Lehigh-FIU Hybrid Wind Simulation Developments

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FIU Wall of Wind
NHERI Experimental Facility

LEHIGH UNIVERSITY.

RTMD
REAL-TIME MULTI-DIRECTIONAL SIMULATION
NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE

NSF

Outline

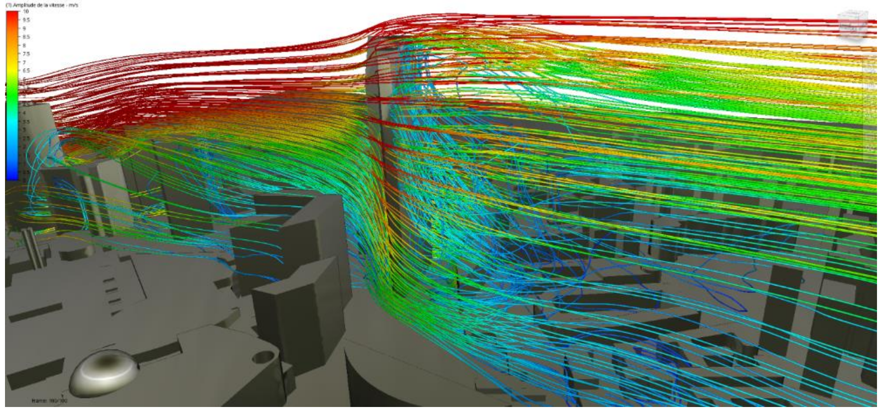
- Individual Tools in Wind Engineering
- Examples of Possible HS Applications in Wind Testing
- RTHS Advantages in Wind Engineering
- FIU-Lehigh NHERI EFs Collaboration
- Case Study: Tall building with Rooftop Mast and Challenges
- Project Description: Phase I and Phase II

Individual Capabilities vs. Hybrid Simulation

Wind Testing (WT)

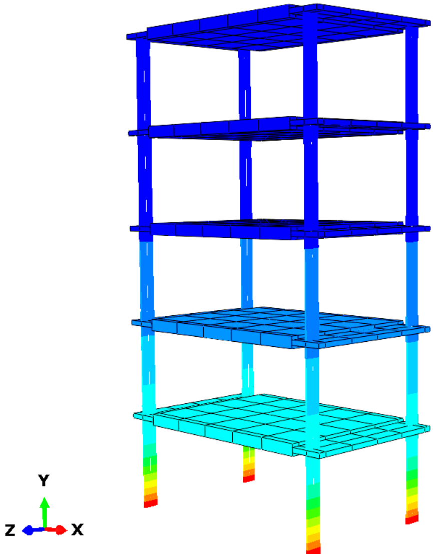
Tamani, Tower Dubai, UAE; Courtesy of BLWT, UWO

CFD Simulation



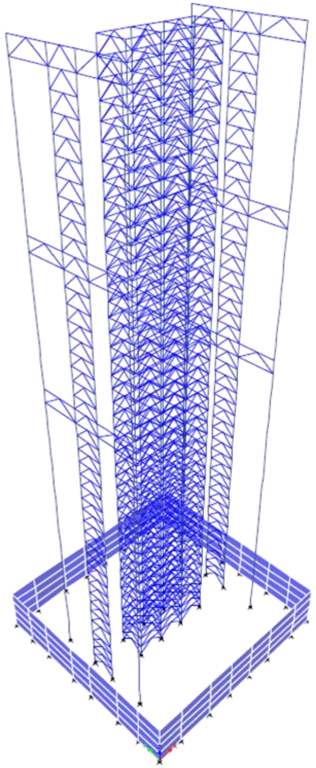
http://www.inex.fr/

Finite Element Modeling + WT or CFD



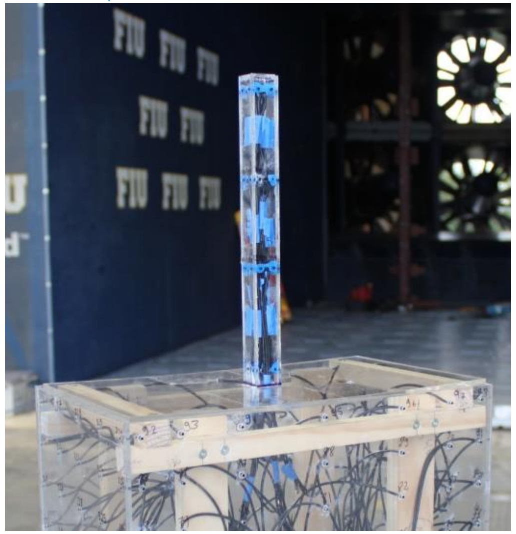
Hybrid Simulation?

Numerical Substructure



Numerical Simulation Data

Physical Substructure



Physical Response Data

Examples of Possible HS Applications in Wind Testing

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- Transmission tower systems: conductors are modeled as <u>substructure</u>.
- Cladding systems vibrations and water penetration: cladding panel as a <u>substructure</u>.
- Offshore structures (wind turbines; floating substructures): wave actions on submerged system modeled using actuators and WT as <u>substructure</u>.
- Damping systems on a tall building: damper system and building potion as <u>substructure</u>.
- Communication infrastructure, Traffic signals, Variable Message Signs.

RTHS Advantages in Wind Engineering

- Allows substructure to be modeled physically at large scales in wind tunnels. This significantly helps to eliminate possible scaling effects.
- Allows coupling wind testing with a numerical model that captures nonlinear effects for the entire structure.
- Allows better simulation of wind-structure interaction and aerodynamic damping effects using large-scale experiments.
- Allows combining different loading scenarios on structures to study multi-hazard effects (e.g. wind and flooding effects).

FIU-Lehigh NHERI EFs Collaboration

- Lehigh RTMD EF – FIU WOW EF collaboration aims at advancing wind testing using Real-Time Hybrid Simulation (RTHS) methodology.
- The collaborative project enables developing RTHS for applications to wind engineering using FIU's Wall of Wind and Lehigh University's Hybrid simulation expertise.
- A case study related to communication towers industry was carefully selected to initiate the collaboration.

Case Study: Tall building with Rooftop Mast

Prudential Tower, Boston, MA

One World Trade Center, NY

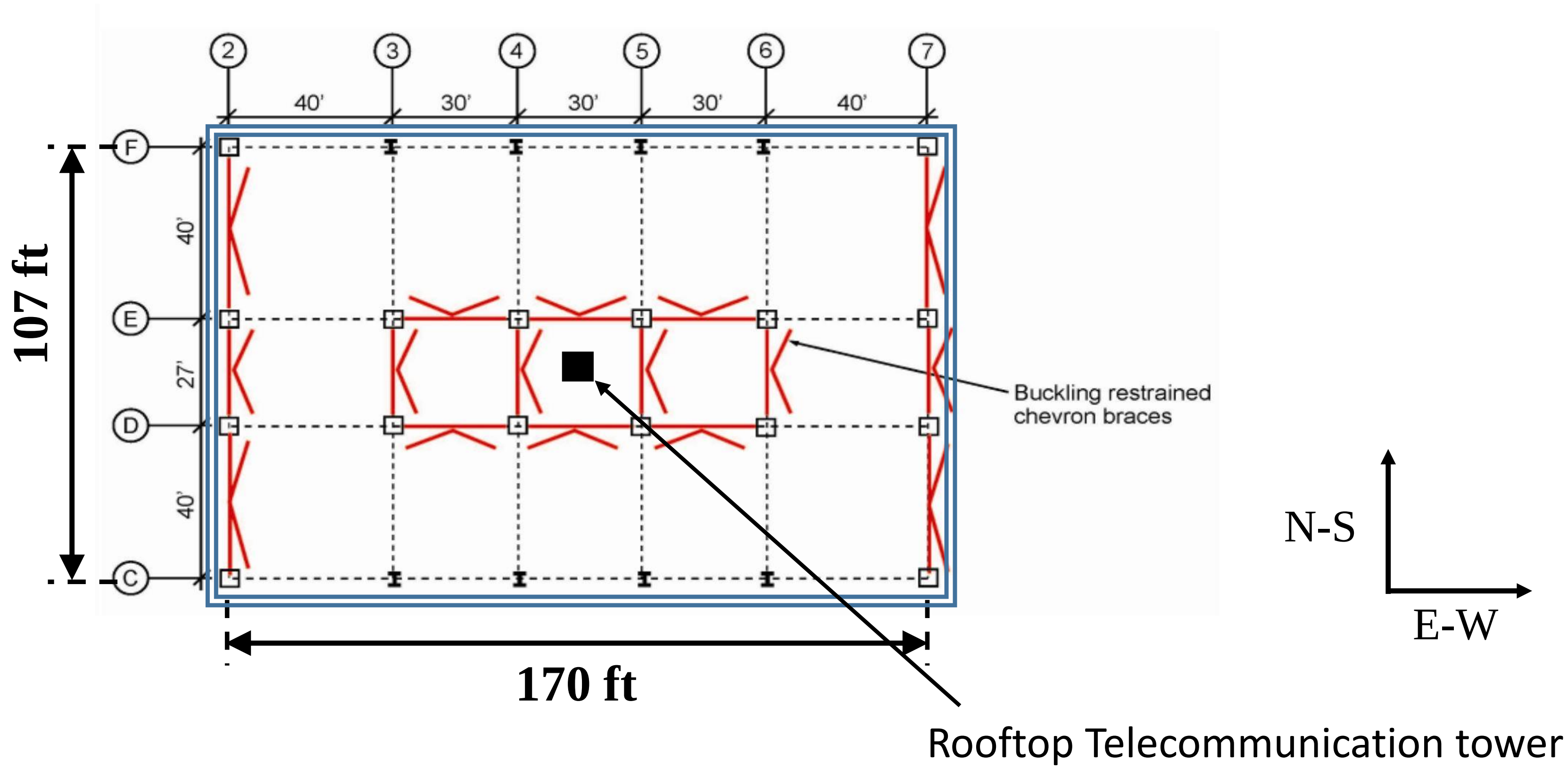
Taipei, Taiwan

Willis Tower, IL

Selected Case Study

Prototype: 40 Story Building:

- Located in Los Angeles designed by SGH for PEER Tall Building Initiative.
- The current study adopts a rooftop monopole communication structure.

