BUILDING AERODYNAMICS – OPTIMIZATION OF WIND-INDUCED STRUCTURAL RESPONSES

Redefining possible.

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RWDI – Company background

Established in 1972

450+ employees

Global presence

In Indonesia since 90's

Three Practice Areas:

- Climate Engineering
- Building Performance
- Environmental Engineering

Talk Overview

1

Tall Building Aerodynamics

- What causes high wind loads ?

2

Reducing structure (i.e., construction materials)

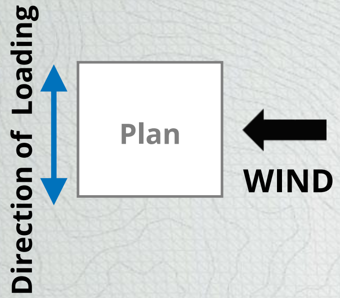
- Orientation
- Shape
- Supplementary damping

3

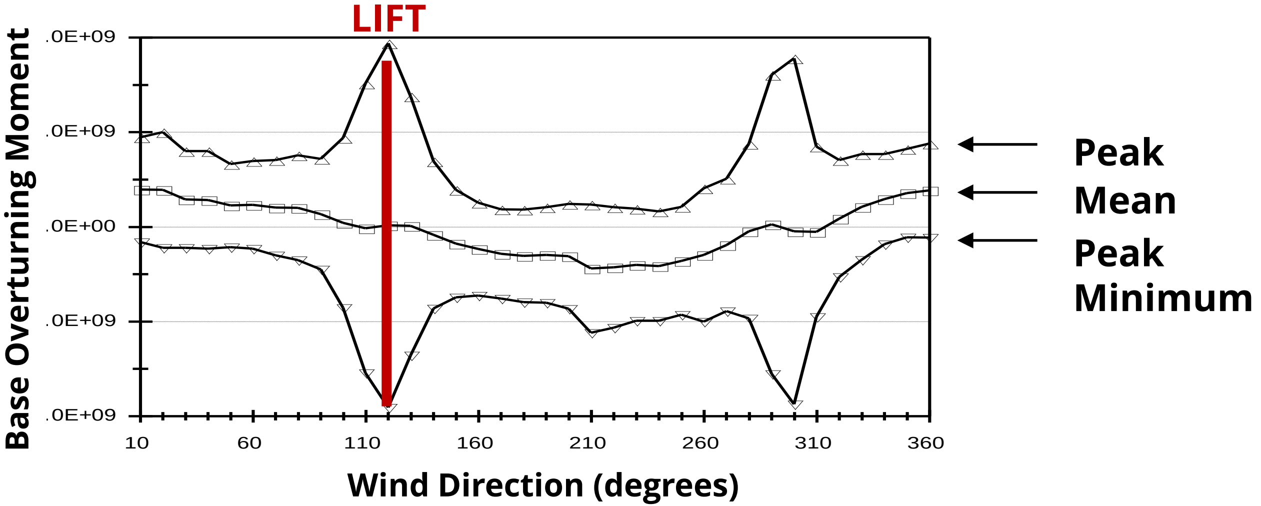
Project examples

What causes high wind loads ?

Response of a Typical Tall Building – Lift (Across Wind)

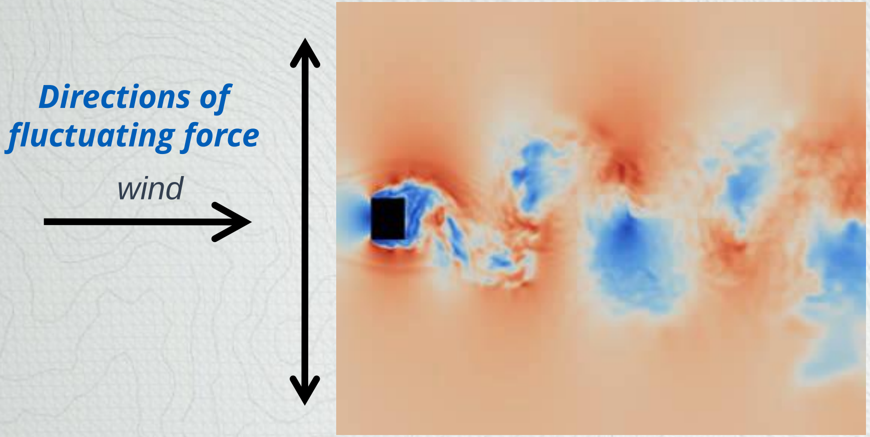


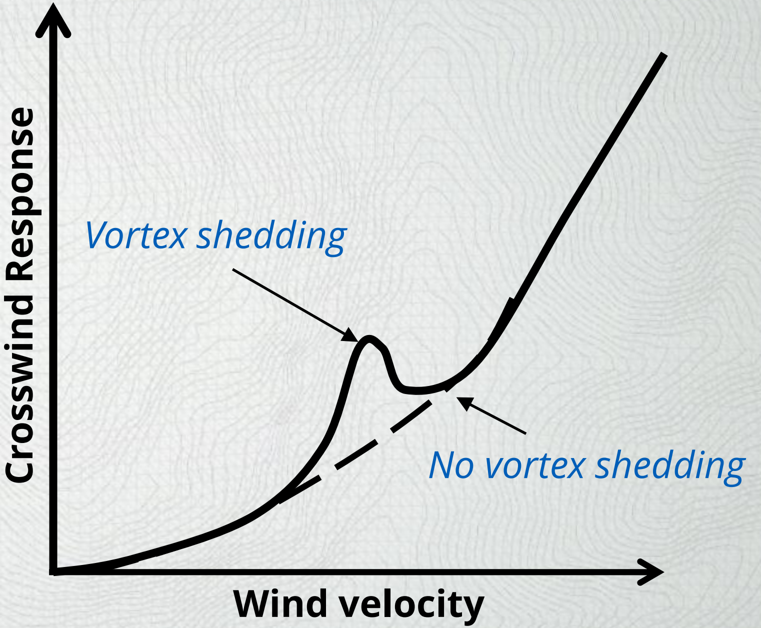
Across-wind response where mean loads are negligible



- High across-wind responses impact strength and serviceability design.
- **Requires additional structure to counter the problem.**

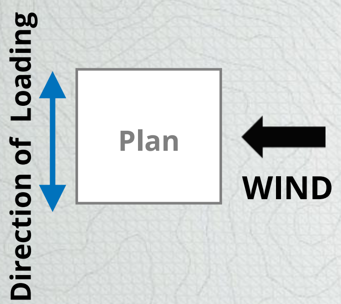
Across-Wind Loading (Vortex Shedding)

