Redefining possible.

ASSESSMENT OF WIND-INDUCED RESPONSES OF STRUCTURES USING WIND TUNNEL TESTING

VLERESIMI I SJELLJES SE STRUKTURAVE NDAJ NGARKESAVE TE ERES NEPERMJET TESTIMIT NE TUNELET E ERES

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RWDI

CANADA

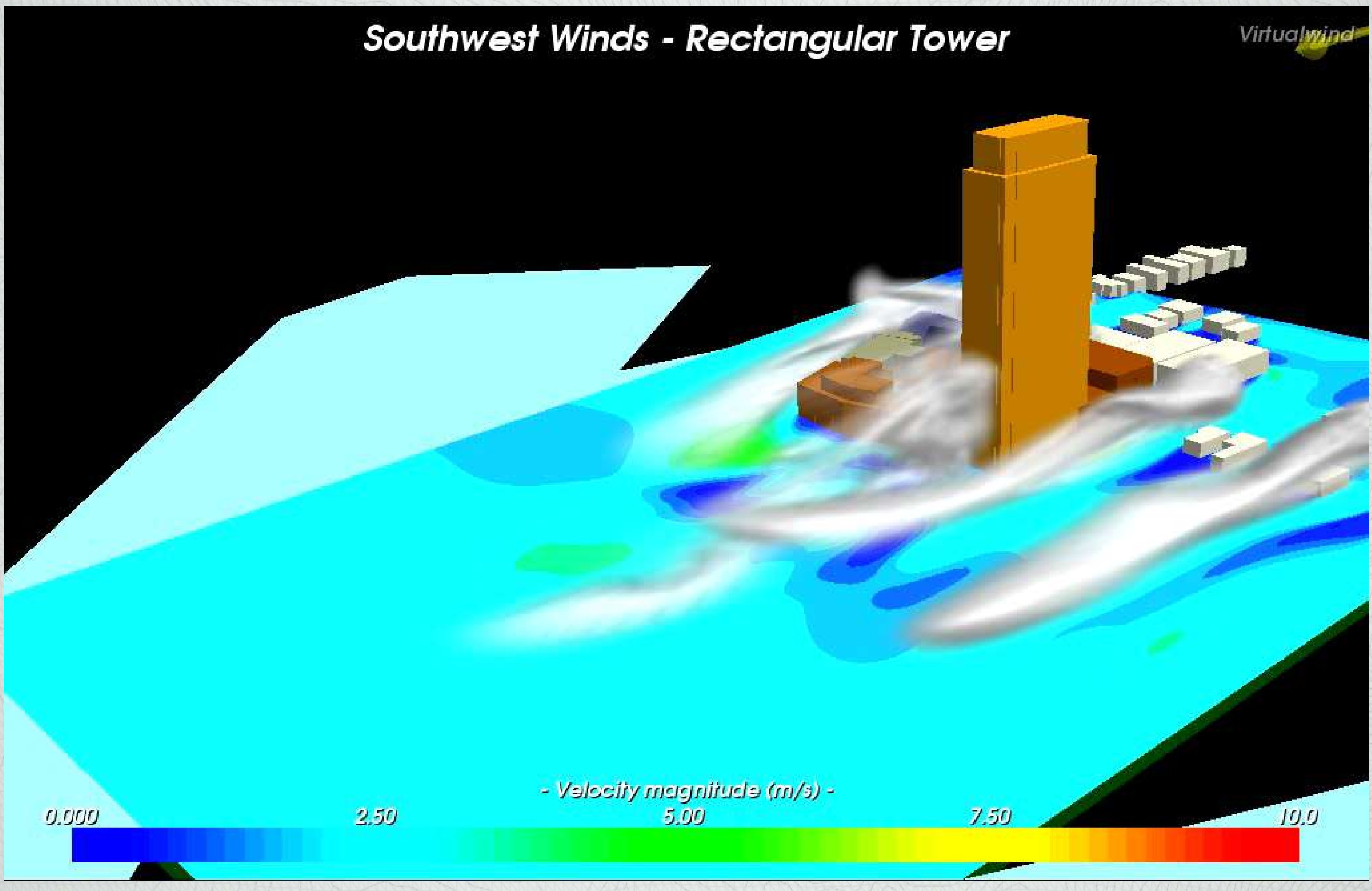
Outline

- Code-based procedures for assessment of wind loading
- The need for wind tunnel testing
- Wind tunnel modeling techniques and methodologies
- Assessment of wind-induced motion comfort
- Aerodynamic shape optimization
- Supplemental damping system implementation

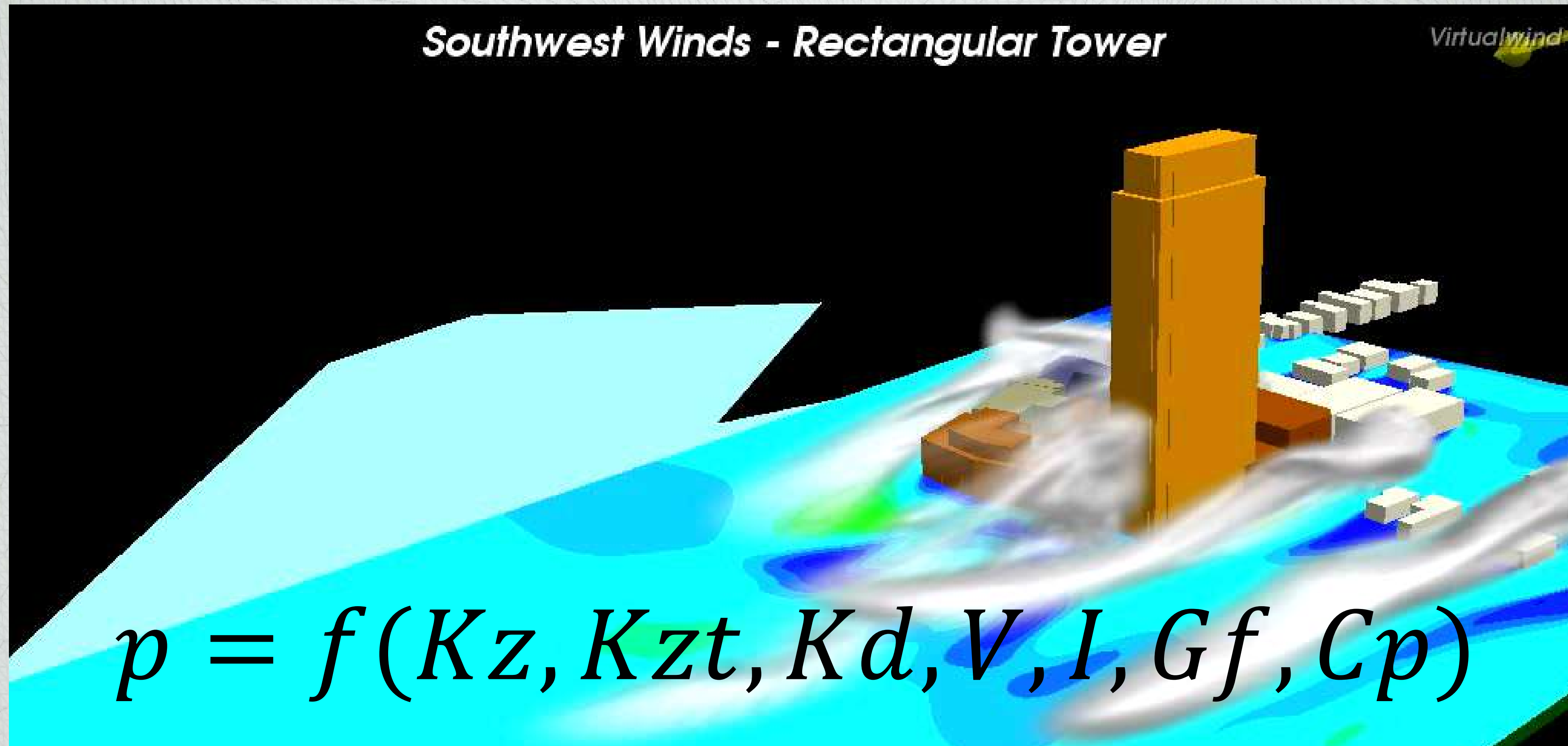
Widely Recognized Code-Based Analytical Procedures for Assessment of Wind Loading

- ASCE 7-16 Standard, Sections 26 – 30
- National Building Code of Canada (NBCC 2015), Section 4.1.7.
- Australian/New Zealand Standard AS/NZS 1170.2:2021, Part 2: Wind Actions.
- Eurocode 1 – Actions on Structures, Part 1-4, General Actions – Wind Actions

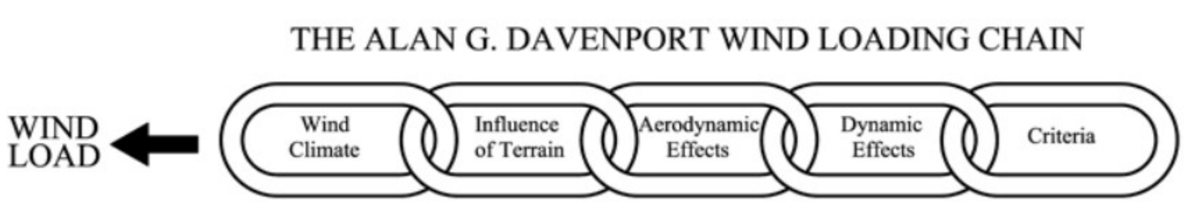
Wind & Structures - How do they interact?



How is this complex interaction represented in the ASCE 7 and other code wind load calculation procedures?



$$p = f(Kz, Kzt, Kd, V, I, Gf, Cp)$$



Definition of Coefficients Used in the ASCE 7-16 Wind Load Calculation Procedure

- K_z – wind exposure category factor.
- $K_{z,t}$ - topographic effects factor
- K_d - wind directionality factor
- *V_b – basic wind speed for the proposed site*
- *I* – building importance or building risk category factor used to determine V_b for the proposed site
- G_f – gust effect factor
- C_p – building aerodynamic shape factor

Note: *It is important to keep in mind that the averaging time used in the definition of basic wind speed V_b is different from code to code.*