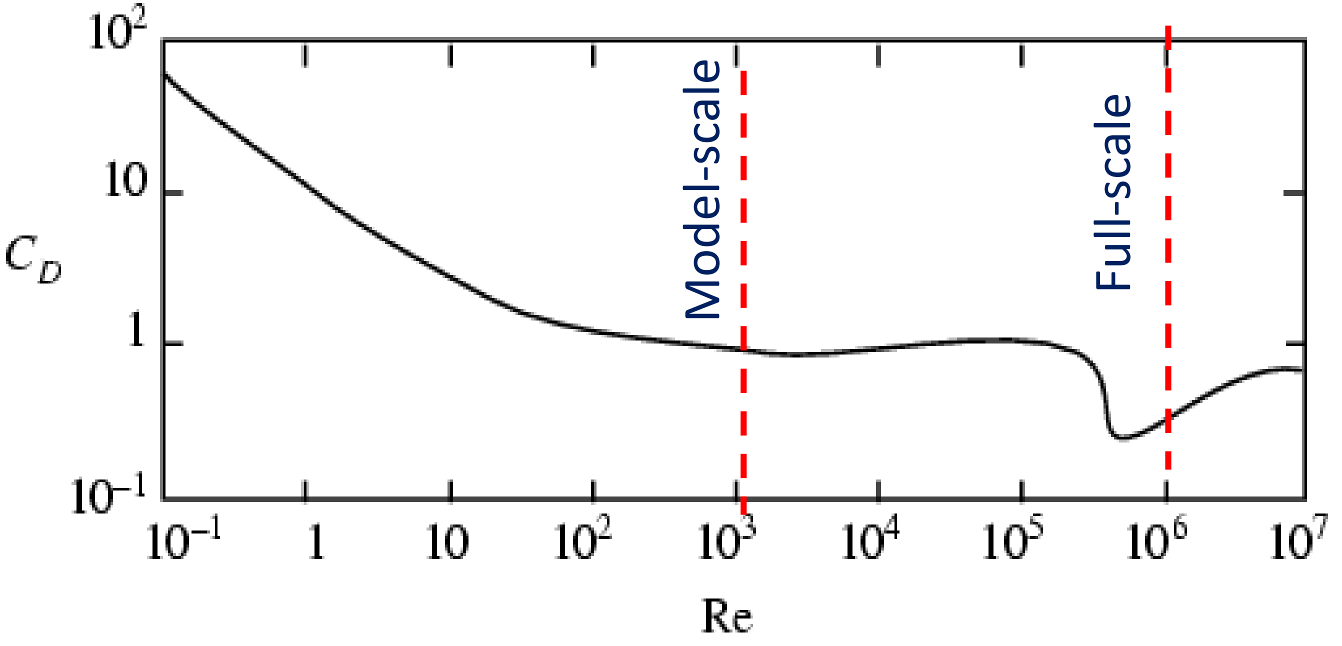


Ref.: Moehle et al., PEER 2011/05

Challenges Facing Rooftop Communication Towers

- Mast could be affected by higher modes of the building.
- The base of mast will be affected by displacements and titling of top portion of the building and there could be possible aeroelastic effects.
- Mast instability can result from galloping or vortex shedding. Such instability and large displacements can highly affect mast’s functionality.
- The aeroelastic effects and Re dependence of the aerodynamics cannot be modeled using FEM or WT testing separately.

Scaling Effects Challenges



Drag coefficient for a cylinder

For example:

Full-scale Re:
V=50 m/s
D=2 m (regular masts)
Re=6.7x10^6

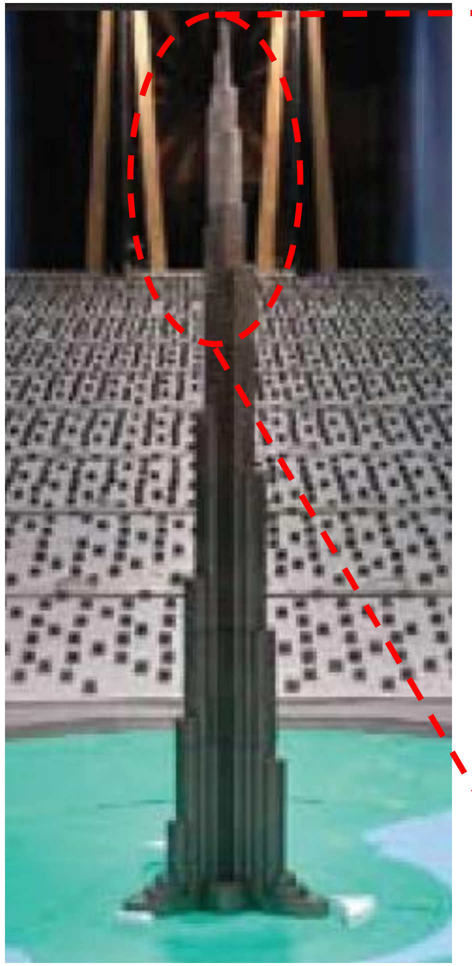
1:500 length scale
1:10 velocity scale

Model-scale Re:
V=5 m/s
D=0.004 m
Re=1.3x10^3

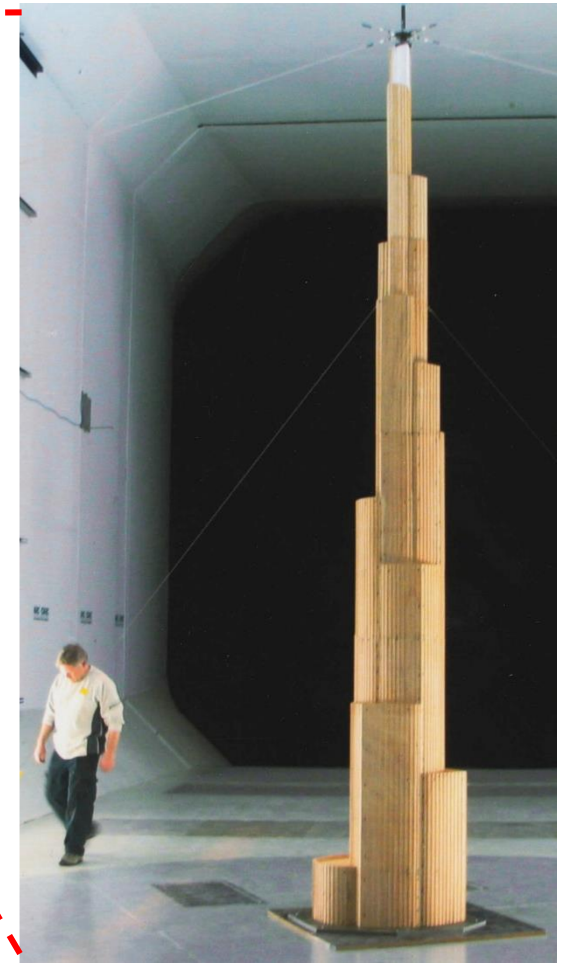
Scaling Effects Challenges

Curved Shanghai Center Tower, 1:500 model

A 1:85 scale model



A 1:500 scale rigid model of the Burj Dubai

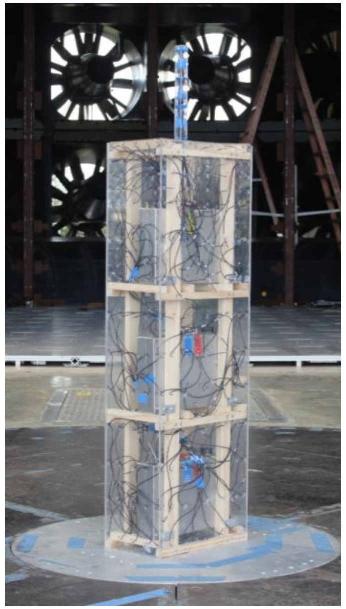


A 1:50 scale model

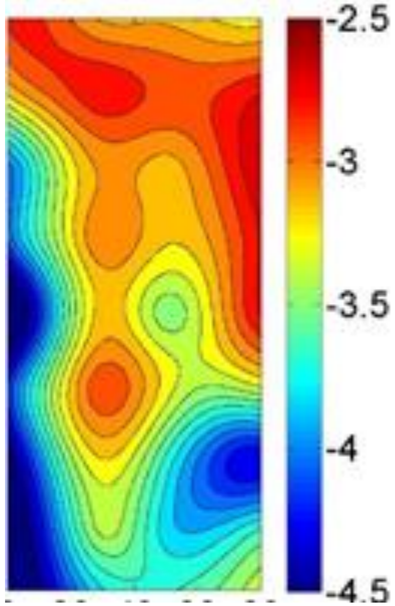
Project Description

Phase I:

- Aerodynamic wind pressure testing at NHERI WOW to establish baseline.

