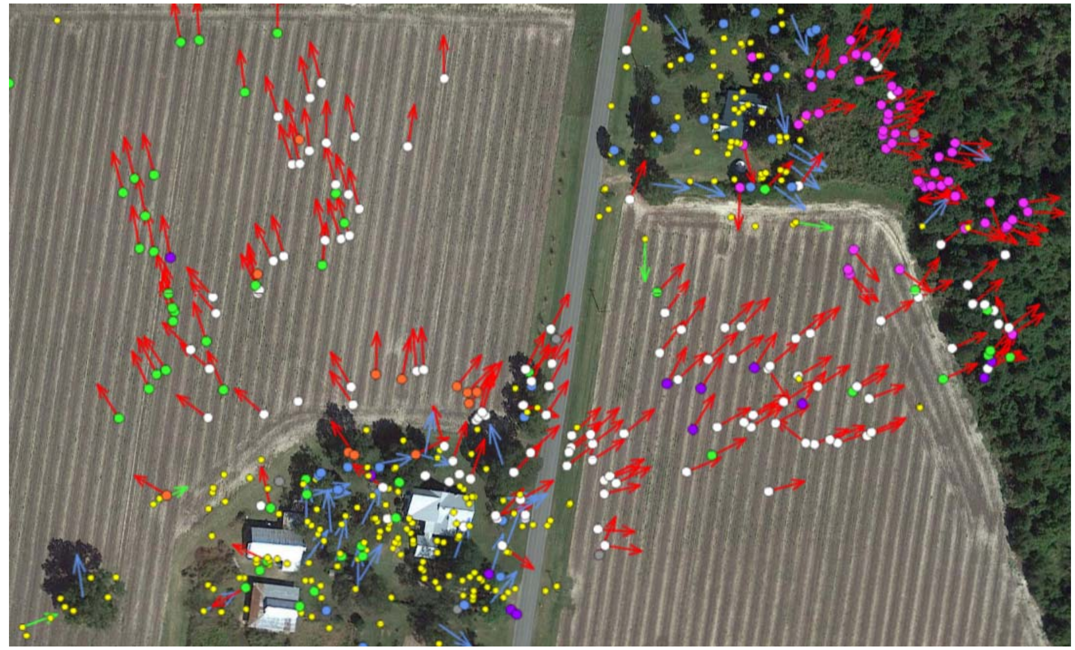
DAMAGE ANALYSIS – SIDNEY, IL

- EF-2 rated tornado in Sept. 2016
- Distinct crop patterns



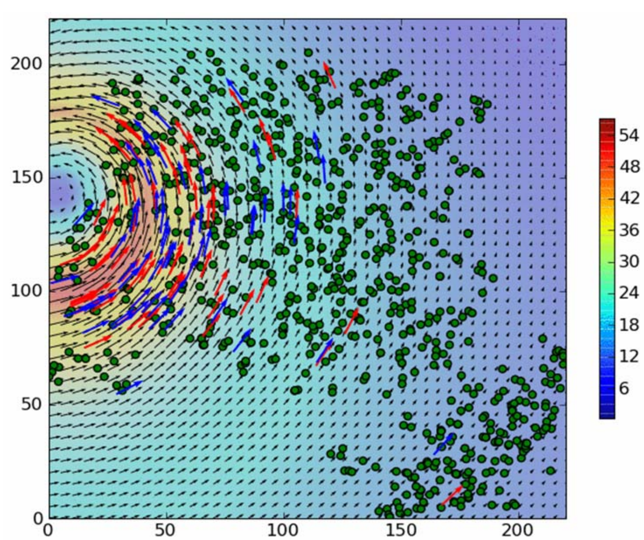
DAMAGE ANALYSIS – ALBANY, GA

Objective: Re-creation of environmental conditions, damage and debris (all events)

