Performance-based Framework for the Evaluation of Non-stationary Wind Loads on Vertical Structures

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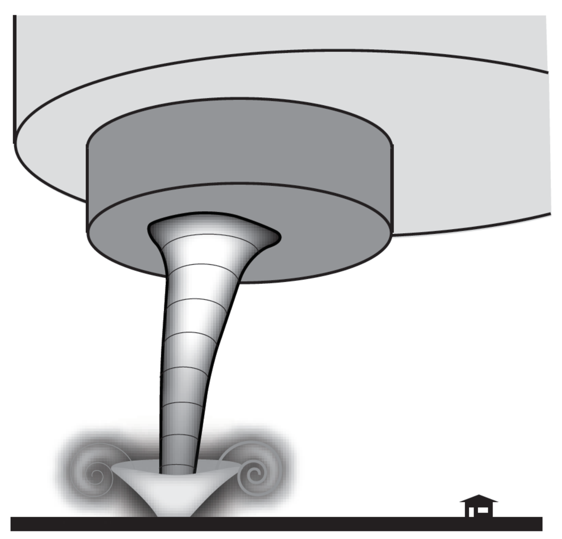
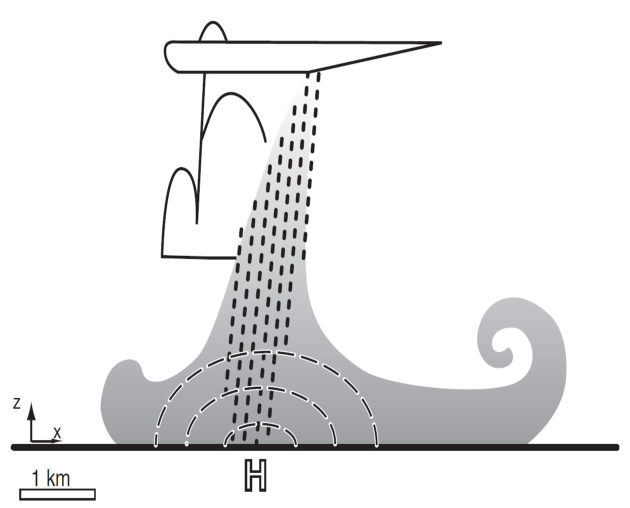
Introduction

Nonstationary Wind Phenomena

- Thunderstorm **downbursts** and **tornadoes** present challenging structural engineering problems due to intense wind loading effects
- Average annual insured losses from severe convective storms in the United States amounted to **11.23 billion dollars** in 2016.





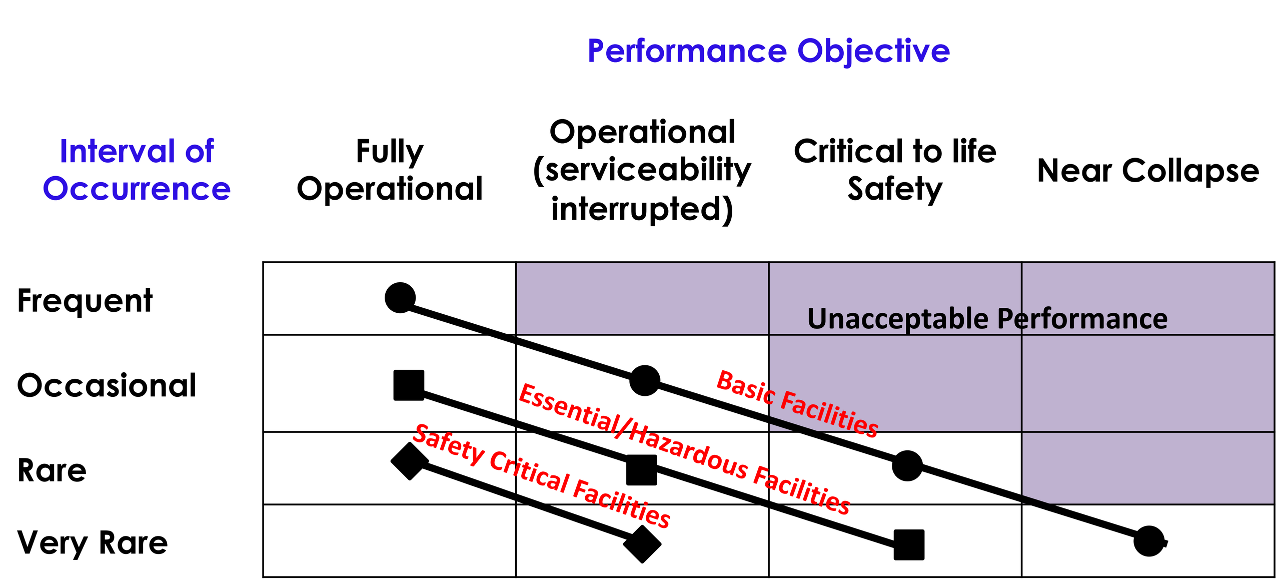
(Left) Schematic of tornado funnel cloud and downburst.
(Source: Stull, R., 2016, "Practical Meteorology: An Algebra-based Survey of Atmospheric Science")

