# WELCOME

*21-JUNE -2023*

# Session 9

# Wind Engineering Studies for Long-Span Bridges

By

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# Dr. SURESH KUMAR – *Vice President Global Consulting*

- **Education**
  - **Postdoctoral studies, Eindhoven University of Technology, Eindhoven, The Netherlands.**
  - **Doctor of Philosophy, Concordia University, Montreal, Canada**
  - **Master of Science (Engineering), Indian Institute of Science, Bangalore, India**
- **Dr. Suresh Kumar based in London, UK, is well recognized leader in the field of wind engineering.**
- **He has over 32 years of experience as a wind engineering researcher and consultant internationally.**
- **He has been with RWDI for the past 21 years.**
- **He has directed the establishment of RWDI's 5th wind tunnel in Trivandrum, India.**
- **He has worked as a wind consultant on many iconic structures worldwide, including the world's tallest tower, the Burj Khalifa in Dubai.**
- **He has published or presented numerous papers in international journals and conferences.**
- **He is also very active in professional organizations around the world.**

# WIND ENGINEERING FOR LONG-SPAN BRIDGES

## – PART 1

Redefining possible

**K. Suresh Kumar,** PhD, PEng, MASCE
**VP – Global Wind Engineering Consultant / Principal**
**RWDI**




# RWDI's Key Experiences

| BRIDGE NAME | SPAN (m) | LOCATION |
|---|---|---|
| Messina Strait (Suspension) | 3300 | Sicily to Calabria, Italy |
| Golden Gate Bridge (Suspension) | 1280 | San Francisco, CA, USA |
| Stonecutters Bridge (Cable-Stayed) | 020 | Hong Kong, China |
| Tacoma Narrows (Suspension) | 853 | Tacoma, USA |
| Millau Viaduct (Cable Stayed) | 342 | Millau, France |

| TALL BUILDING NAME | HEIGHT (m) | LOCATION |
|---|---|---|
| Kingdom Tower | 1000 | Jeddah, Saudi Arabia |
| Burj Khalifa | 828 | Dubai, UAE |
| Shanghai Tower | 632 | Shanghai, China |



# Outline

- **Introduction**
- **Wind Climate Analysis (for deck, pylons, cables)**
- **Desktop Stability Assessment (for deck, pylons)**
- **Sectional Model Test (for deck)**
- **3D Buffeting Analysis (for deck, pylons, cables)**
- **Concluding Remarks**

**Future Webinar:**

**Aeroelastic wind tunnel study, Vehicle-induced vibrations, Pedestrian-induced vibrations, Supplementary damping considerations, Cable stability analysis, Full-scale measurements, Health monitoring and retrofitting.**

# Introduction

# Introduction

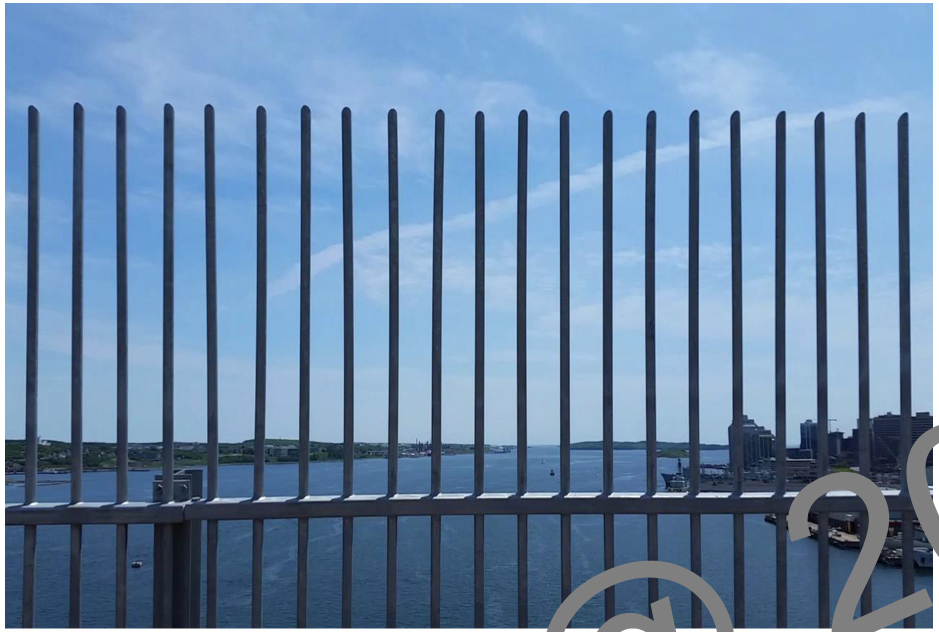
Tacoma Narrows, Washington, USA

**<u>Tacoma Narrows:</u>**
**Span/Width – 1:72**
**Span/Depth – 1:350**
**Weight – 4.25 ton/m**

**<u>Golden Gate:</u>**
**Span/Width – 1:46**
**Span/Depth – 1:168**
**Weight - 21 ton/m**

Volvograd Bridge, Russia

# Introduction



Angus Macdonald Bridge, Halifax, Canada

Millennium Bridge, London

# Introduction

- Light Weight (10 - 50 ton/m) ; Pedestrian (<5 ton/m)
- Supports only at ends (Contrary to tall buildings where gravity advantage)

Weight - 100,000 ton

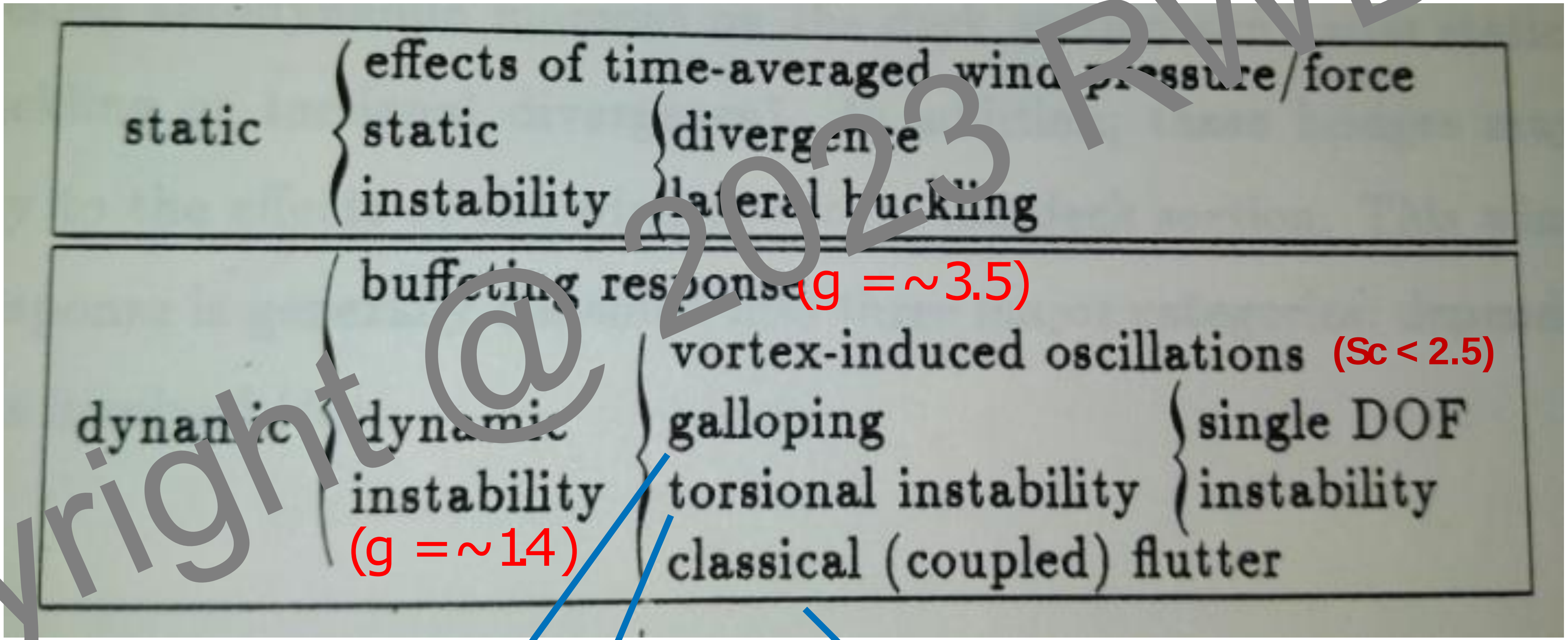
Weight ~ 1500 ton/floor
(500 ton/m)

550 ton

# Classification of Wind Effects on Bridges

No Vibrations

Vibrations



static
effects of time-averaged wind pressure/force
static instability: divergence, lateral buckling

dynamic
buffeting response ($g = \sim 3.5$)
dynamic instability ($g = \sim 14$)
- vortex-induced oscillations (Sc < 2.5)
- galloping
- torsional instability
- classical (coupled) flutter

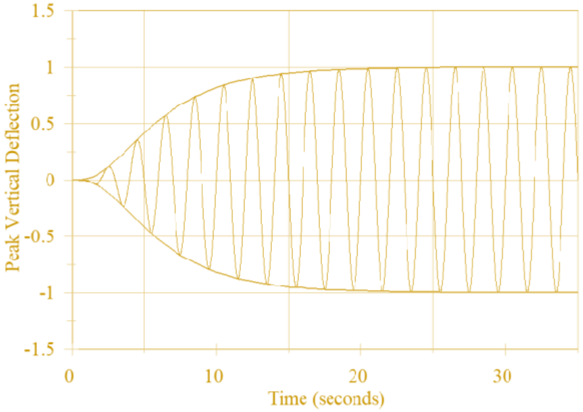
single DOF instability

($dC_z/d\alpha < 0$, $B/D < 5$)