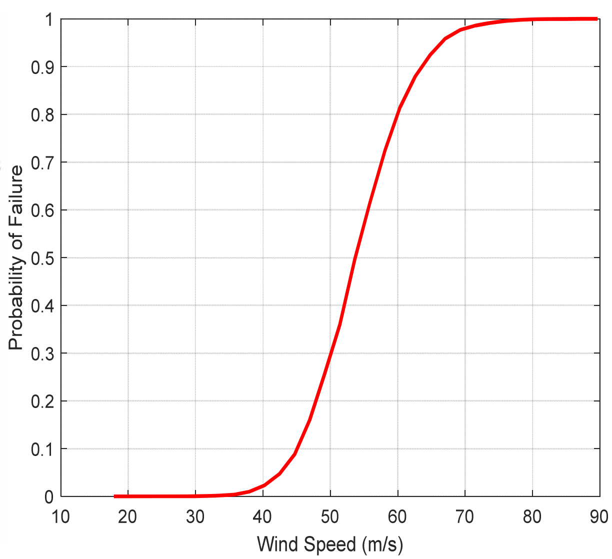


Blue – tree-fall
Red – debris
Green - crops

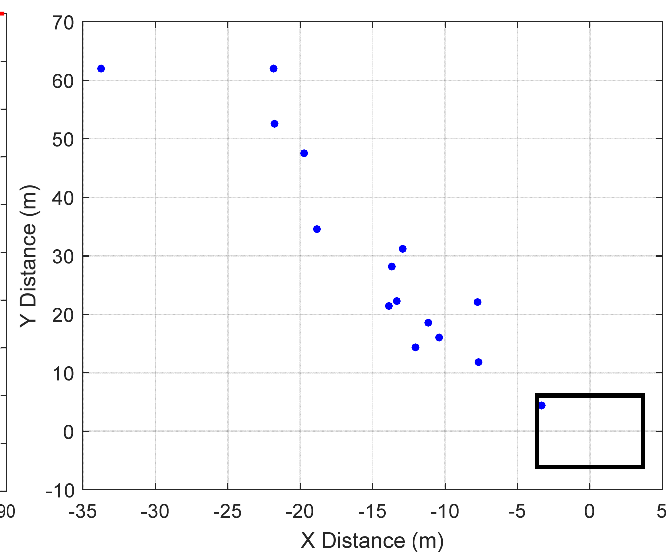
Estimate Wind Field



Fragility Curves

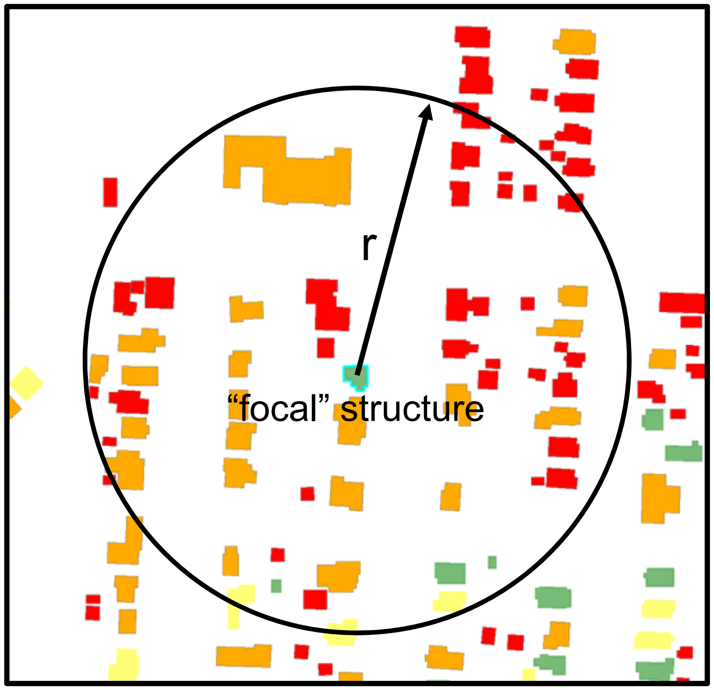


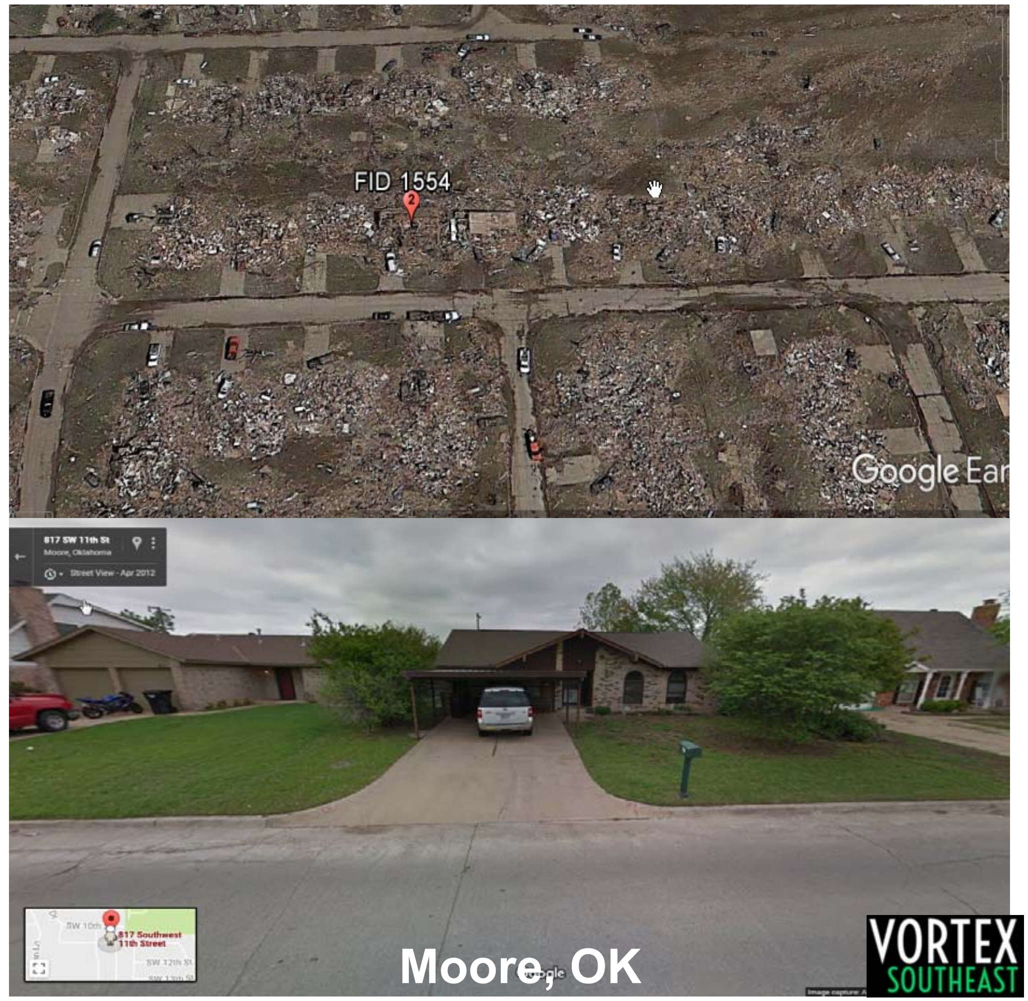
Debris Scatter



DAMAGE ANALYSIS – MOORE, OK

- What other effects contribute to damage? – Outlier analysis (e.g., ± 2 EF)
- Gives us a chance to look at individual structures but from a *neighborhood* perspective – identify potentially unusual behavior (sheltering, poor construction)