Averaging Times Used in the Definition of Basic Wind Speeds of Different Codes

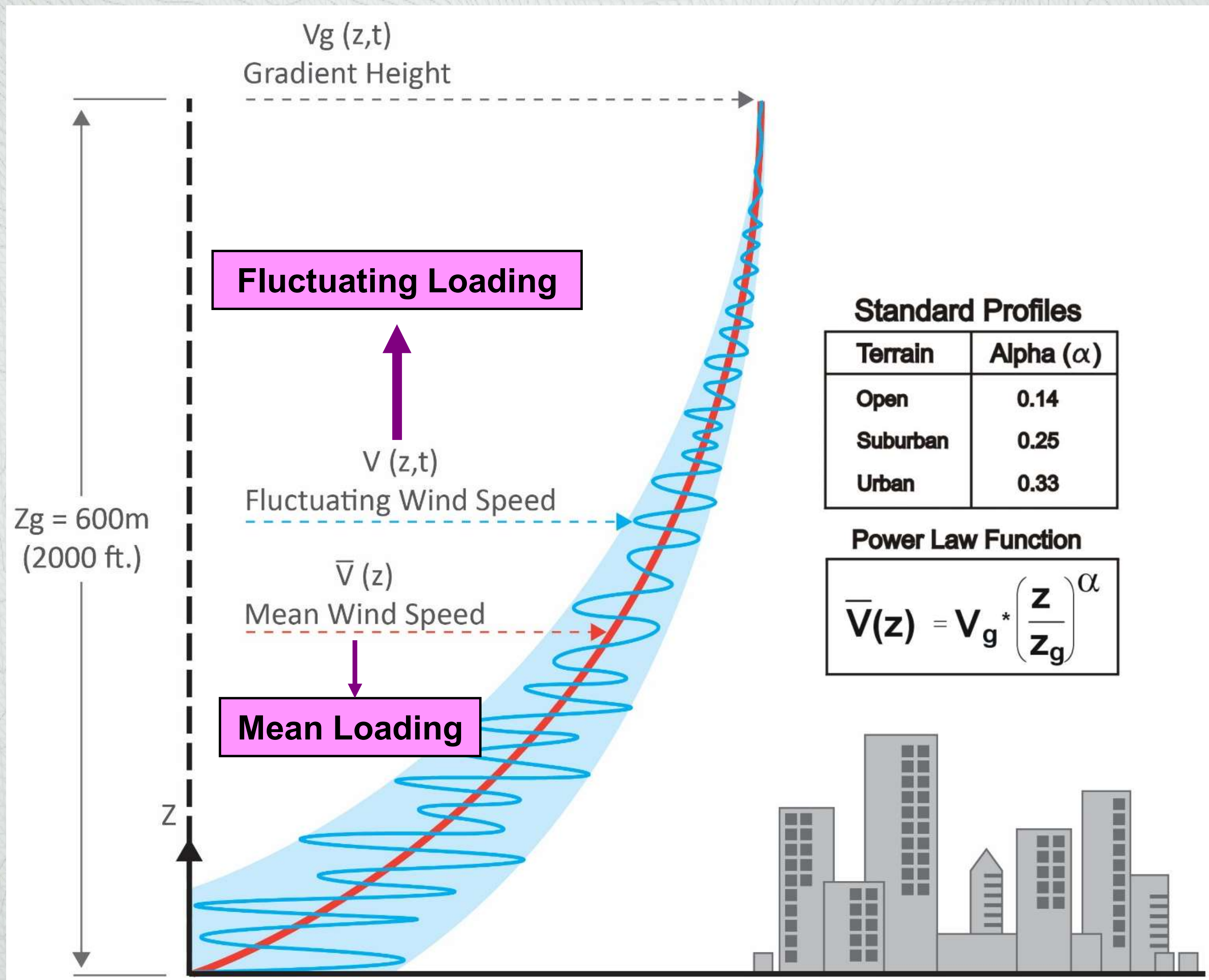
Code or Standard Name	Averaging Time Used in the Definition of V_b
ASCE 7-16	3-seconds
NBCC 2015	1-hour
AS/NZS 1170.2:2021	3-seconds
EUROCODE 1	10-minutes

Conversion Factors to Convert the V_b from One Averaging Time or Code to Another

From - To	From - To	Conversion Factor
10-minutes to 1-hour	EUROCODE 1 to NBCC 2015	0.939
10-minutes to 3-seconds	EUROCODE 1 TO ASCE 7-16 EUROCODE 1 TO AS/NZS 1170.2:2021	1.432

Example: *If it is desired to run wind loading calculations for a high-rise building in Tirana using NBCC 2015 or ASCE -16 procedure, then the corresponding mean hourly and 3-sec gust basic wind speeds applicable for NBCC 2015 and ASCE 7-16 will be 30 x 0.939 = 28.2 m/s and 30 x 1.432 = 43 m/s, respectively.*

How Does Wind Speed Vary with Height?



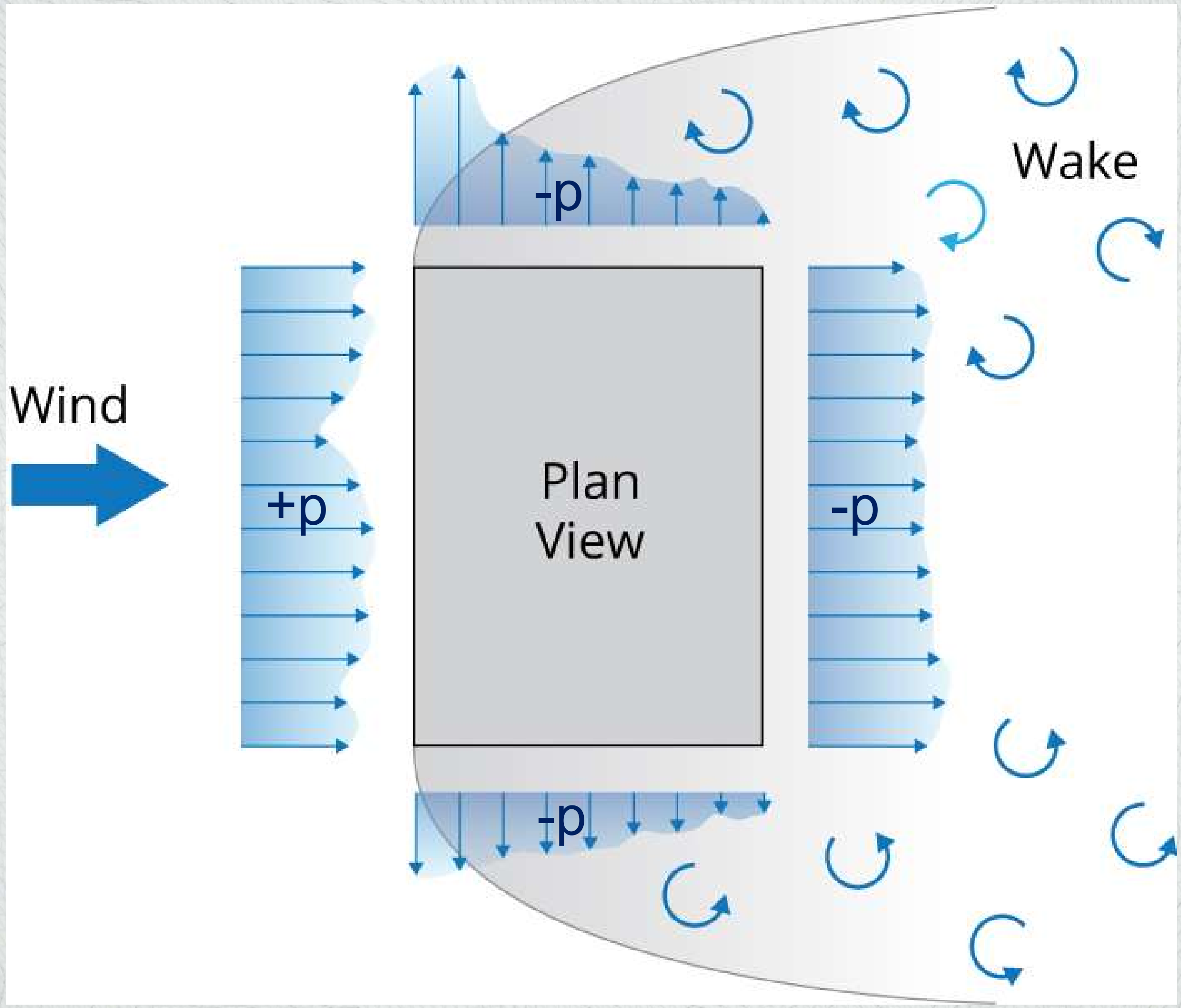
Standard Profiles

Terrain	Alpha (α)
Open	0.14
Suburban	0.25
Urban	0.33

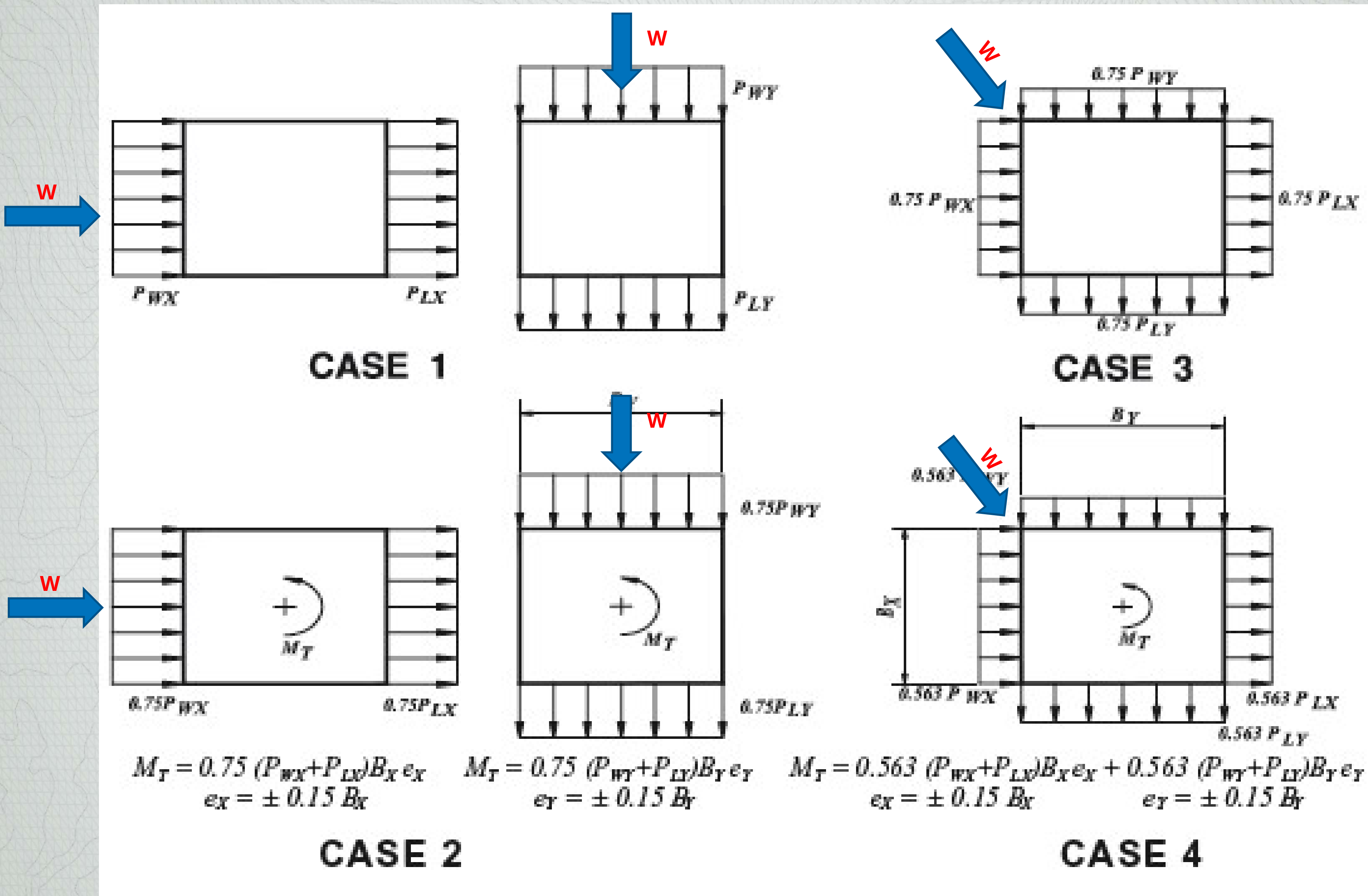
Power Law Function

$$\overline{V}(z) = V_g{}^{*}\left(\frac{z}{z_g}\right)^{\alpha}$$

Instantaneous Pressure Distribution Around a Building



How is the Simultaneous Action of Wind Pressures Around a Building Considered in ASCE 7 Procedures?