(cross-section (H), $f_t$ low

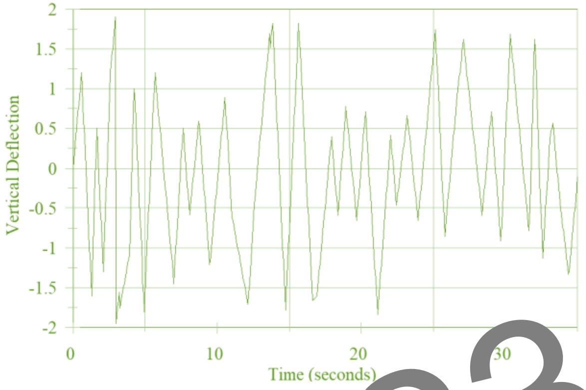
($f_t / f_v < 2$)

# Flow Phenomenon

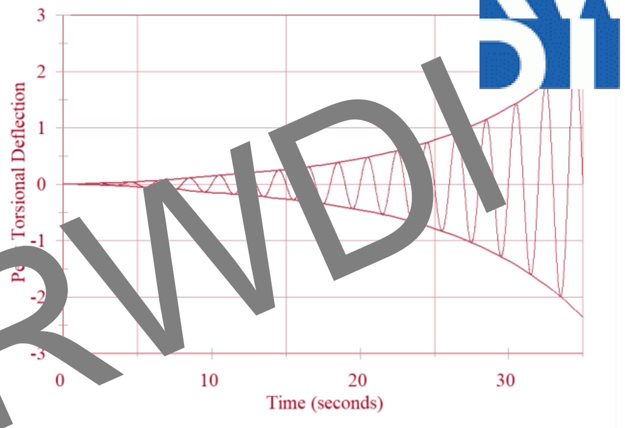


**Vortex Induced Oscillations**

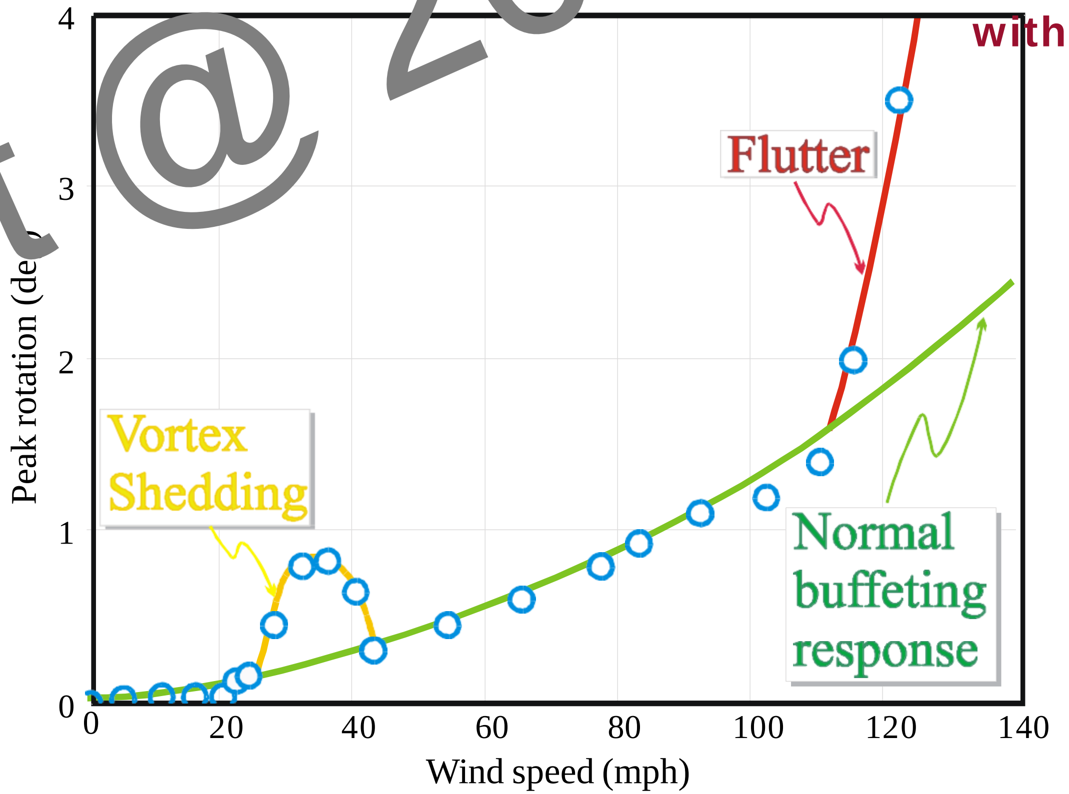
**self limiting response**



**Turbulence Induced Buffeting : random excitations due to the approaching wind**

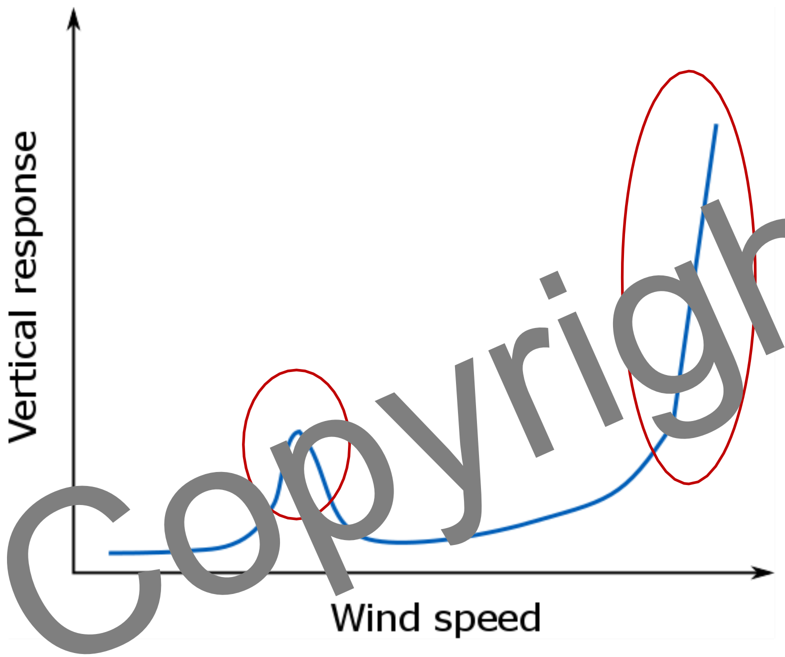


**Flutter : self-excited response that increases in amplitude with wind speed**

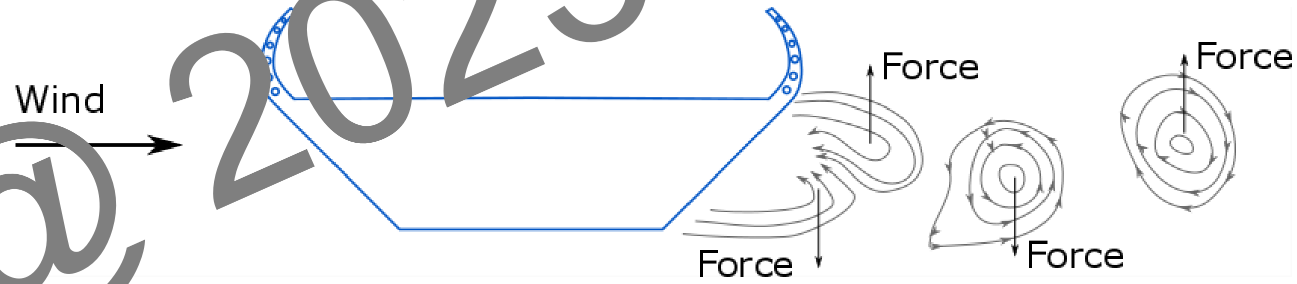


# Flow Phenomenon

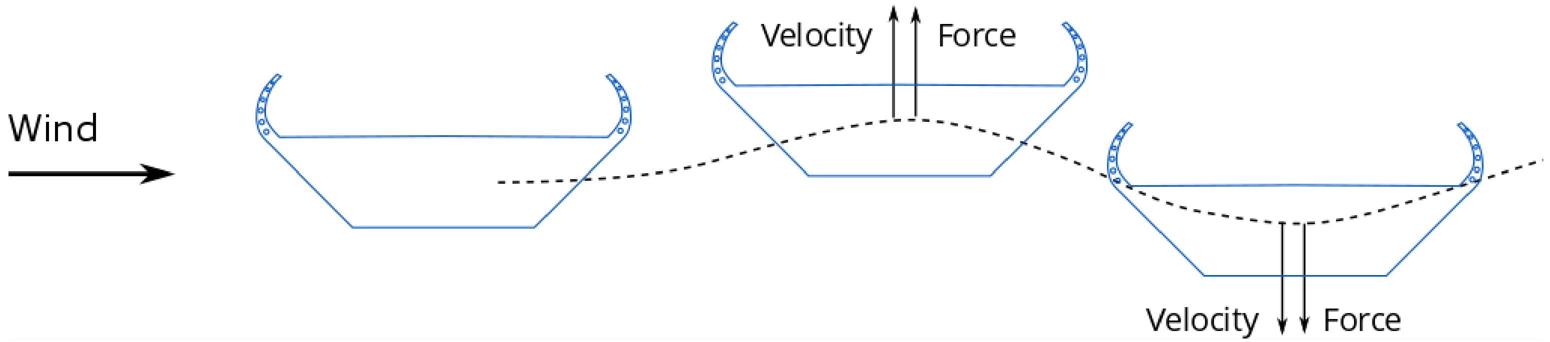
## Vertical motions



### Vortex-induced oscillations

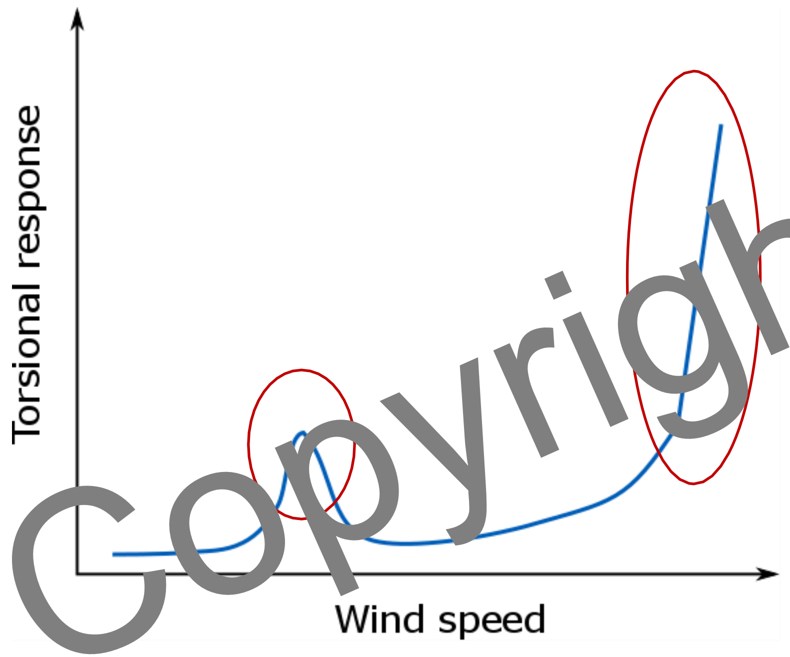


### Galloping - Negative aerodynamic damping

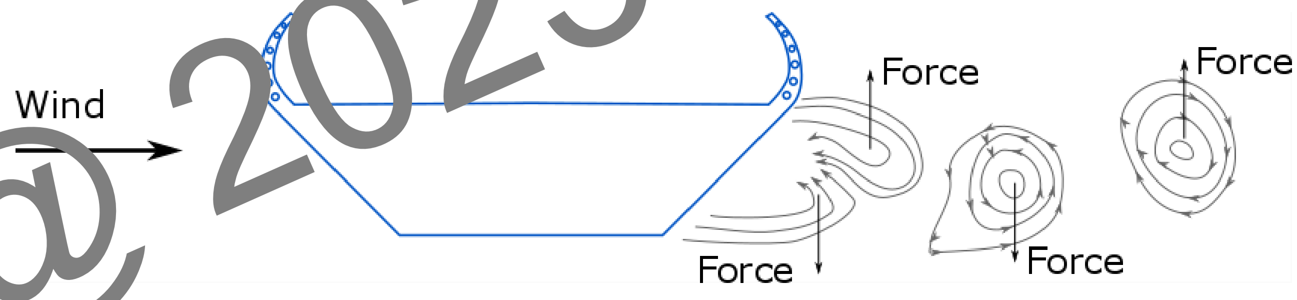


# Flow Phenomenon

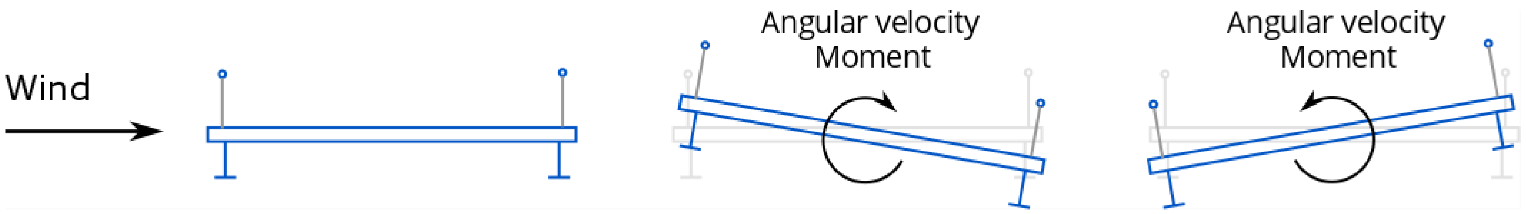
