Wind Effects on Tall Buildings and Wind Tunnel Model Tests
Tall Buildings

1. Height relative to context

2. Embracing technologies

3. Proportion

4. [Diagram or image related to embracing technologies]
Wind Effects on Tall Buildings

Importance of Wind Load

<table>
<thead>
<tr>
<th>Height, m</th>
<th>Normalized Mean Wind Speed, $\frac{U_i}{U_g}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>0.2</td>
</tr>
<tr>
<td>40</td>
<td>0.4</td>
</tr>
<tr>
<td>60</td>
<td>0.6</td>
</tr>
<tr>
<td>80</td>
<td>0.8</td>
</tr>
<tr>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>120</td>
<td>1.2</td>
</tr>
<tr>
<td>140</td>
<td>1.4</td>
</tr>
<tr>
<td>160</td>
<td>1.6</td>
</tr>
<tr>
<td>180</td>
<td>1.8</td>
</tr>
<tr>
<td>200</td>
<td>2</td>
</tr>
</tbody>
</table>

Mean Wind Speed Profile

- Open-terrain
- Suburban
- Urban

Normalized spectral density

- Tall buildings
- Low rise buildings

- Long span bridges
- Wind
- Earthquake
Wind Effects on Tall Buildings

Shiten'noji Pagoda (Osaka, Japan 1934)
Wind Effects on Tall Buildings

555 17th Street (Denver, Colorado 2012)
Wind Effects on Tall Buildings

- John Hancock Tower (Boston, United States)
- Building swayed in the wind
  - Upper-floor occupants suffered from motion sickness
  - Retrofitting
    - Tuned Mass Damper
      - $3 million USD
    - Bracing
      - $5 million USD
Wind Effects on Tall Buildings

10,344 window panes were replaced

$5 to $7 million USD

John Hancock Tower (Boston, United States)
Wind Effects on Tall Buildings

1. Cladding
2. Cladding Support
3. MWFRS*

*Main Wind Force Resisting System (MWFRS)
Wind-induced Overall Response of Structures

Overall response = Mean response + Background response + Resonant response

Inertial force
Wind-induced Overall Response of Structures

Main Wind Force Resisting System

Wind-induced Overall Response of Structures

Wind-induced Force

Building Code Approach  Wind Tunnel Model Test
Building Code vs Wind Tunnel Model Test

Comparison of Peak Base Moment

Wind Tunnel = 1.59 x ASCE

Peak Base Moment

Wind Tunnel = 1.35 x ASCE

Mx

My
Limitations of Building Codes

- Building Codes do not account for interference effects caused by nearby buildings and other obstructions.
Limitations of Building Codes: Interference Effect

\[ i_f = \text{Response with interfering building} \]

\[ R = \text{Response of isolated building} \]
Limitations of Building Codes: Interference Effect

IF of Mean Response in Y-direction

IF < 1, force reduction
IF > 1, force amplification
Limitations of Building Codes: Interference Effect

IF of Background Response in Y-direction

IF < 1, force reduction
IF > 1, force amplification
Limitations of Building Codes: Interference Effect

IF of Resonant Response in Y-direction

IF < 1, force reduction
IF > 1, force amplification

Wind direction
Limitations of Building Codes: Interference Effect

IF of Maximum Response in Y-direction

IF < 1, force reduction
IF > 1, force amplification
Limitations of Building Codes: Interference Effect

- Reduce mean response
- Increase background and resonant response
- Increase overall response

Overall response = Mean response + Background response + Resonant response
Limitations of Building Codes: Interference Effect

Research

Practice
U.S. Department of Commerce Bureau of Standards

Research Paper RP637

Part of Bureau of Standards Journal of Research, vol. 12, January 1934

Influence of Neighboring Structures on the Wind Pressure on Tall Buildings

By C. L. Harris¹
Limitations of Building Codes: Response prediction
Limitations of Building Codes: Response prediction

- Drag Force $C_D$
- Side Force $C_L$
- Torsion $C_T$

Wind direction:
- Front
- Back
- Right
- Left

Forces:
- $F_x$
- $F_y$
- $M_z$
Limitations of Building Codes: Shape
TU-AIT Boundary Layer Wind Tunnel Laboratory

- 23m X 2.5m X 2.5m
- Open-circuit, Blowing Type
- Test Section: 18.5m X 2.5m X 2.5m
TU-AIT Boundary Layer Wind Tunnel Laboratory
TU-AIT Boundary Layer Wind Tunnel Laboratory
Boundary Layer Wind Profile

**Mean Wind Speed Profile**

- **Full Scale Height, m**
- **Normalized Mean Wind Speed, \( \frac{\bar{U}_i}{\bar{U}_g} \)**

Power Law, \( \frac{\bar{U}_i}{\bar{U}_{g,ref}} = \left( \frac{i}{i_{ref}} \right)^{n} \)

**Turbulence Intensity Profile**

- **Full Scale Height, m**
- **Longitudinal Turbulence Intensity, \( I_{u_l} \)**

Longitudinal Turbulence Intensity, \( I_{u_l} = \frac{0.4 \sqrt{\beta}}{\ln \left( \frac{i}{i_0} \right)} \)
Boundary Layer Wind Simulation
Boundary Layer Wind Simulation
Boundary Layer Wind Simulation