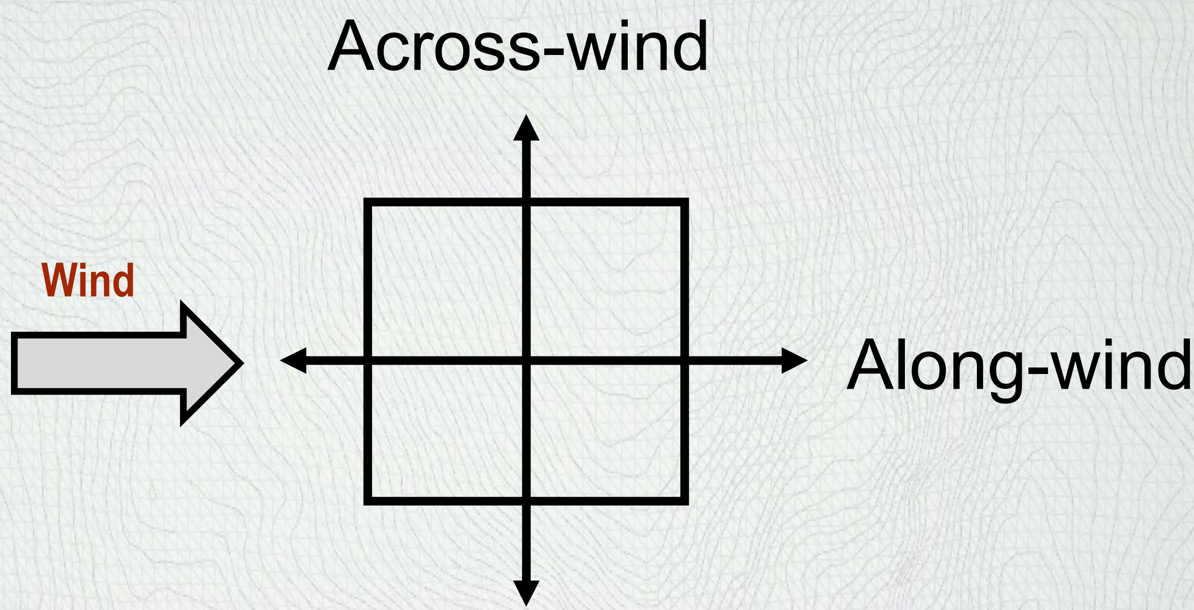
The ASCE 7 wind load calculation procedure applicability and limitations

1. The building ***is a regular-shaped*** building or structure as defined in Section 26.2.

2. The building ***does not have*** response characteristics making it subject to across wind loading, vortex shedding, instability due to galloping or flutter; or does not have a site location for which channeling effects or buffeting in the wake of upwind obstructions warrant special consideration.

LIMITATIONS: Buildings or other structures not meeting the above requirements or ***having unusual shapes*** or response characteristics, shall be designed using recognized literature documenting such wind load effects or shall ***use the wind tunnel procedure*** specified in Chapter 31.

Simultaneous Components of Wind-Induced Responses



Along-wind => addressed by code analytical procedures

Across-wind => NOT addressed by code procedures!!

Across-wind vibrations are usually greater than along-wind vibrations for buildings of heights greater than 120m

Illustration of Simultaneous Components of Wind-Induced Responses

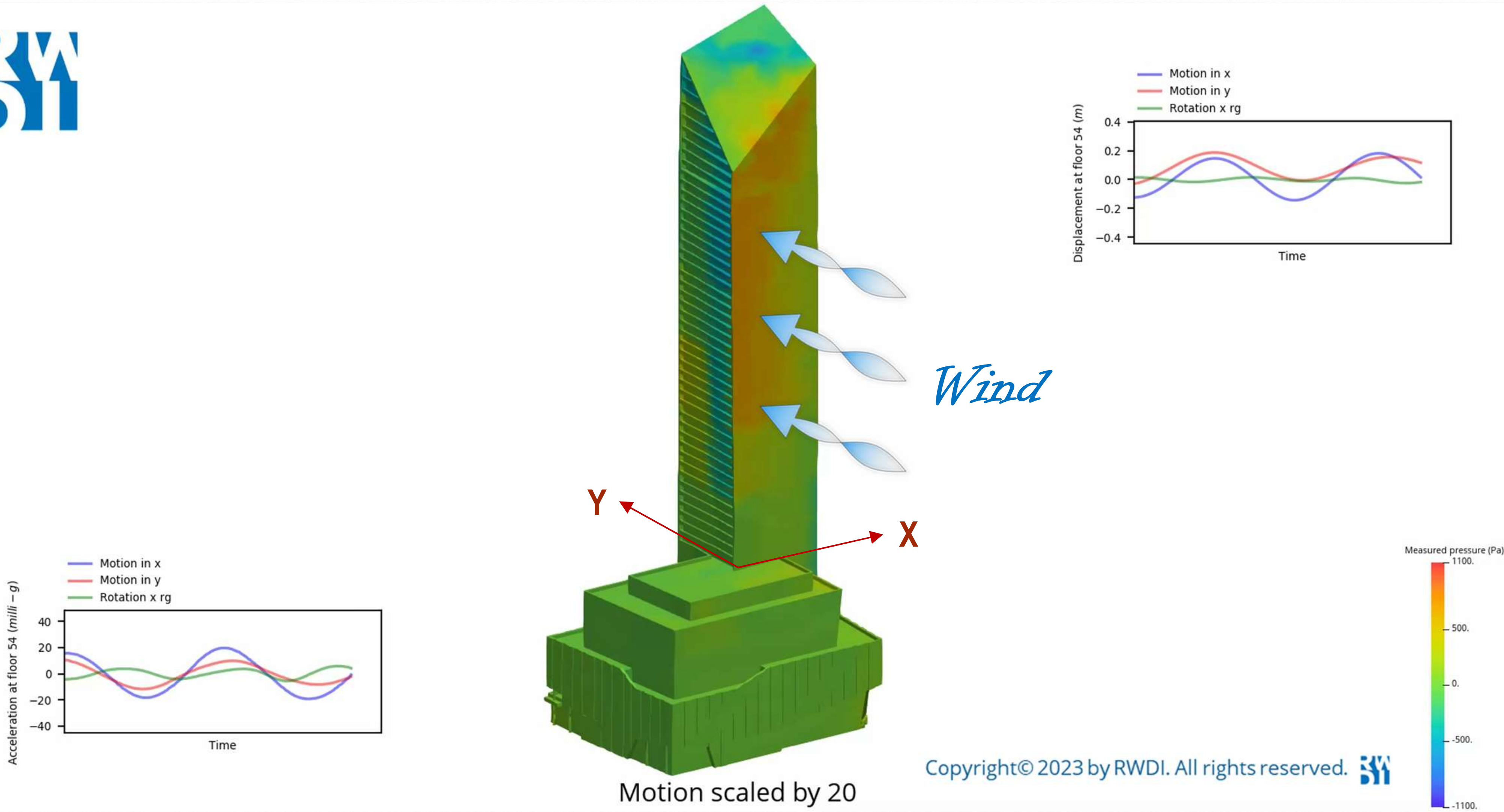
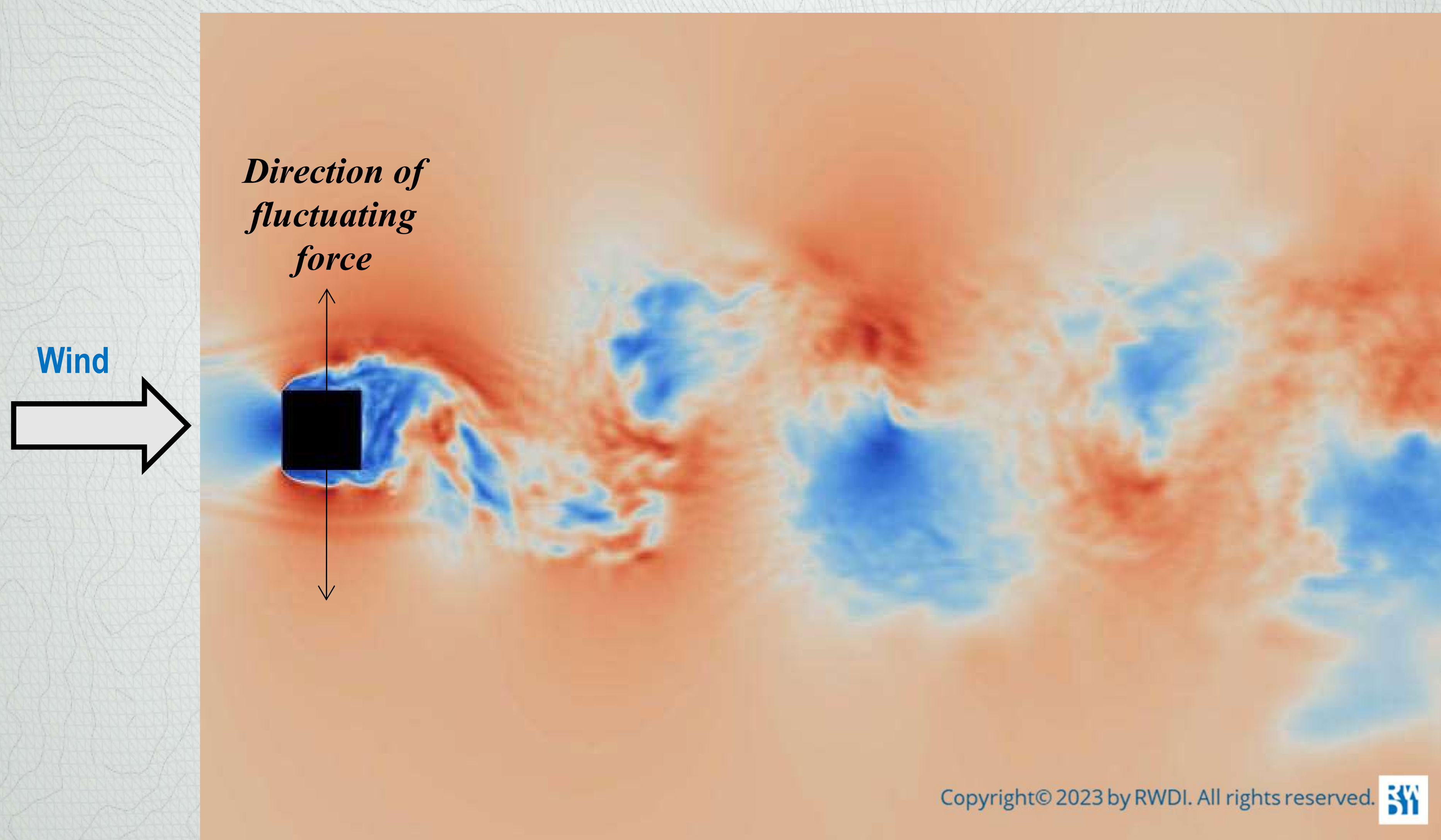


Illustration of Across-Wind Response in a Square Section



Why would we conduct an experiment to determine wind loads?