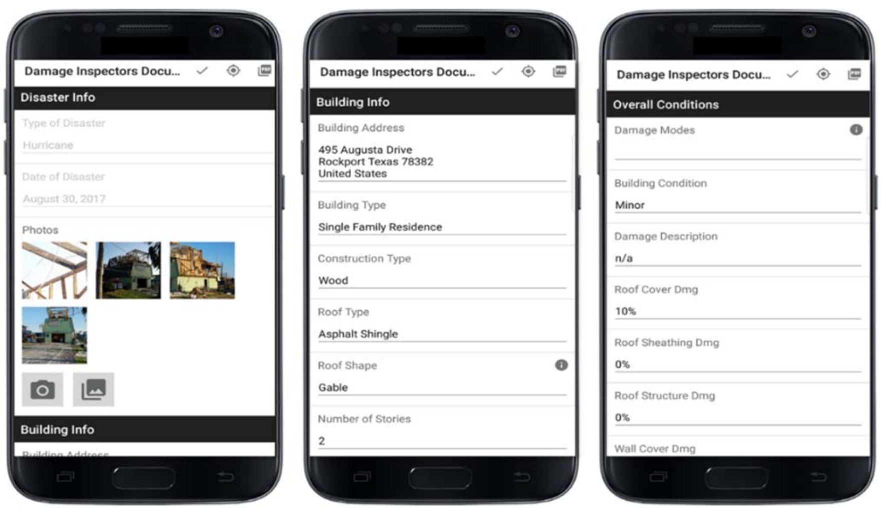


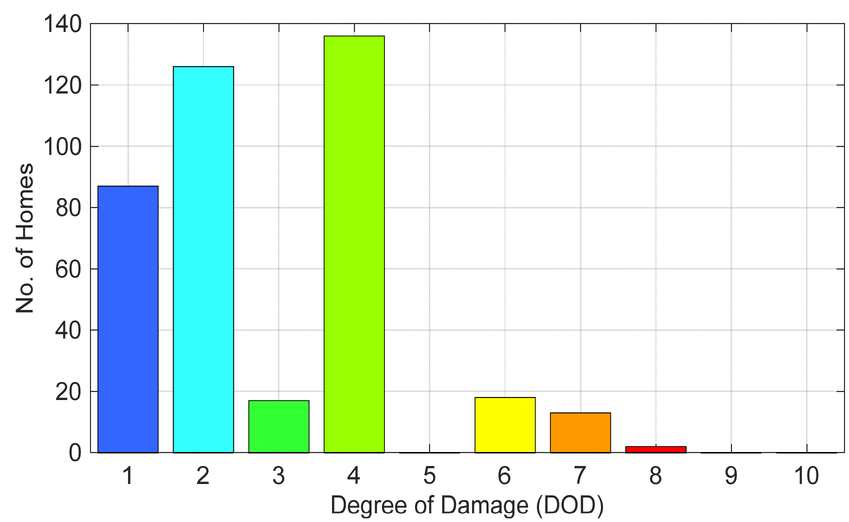
DAMAGE ANALYSIS – HURRICANE HARVEY

- UIUC Team Deployed from Sept. 29 – Oct. 1, 2017

Mostly minor roof damage

A few homes suffered complete collapse





DAMAGE ANALYSIS – CITIZEN SCIENCE/SOCIAL MEDIA

- Over 1,000 tornadoes/year in U.S.; detailed surveys for very few
- Citizen science project to assess damage (set of 14 questions)

Illustrative Example: Which illustration most closely resembles “image”?

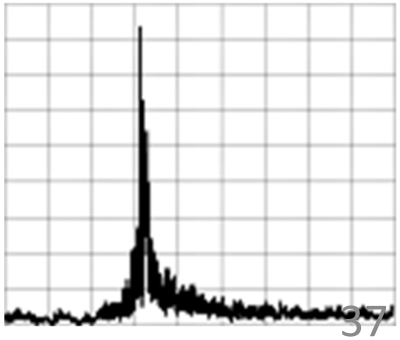
Result: Citizen scientists generally underestimate damage visually

Next Step: Use social media data (unstructured) in surveys

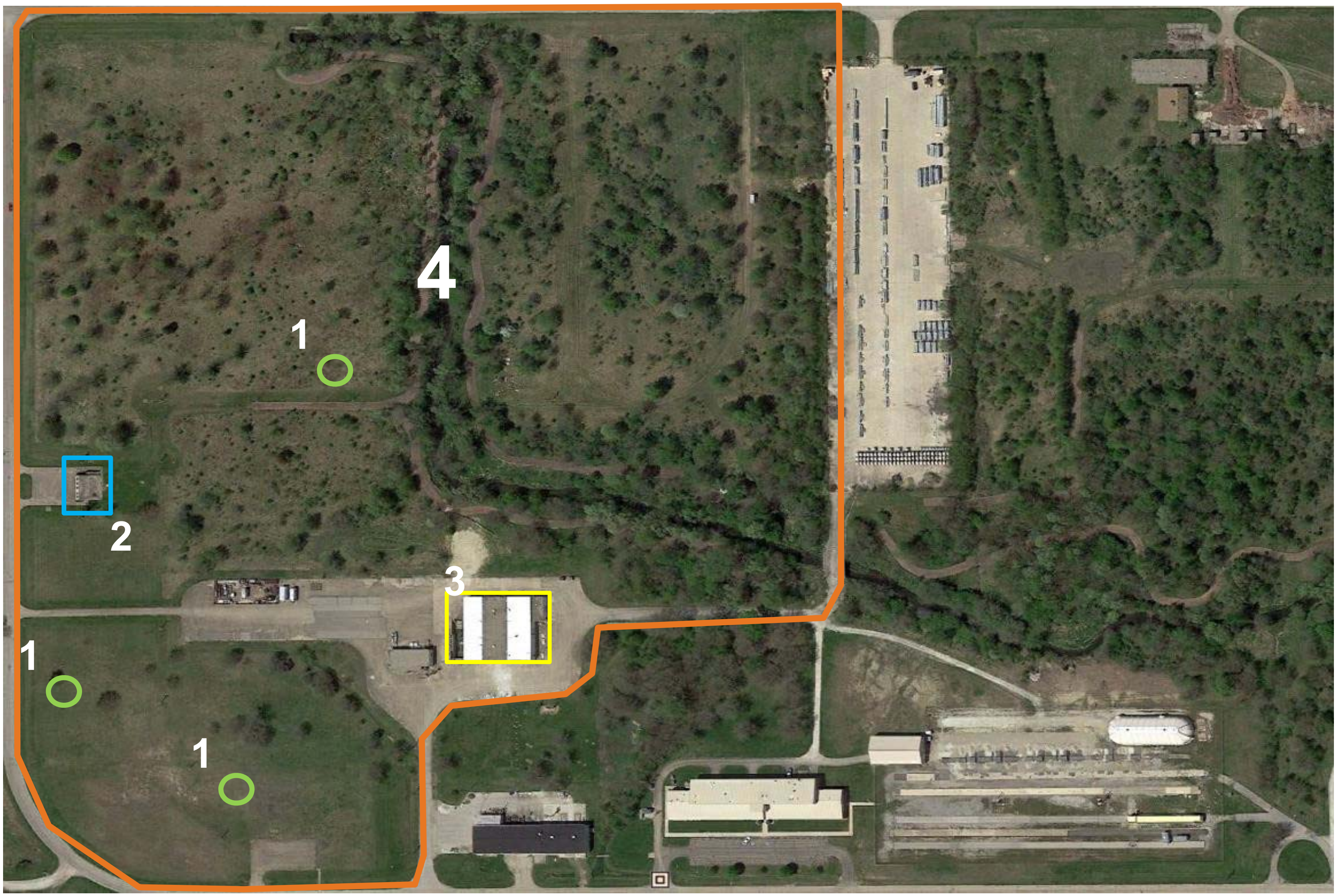
Smart Wind Engineering Research Facility (SWERF)