## Torsional motions



Vortex-induced oscillations

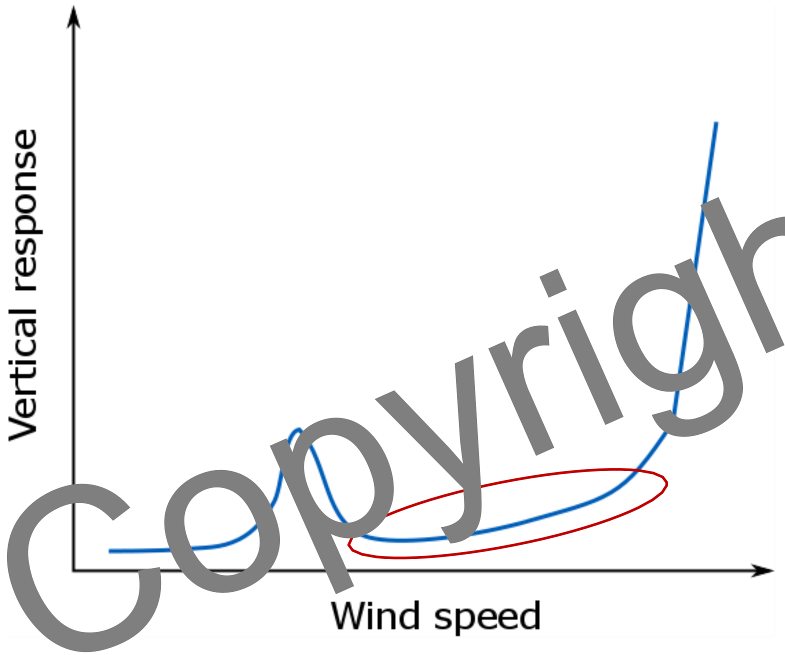


Flutter - Negative aerodynamic damping

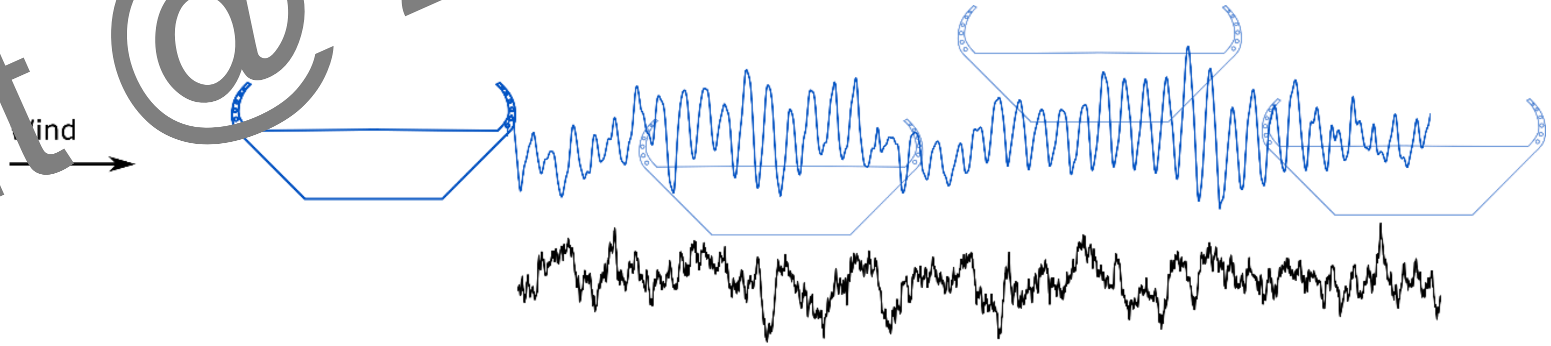


# Flow Phenomenon

## Vertical motions



Turbulent buffeting response



Applied wind force

# Flow Phenomenon

# When to consider wind study?

## Suggested Screening Criterion

if $W_T < 1.0$, $W_T = (Sc)\,(B/L)\,(B/D)\,(fB/V)$;

then consider wind engineering study

where

$Sc = m\zeta/\rho B^2$ (Scruton number);
$m$ - mass per deck length;
$\zeta$ - structural damping ratio;
$\rho$ - air density;
$D$ - deck depth (should include height of traffic barriers);
$B$ - deck width edge to edge;
$L$ - main span length;
$f$ - lowest torsional frequency;
$V$ - 50-year return period speed.