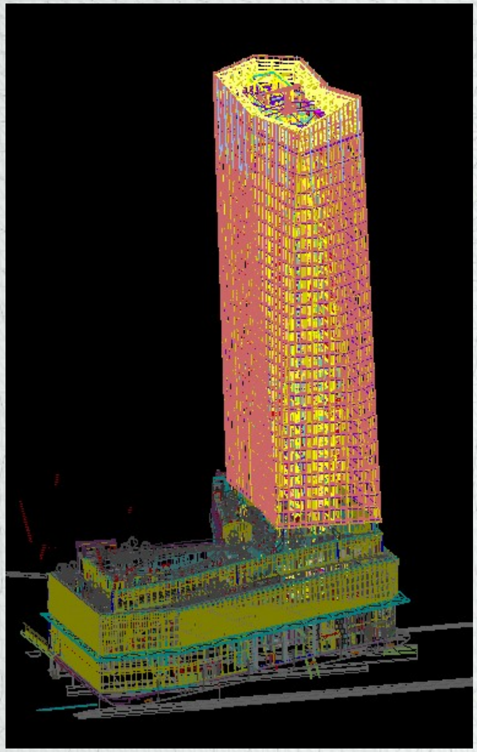
Wind loads may be difficult to predict because:

- Complexity of building shapes
- Interference effects from neighboring buildings
- Complexity of upwind terrain
- Dynamic behavior under wind action
- *Lack of resolution provided by building codes and standards*

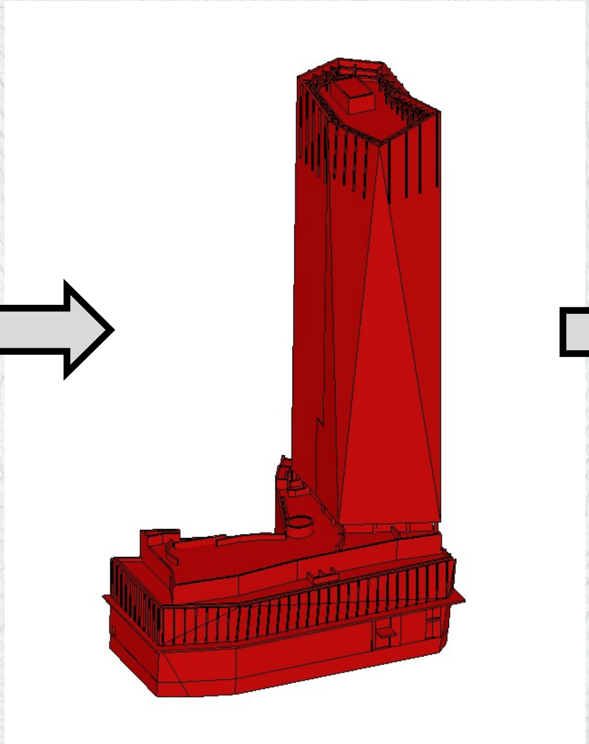
Building Shapes non Compliant with Code

Building Shapes non Compliant with Code

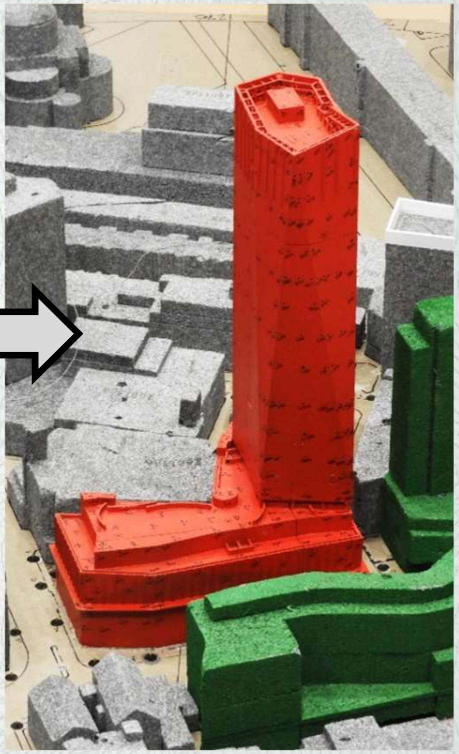
Wind Tunnel Study Model



Architect's 3D Model



RWDI's 3D Model

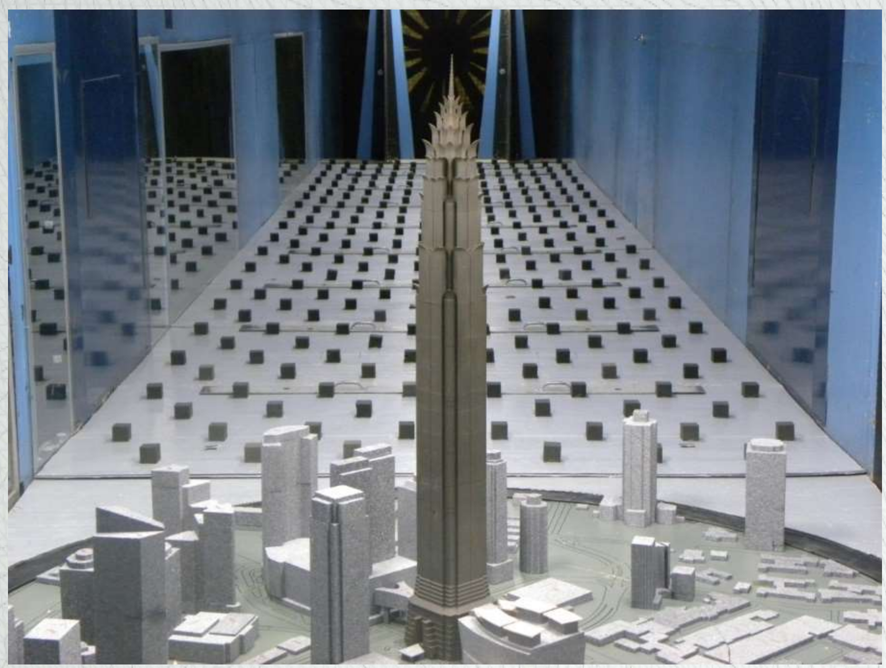


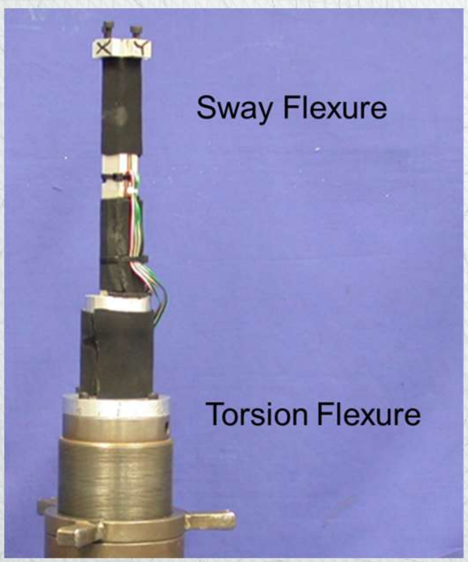
Physical Model

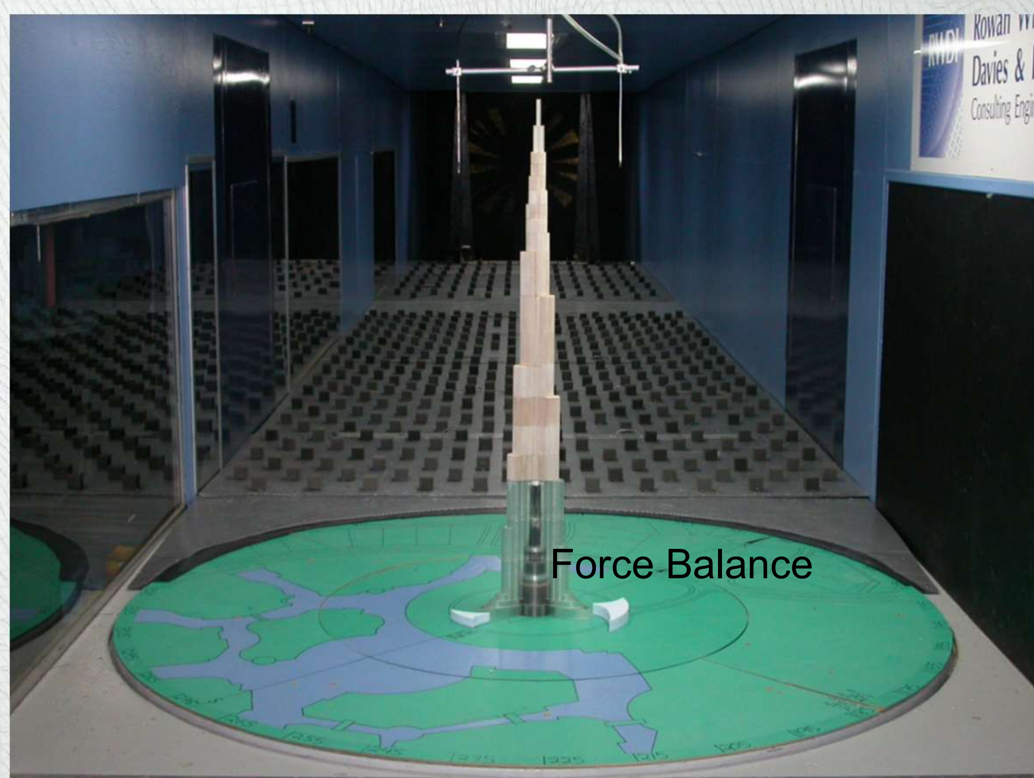
Wind Tunnel Study Types Conducted for Buildings and Other Structures

- Structural wind load studies
  - Buildings
  - Long span roof
  - Complex shape structures
- Cladding wind load studies
  - **Buildings**
  - **Long-span roof**
  - **Complex shape structures**
- Aeroelastic wind response studies
  - Tall, slender buildings
  - Bridges
  - Spires and other dynamically sensitive structures

Wind Tunnel Modeling and Testing Techniques Used for Buildings and Other Structures