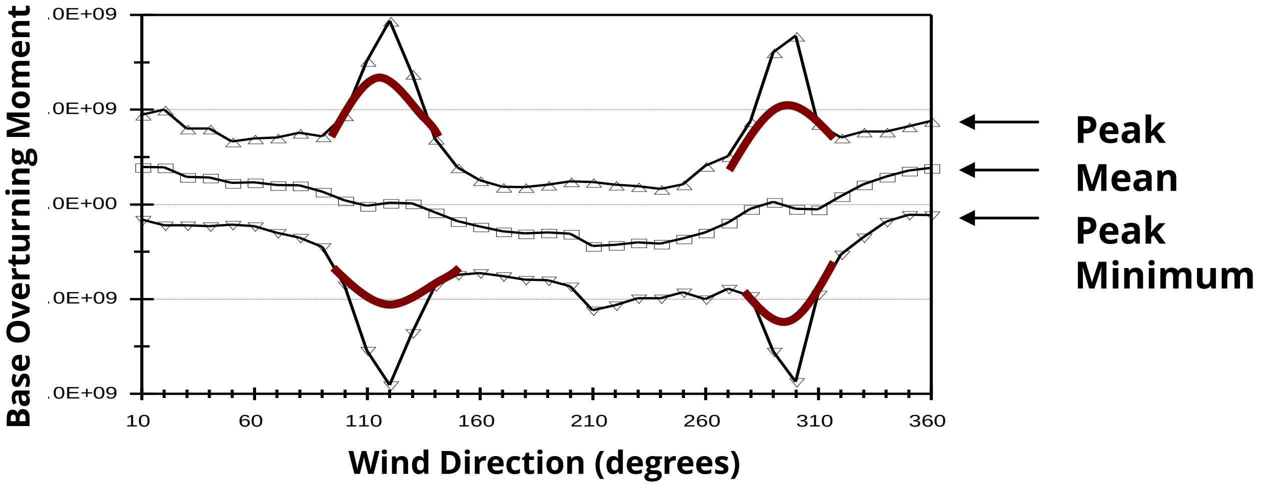




- Sometimes vortex shedding affects serviceability design only
- Requires additional structure to satisfy serviceability demands

Reduction of structure through wind tunnel testing



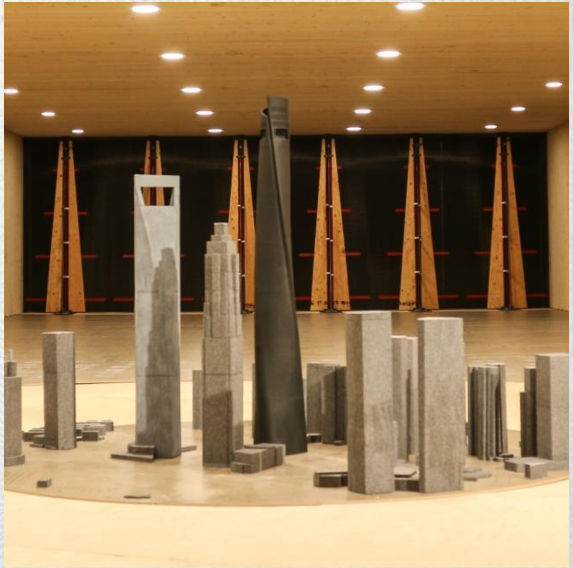


- Reduction of wind loads often translates into **reduced construction materials**
- Realizing material savings translates into other benefits such as emission reductions for transportation of materials from source to site

Wind Tunnel Testing

Wind tunnel testing accounts for project specific

- Wind climate
- Aerodynamic shape
- Immediate Surroundings and Upwind Terrain Conditions
- Detailed structural properties (mass and stiffness designed by structural engineer)
- Damping (inherent and/or supplementary)