SWERF

- 40 acre space in Rantoul, IL – 20 min. from UIUC campus
- Four major objectives:
  1) Measuring extreme wind characteristics and loading
  2) Novel wind engineering experimentation
  3) Full-scale “wind tunnel”
  4) Multidisciplinary research hub



SWERF



1 – SWERF Towers

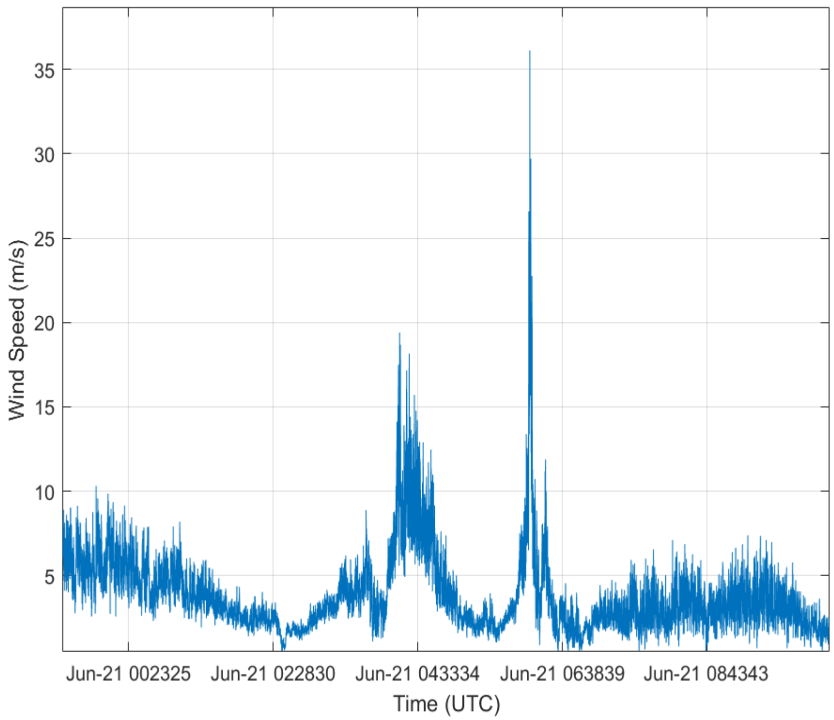
10 m Tower (Loaned – Summer 2016)

10 m Tower (Operational as of Sept. 2017)

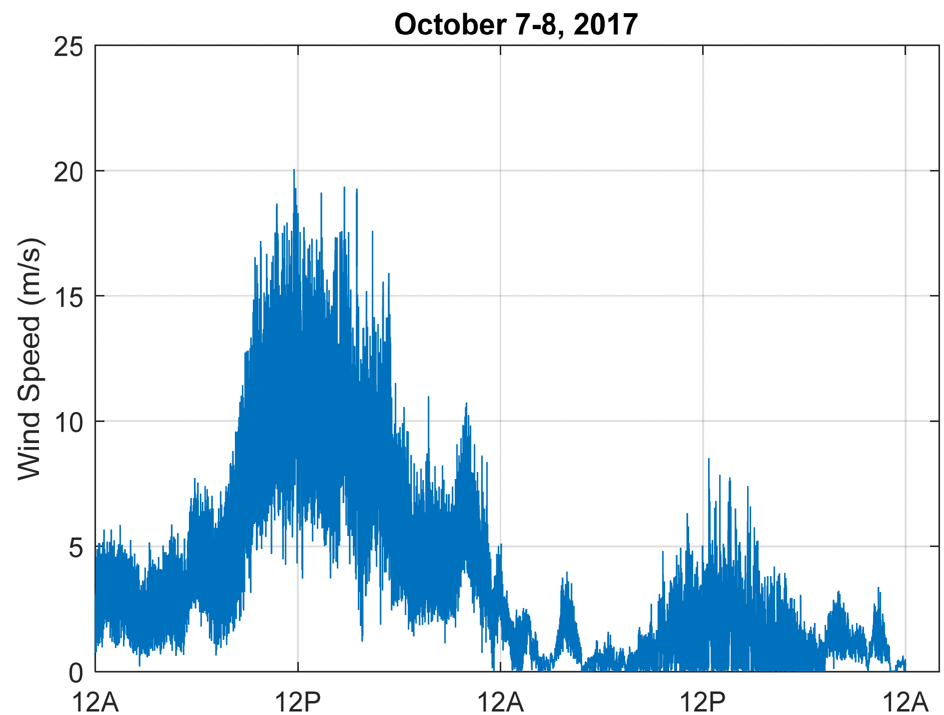
50 m Tower (to be erected Spring 2018)

