BUILDING AERODYNAMICS – OPTIMIZATION OF WIND-INDUCED STRUCTURAL RESPONSES

Redefining possible.

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Regional Manager | Associate
Rowan Williams Davies & Irwin Inc. (RWDI)
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)

Directions of fluctuating force
wind

- 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
Requires less structure

Peak response aligned with prevailing winds
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
## Benefits of Optimization due to Twist & Building Orientation

### Reference

Assume the same structural properties for all configurations

\( V_r = 52 \text{ m/s}, \) 100-yr wind, damping=2.0%

### 32% reduction in construction materials !!!

### Table: Comparison of Base Overturning Moments

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

**Ref. Resultant**

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

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

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Final Configuration
TAIPEI 101: Sensitivity to Corner Details

25% reduction in base moments !!!
Sensitivity to Corner Details

Exposed structure at edges

“Softened” corners

“Hardened” corners

Big increase in response
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
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

Open/Suburban Terrain

Open Terrain

50-year Return Period Wind Speed (m/s)
My Base Moment vs Wind Speed, angle 300°

40% reduction in base moments
Influence of damping
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

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 m³
Reinforcement: 250,500 kg
Formwork: 10,600 m²

INCREASED COST: $1.6 Million

Gain of Usable Floor Space: 60,000 ft²

INCREASED REVENUE: $36 Million
Results – Case B

Reduction in Structural Materials

Concrete: 1,400 m³
Reinforcement: 88,000 kg
PT Strand: 9,300 kg

COST SAVINGS: $450,000

Gain of Usable Floor Space: 2,800 ft²

GHG SAVINGS: 875 tons of CO₂

INCREASED REVENUE: $1.7 Million

Equivalent to over 68,000 cars off the road for one day.
THANK YOU 😊

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