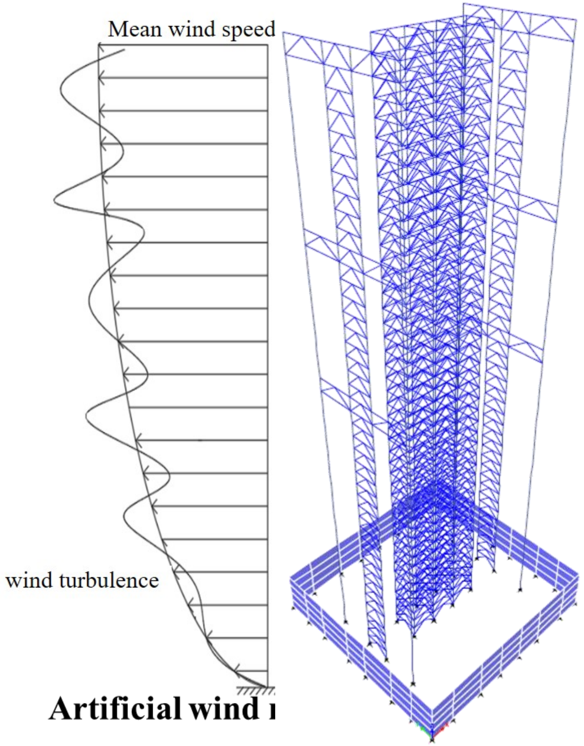


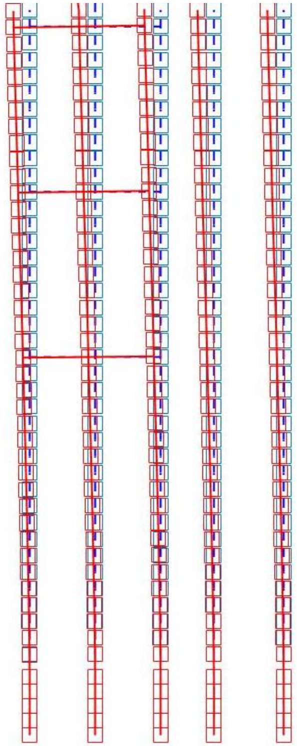
Aerodynamic model



Peak Cp contours

- Developing a 3D Finite Element Model for the building with the mast





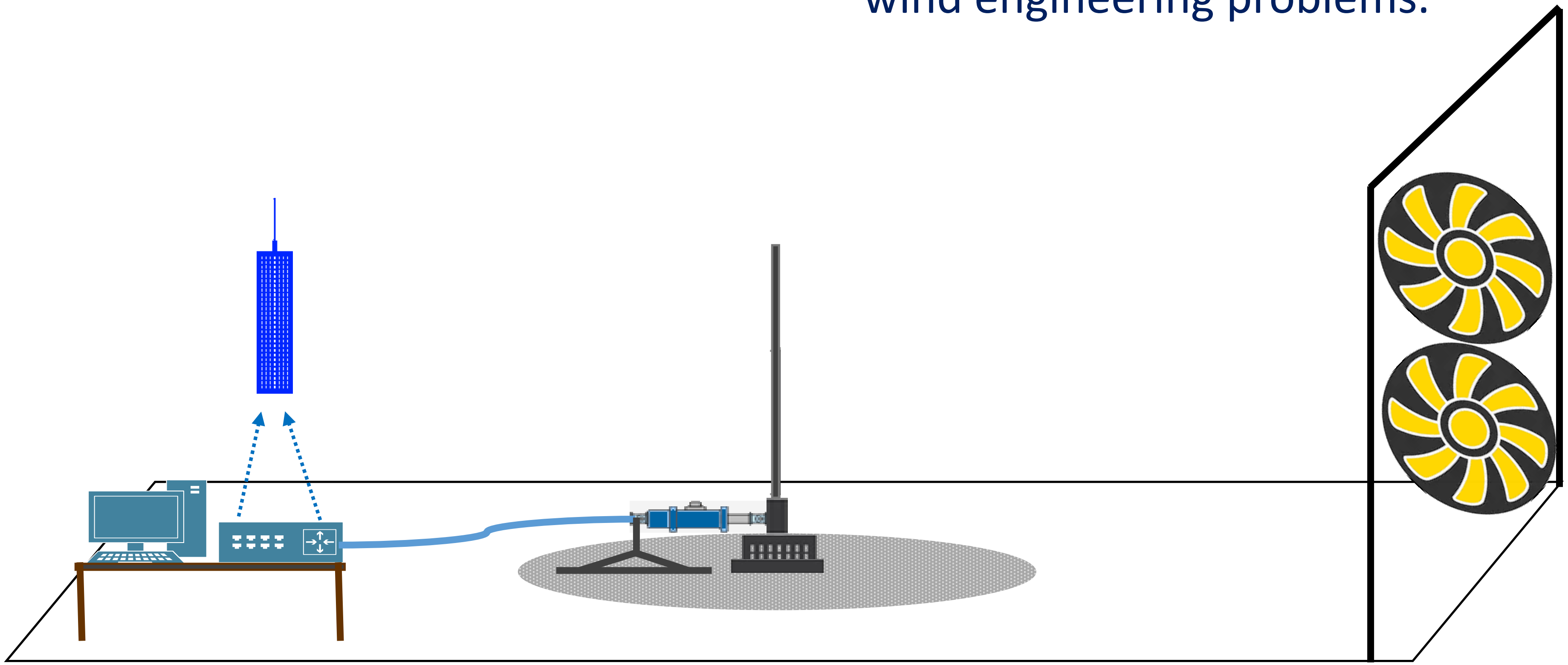
Project Description

Wall of Wind

NHERI Experimental Facility

Phase II:

- Aeroelastic RTHS testing at NHERI WOW.
- Assess RHTS results and broaden applications to wind engineering problems.



Project Description

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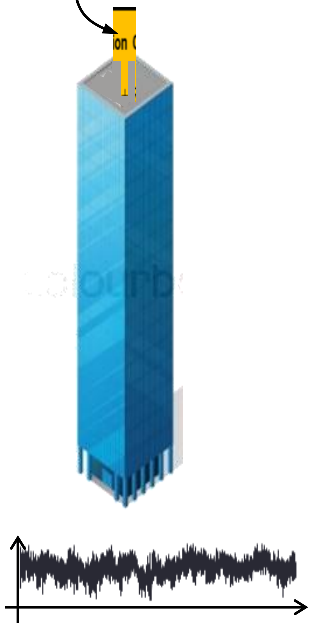
Structural System

40-Story Building with Outriggers and Supplemental Dampers

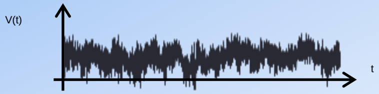
Monopole



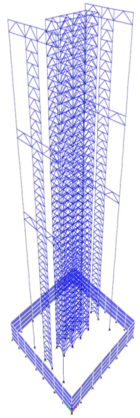
Wind Loading

Hybrid Wind Simulation Experiments

Real-time input (Wind Speed): Wind Tunnel



Analytical substructure



(Modeled in the computer)

Cmd Displ

$\mathbf{X}^a_{i+1}$

$\mathbf{R}^a_{i+1}$

Restoring Force

Simulation Coordinator

$$\mathbf{M}\ddot{\mathbf{X}}_{i+1} + \mathbf{C}\dot{\mathbf{X}}_{i+1} + \mathbf{R}^a_{i+1} + \mathbf{R}^e_{i+1} = \mathbf{F}^a_{i+1}$$

Integrates Eqns of Motion

Real-time structural response

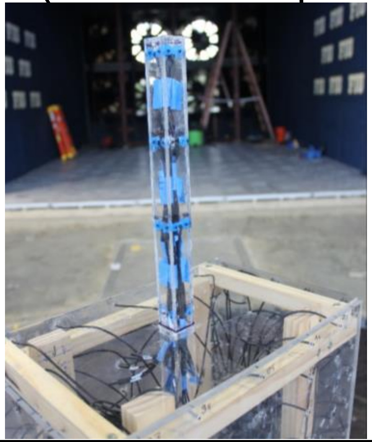
Cmd Displ

$\mathbf{X}^e_{i+1}$

$\mathbf{R}^e_{i+1}$

Interface Restoring Force

Experimental substructure (Elastic monopole)



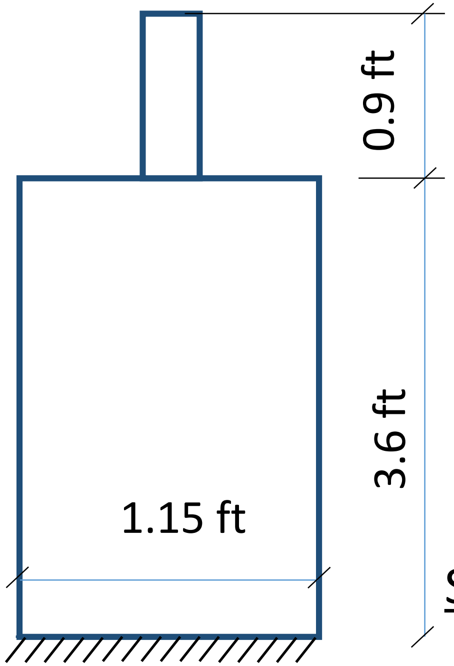
(Modeled in wind tunnel)

NHERI WOW Testing

Phase I

WOW testing-Phase I

- Aerodynamic wind testing at the NHERI WOW to obtain wind pressure time histories distributed on both the building and the mast.
- Model length scale is taken to be 1:150.
- Varying wind directions are considered.
- Mean wind speed of 40 mph.