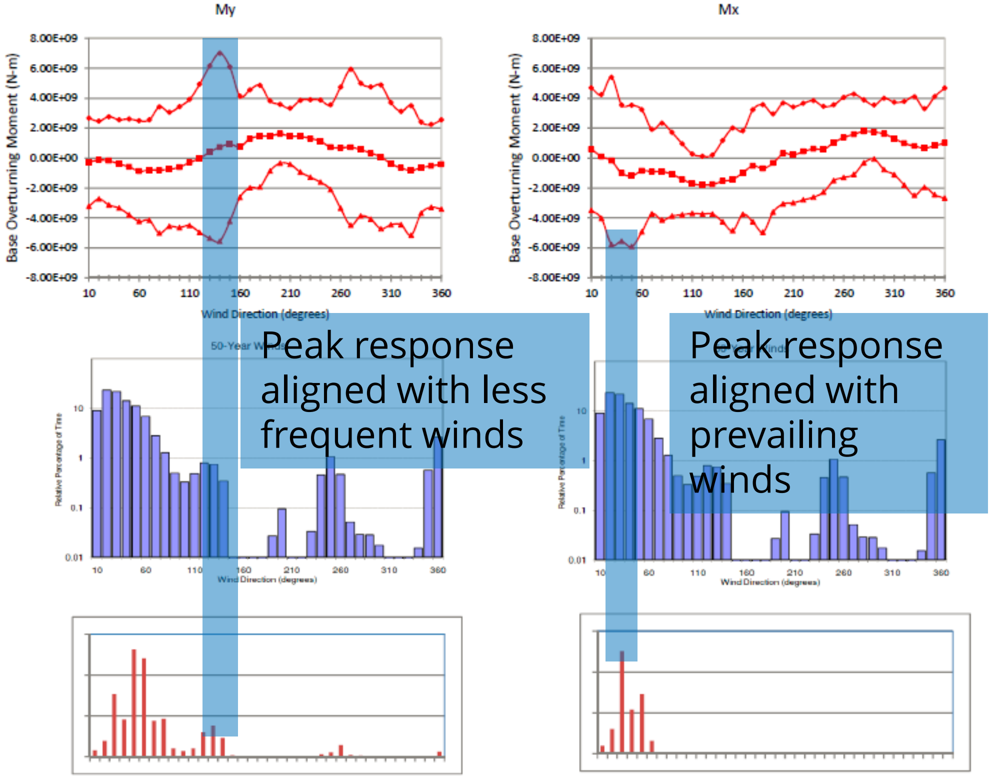


Influence of the Wind Climate

Aerodynamic Response

Wind Climate Model

Combination of Response and Directionality



Peak response aligned with less frequent winds

Peak response aligned with prevailing winds

Requires less structure

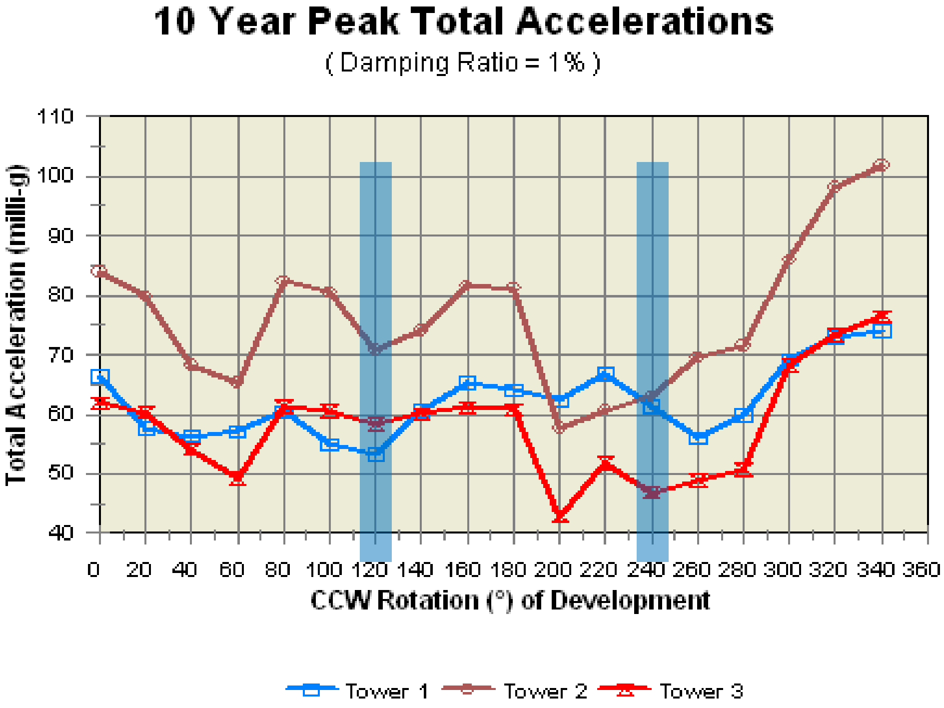
Requires more structure

Influence of the Wind Climate – Three Tower Complex

Three linked supertall towers of varying heights with strong interactions between towers – structural and aerodynamic

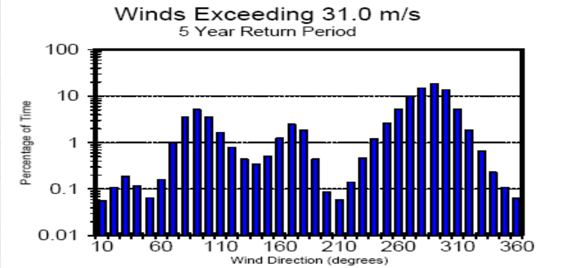
Data analyzed for rotation of the wind climate at 20° increments around the compass

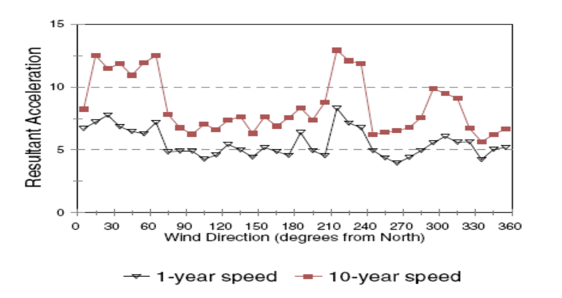
Apparent that certain orientations are more favorable

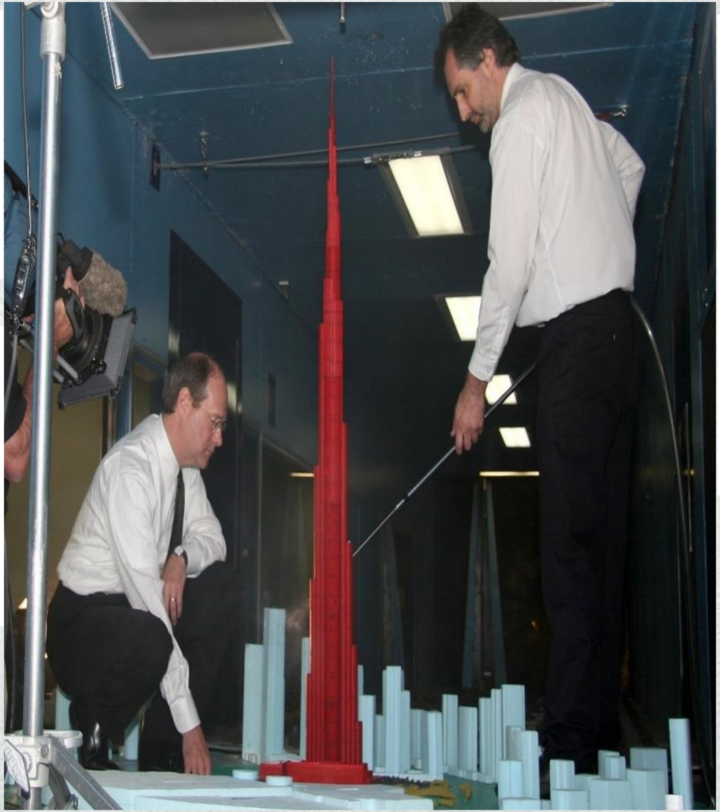


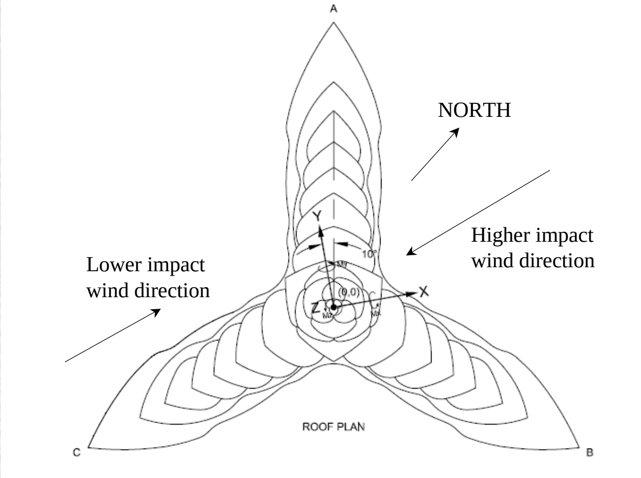
Optimizing building form

Burj Khalifa: Changing Cross Section, Orientation & Taper.