Mean Wind Speed Profile

Normalized Mean Wind Speed, $\frac{U_i}{U_{ref}}$

Full Scale Height, m

Length Scale=1:300

Power Law, $\frac{U_i}{U_{ref}} = \left( \frac{i}{i_{ref}} \right)^n$

Open-terrain
Suburban
Urban
Boundary Layer Wind Simulation

Turbulence Intensity Profile

- Open terrain
- Suburban
- Urban

Length Scale = 1:300

Longitudinal Turbulence Intensity, $I_{u_i} = \frac{(0.4) \sqrt{B}}{\ln \left( \frac{z}{z_0} \right)}$

$x_i$ Length ($\text{m}$)

$\sigma_{u_i}$ Turbulence Intensity
Wind-induced Force Measurement

- High Frequency Force Balance (HFFB) Technique
- High Frequency Pressure Integration (HFPI) Technique
High Frequency Pressure Integration (HFPI) Technique

1:300 Scale

48 cm

144 m
High Frequency Pressure Integration (HFPI) Technique
High Frequency Pressure Integration (HFPI) Technique
High Frequency Pressure Integration (HFPI) Technique

**Basic Parameters**

Length Scale, $\lambda_L = \frac{L_m}{L_p} = 1/300$

Velocity Scale, $\lambda_V = \frac{\bar{U}_m}{U_p} = 6.5/49$

Time Scale, $\lambda_T = \frac{\lambda_L}{\lambda_V}$

Test Duration, $T_m = \lambda_T \times 3600$

Prototype Pressure: $P_{pij} = P_{pij}^C \times \frac{1}{2} \rho \ U_m^2$

Time-Varying Pressure Coefficient: $C_{p_{pij}}^t = \frac{P_{pij}^C}{\frac{1}{2} \rho \ U_m^2}$
High Frequency Pressure Integration (HFPI) Technique

Drag Force:
\[ F_{ix}^T = \sum_{j=1}^{n_i} p_{ij}^T A_{P_{ij x}} \]

Modal Drag Force:
\[ Q_{ix} = \sum_{l=1}^{N} F_{lx}^T \Phi_{lxx} \]

Modal Response Spectrum: \( S_{f1xm} = \frac{s_{q1xm}^T}{K_{1x}^T} |\eta_{1x}|^2 \)

Mean Displacement Response,
\[ \bar{x}_{11x} = \frac{Q_{1x}}{K_{1x}} \Phi_{11x} \]

Background Displacement Response,
\[ \sigma_{B11x}^2 = \Phi_{11x}^2 \sigma_{B11x}^2 \]

Resonant Displacement Response,
\[ \sigma_{R11x}^2 = \Phi_{11x}^2 \sigma_{R11x}^2 \]

Fluctuating Displacement Response,
\[ \sigma_{x11x} = \sqrt{(g_{B11x}^2 \sigma_{B11x}^2 + g_{R11x}^2 \sigma_{R11x}^2)} \]

Total Displacement Response,
\[ X_{D11x} = \bar{x}_{11x} + \sigma_{x11x} \]

Equivalent Static Drag Force,
\[ F_{DX} = \frac{X_{D11x}}{\bar{x}_{11x}} F_{lx} \]

Frequency, \( f_p = f_m \times \lambda_f \)
Design Wind Load Cases

Equivalent Static Drag Force,

\[ F_{Dx}, F_{Dy}, M_{T0} \]
Design Wind Load Cases: Wind Tunnel Test

Effective Equivalent Static Force

\[ F_x = \bar{P}_x F_{D_x} \]
\[ F_y = \bar{P}_y F_{D_y} \]
\[ M_\Theta = \bar{P}_\Theta M_{T_0} \]

\[ (\bar{P}_x = \frac{\bar{F}_x}{F_x} = 1) \]
\[ (\bar{P}_y = \frac{\bar{F}_y}{F_y} = 0.59) \]
High Frequency Force Balance (HFFB) Technique
High Frequency Force Balance (HFFB) Technique

\[ f_n = \frac{1}{2\pi K_M} \]
High Frequency Force Balance (HFFB) Technique

Mean Displacement Response,
\[ \bar{X}_{1lx} = \frac{\bar{Q}_{lx}}{K_{lx}} \phi_{ikx} \]

Background Displacement Response,
\[ \sigma_{B1lx}^2 = \phi_{1lx}^2 \sigma_{B1xm}^2 \]

Resonant Displacement Response,
\[ \sigma_{R1lx}^2 = \phi_{1lx}^2 \sigma_{R1xm}^2 \]

Fluctuating Displacement Response,
\[ \sigma_{x1lx} = \sqrt{\left(g_{1lx}^2 \sigma_{B1lx}^2 + g_{1lx}^2 \sigma_{R1lx}^2\right)} \]

Total Displacement Response,
\[ X_{D1lx} = \bar{X}_{1lx} + \sigma_{x1lx} \]

Equivalent Static Drag Force,
\[ F_{Dx} = \frac{X_{D1lx}}{X_{1lx}} F_{lx} \]

\[ F_{x} (Drag force) \]
\[ F_{y} (Side force) \]
\[ M_{\theta} (Torsion) \]
HFPI vs HFFB
HFPI vs HFFB

Mean Modal Force Coefficients in X Direction

Mean Modal Force Coefficients in Y Direction

Mean Modal Force Coefficient in Torsional Direction
Advantage of HFPI: Cladding design

Recommended Positive Wind Pressure for Cladding Design

*Considering all possible wind attack angles*
Advantage of HFPI: Cladding design

Recommended Negative Wind Pressure for Cladding Design

*Considering all possible wind attack angles*
Advantage of HFPI: Appropriate force distribution
Advantage of HFPI: Applicable to any enclosed structure
Advantage of HFPI: Applicable to any enclosed structure
Advantage of HFPI: Applicable to any enclosed structure