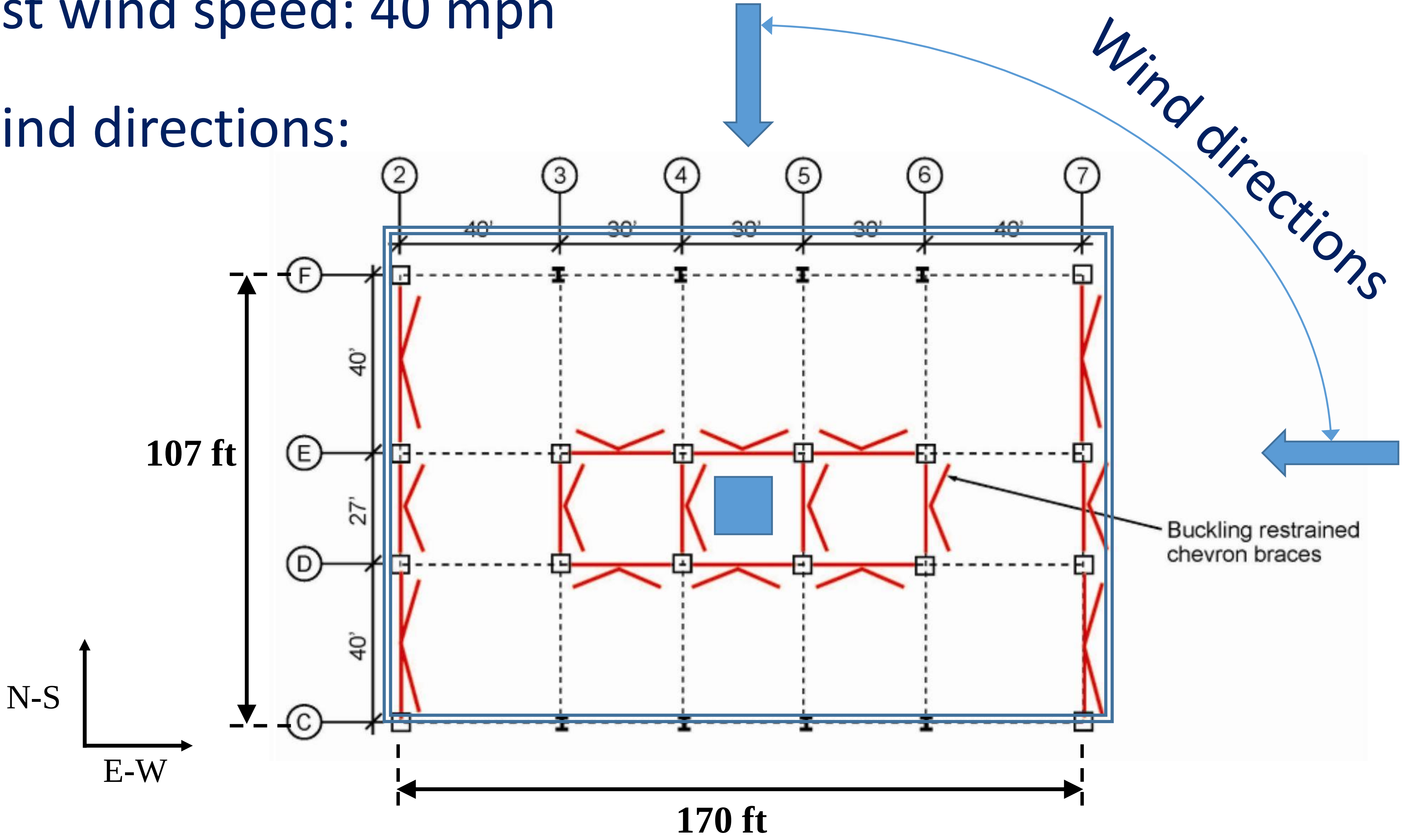
Scaled model 1:150

- The pressure time histories obtained from this phase of testing are used to perform FEM dynamic analysis of the building-mast system responses to determine configurations of the actuators needed for the aero-elastic test setup.

WOW testing

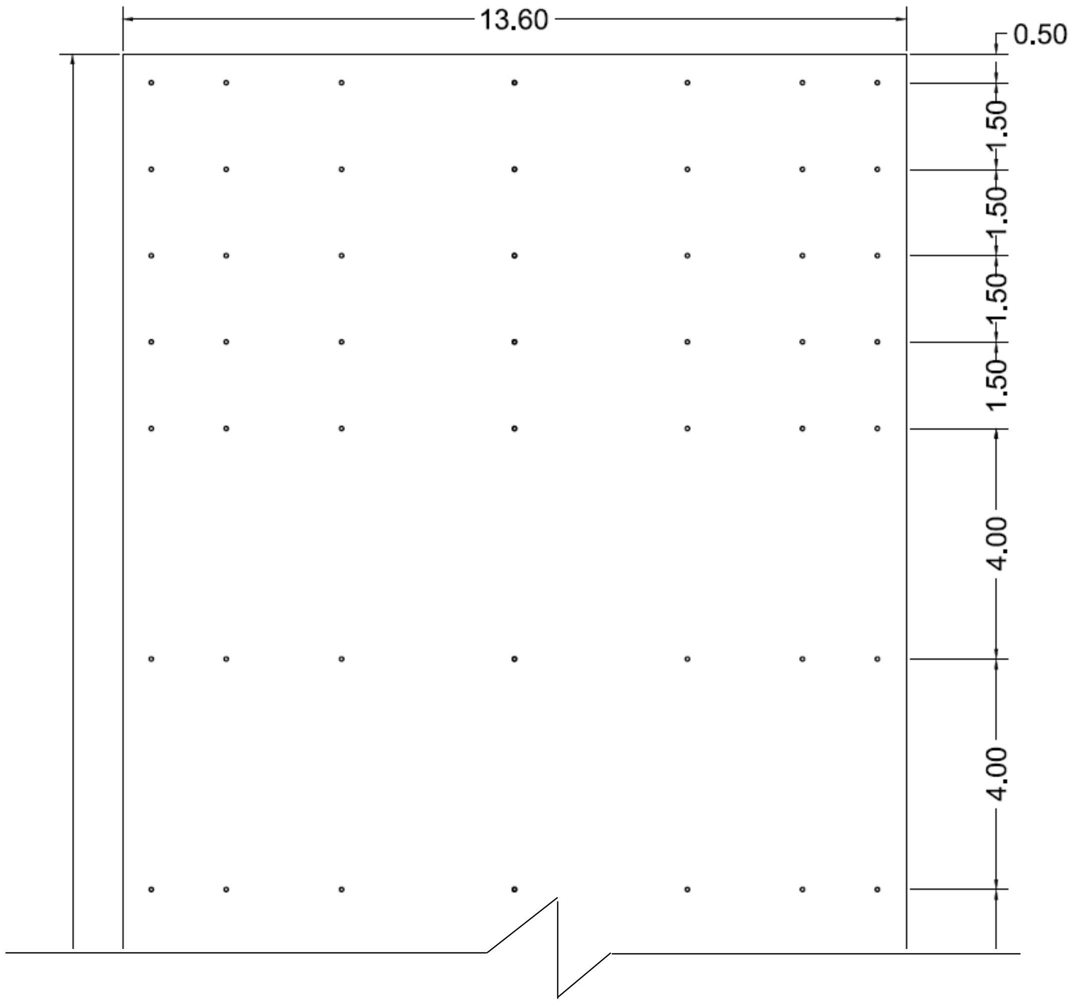
Test wind speed: 40 mph

Wind directions:

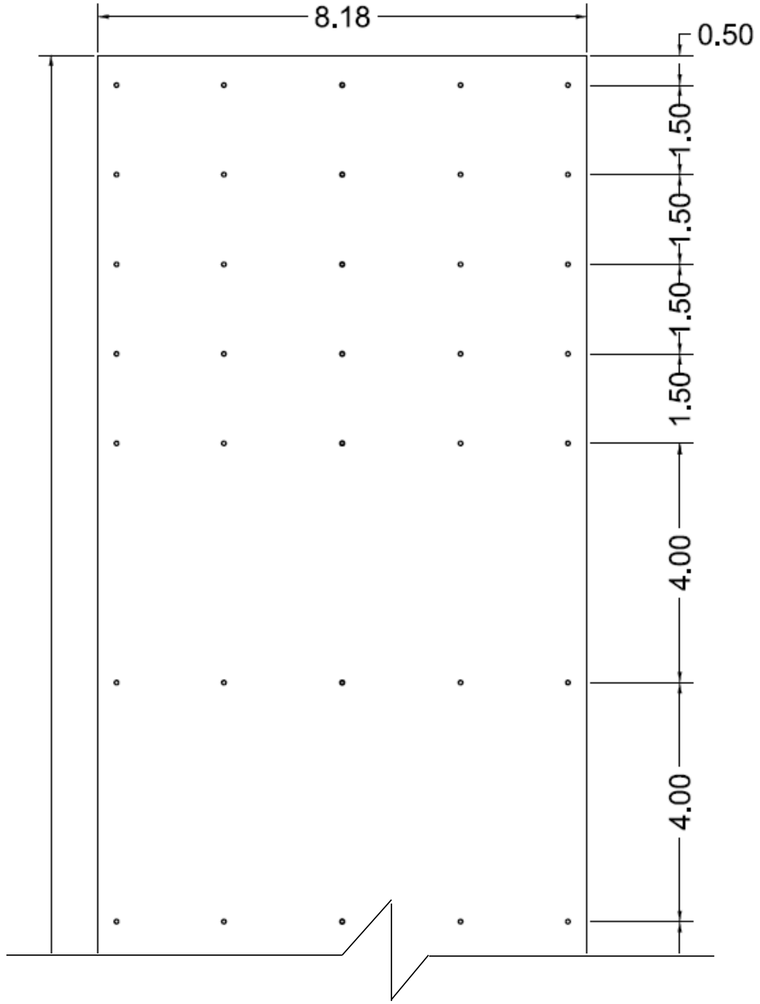


Pressure tap distribution

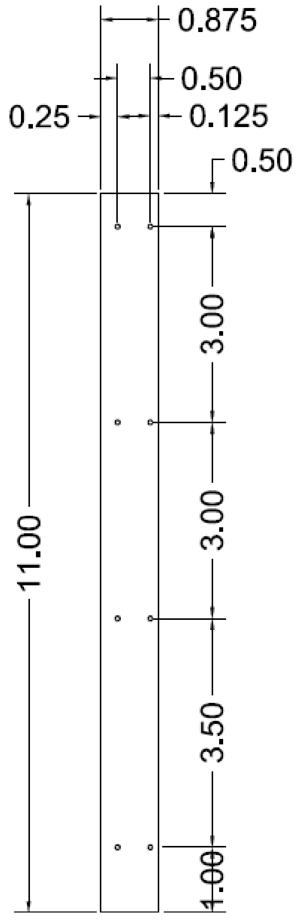
All dimensions are in inches



Building Front Wall



Building Side Wall



Spire Wall

WOW testing

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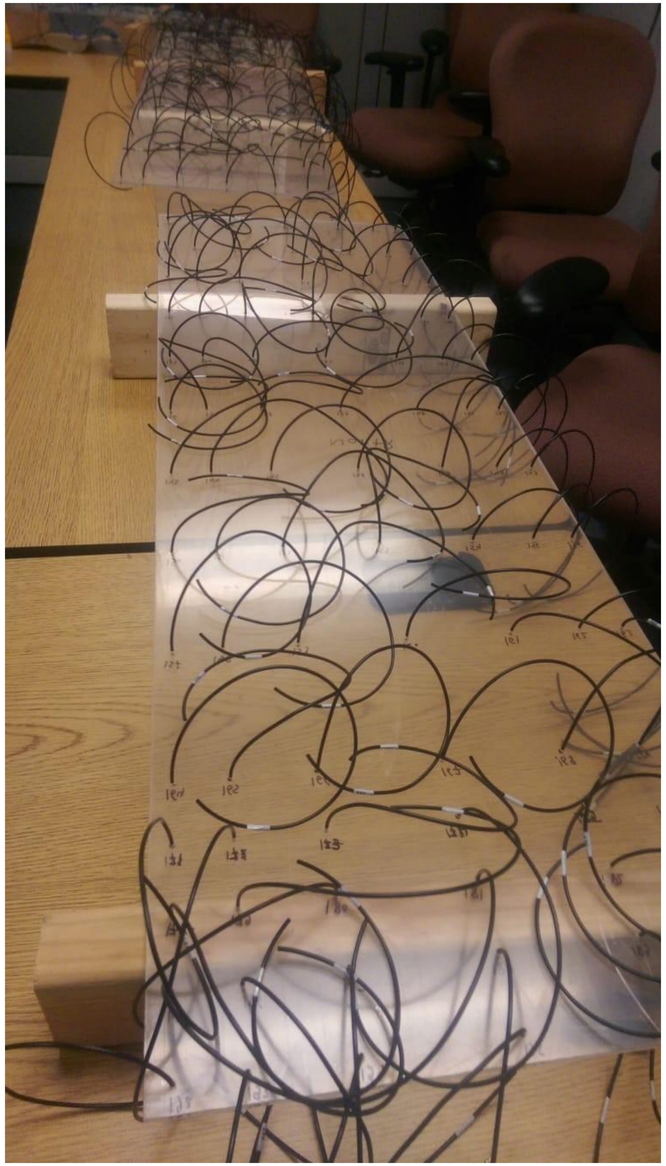
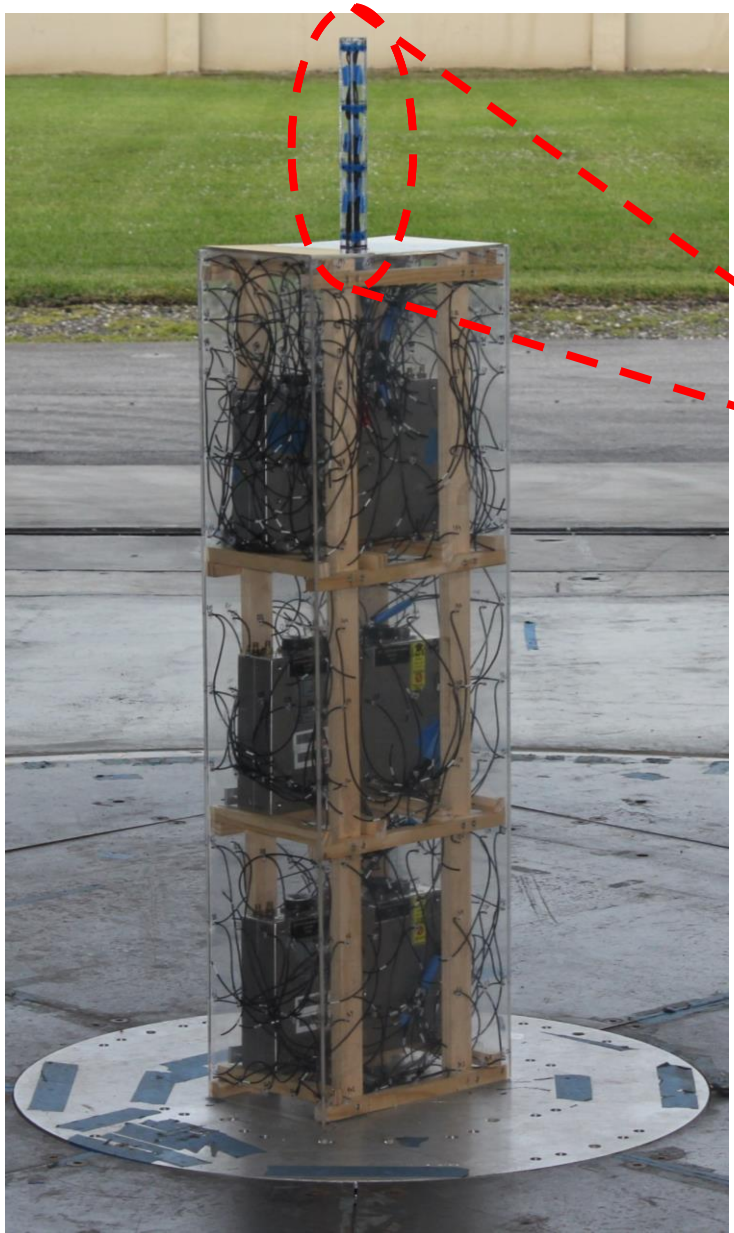
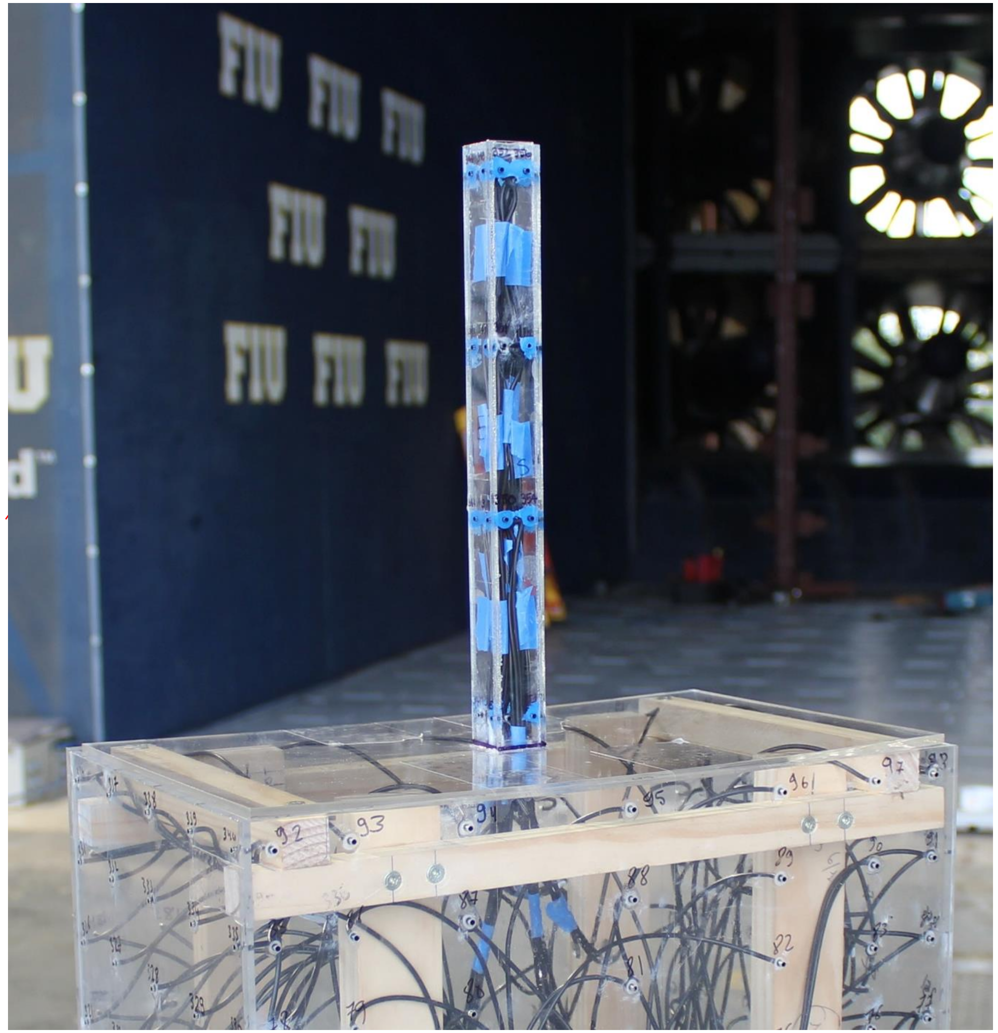