# When to consider wind study?

## Database of 44 bridges, wind tunnel tested by RWDI

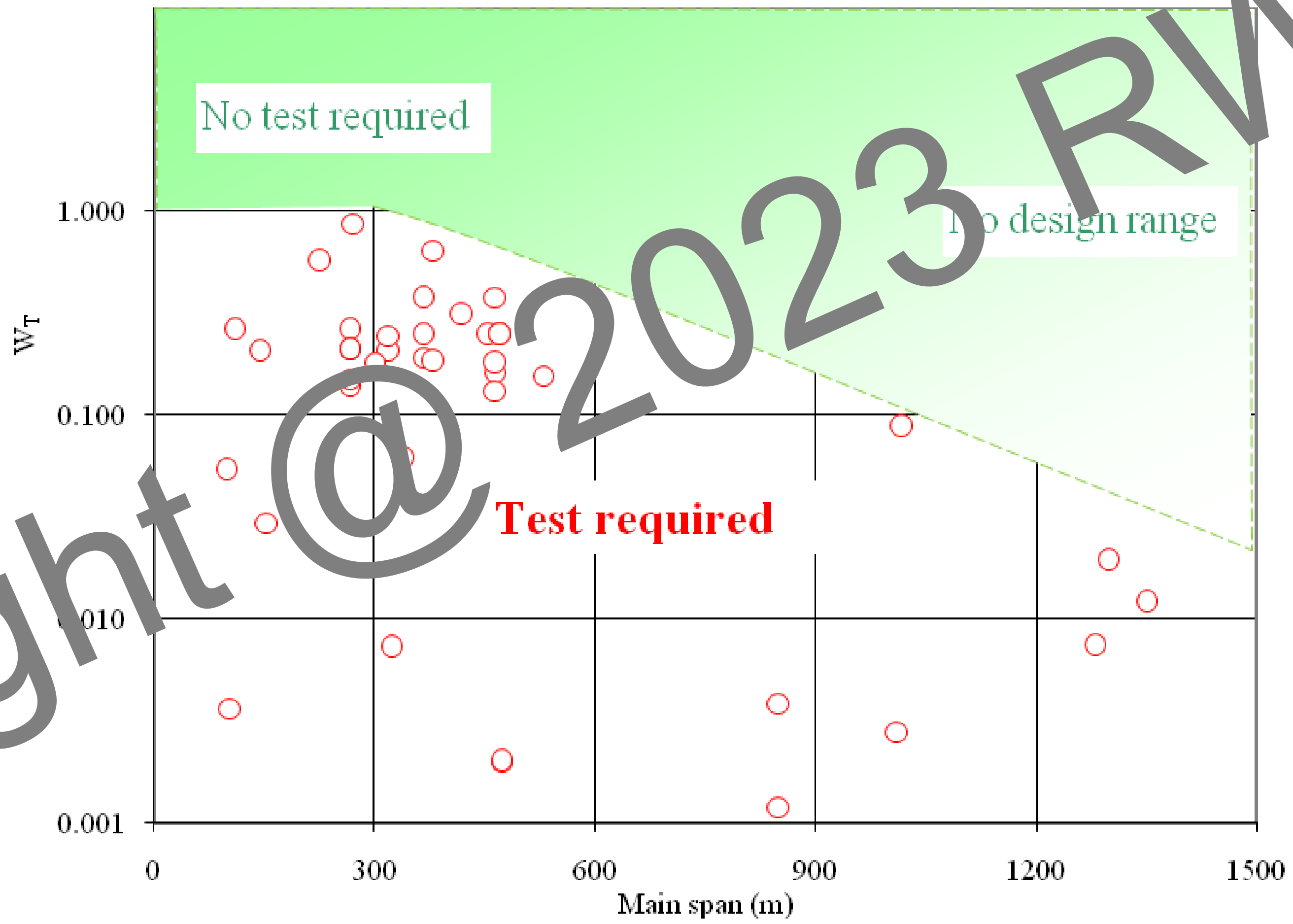


**Figure 3:** Parameter $W_T$ vs. span for various wind tunnel tested bridges

# When to consider wind study?

## Criterion Interpretation

$W_T<1.0$ is a sign that wind study may be required

## Other simple indications

- Footbridges, main span longer than about 200 ft (50~60 m)
- Highway bridges, main span longer than about 300 ft (100 m)
- Fundamental period higher than 1 sec (lower than 1 Hz)
- Bluff deck cross-section with solid or high barriers

Advice:

1. Take the opinion of a wind engineering specialist
2. Early proper planning could be critical

# Introduction

## Essential wind engineering studies required are

Wind climate analysis - wind characteristics required for verification of aerodynamic stability and derivation of design loads

↓

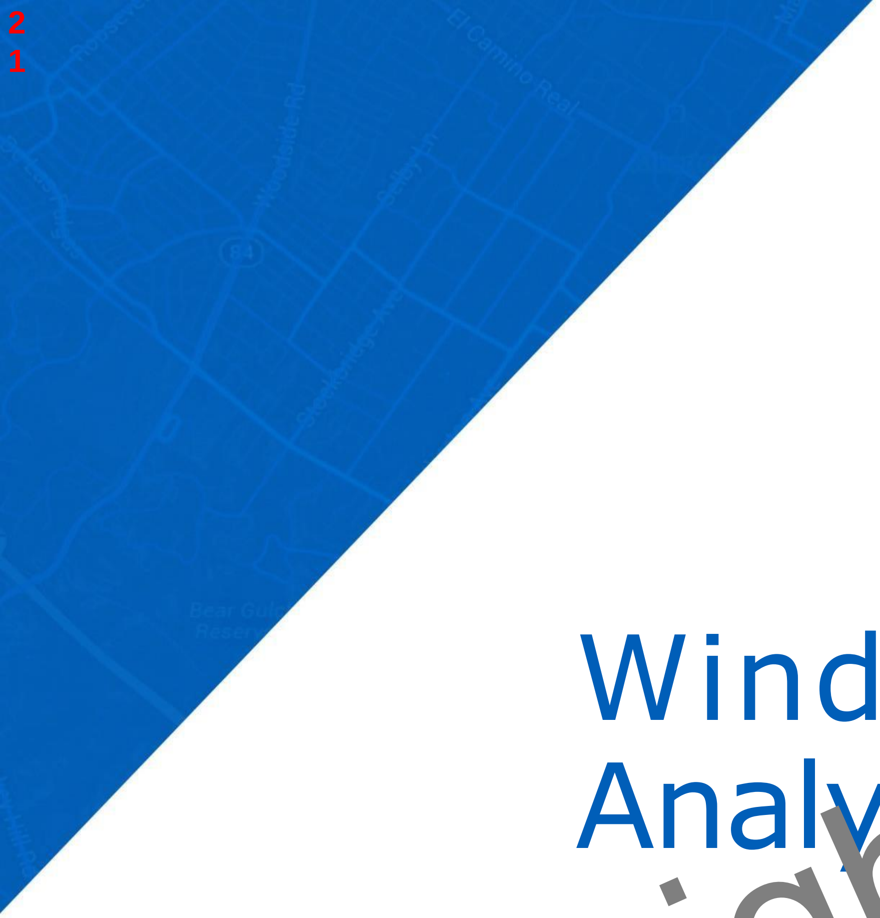
Desktop stability assessment - performed to verify stability of bridge at early stages of planning

↓

Sectional model test - performed to verify the stability of the bridge, unacceptable motions, mitigation measures, force coefficients

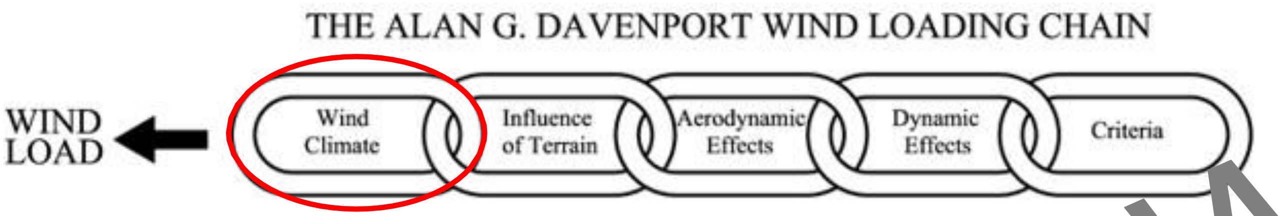
↓

Buffeting analysis - analytical simulations to determine structural responses & load distributions



