RISE:2019

Abstract ID#: 2502
Category: Engineering and Technology
Graduate

Northeastern University

Analytical Methodology for the Performance-based Assessment of Vertical Structures Impacted by Thunderstorm Downburst and Tornado Wind Loads

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OPPORTUNITY

- Average annual insured losses from severe convective storms (including ***tornadoes*** and ***thunderstorm downbursts***) in the United States amount to ***11.23 billions dollars*** (adjusted for 2016).
- Despite significant strides made in improving investigations of microscale transient wind actions on the built environment, the ***stochastic, non-stationary numerical structural analysis*** is still hampered by its ***heavy computational demand***.
- The study proposes a computationally efficient ***performance-based wind engineering (PBWE)*** methodology that will enable ***smarter, more risk-informed decisions*** in severe-windstorm-prone environments using numerical (e.g. machine learning algorithms) and physical simulations (e.g. wind tunnel experiments).

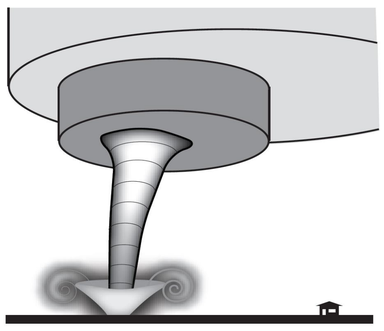
Introduction

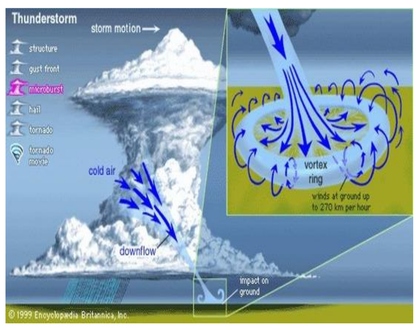
Tornado

- Microscale columns of violently ***rotating*** and ***ascending*** air
- Average radius 100 m
- Tangential velocities between 18 (EF0 - Enhanced Fujita scale, Cat. 0) and 140 m/s (EF5)

Thunderstorm Downburst

- Strong ***descending*** downdraft of air
- Usually less than 4 km in diameter
- Capable of wind speeds comparable to those of EF3 tornado (74 m/s)

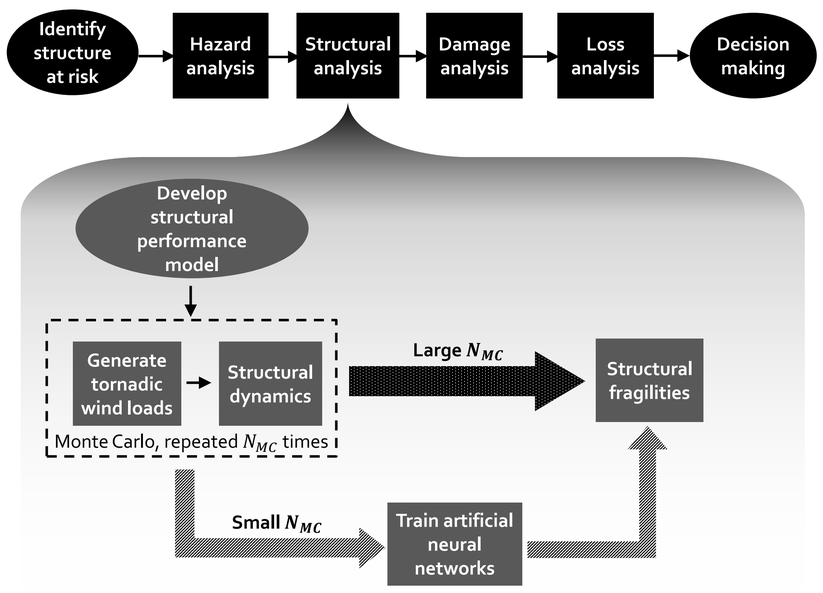




(Left) Schematic of formation of tornado funnel cloud from thunderstorm (Source: Stull, R., 2016, "Practical Meteorology: An Algebra-based Survey of Atmospheric Science")