- Numerous u-v-w anemometers installed at various heights
- Temperature, pressure, humidity sensors

1 – SWERF Towers



June 21, 2016 – 36 m/s peak gust (with nearby damage)



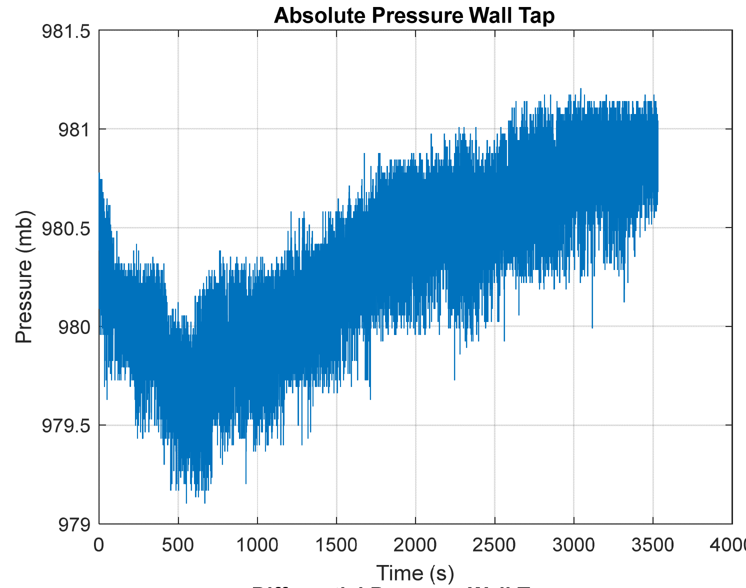
October 7-8, 2017 – First 'high' wind day at SWERF with new tower

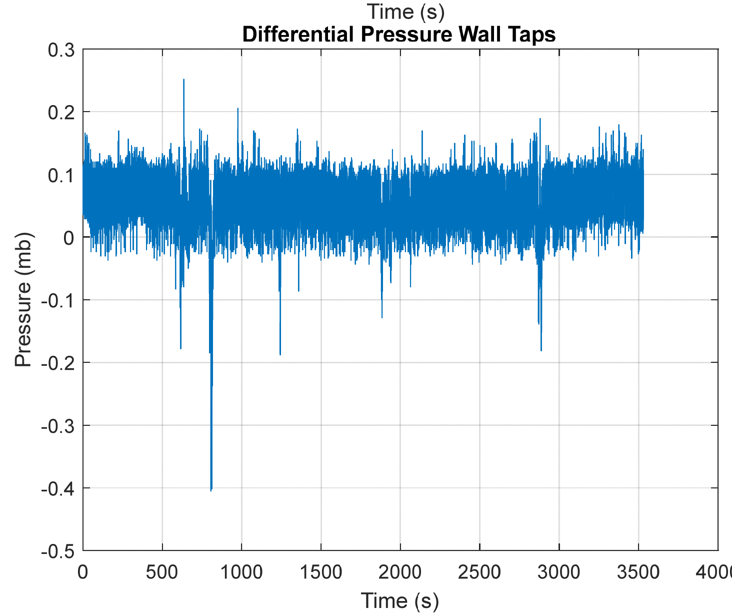
2 – SWERF Low-Rise Building

- Instrument with absolute/differential pressure sensors in 2017
- Will serve as ‘hub’ for SWERF operations