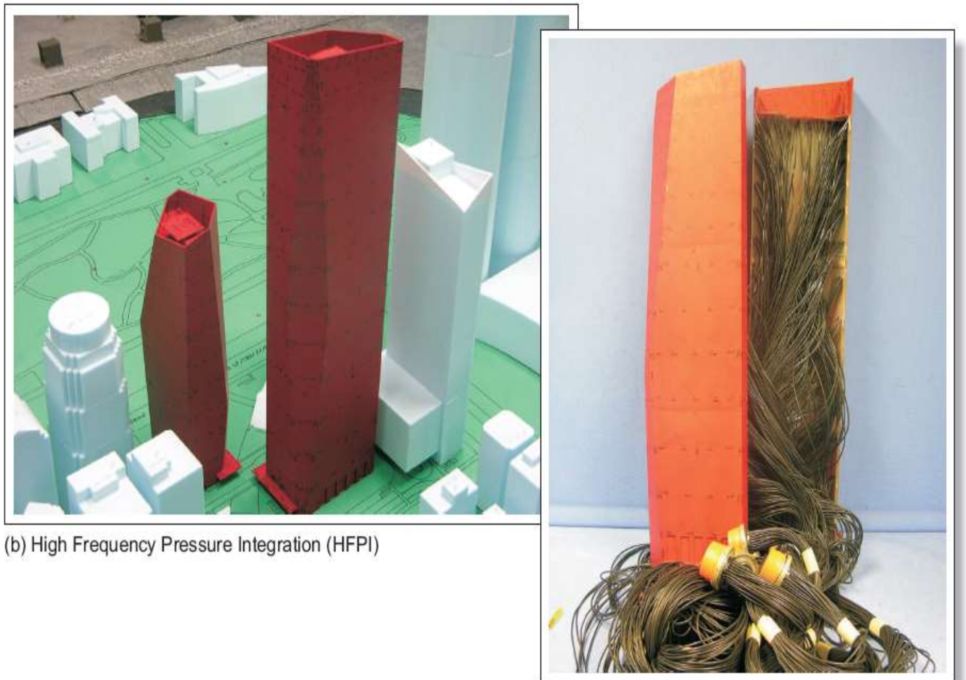




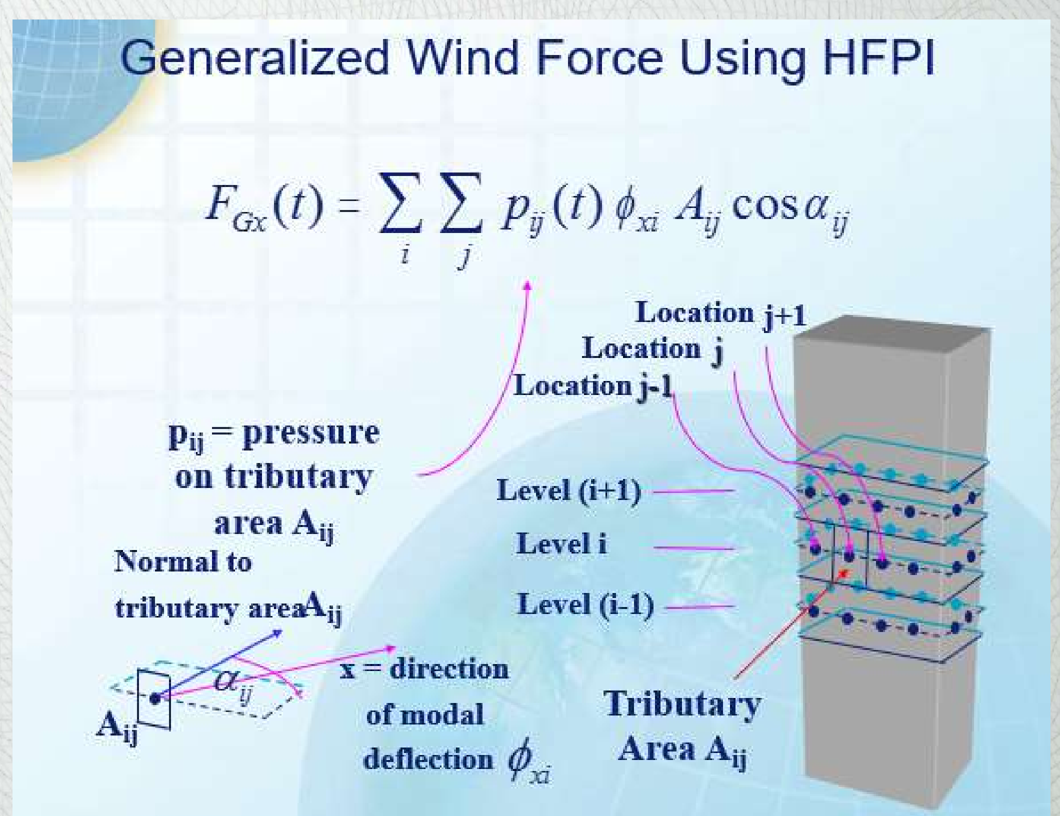


High-Frequency-Force-Balance (HFFB)

Wind Tunnel Modeling and Testing Techniques Used for Buildings and Other Structures

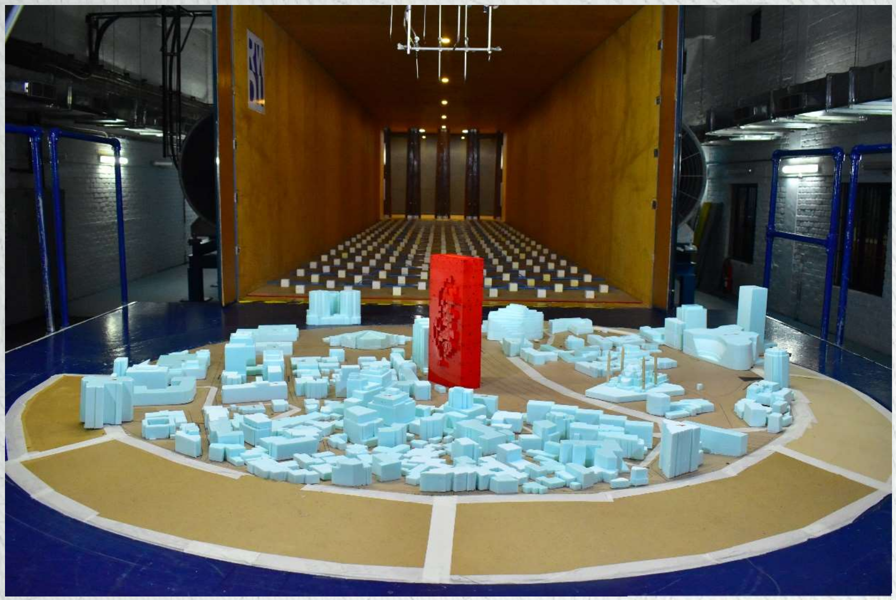


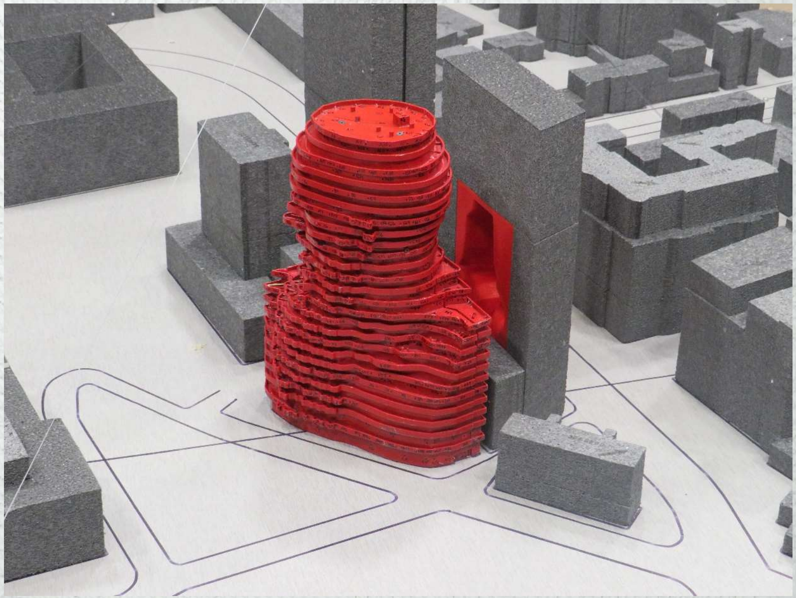
(b) High Frequency Pressure Integration (HFPI)



High-Frequency-Pressure-Integration (HFPI)

The First High-Rise Buildings of Albania Evaluated Through Wind Tunnel Modeling and Testing



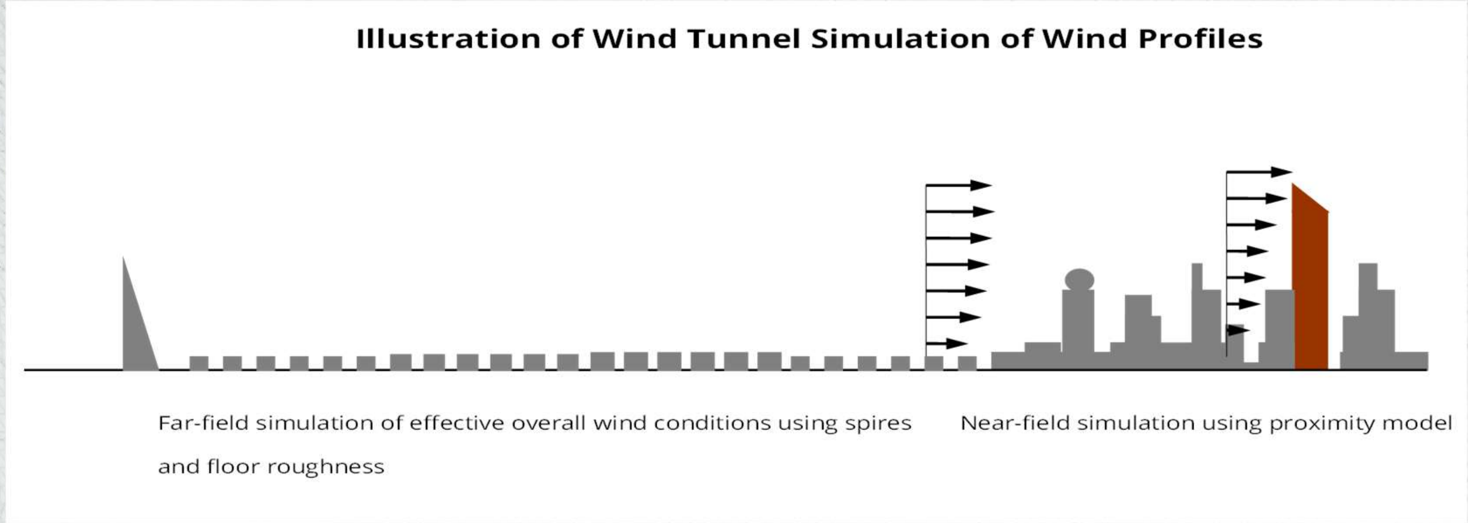


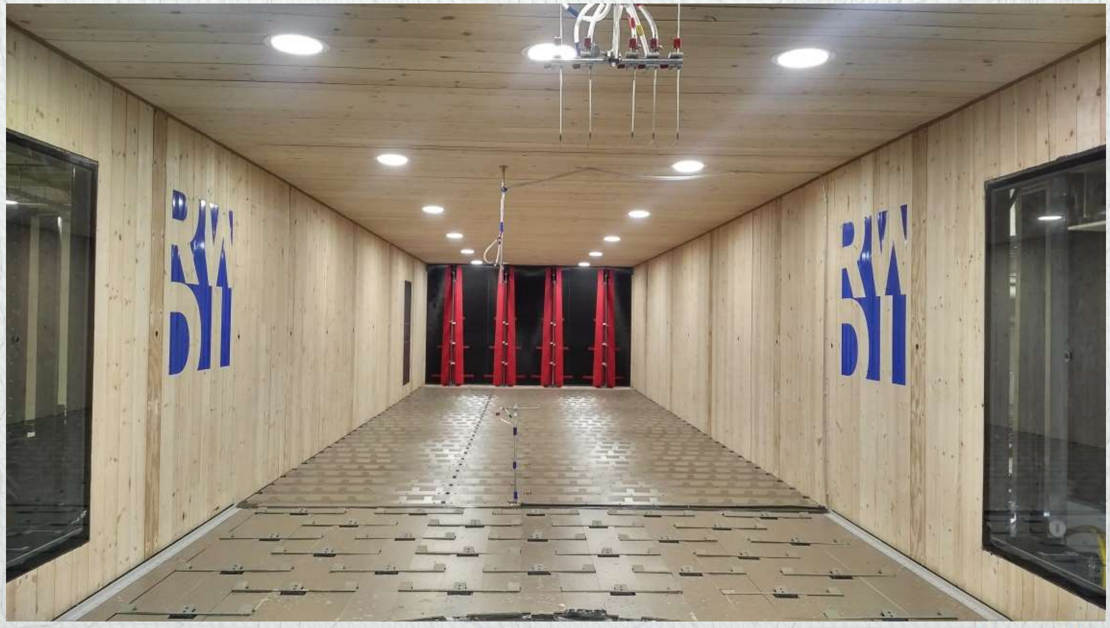
Downtown One Tirana Tower

Tirana's Rock

RWDI's Wind Tunnel Testing Facilities

Atmospheric Boundary Layer Simulation
Wind Profile Development





Summary of Steps Involved in a Detailed Wind Tunnel Study

- Assess surrounding terrain (i.e. wind exposure/profile) at the project site
- Evaluate the local wind climate
- Construct a physical model
- Test the model in the wind tunnel
- Record and process the data, combine them with the dynamic properties of the structure (i.e. frequencies, masses, mode shapes & damping)
- Integrate the results with the local wind climate
- Summarize/Interpret results in a user-friendly format