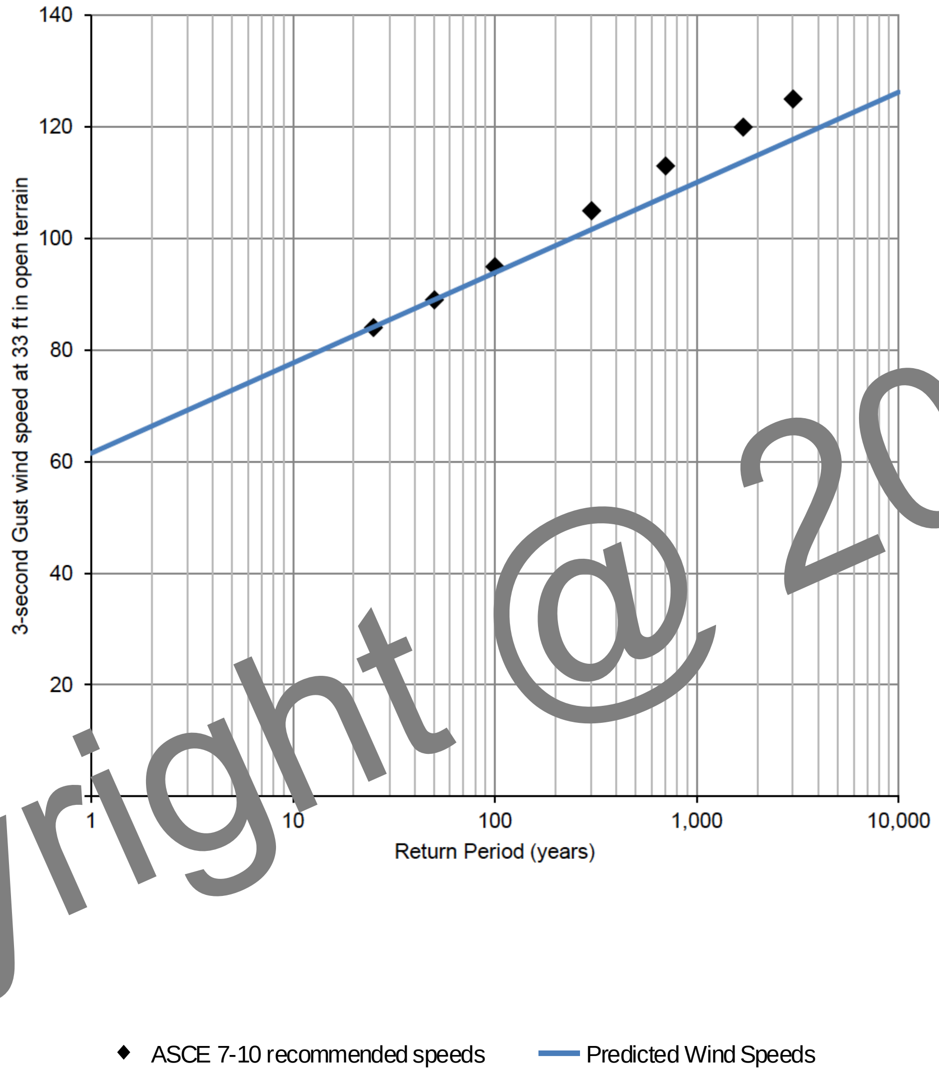
# Wind Climate Analysis

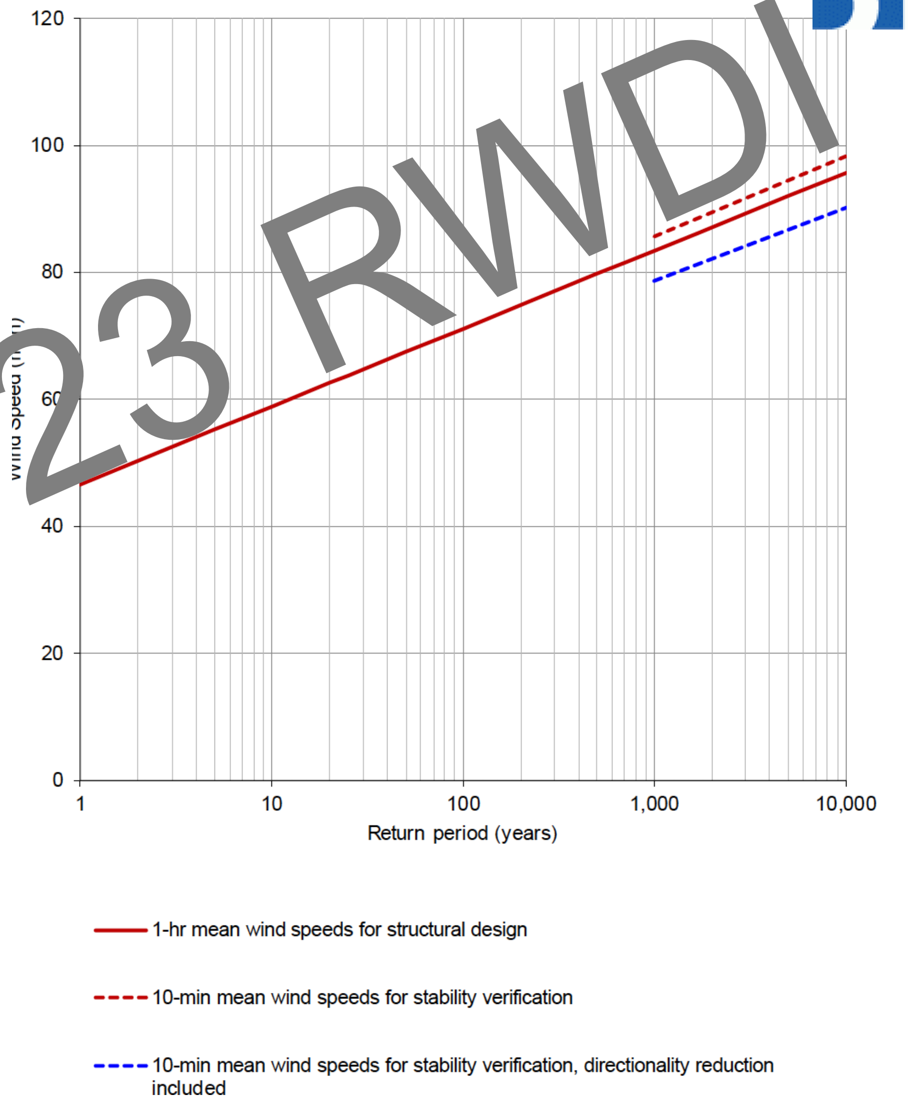
# Wind speed vs return period



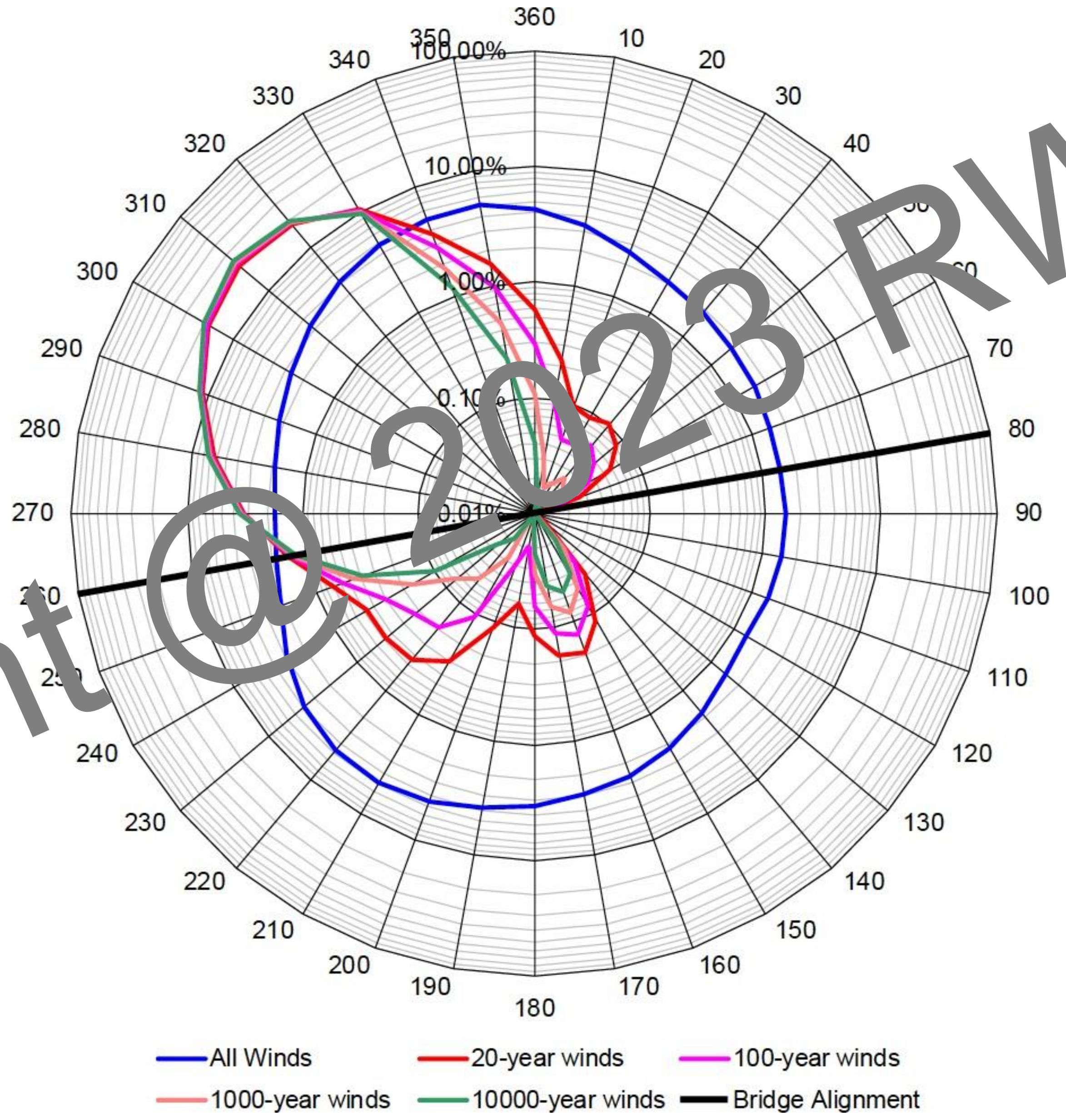
- Meteorological data from airports, weather stations, masts, balloon data etc.
- Reliability of existing data??
- Monte-Carlo based cyclonic simulations are essential for the coastal regions in tropical climates in the absence of real measurements
- WRF numerical modeling could be adopted to simulate a large set of data for the interior regions of India (absence of data & topographical effects)
- Return Periods - 20, 100, 1000, 10000
- Uncertainty in speeds leads to conservative assumptions - elevate design demands, uneconomical structures