2 – SWERF Low-Rise Building

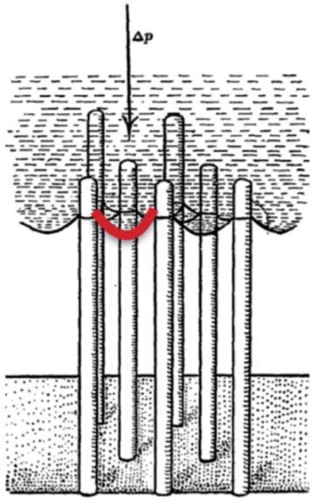
- First measurements taken in June 2017



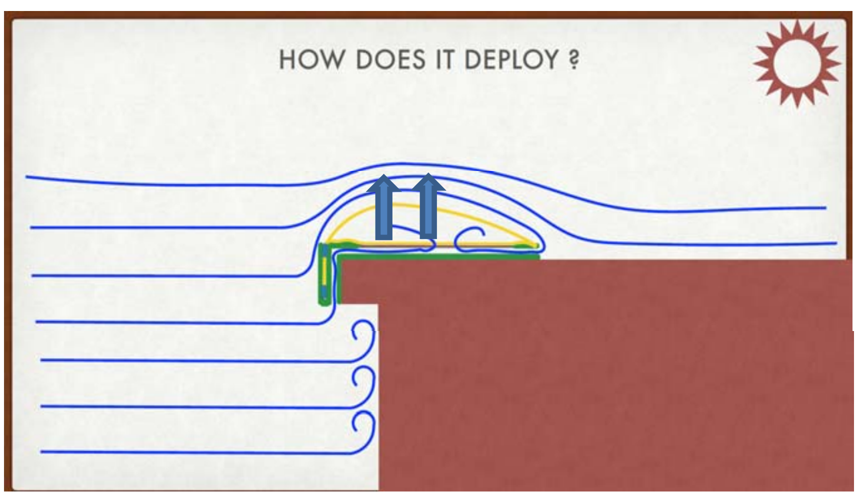


2 – SWERF Low-Rise Building

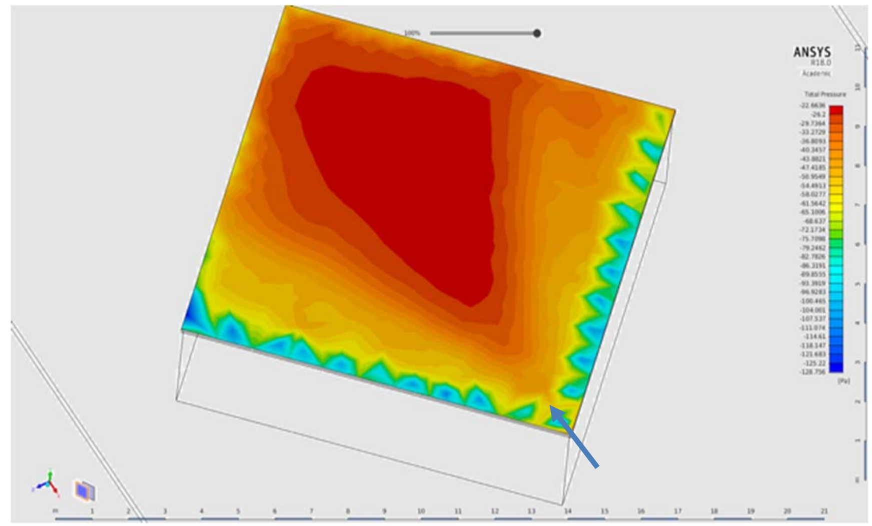
- Bioinspired Design



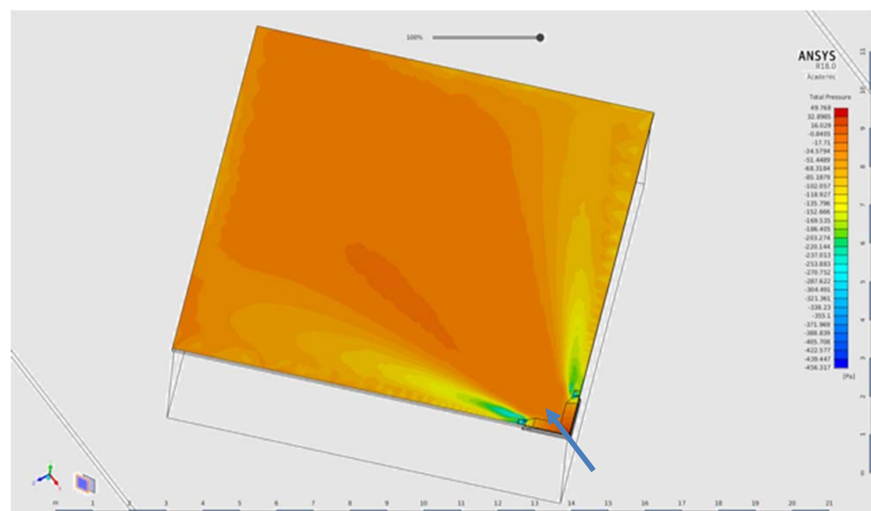
‘Plastrons’ – change shape under hydrostatic pressure to keep air in