WOW testing

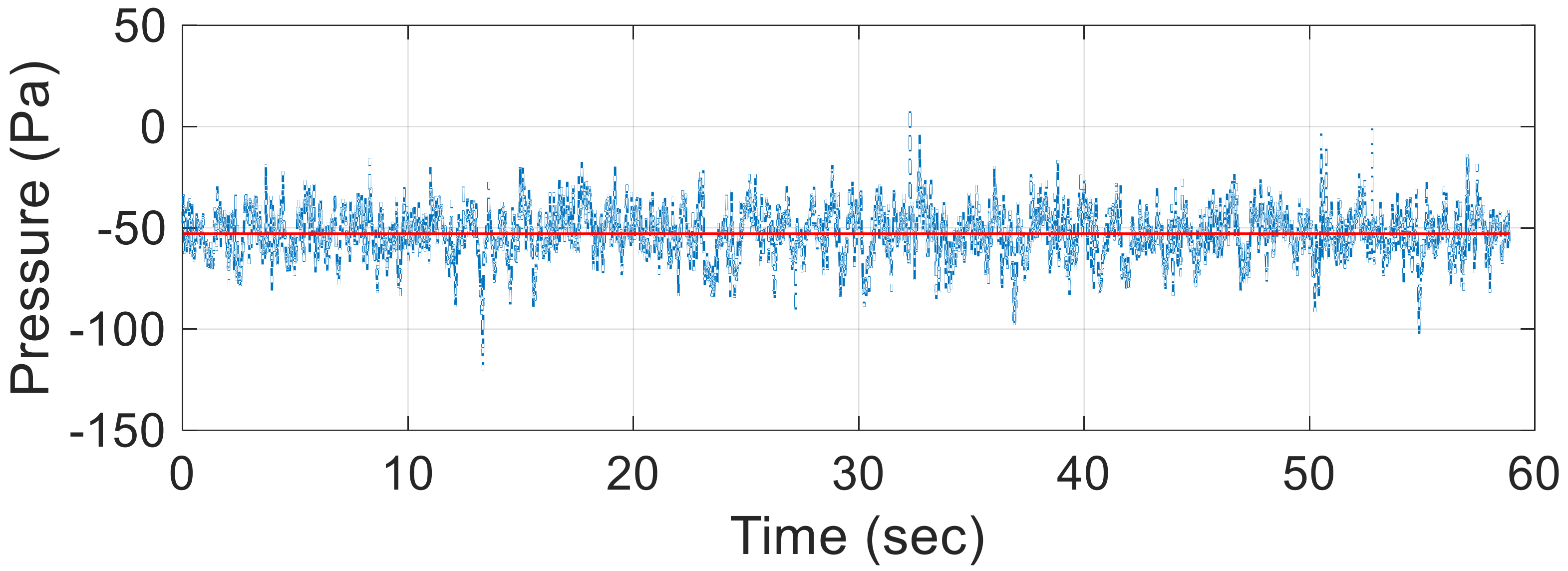




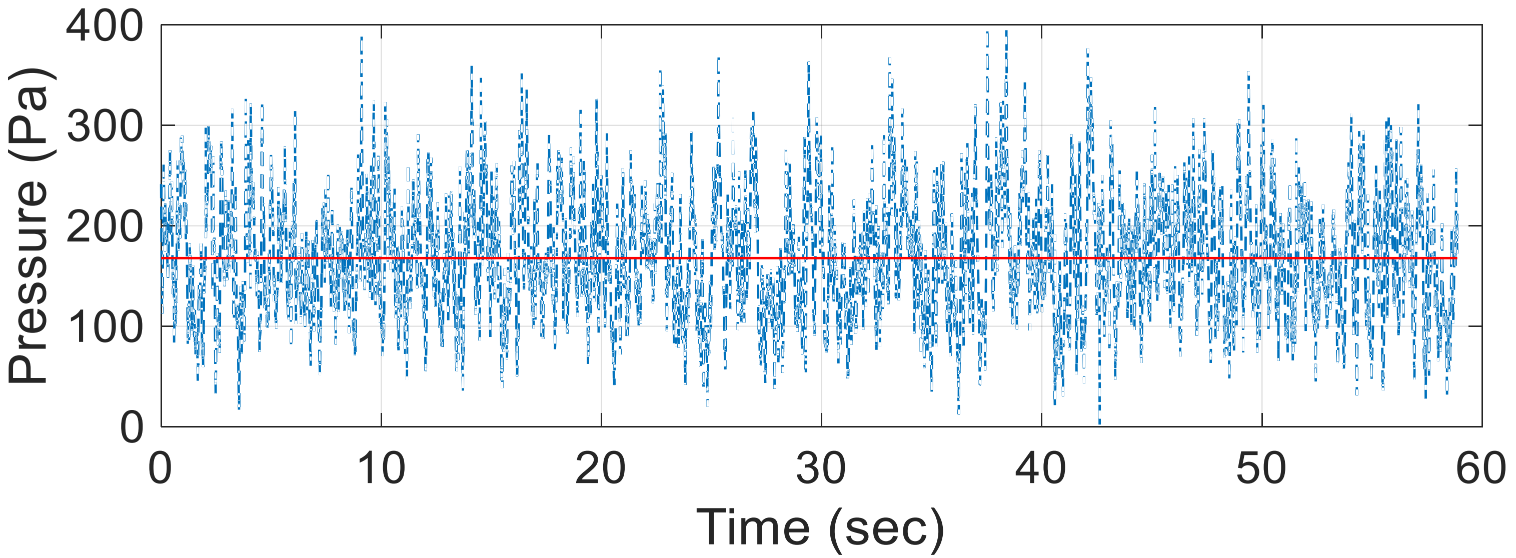
Roof top mast

Aerodynamic test: Scale 1:150

WOW testing



South wall



North wall

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NHERI WOW Testing

Phase II: RTHS

(Aeroelastic + Numerical Modeling)