# Wind speed vs return period





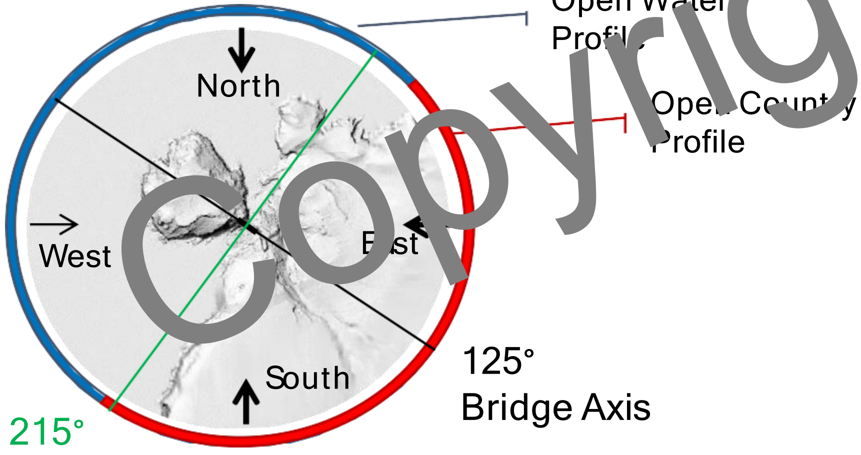
# Directionality

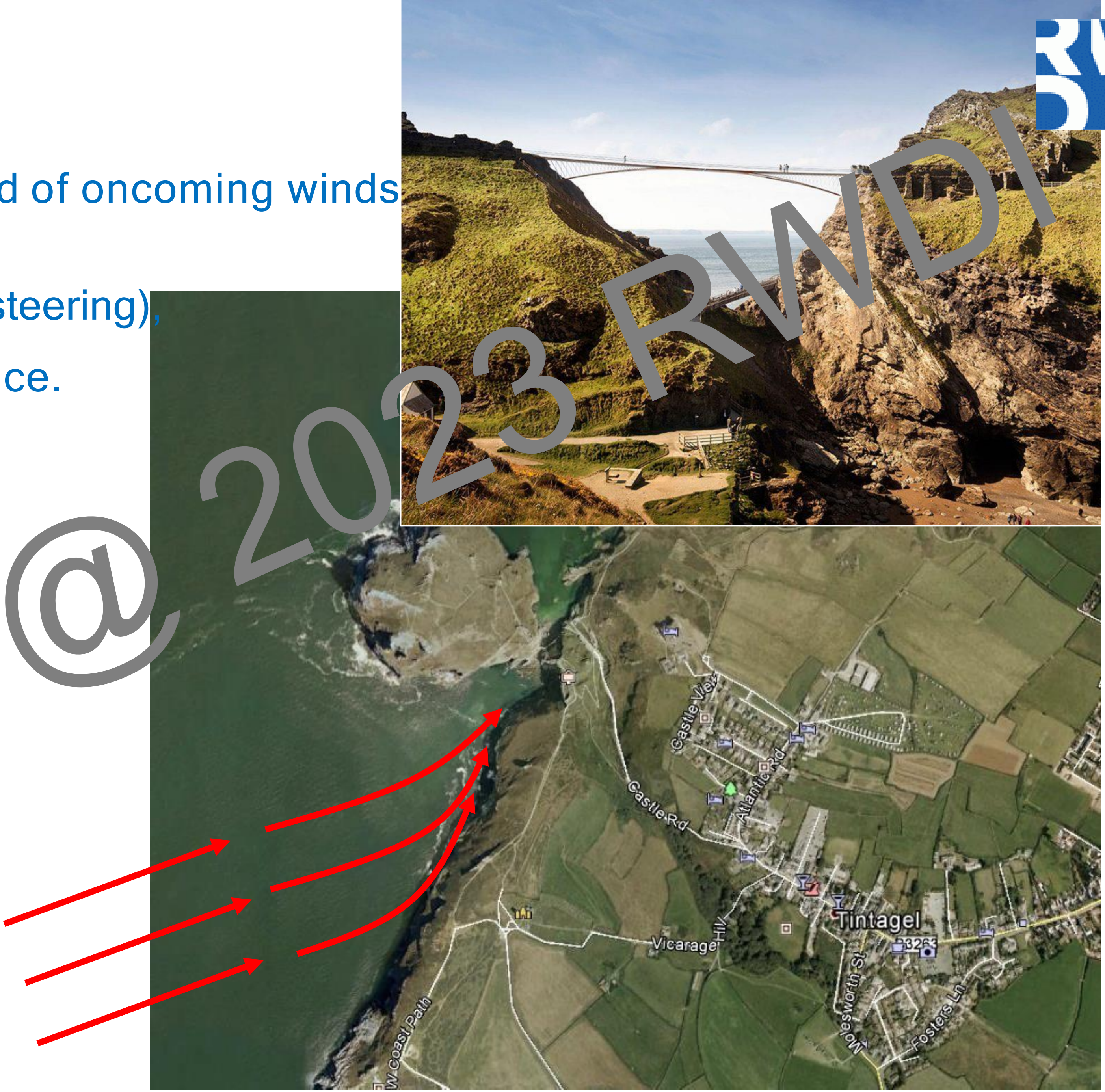


# Wind Climate

Effects of topography:

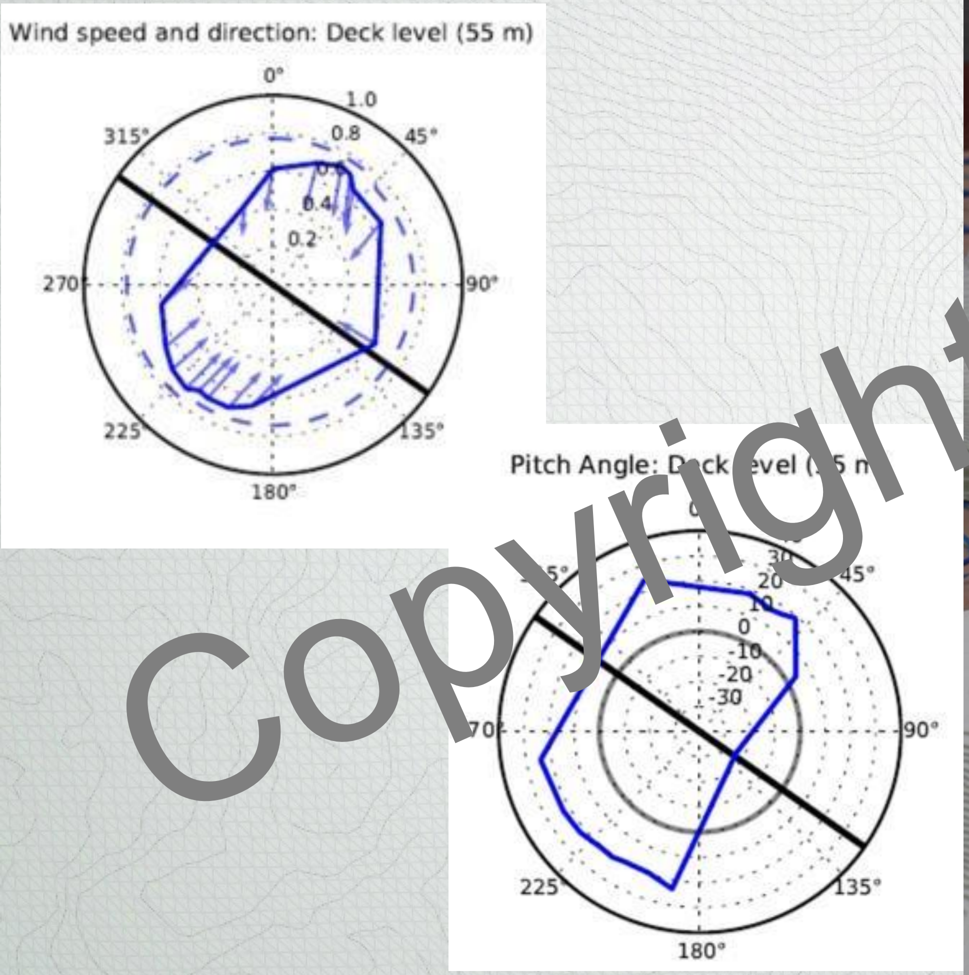
- Increasing the speed of oncoming winds (funnelling),
- Redirecting winds (steering),
- Changes in turbulence.