***Without* Membrane**

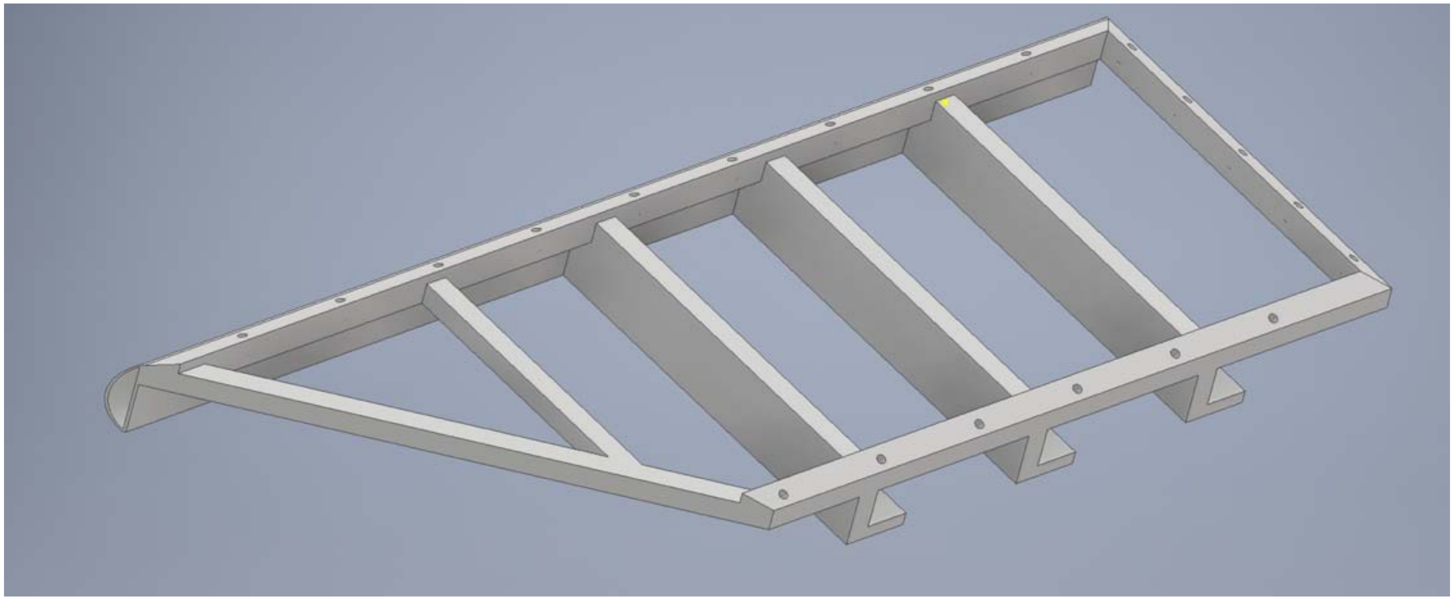


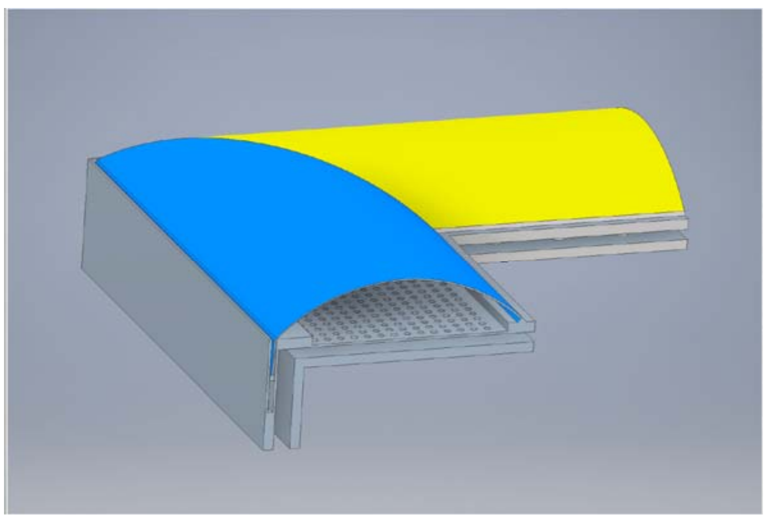
***With* Membrane**



2 – SWERF Low-Rise Building

- Design being finalized – experimentation Summer 2018



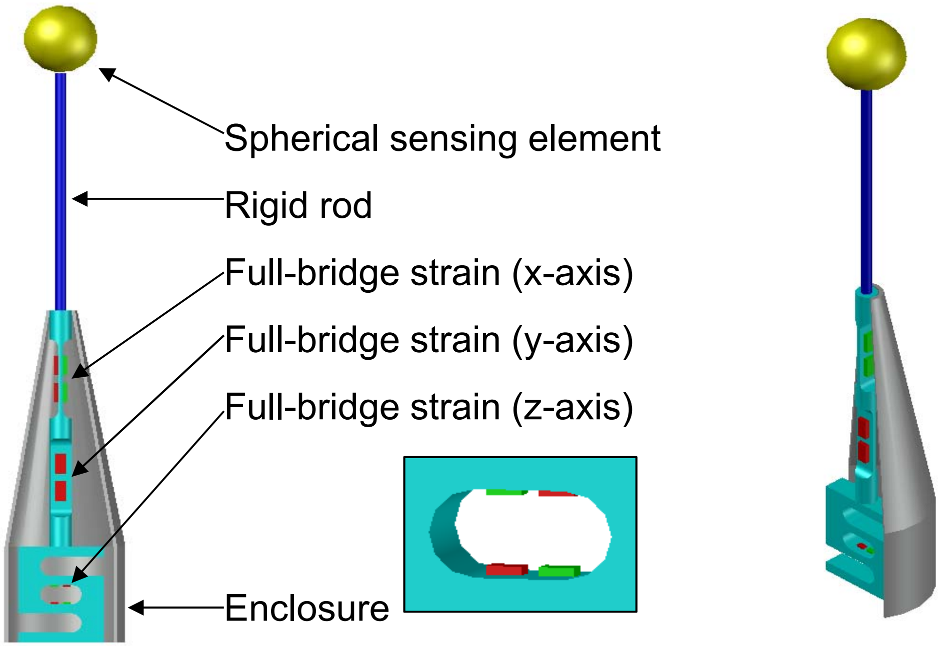


3 – SWERF Wind Tunnel

- Eiffel design
- Controls just installed – need to create 'wind'

4 – Mobile SWERF

- Novel wind speed and wind pressure measurement sensors
- Deployable upon a very short notice