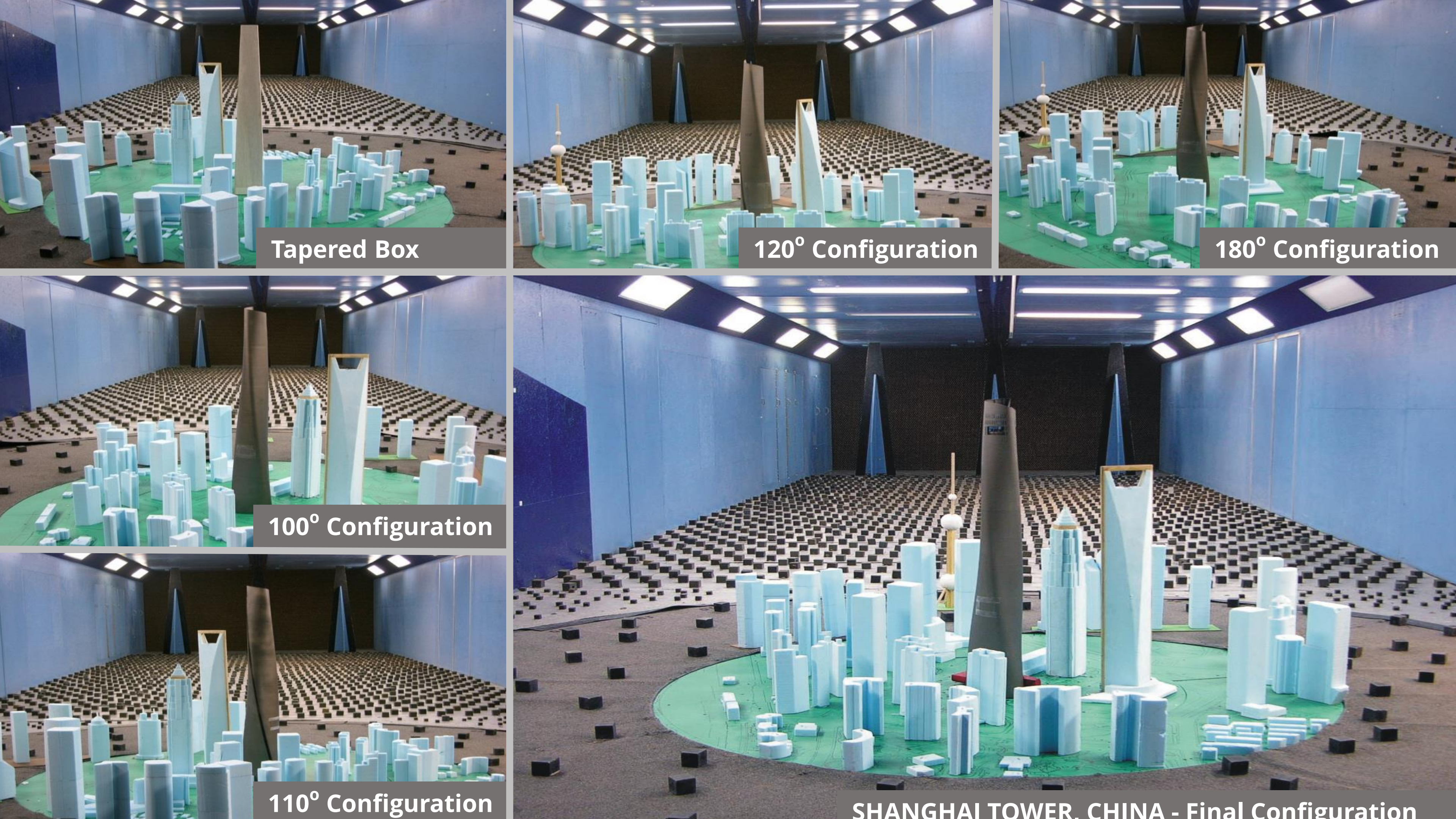






"We virtually designed [the tower] in a wind tunnel"

Bill Baker of SOM
Discussing the Burj Khalifa Project


Tapered Box
120° Configuration
180° Configuration
100° Configuration
110° Configuration
SHANGHAI TOWER, CHINA - Final Configuration

Comparison of Base Overturning Moments

Benefits of Optimization due to Twist & Building Orientation

Assume the same structural properties for all configurations

(Vr=52m/s, 100-yr wind, damping=2.0%)

Reference →

Configuration	Test Date	My (N-m)	Ratio	Mx (N-m)	Ratio	Ref. Resultant	Ratio
Base (Tapered Box)	08/22/2008	5.45E+10	100%	4.98E+10	100%	6.22E+10	100%
100° (107°)	07/28/2008	4.53E+10	83%	4.19E+10	84%	5.18E+10	83%
110° (118°)	08/22/2008	3.97E+10	73%	4.31E+10	87%	4.92E+10	79%
180° (193°)	07/28/2008	3.39E+10	62%	3.65E+10	73%	4.18E+10	67%
120° (129°) - 0° Rot.	Estimated	3.43E+10	63%	4.29E+10	86%	4.75E+10	76%
110° (118°) - 30° Rot.	09/29/2008	3.92E+10	72%	3.60E+10	72%	4.48E+10	72%
120° - 40° Rot.	09/29/2008	3.57E+10	66%	3.53E+10	71%	4.15E+10	67%

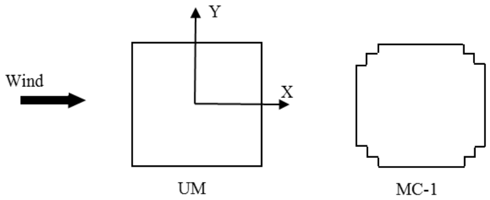
32% reduction in construction materials !!!

$$\text{Ref.Resultant} = \sqrt{(Max)^2 + (0.6 \times Min)^2}$$

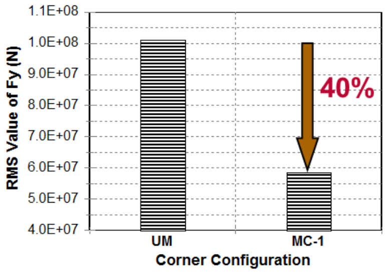
Final Configuration

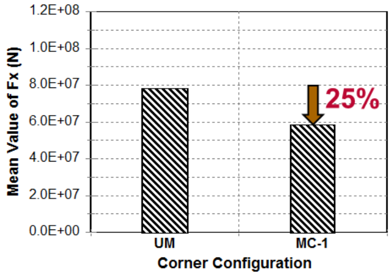
0° Rot. – Original 110° Shape Footprint Position
30° Rot. – Optimal Orientation of 110° Shape
40° Rot. – Optimal Orientation of 120° Shape

TAIPEI 101: Sensitivity to Corner Details



25% reduction in base moments !!!