Commonly Used Wind-Induced Motion Comfort Criteria
(10-year return period wind events)

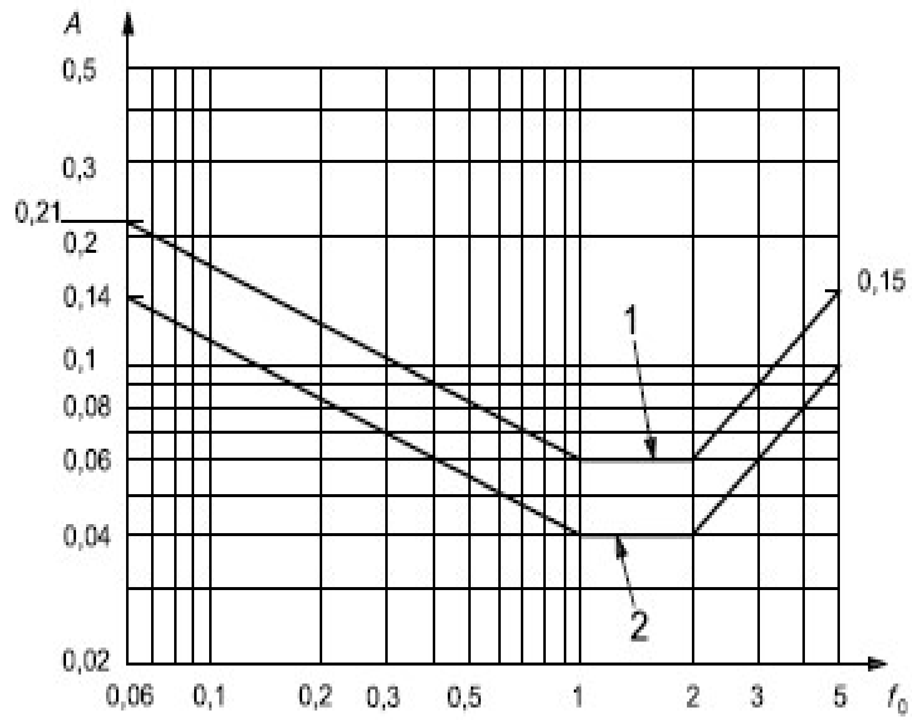
Building Type	10-Year Peak Acceleration in milli - g
Residential	15 - 18
Hotel	18 - 20
Office	20 - 25

Note: 1-milli-g = 1/1000 of gravity acceleration

ISO Wind-Induced Motion Comfort Criteria

1-year return period wind events

Frequency dependence



Key

A peak acceleration, m/s^2

f_0 first natural frequency in a structural direction of a building and in torsion, Hz

1 offices

2 residences

Figure D.1 — Evaluation curves for wind-induced vibrations in buildings in a horizontal (x, y) direction for a one-year return period

RWDI Suggested Torsional Velocity Criteria*

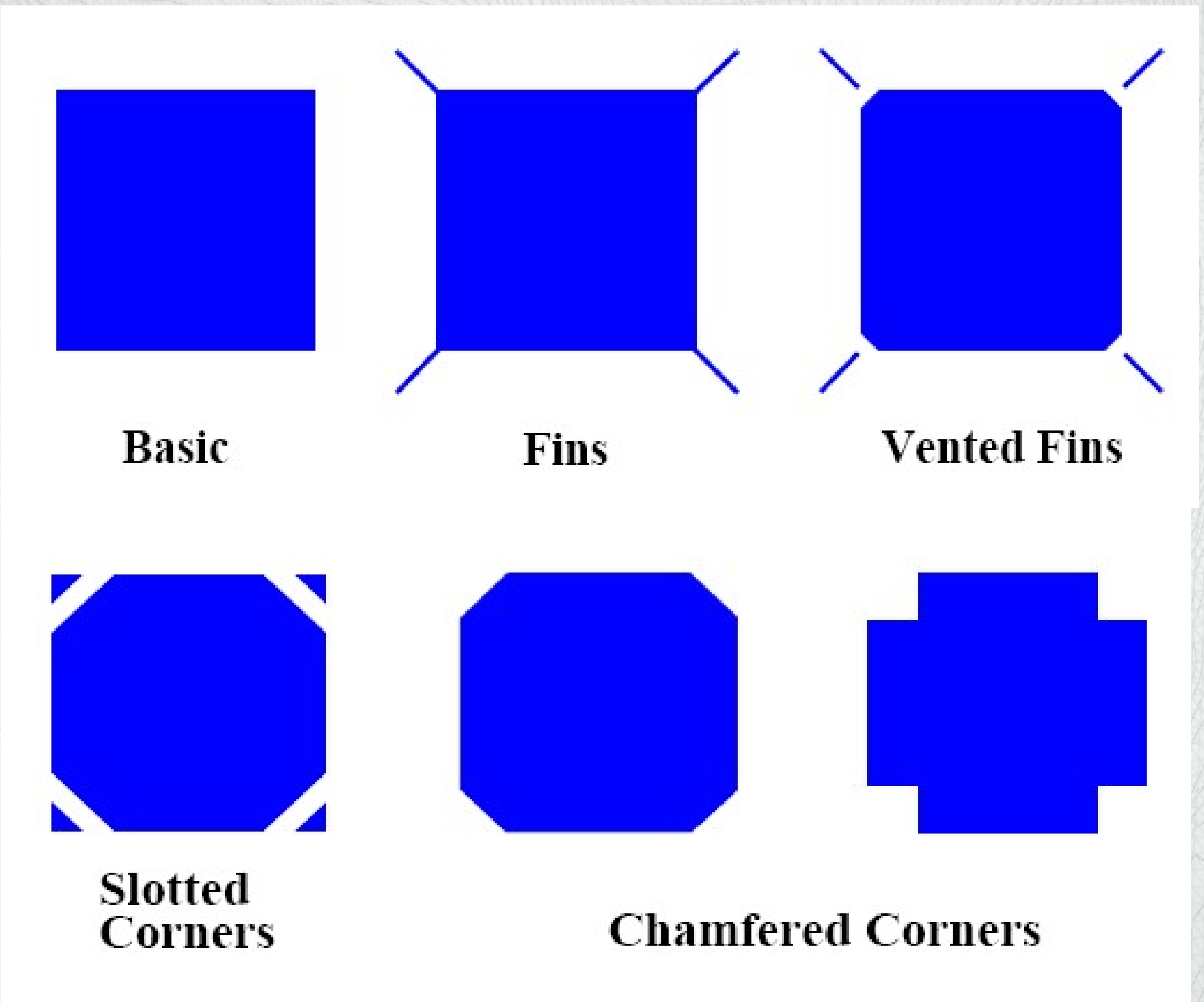
Peak torsional velocity at the top occupied floor of the building should be at or below the following values:	Acceptable hourly peak values of Torsional Velocities	
	1-year RP event	10-year event
	(milli-rad/sec)	(milli-rad/sec)
- **Residential Occupancy**	**2.0**	**4.0**
- **Office Occupancy**	**2.5**	**5.0**

** Based on RWDI's experience including motion simulator experiments.*

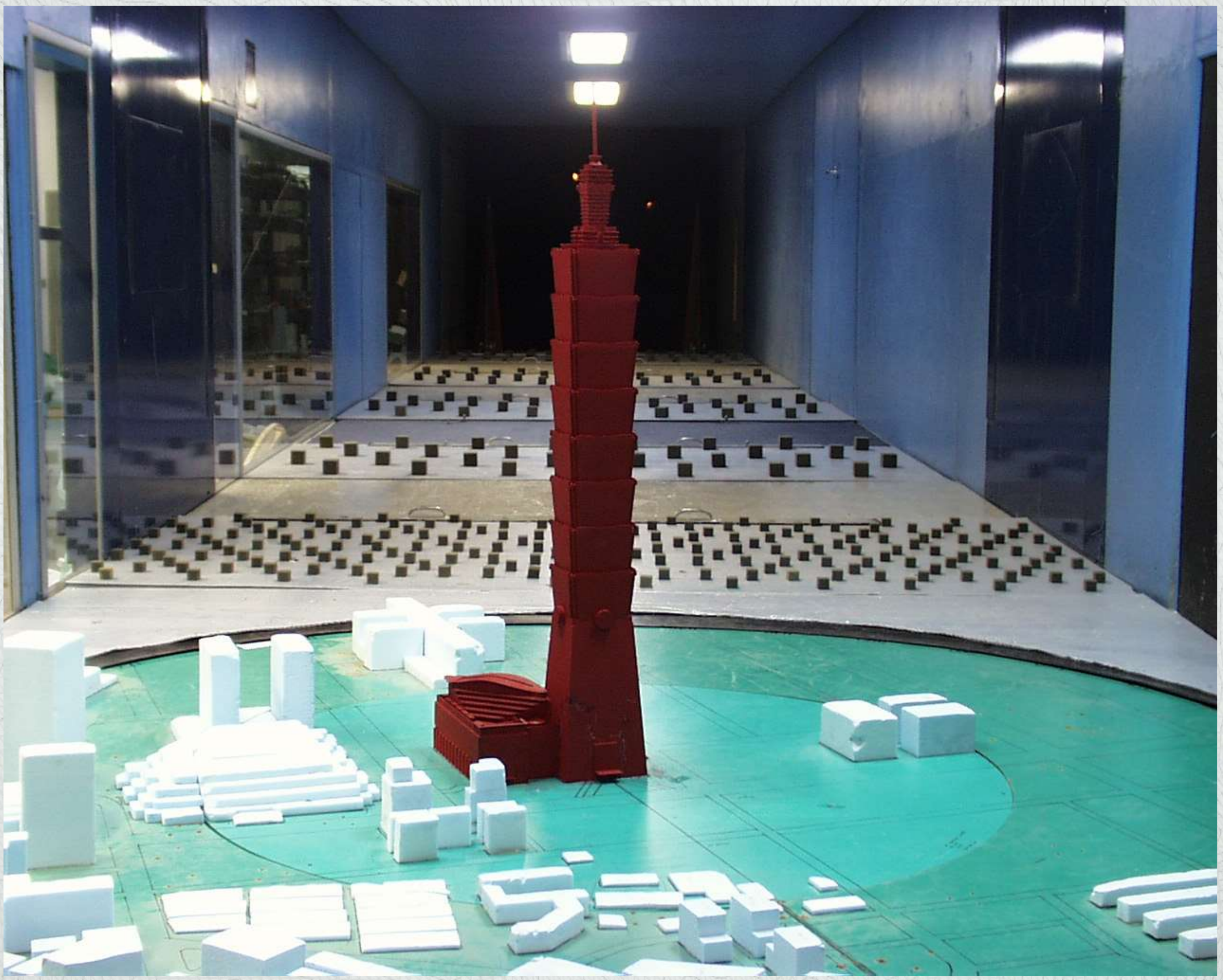
What are the factors affecting wind-induced responses of structures?