WOW testing: Aeroelastic-Numerical

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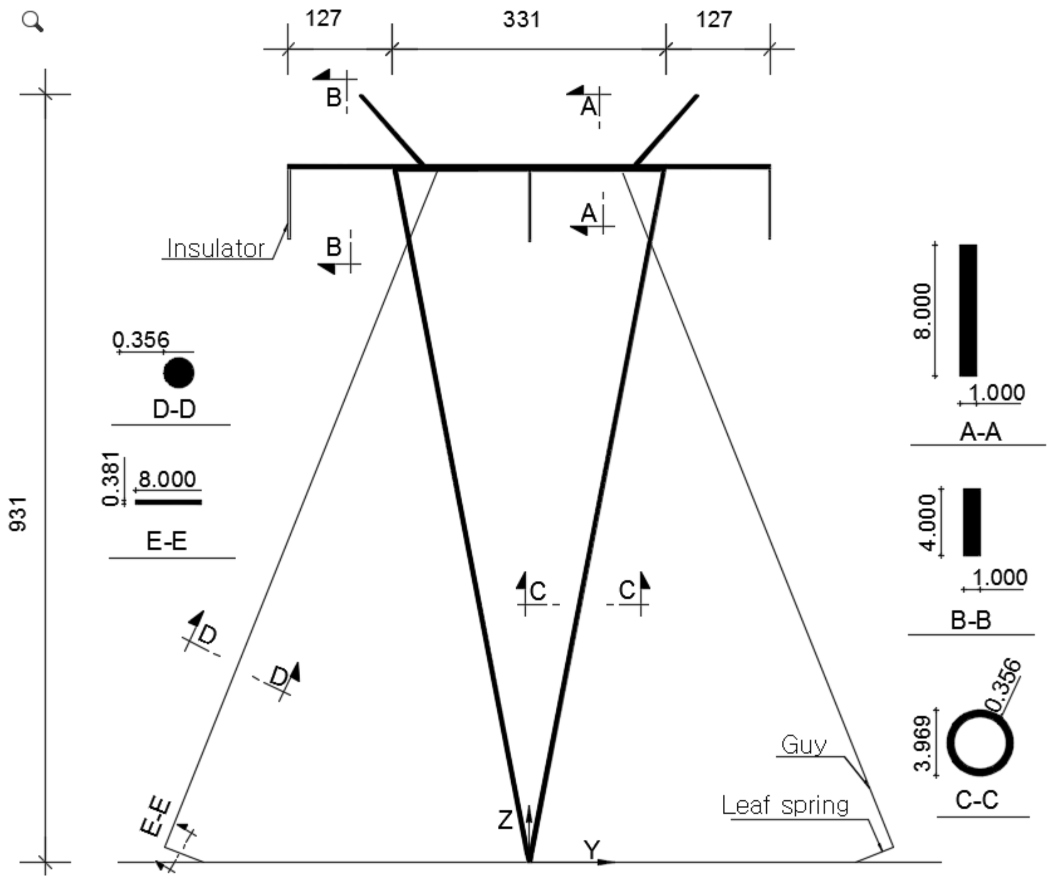
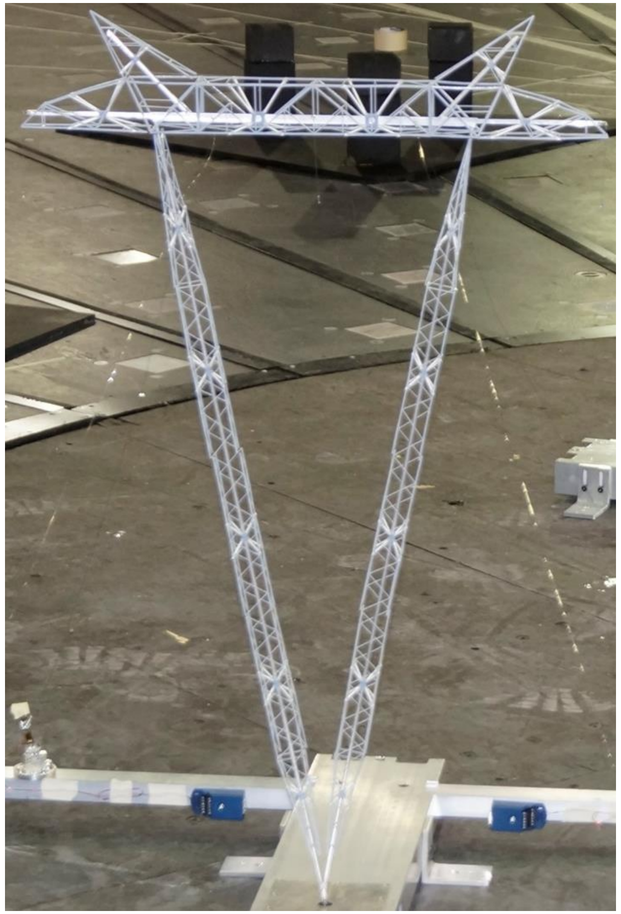
- Certain structures may experience significant aerodynamic forces generated by structural motions.
- The structural behavior associated with self-excited motions is called aeroelastic.