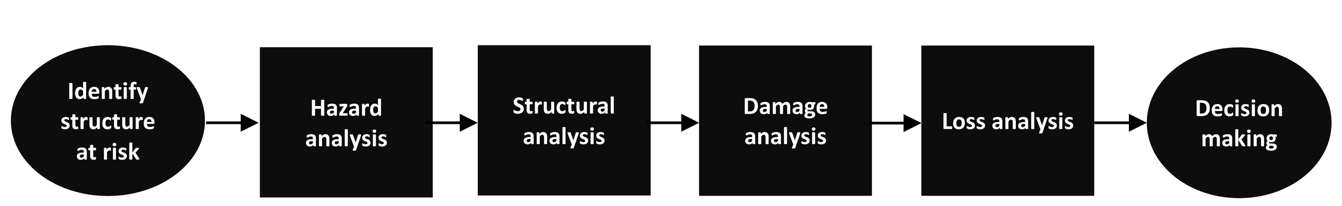
(Top right) Tornado touching down in Laramie, Wyoming.
(Source: Amateur photograph from Time magazine)

(Bottom right) Thunderstorm downburst touching down over Phoenix, Arizona .
(Source: Amateur photograph from Chopperguy Aerial Productions)

Performance-based Engineering (PBE)

- Enables flexibility in engineering design while maintaining cost-effectiveness, satisfying **performance objectives**, and ensuring structural safety for occupants and users.
- Incorporates aleatory and epistemic sources of **uncertainty**