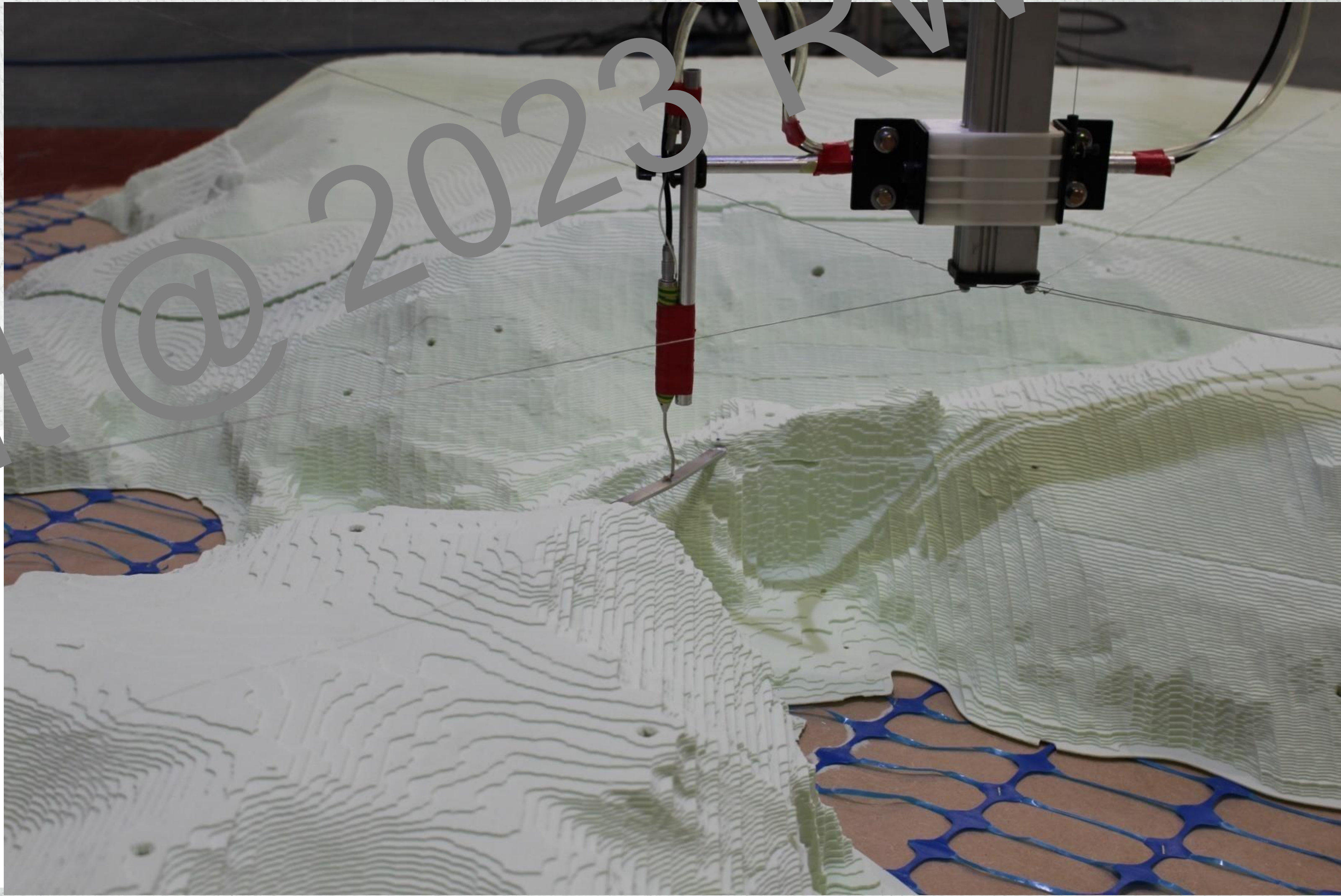




# Wind Climate

**Detailed topography tests:**

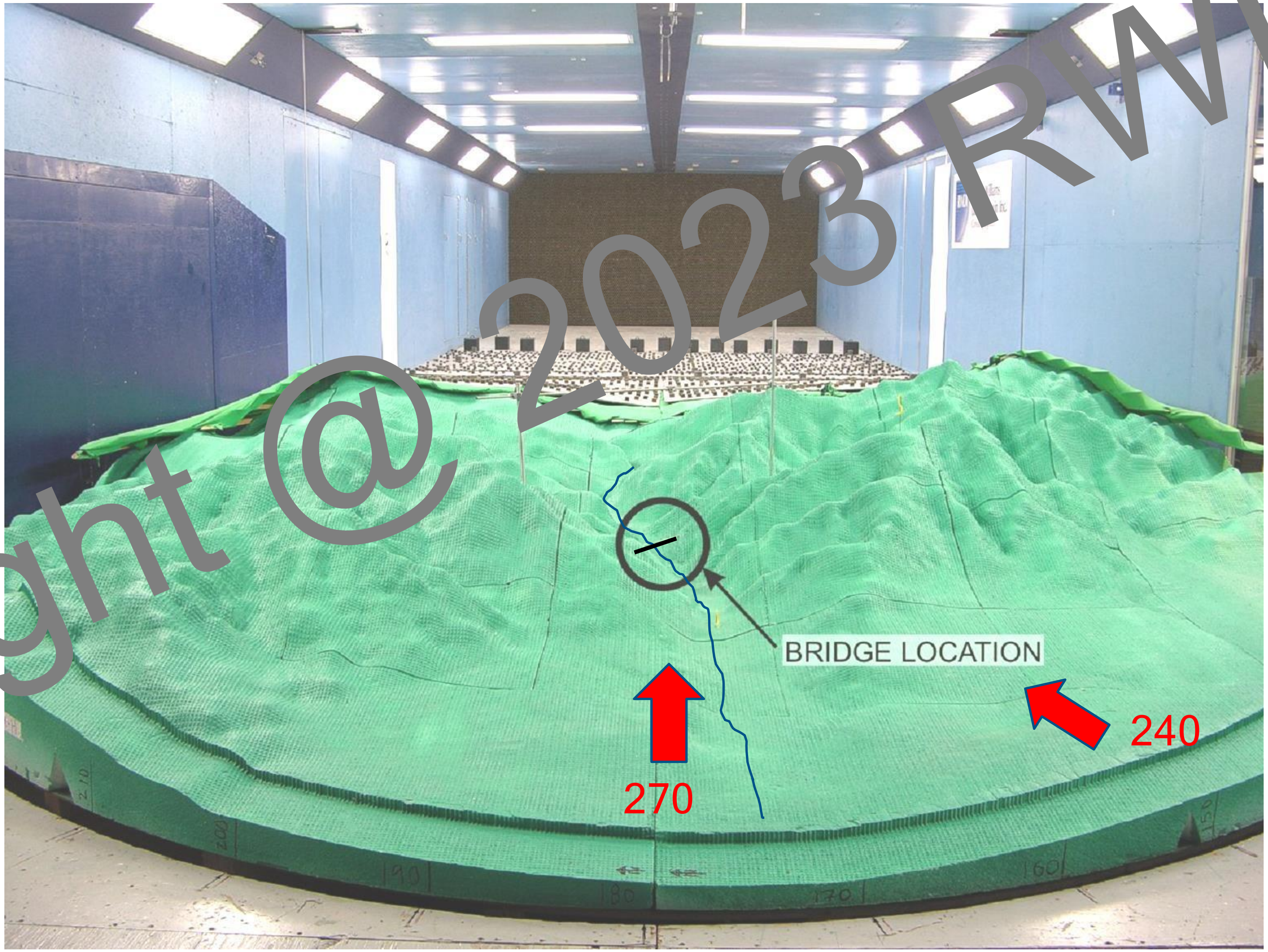




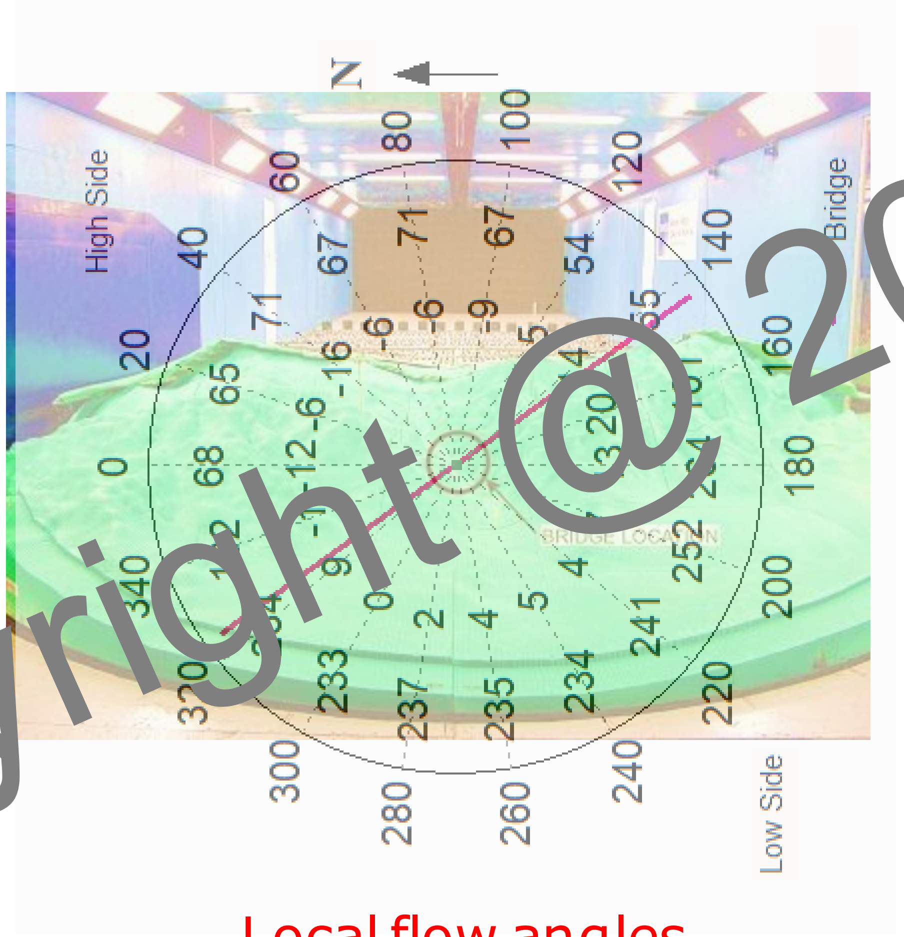
# Complex surroundings

Topographical Model

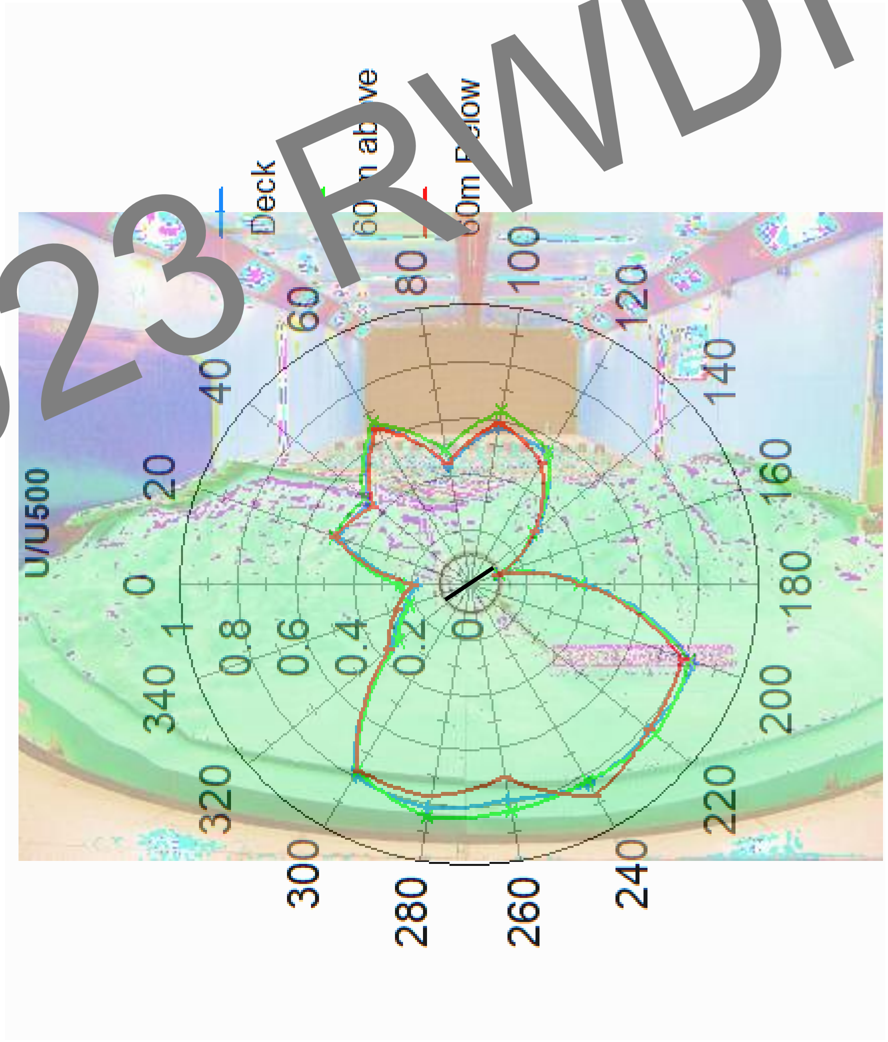
# Anji Khad Arch Bridge, Jammu & Kashmir