- Wind Speed and Direction
- Aerodynamic Shape
- Structural Stiffness - ***K***
- Mass - ***M***
- Damping - ξ

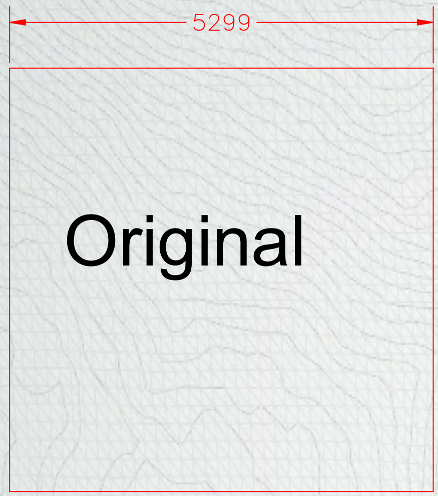
Aerodynamic Modifications

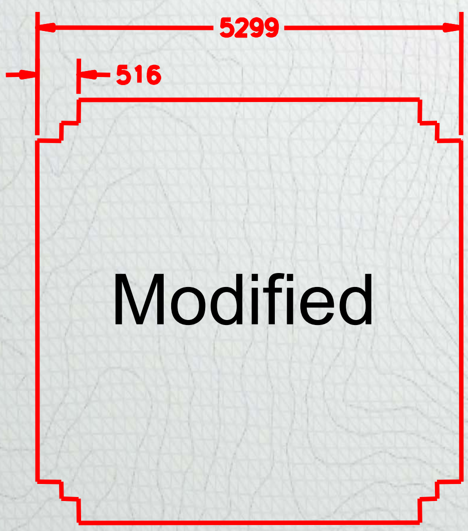


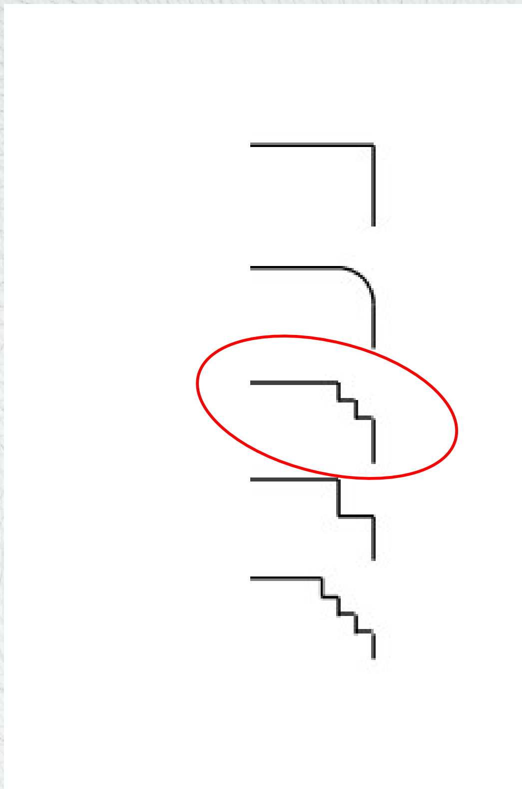
Taipei 101
Aerodynamic Modification Effects