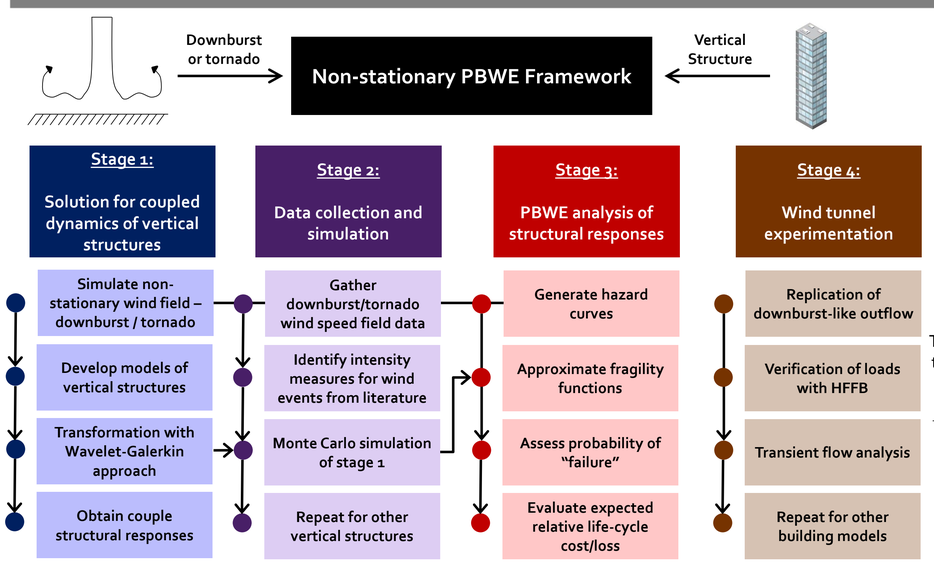
(Right) Schematic of formation of thunderstorm downburst (Source: Krider, Phillip E., "Britannica Encyclopedia: Thunderstorm")

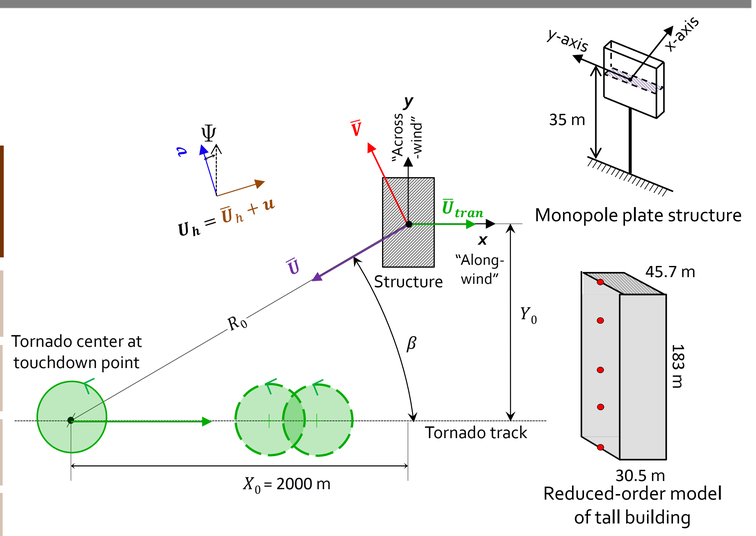
Performance-based Wind Engineering



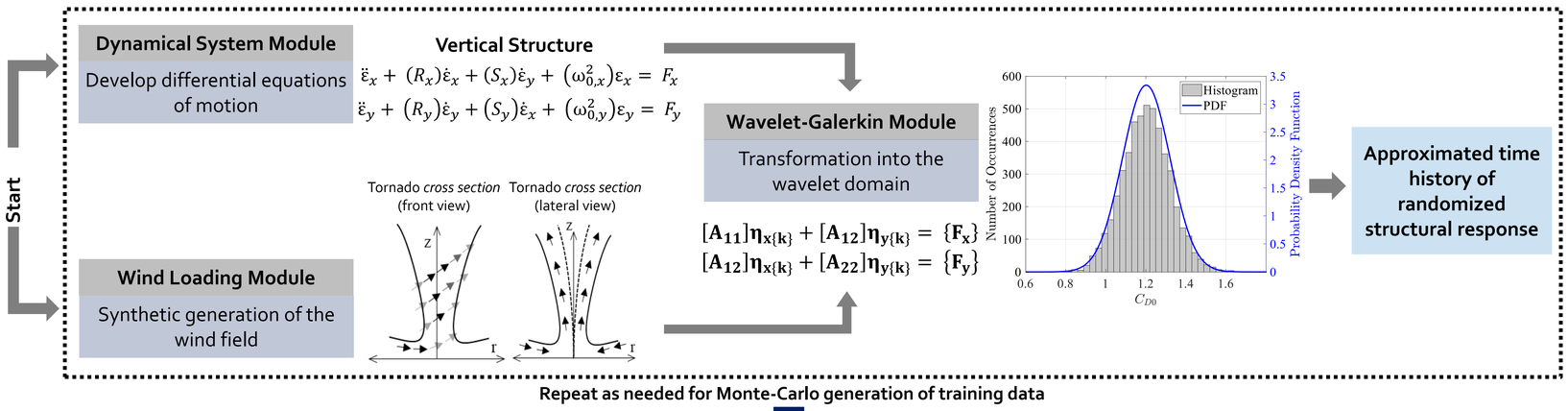
Work flow of performance-based methodology

APPROACH





Stages 1 and 2



DATA/RESULTS (STAGE 3)