Sensitivity to Corner Details

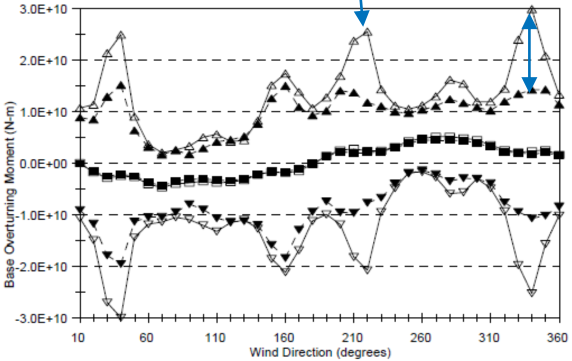
Slotted Corners

Chamfered Corners

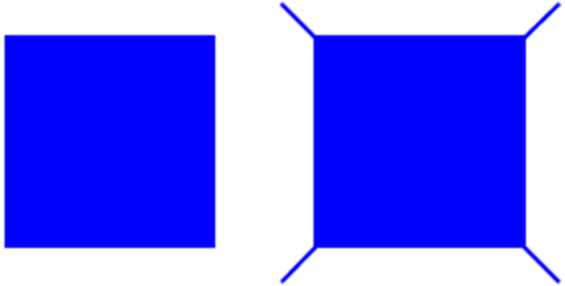
“Softened” corners

“Hardened” corners

Exposed structure at edges



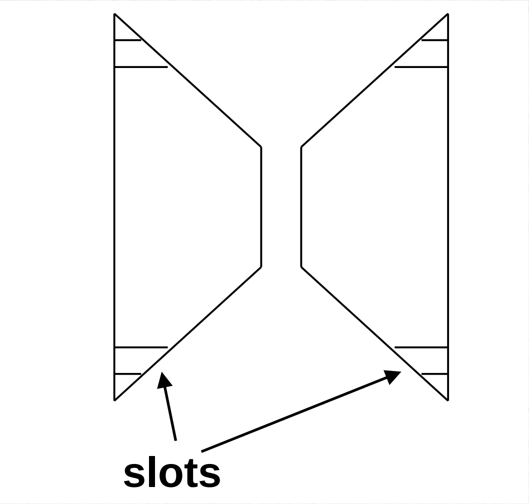
Big increase in response

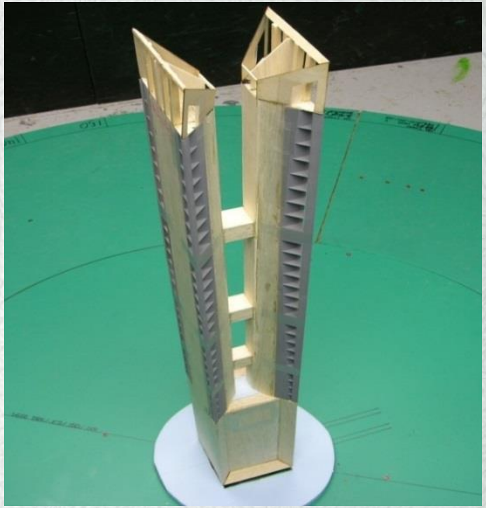


Basic

Fins

151 Incheon Tower – Korea: Corner openings





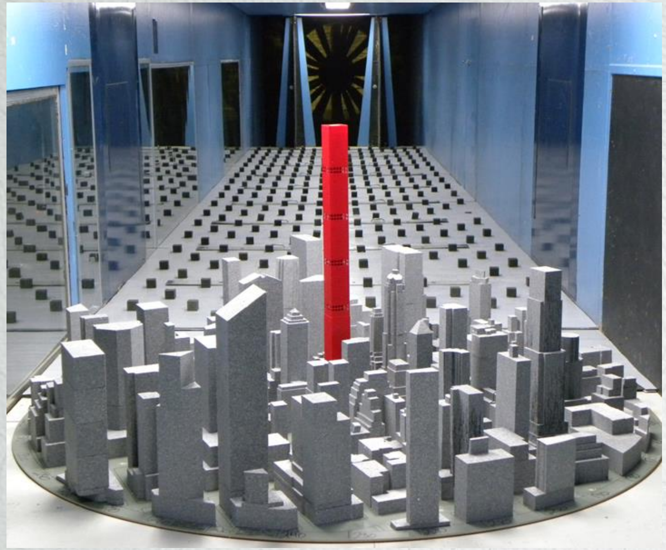
- In order to mitigate the high vortex shedding responses a variety of aerodynamic modifications were explored which focused on changes to outer corners with the inclusion of slots in the building.
- Modified roof, made more porous
- **60% reduction in base moments**