Taipei 101 Tower
Original and Modified cross-sections

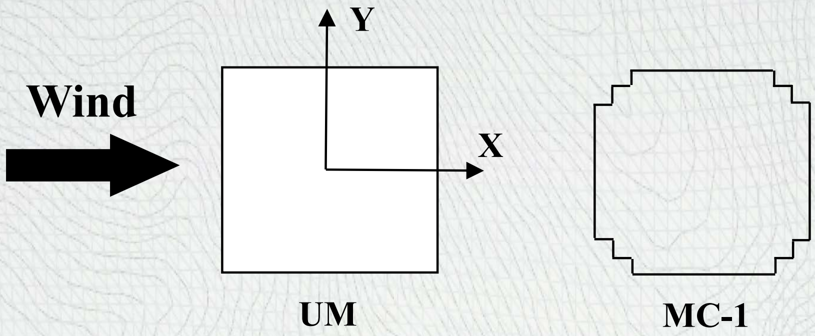


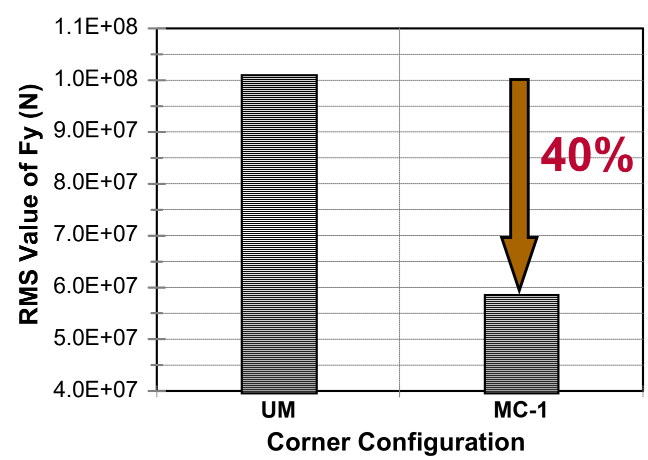


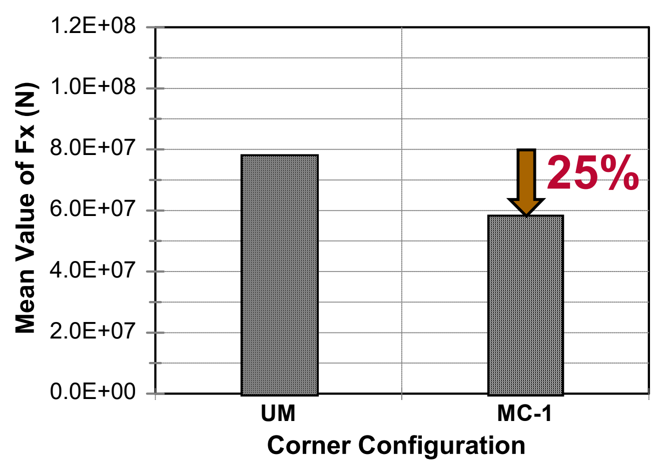


25% REDUCTION IN BASE MOMENT

Reduction of Wind-Induced Responses

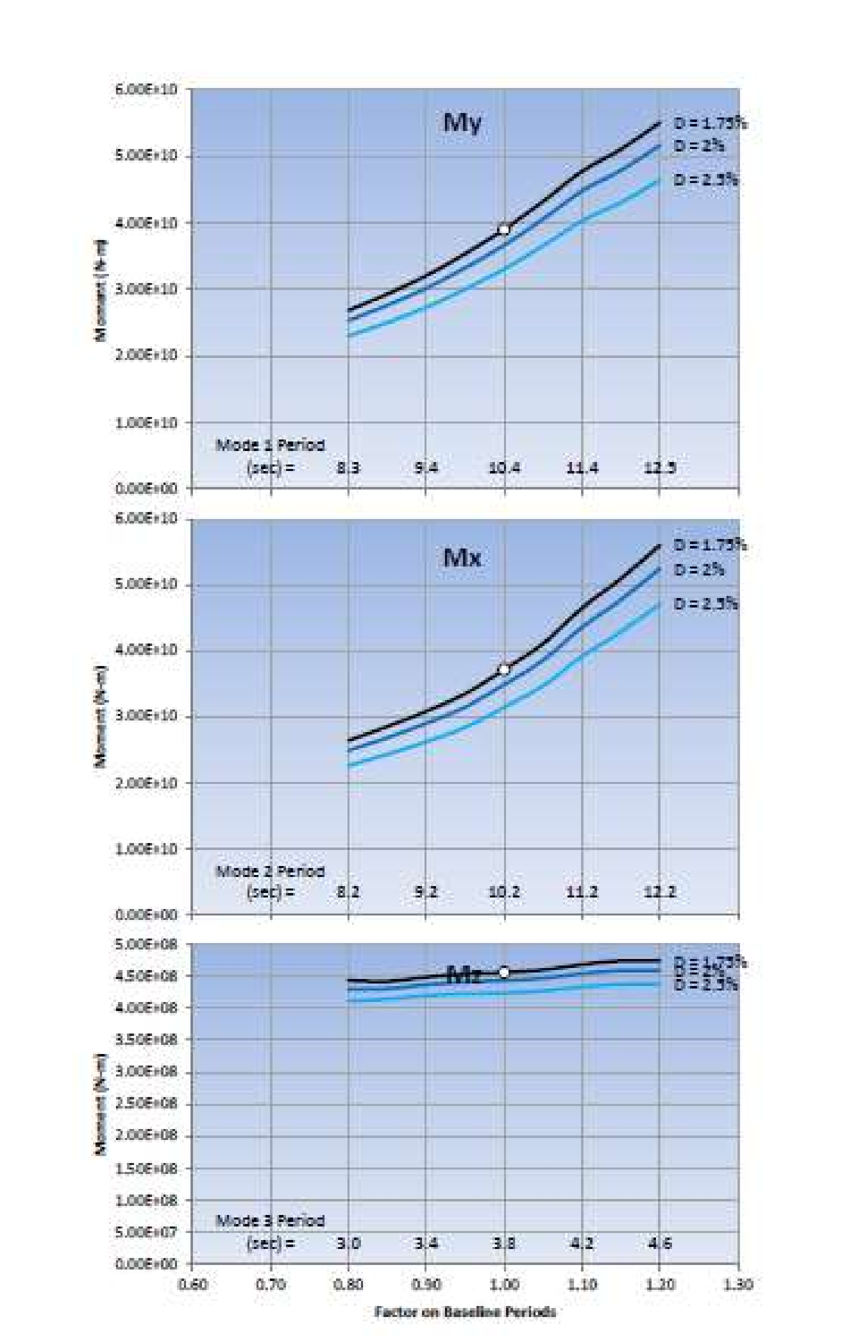




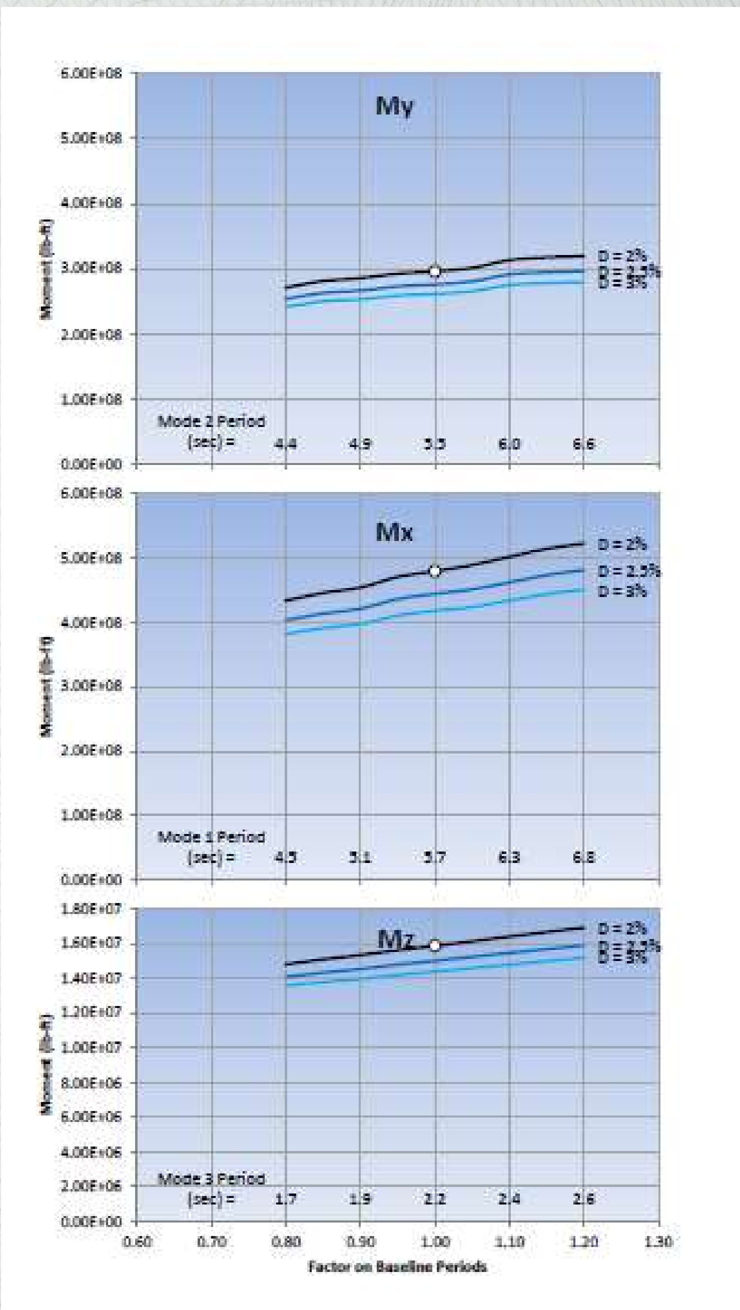


Aerodynamic Modification Effects

Structural Dynamic Optimization

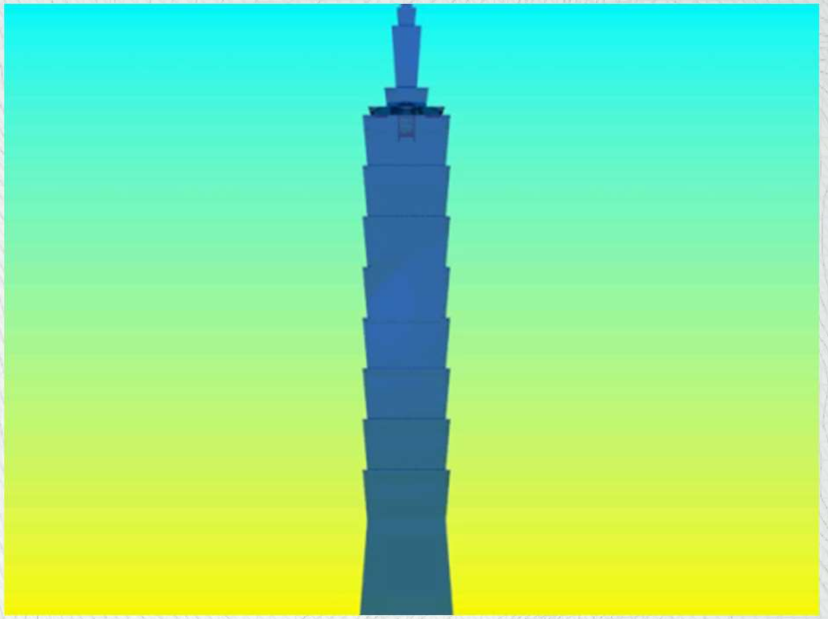


Building A – Overall Wind Loading at Base



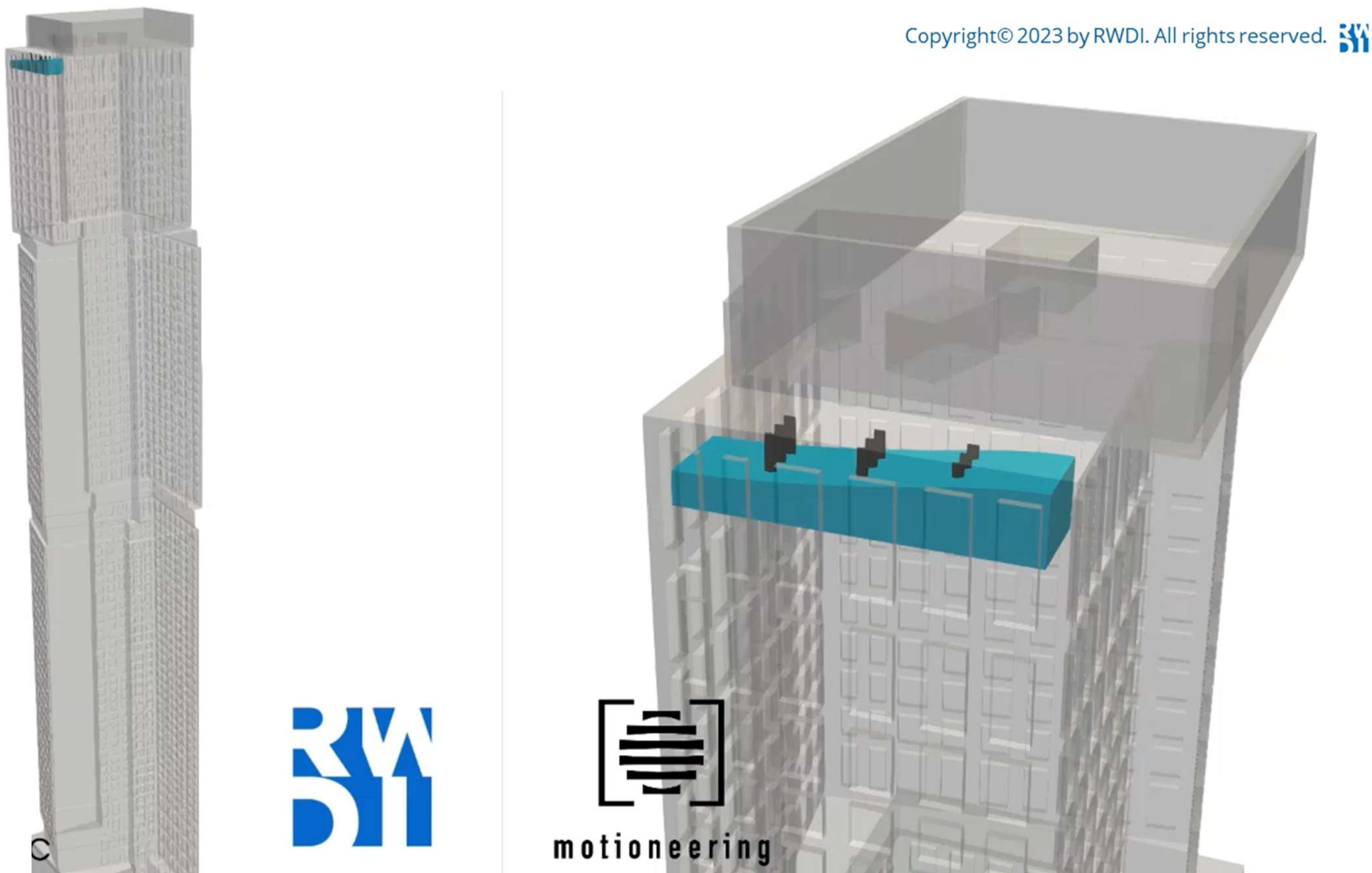
Building B – Overall Wind Loading at Base

Supplemental Damping System Implementation



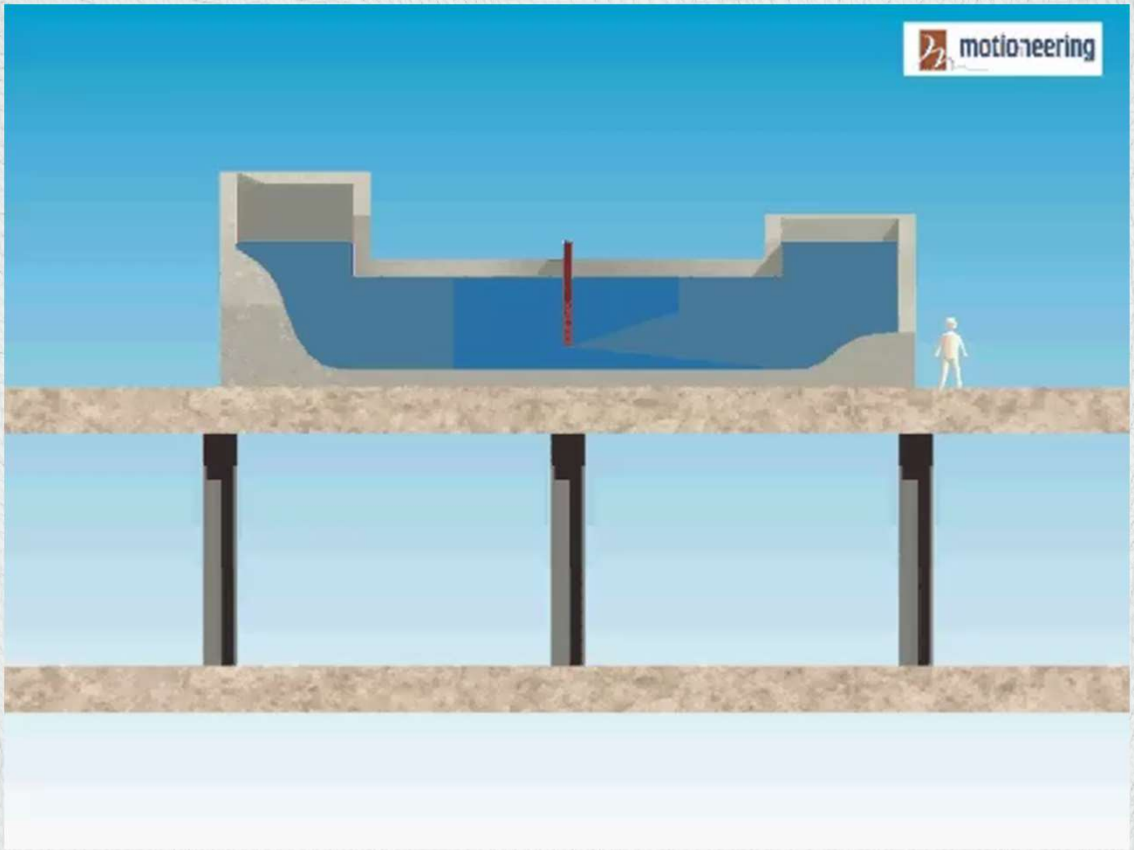
Tuned Mass Dampers (TMD) – Taipei 101 Tower – Taipei - Taiwan

Supplemental Damping System Implementation



Tuned Sloshing Damper (TSD)

Supplemental Damping System Implementation



Tuned Liquid Column Damper (TLCD)

Redefining possible.

THANK YOU