Fragility Module

Approximate fragility functions

Limit State Thresholds, T_C and T_P

$$T_C = \frac{183}{400}\text{m}$$

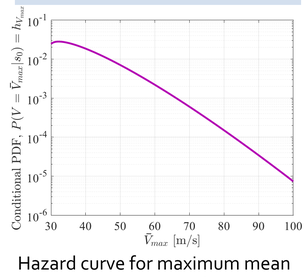
$$T_P = \frac{35}{10}\text{m}$$

Complementary Cumulative Distribution Function

$$F_T(IM) = P[q^{max} > T_i | IM]$$
$$i = C, P$$

Hazard Module

Develop hazard curves

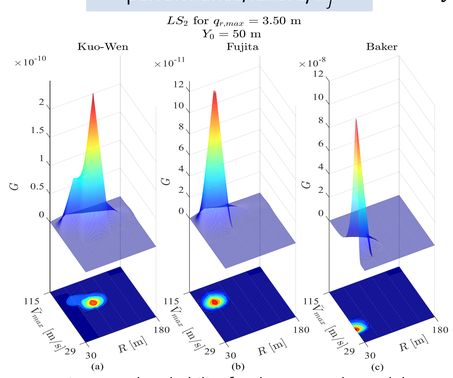


Hazard curve for maximum mean tangential velocity of tornado

Risk Assessment Module

Calculate probability of performance/failure, P_f

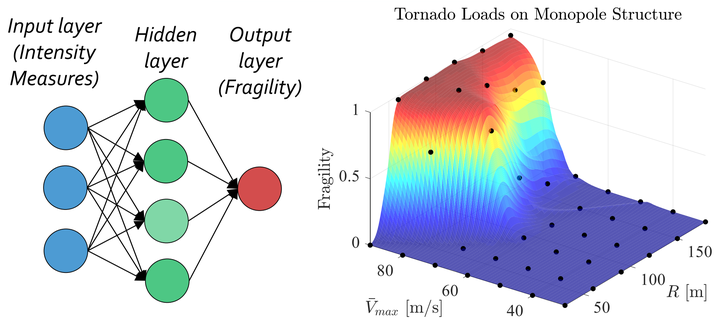
$$P_f = \int F_T(IM)h(IM)\mathrm{d}IM$$



Integrand probability for three tornado models

Machine-learning Module

Smart predictions

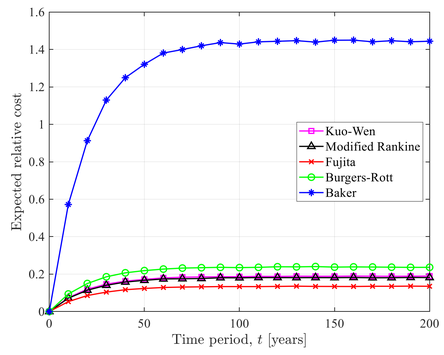


(Left) Schematic of example feedforward neural network.
(Right) Neural network fitting of a fragility surface. R tornado vortex radius, V_{max} max. mean tangential wind speed

Cost Module

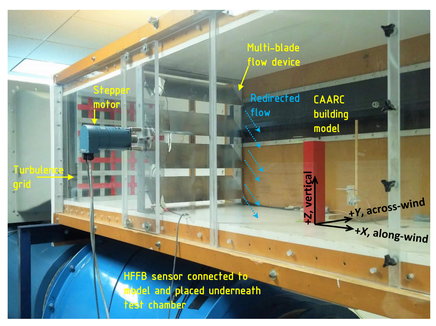
Evaluate life-cycle intervention costs

$$\mathrm{E}\left[\frac{C(t) - C_0}{C_0}\right] = \mathrm{E}\left[\sum_{i=1}^{N(t)}\sum_{j=1}^{k}\epsilon_j e^{-\lambda t_i} P_j\right]$$

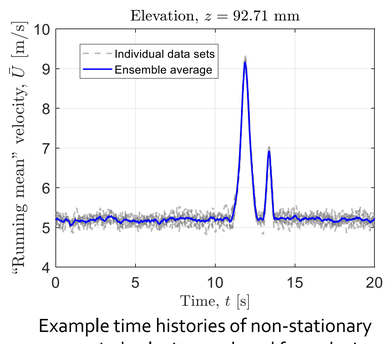


Relative cost curves for *tornado* loading on monopole, plate structure, using several tornado models (Kuo-Wen, Modified Rankine, Fujita, Burgers-Rott and Baker)

DATA/RESULTS (STAGE 4)



Experimental setup – multi-blade flow device



Example time histories of non-stationary mean wind velocity produced from device

IMPACTS

- More efficient, risk-informed decisions will aid owners and stakeholders in evaluating their investments. Resources can be reallocated to adequately meet the performance needs of their target structures.
- Flexible simulation framework can be extended to a variety of building types under a range of non-stationary wind loading scenarios.
- The novel multi-blade transient flow device (wind tunnel) opens up opportunities to replicate non-stationary wind loads, overcoming the physical constraints of small-scale wind tunnels.

Acknowledgements

- National Science Foundation (USA), Grant CMMI 1434880 (2014 to 2018)
- Robert W. Bordewieck Endowed Engineering Fund, College of Engineering, NEU (Summer 2019)
- MathWorks Inc. Micro-grant for seed funding, awarded through Prof. Miriam Leeser, ECE Department (2019-2020)
- Dr. Thai-Hoa Le (SOH Wind Engineering, Williston VT, USA), for numerical code development