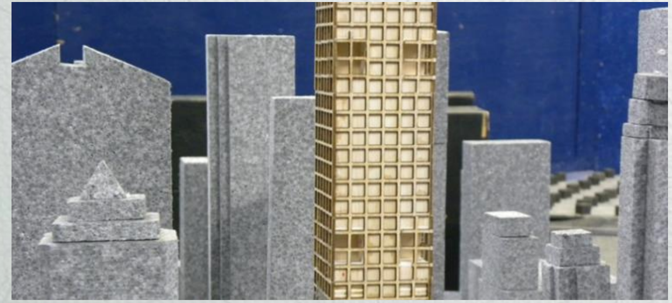
432 Park Avenue – NYC

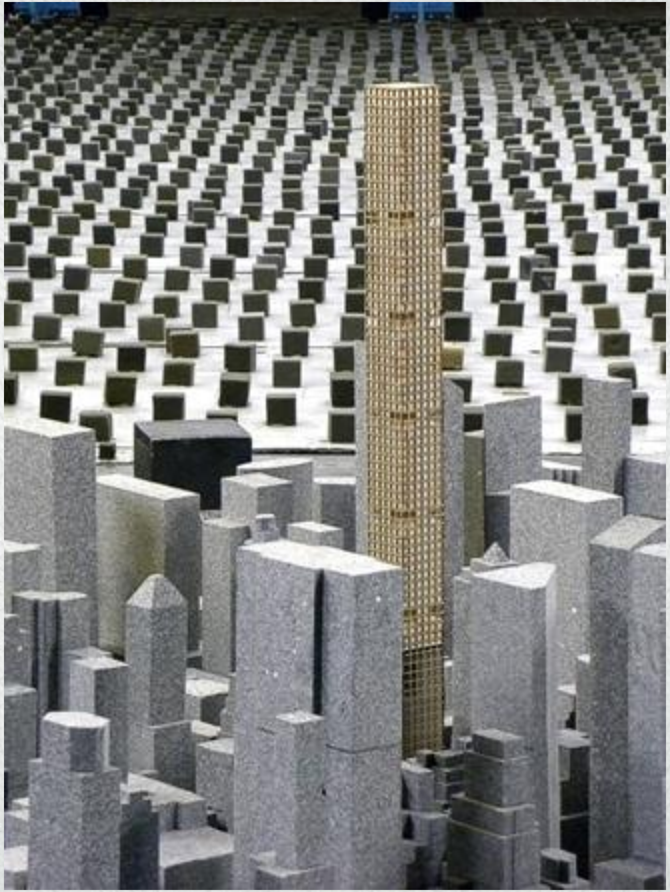
96 Stories Residential Tower (15:1 Aspect Ratio)

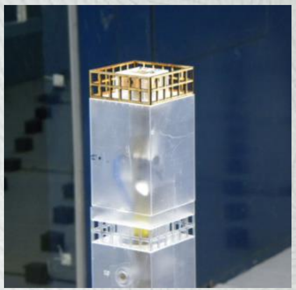
Period >> 10 secs

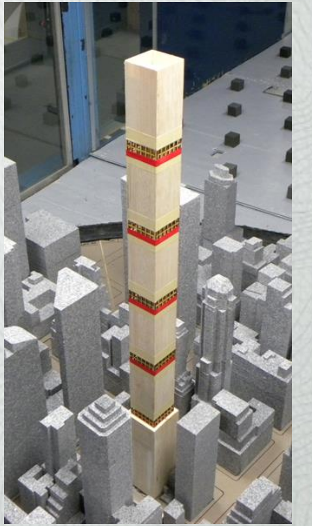
Exploration of Openings











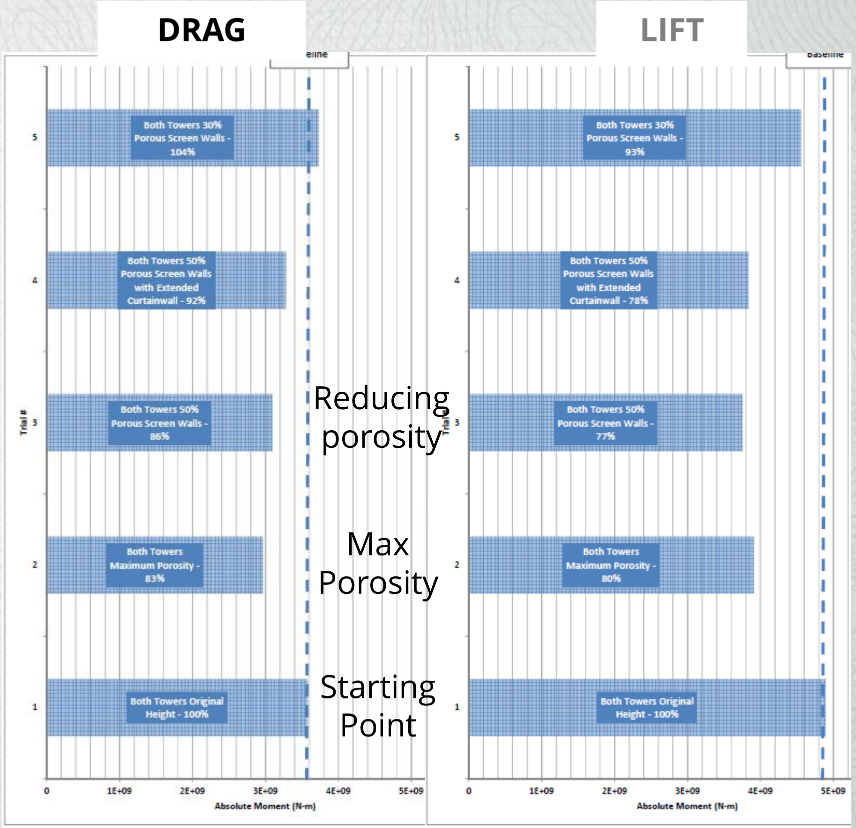

MetLife

Twin Towers – Fine tuning for Height Increase

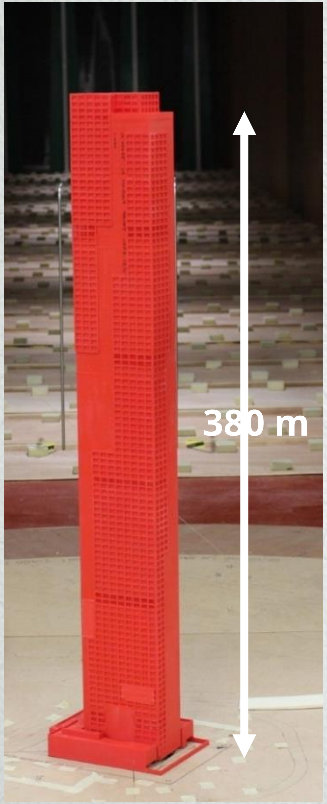
Design completed based on wind tunnel testing