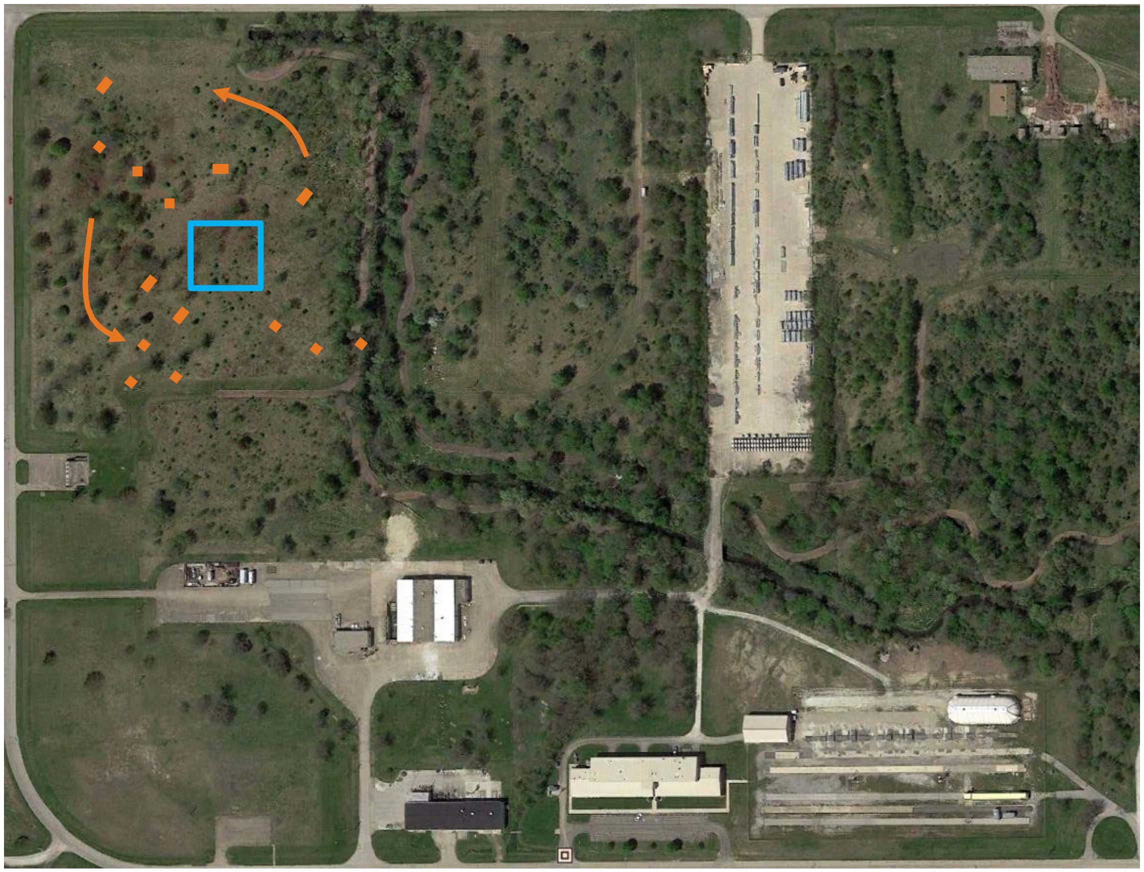


Strain-Gage Anemometer

P³ (Portable Pressure Panel)

4 – SWERF Additional Experiments

- Full-scale "wind tunnel"



- Rapidly modify building components ("lego-like")
- Rapidly modify surrounding terrain and obstacles
- Validation for wind-tunnel and CFD experiments for any structure type
- Test infrastructure – including transportation (e.g., traffic signs)

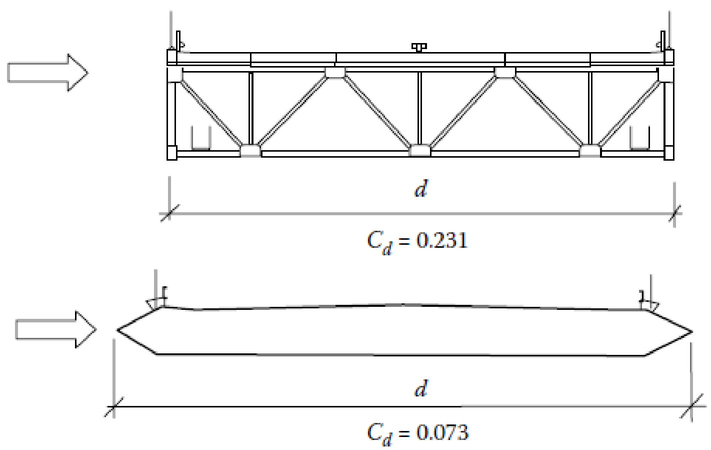
Transportation and Wind

TRANSPORTATION AND WIND

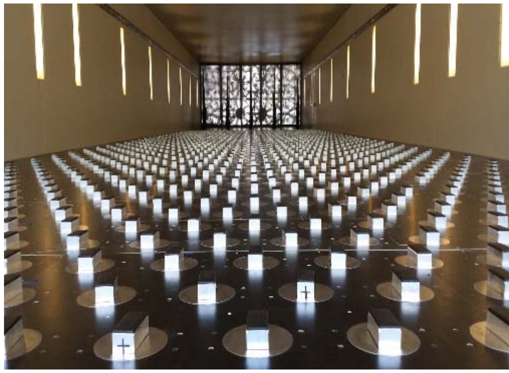
- Early warning, prediction, and understanding of extreme wind events
- Disaster resilience and performance of transportation-related infrastructure

TRANSPORTATION AND WIND

- Vortex-induced vibration of transportation structures
- Load characterization of transportation structures



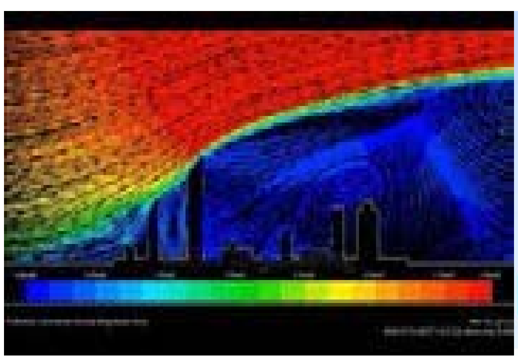
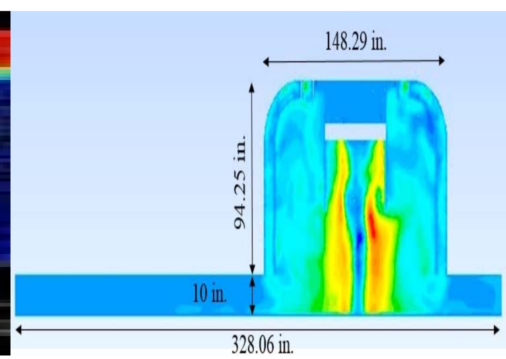
RESEARCH FRONTIERS

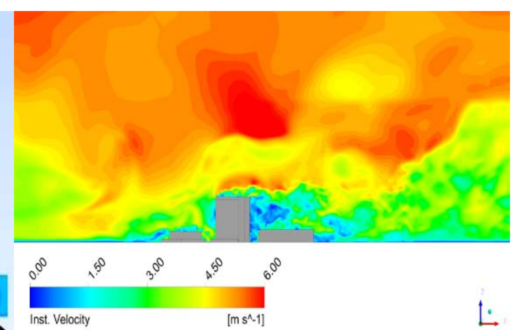


Wind Tunnel



Full-Scale (SWERF)



Computational

THANK YOU!

Research Website: http://publish.illinois.edu/ftlombardo/