Aeroelastic Model Example

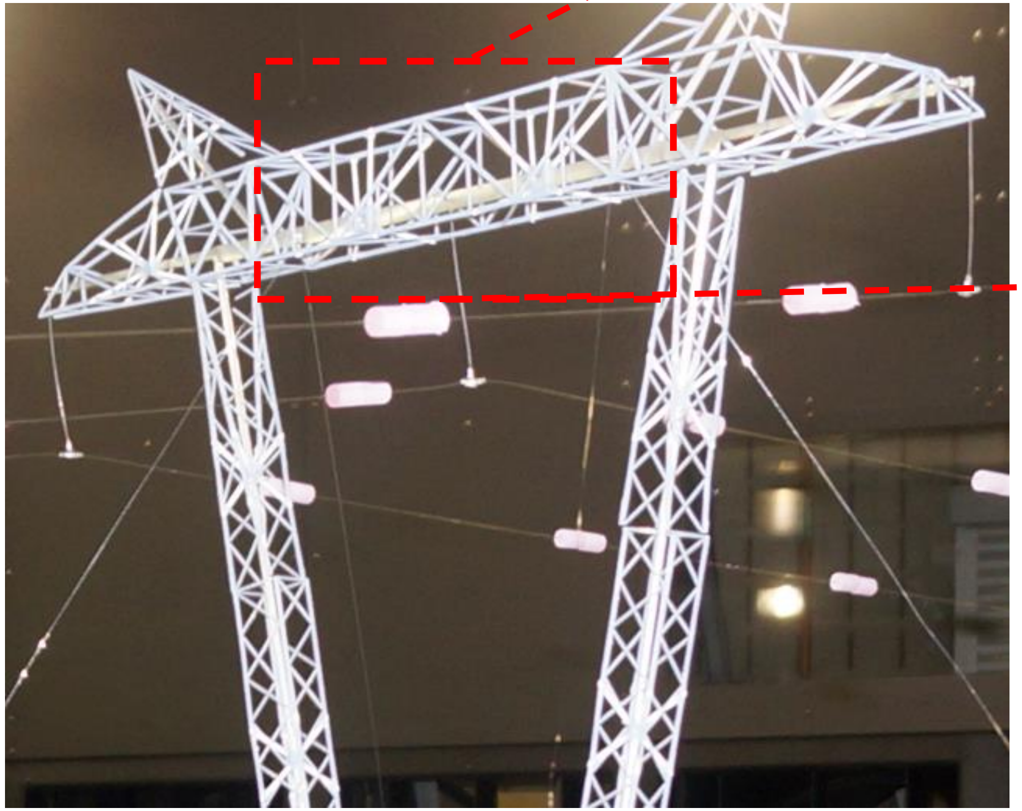


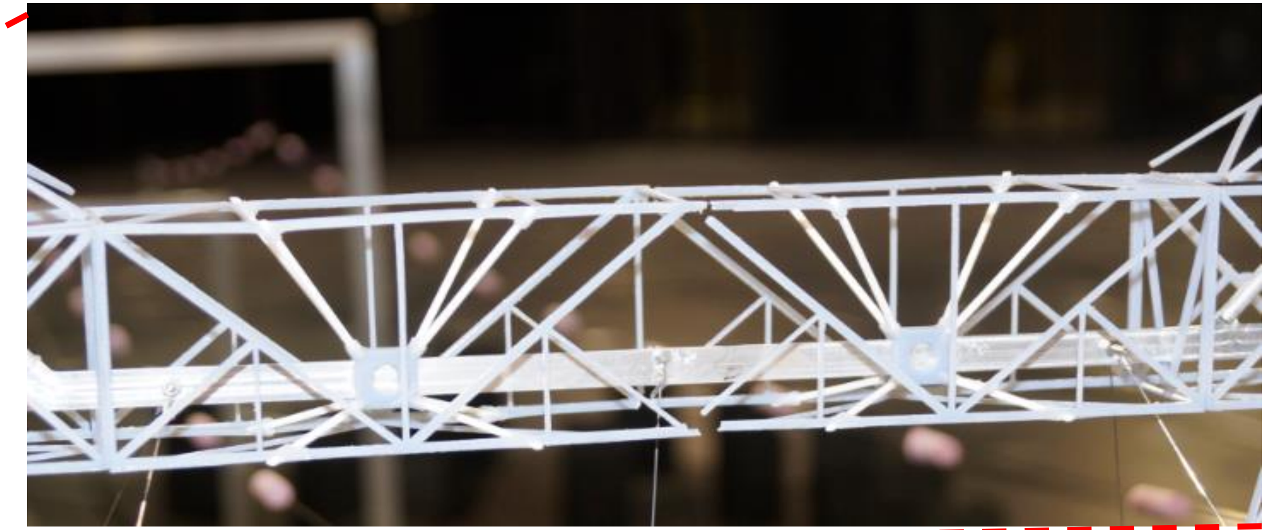


All dimensions are in mm

WOW testing: Aeroelastic-Numerical

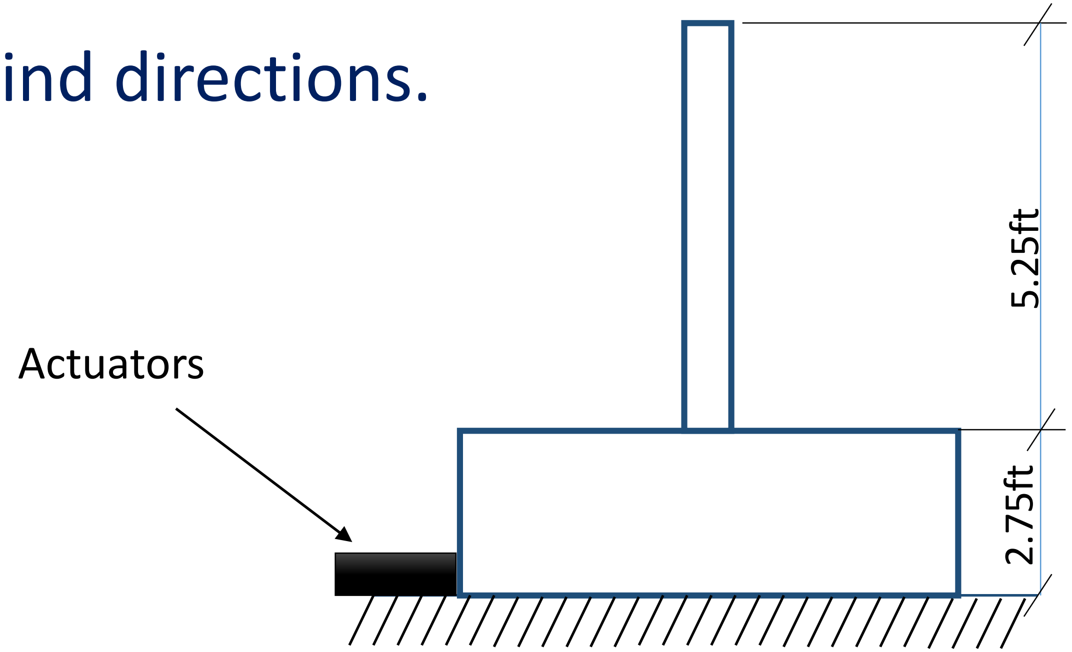
Aeroelastic Model Example





WOW testing: Aeroelastic-Numerical

- A large length-scale of 1:25 will be adopted in this phase.
- Test mean wind speed will vary from 20 mph to 40 mph (equivalent to full scale wind speeds of 100 mph to 200 mph).
- Varying wind directions.



Scaled model 1:25

WOW testing: Aeroelastic-Numerical

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- Length scale: 1:25
- Velocity Scale: 1:5
- Frequency scale: 5:1

PARAMETER	SIMILITUDE REQUIREMENT	VALUE
Length*	$\lambda_L = \mathbf{L}_m / \mathbf{L}_p$	4.00E-02
Density	$\lambda_\rho = \rho_m / \rho_p$	1.00E+00
Velocity**	$\lambda_v = \mathbf{V}_m / \mathbf{V}_p$	2.00E-01
Mass per Unit Length	$\lambda_m = \lambda_\rho \lambda_L^2$	1.60E-03
Mass	$\lambda_M = \lambda_\rho \lambda_L^3$	6.40E-05
Mass Moment of Inertia per Unit Length	$\lambda_i = \lambda_m \lambda_L^2$	2.56E-06
Mass Moment of Inertia	$\lambda_I = \lambda_M \lambda_L^2$	1.02E-07
Time	$\lambda_T = \mathbf{T}_m / \mathbf{T}_p = \lambda_L / \lambda_V$	2.00E-01
Acceleration	$\lambda_a = a_m / a_p = \lambda_v / \lambda_T$	1.00E+00
Damping	$\lambda_\zeta = \zeta_m / \zeta_p$	1.00E+00
Elastic Stiffness	$\lambda_{EI} = \lambda_{GC} = \lambda_V^2 \lambda_L^4$	1.02E-07
	$\lambda_{EA} = \lambda_V^2 \lambda_L^2$	6.40E-05
Force per Unit Length	$\lambda_f = \lambda_V^2 \lambda_L = \lambda_L^3 / \lambda_T^2$	1.60E-03
Force	$\lambda_F = F_m / F_p = \lambda_V^2 \lambda_L^2$	6.40E-05
Bending and Torsional Moment	$\lambda_{BM} = \lambda_V^2 \lambda_L^3$	2.56E-06
Warping Stiffness	$\lambda_{CwE} = \lambda_V^2 \lambda_L^6$	1.64E-10

WOW testing: Aeroelastic-Numerical

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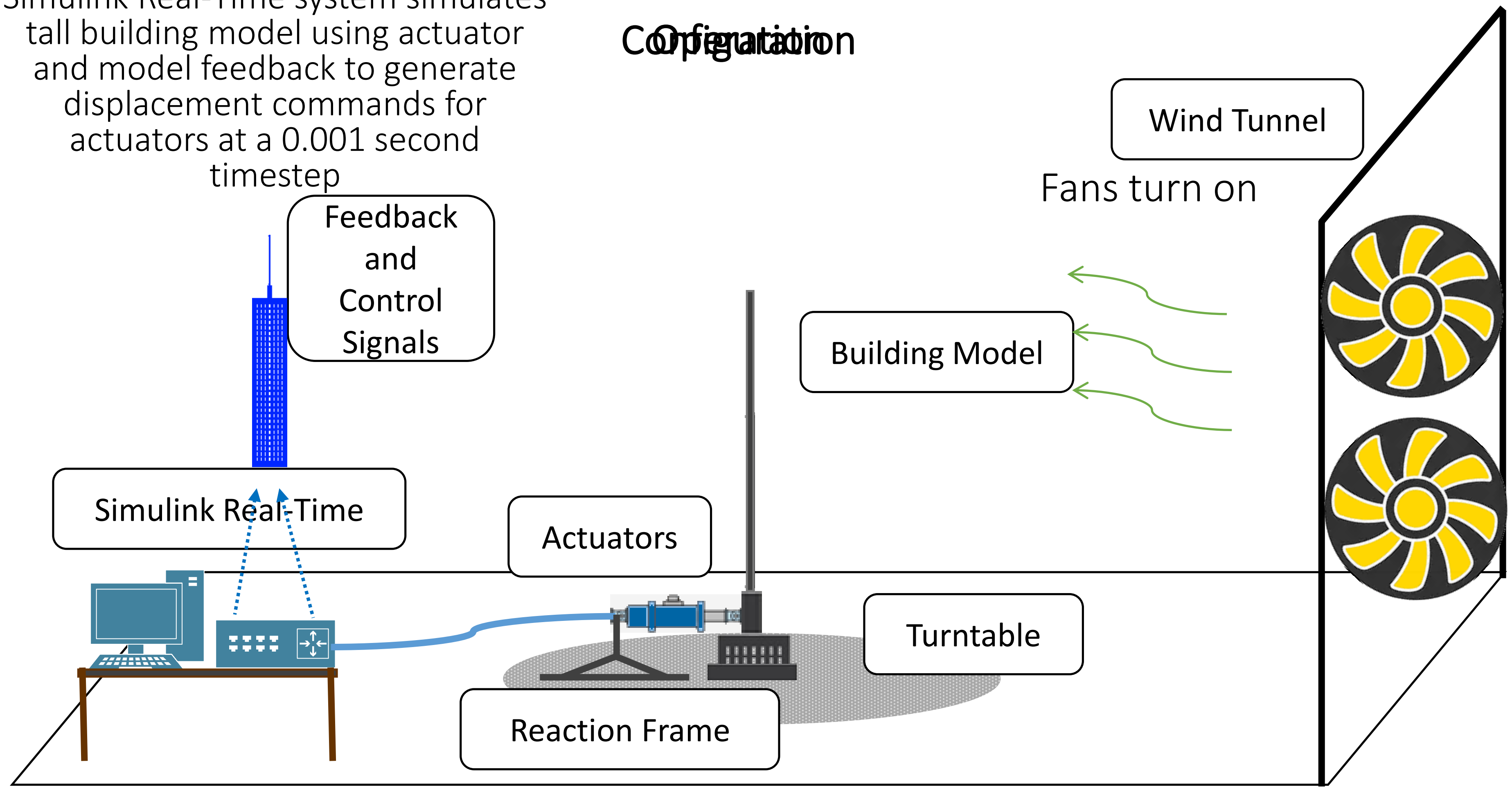
Real-Time Multi-Hazard Simulation

Simulink Real-Time system simulates tall building model using actuator and model feedback to generate displacement commands for actuators at a 0.001 second timestep

Configuration
Operation



WOW testing: Aeroelastic-Numerical

Two test philosophies can be adopted:

- **Serviceability testing (low wind speed testing):** Vortex shedding instability can be investigated for the mast. This testing will assume minimal interaction between the building and the spire. Therefore, correlations between the building and the mast Cps will be neglected.

- **Ultimate loading testing (high wind speeds):** This test is expected to involve high interaction between the mast and the building.

RTHS advantage for testing Rooftop Masts

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- Enables large scale simulation for the mast — near-prototype Reynolds number.
- Enables studying the aeroelastic response of flexible masts.
- Enables considering the material nonlinearity and P-delta effects for the building supporting the mast.
- Enables simulating potential wind-induced instabilities in masts during wind events--- a serviceability problem that affects their functionality.

Thanks!

Questions?