Desired to increase the height without increasing base loads

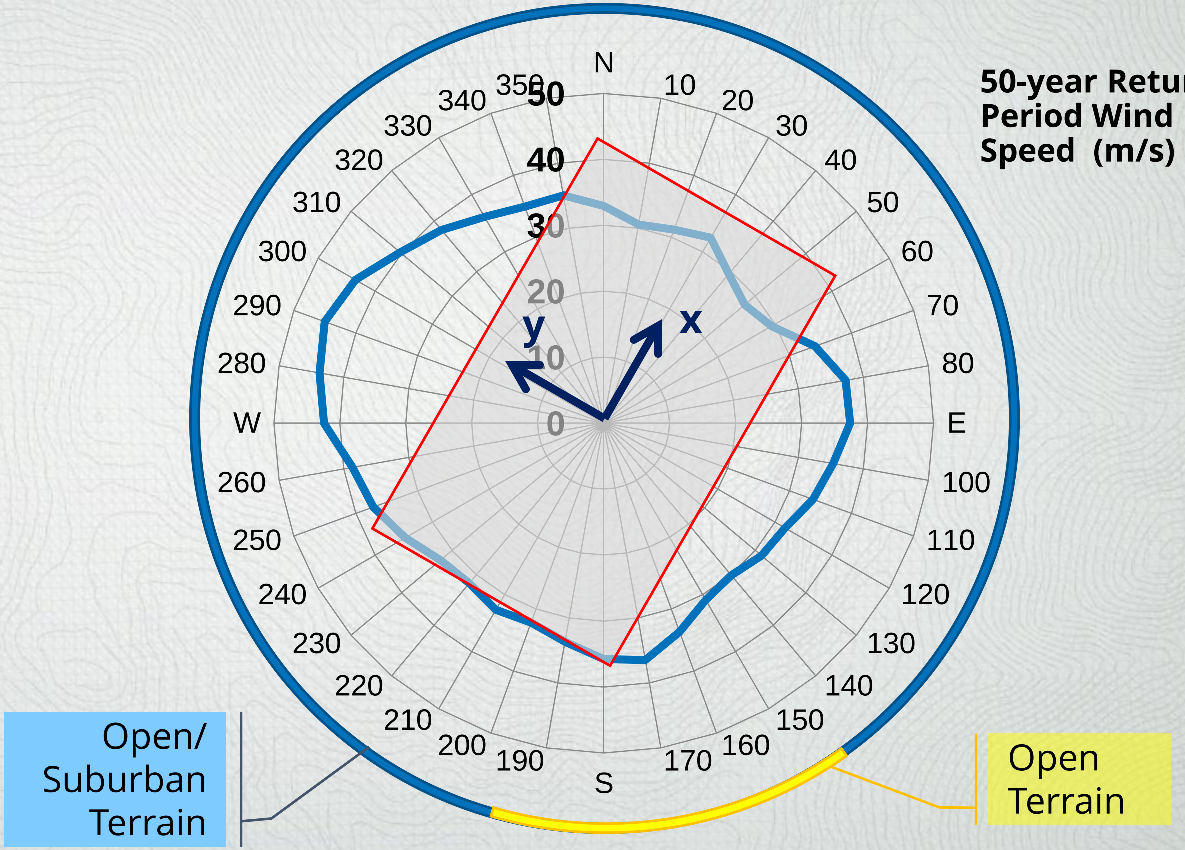
Porosity introduced at the top



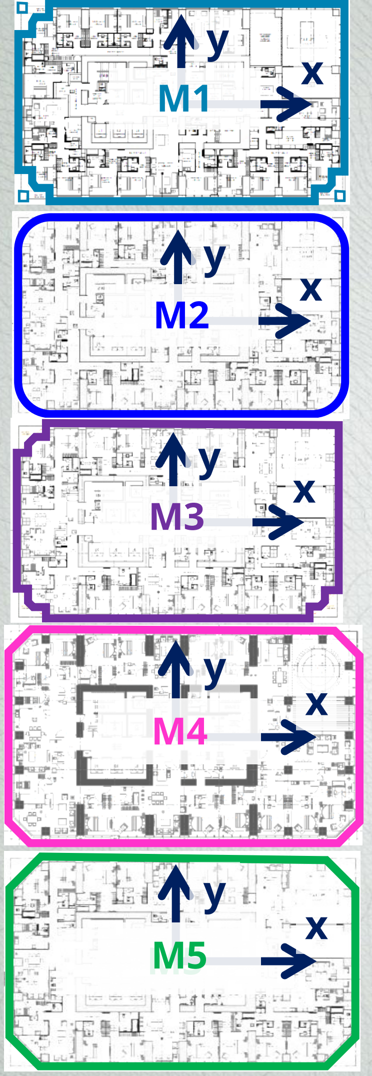
380 m Residential Tower



1:400 scale

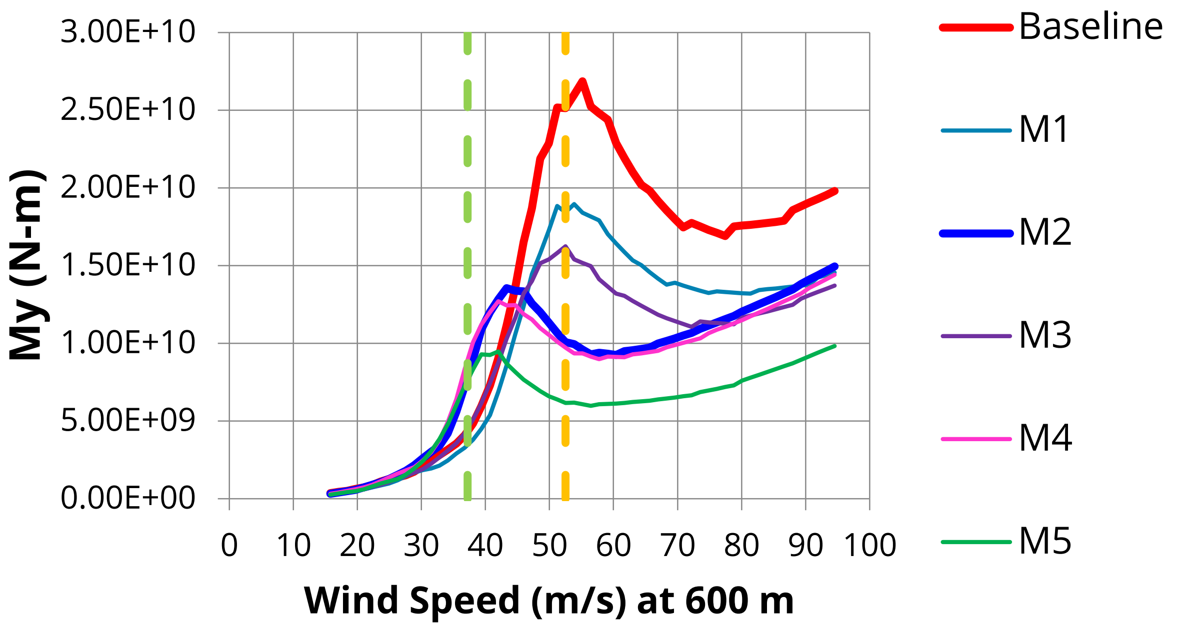


50-year Return Period Wind Speed (m/s)



My Base Moment vs Wind Speed, angle 300°

40% reduction in base moments



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Influence of damping

Damping in Structures – How much?