Methodological Framework

Stage 1: Solution for coupled dynamics of vertical structures

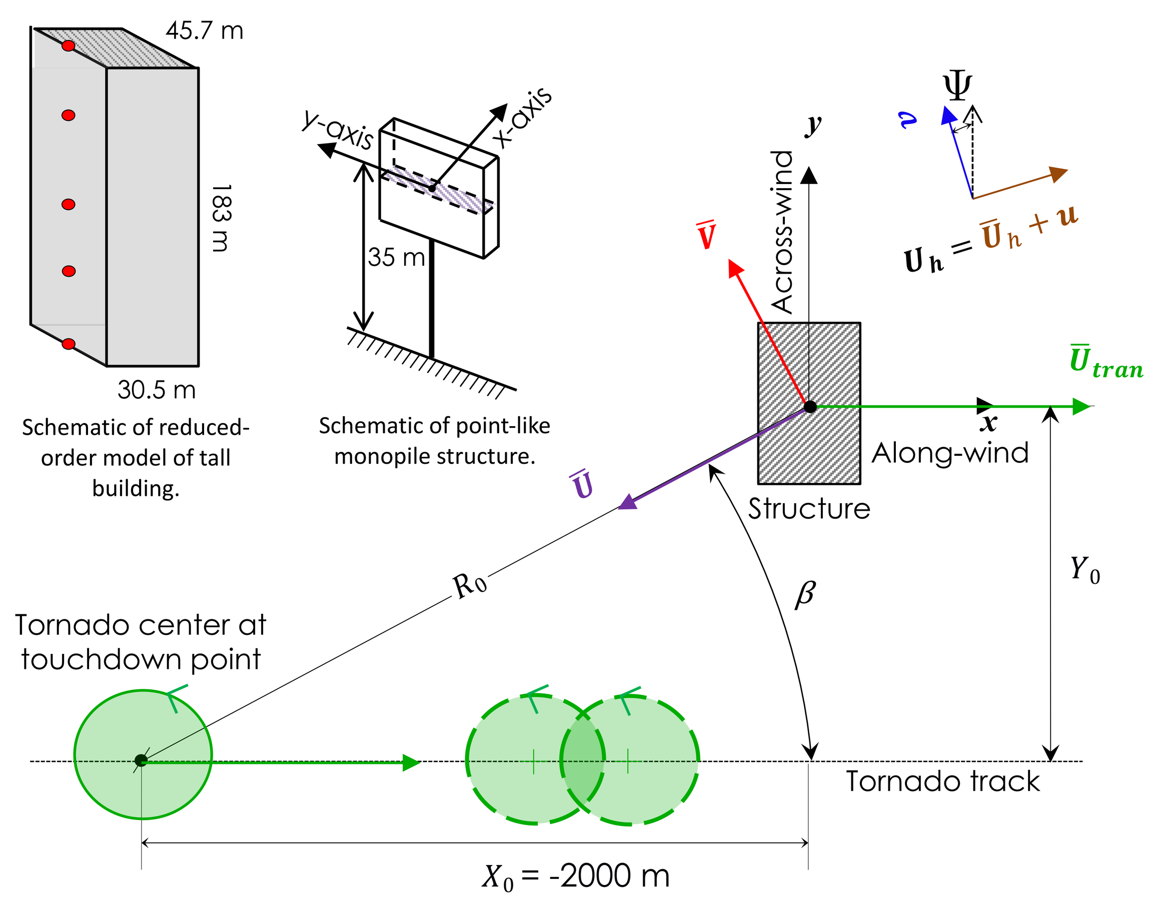
Stage 2: Data collection and simulation

Stage 3: PBE analysis of structural responses

Stage 4: Wind tunnel experimentation

Stage 1 and Stage 2

- Select a **monopole structure** and a **benchmark tall building**
- Replicate downburst and tornado **wind field**
- Solve for the dynamics of the structures
- Reproduce **stochastic variability** with Monte Carlo sampling

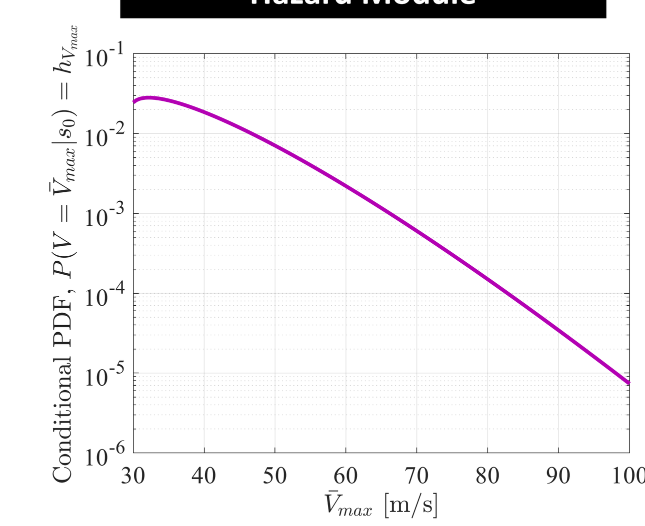


Plan view schematic of fluid-structure system

Stage 3

- Approximate **fragility functions**
- Use machine learning (**artificial neural networks**) to expedite approximations
- Develop **hazard curves**
- Evaluate risk by convolution of probabilities
- Translate risk into economic terms through **life-cycle cost assessment**