Considerable scatter in available data

Tall buildings certainly don't seem predisposed to *high* levels of as-built inherent structural damping

Damping is often observed to be amplitude-dependent

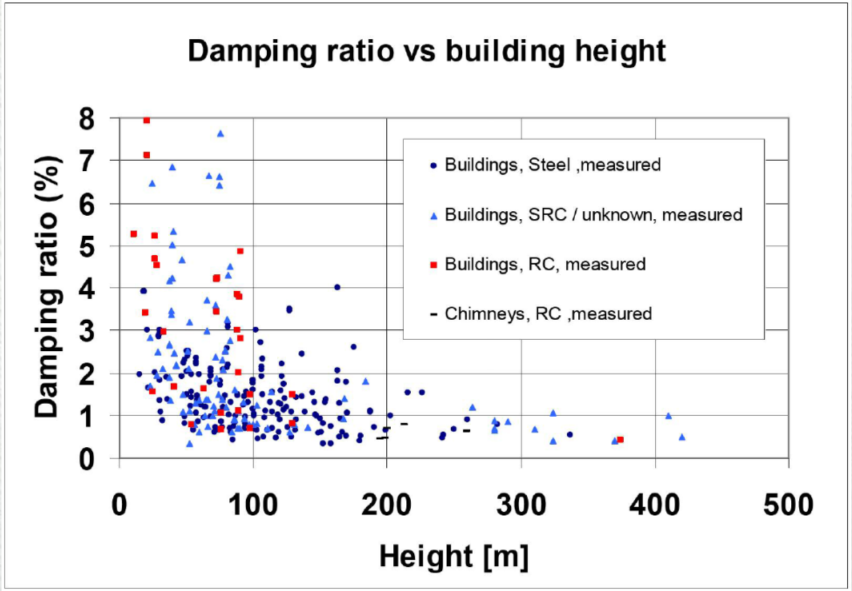
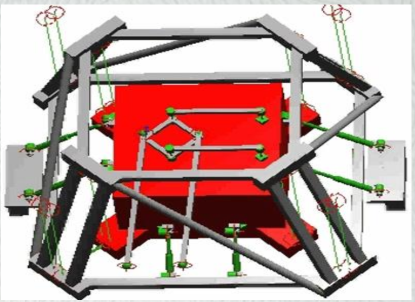


Image Credit: Smith & Willford, Arup, "Damping in tall buildings – uncertainties and solutions", 17th Congress of IABSE, 2008

Types of Supplemental Damping Systems

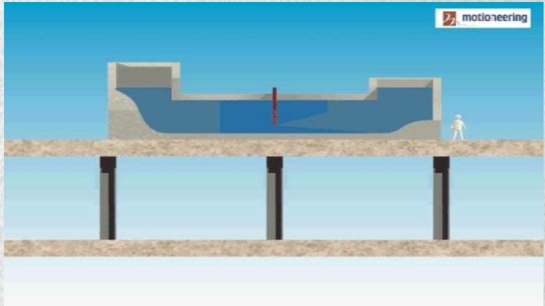
Solid Mass Type:

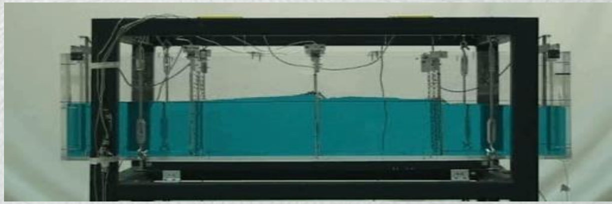
- Tuned Mass Damper (TMD)
- Various configurations possible



Water/Liquid Type:

- Tuned Liquid Column Damper (TLCD)
- Tuned Sloshing Damper (TSD)





Benefits of Supplementary Damping for Buildings

- Achieve "High-Quality Building" standard in terms of comfort
- Save quantity of structure needed …. cost savings
- Increased revenue through increased floor space
- Sustainable Design / Green Benefits

Case Study Example

75-storey concrete, residential tower in an urban location

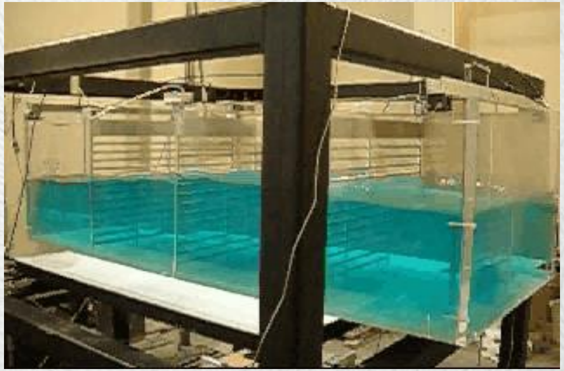
Early design involvement with RWDI

Tuned Sloshing Damper used to *optimize structure*

At least 3% damping WILL be achieved

Case A: explore adding floors without thickening shear walls

Case B: explore reductions in structure



Tuned Sloshing Damper
– integrated into design EARLY

Results – Case A

5 more floors, no increase in shear walls, additional materials

Concrete:	**2,100 m^3**
Reinforcement:	**250,500 kg**
Formwork:	**10,600 m^2**
INCREASED COST:	**$1.6 Million**
Gain of Usable Floor Space:	**60,000 ft^2**
INCREASED REVENUE:	**$36 Million**

Results – Case B

Reduction in Structural Materials

Concrete:	**1,400 m^3**
Reinforcement:	**88,000 kg**
PT Strand:	**9,300 kg**
COST SAVINGS:	**$450,000**
Gain of Usable Floor Space:	**2,800 ft^2**
INCREASED REVENUE:	**$1.7 Million**

GHG SAVINGS: 875 tons of CO_2

Equivalent to over 68,000 cars off the road for one day

THANK YOU ☺

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Redefining possible.