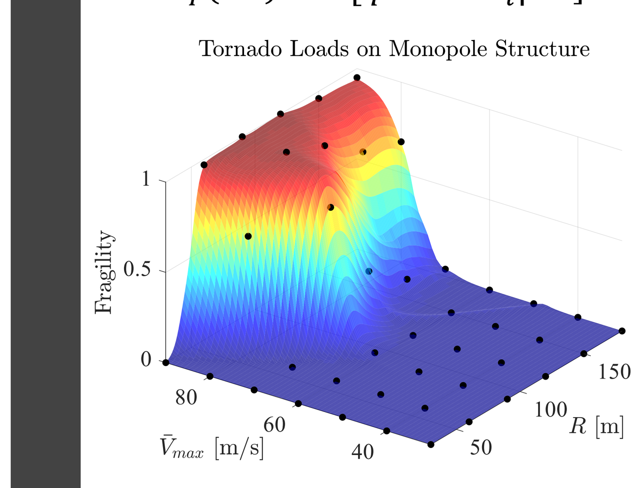
Hazard Module



Hazard curve for maximum mean tangential velocity of tornado

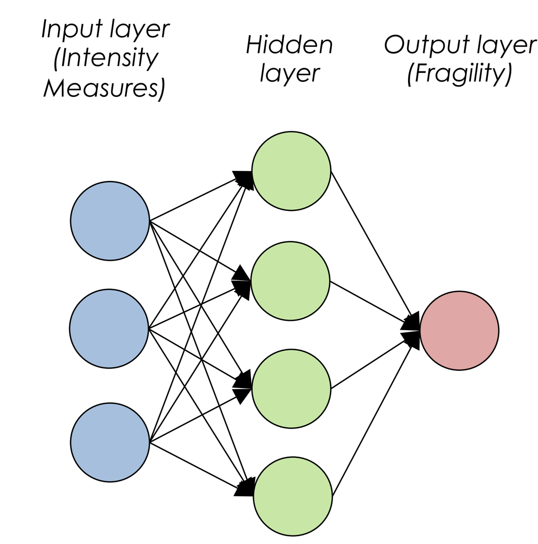
Fragility Module

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



Numerically generated fragility surface

Machine-learning Module

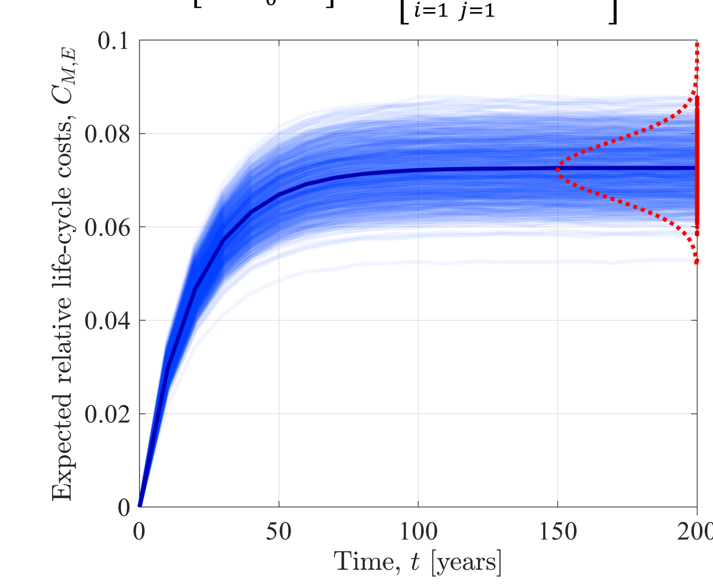


Artificial neural network serving as surrogate models for fragility

$$P_f = \int_{x=0}^{x=\infty} F_T(IM)h(IM)dIM$$

Cost Module

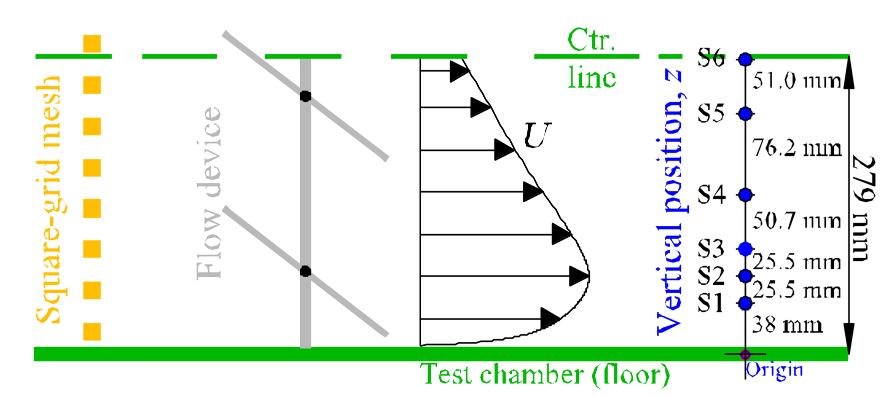
$$E\left[\frac{C(t)-C_0}{C_0}\right] = E\left[\sum_{i=1}^{N(t)}\sum_{j=1}^{k} \epsilon_j e^{-\lambda t_i} P_j\right]$$



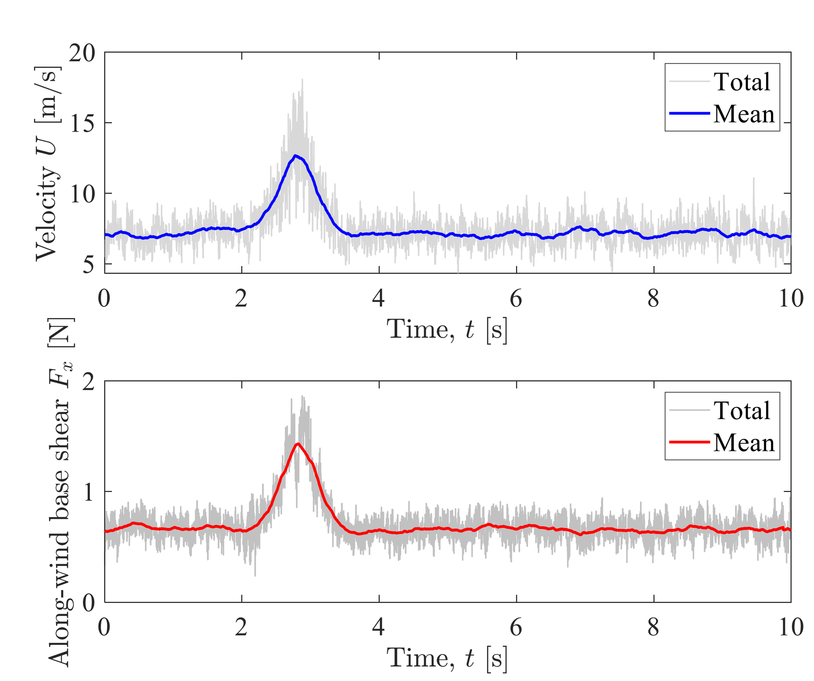
Life cycle costs considering repair or intervention

Stage 4

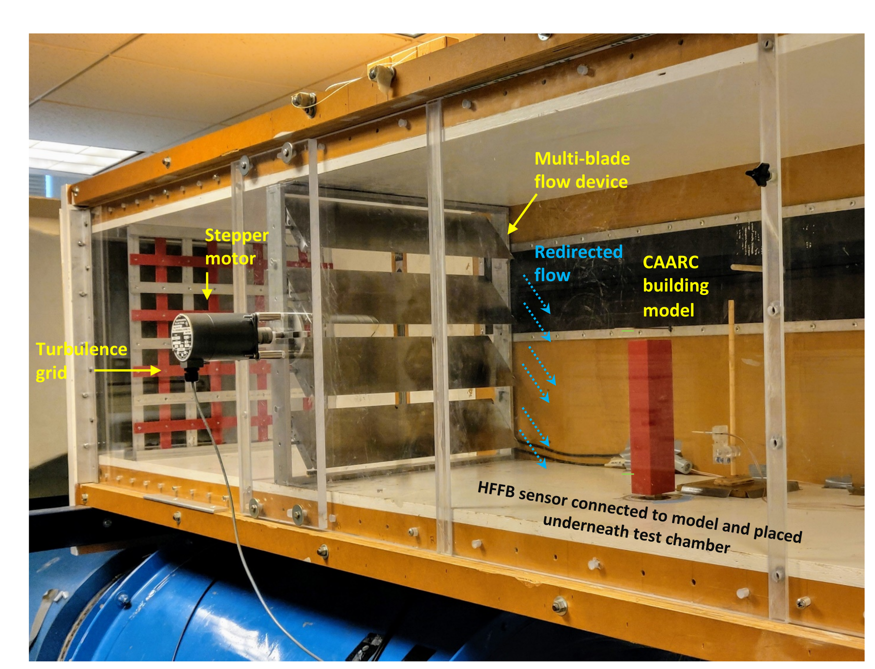
- Design a **multi-blade flow device**
- Replicate downburst-like outflow (**nose-like profile**)
- Verify loads with **high frequency force balance (HFFB)** sensor
- Compute structural responses
- Physically-informed numerical Monte Carlo simulations



Schematic of flow device and induced nose-like wind velocity profile



Example of experimental results



Experimental setup: multi-blade flow device

Impacts

- More efficient, risk-informed decisions will aid owners and stakeholders in evaluating their investments. Resources can be reallocated to 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.

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