# Anji Khad Arch Bridge, Jammu & Kashmir



Local flow angles (horizontal & vertical)



Mean wind speed

Topographical Model

# Anji Khad Arch Bridge, Jammu & Kashmir

**Table 1:** Design Wind Speeds for the Anji Khad Arch Bridge

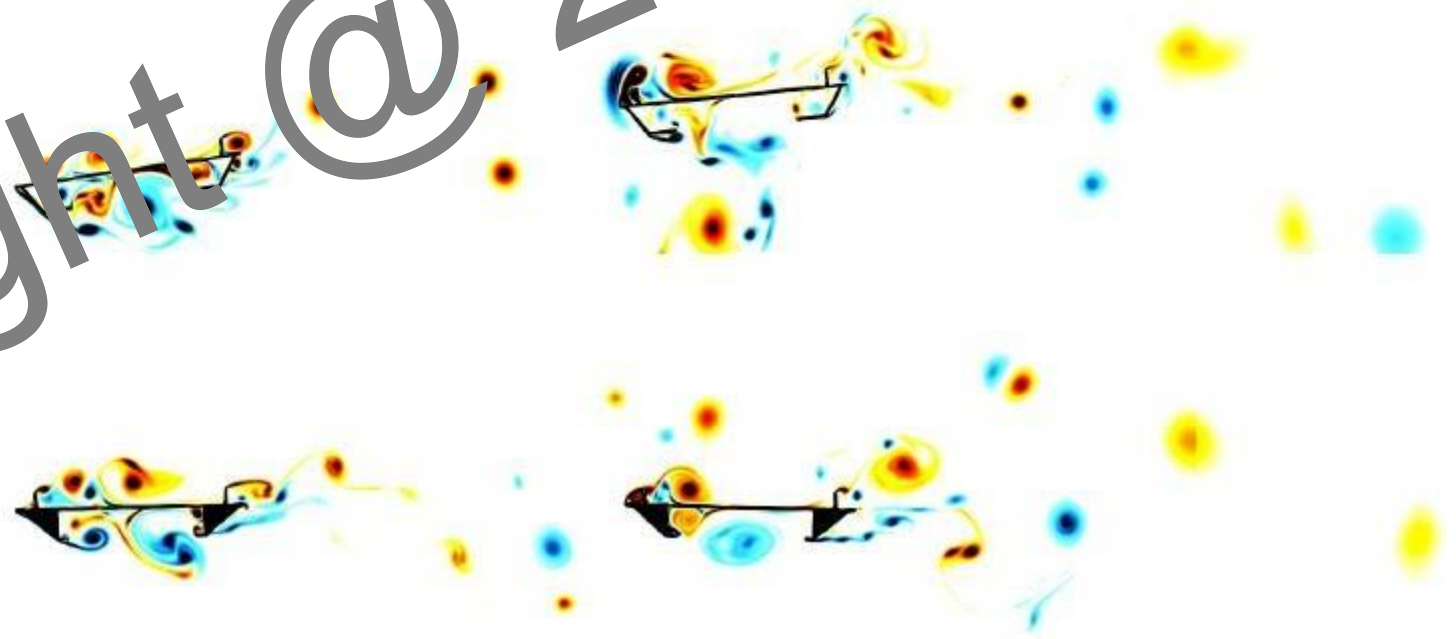
| **Return Period (years)** | **Application** | **A** | **Corresponding Wind Speed at Deck Height (m/s)** | | |
|---|---|---|---|---|---|
| | | 3-Second Gust | Mean Hourly | 10-Minute Mean | 3-Second Gust |
| 10 | Construction Stage Loading | 32.4 | 28.3 | 30.0 | 41.1 |
| 50 | Basic Design Wind Speed – IS:875 | 39.0 | 34.0 | 36.1 | 49.5 |
| 100 | Structural Design of Completed Bridge | 41.4 | 36.1 | 38.3 | 52.5 |
| 1000 | Stability - Construction Stage | 50.4 | 43.9 | 46.6 | 63.9 |
| 10000 | Stability - Completed Bridge | 59.3 | 51.8 | 54.9 | 75.3 |

Note: A = Wind speed at 10 m in Category 2 terrain (m/s)

# Desktop Stability Assessment

# Desktop Stability Assessment

- Analytical calculations based on past experience and RWDI database of past wind tunnel tests
- Early notification of potential problems, and identify way forward
- May require simple 2D CFD studies if deck geometry is unusual



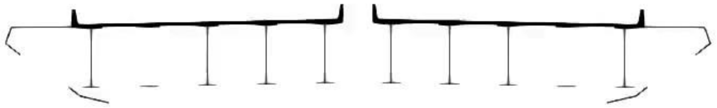
# Preliminary evaluation using CFD

Understand the flow patterns

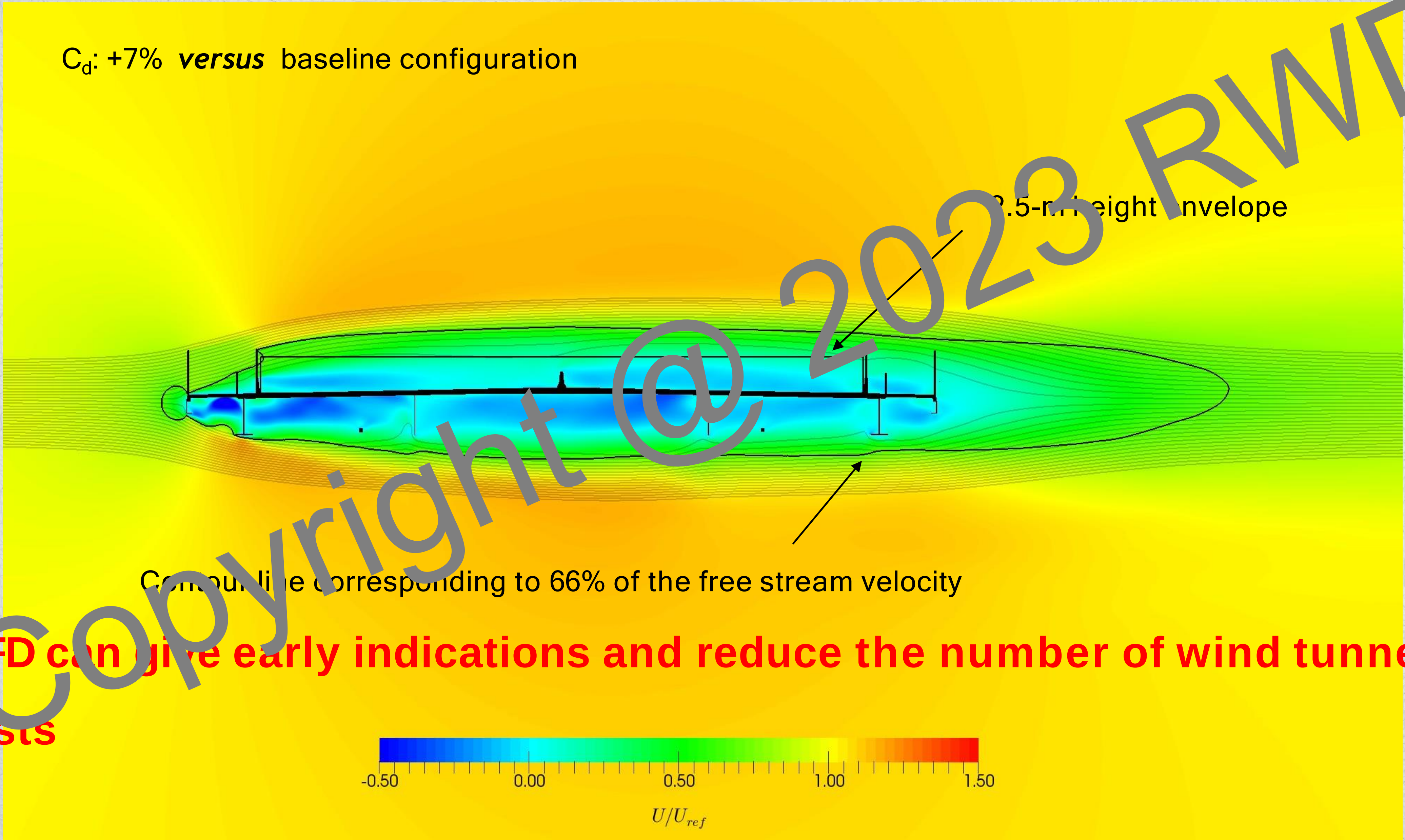
Identify possible instabilities

Evaluate mitigations and their effects on the flow

Estimate the mean forces (drag, lift and moment)



# Recent study – using CFD and sectional model tests



$C_d$: +7% ***versus*** baseline configuration

2.5-m height envelope

Contour line corresponding to 66% of the free stream velocity

**CFD can give early indications and reduce the number of wind tunnel tests**

# Sectional Model Test

Sectional Model Test

# Stability Design Criteria

**Flutter**

**Construction:** 1,000-year return period, zero angle of wind incidence
Onset speed > 1000-year return period speed at bridge deck

**Completed:** 10,000-year return period, zero angle of wind incidence
Onset speed > 10000-year return period speed at bridge deck

- For higher angles of attack, one can reduce wind speed criteria (~20%)
- State of flutter if the torsional amplitude exceeds 1.5 degrees

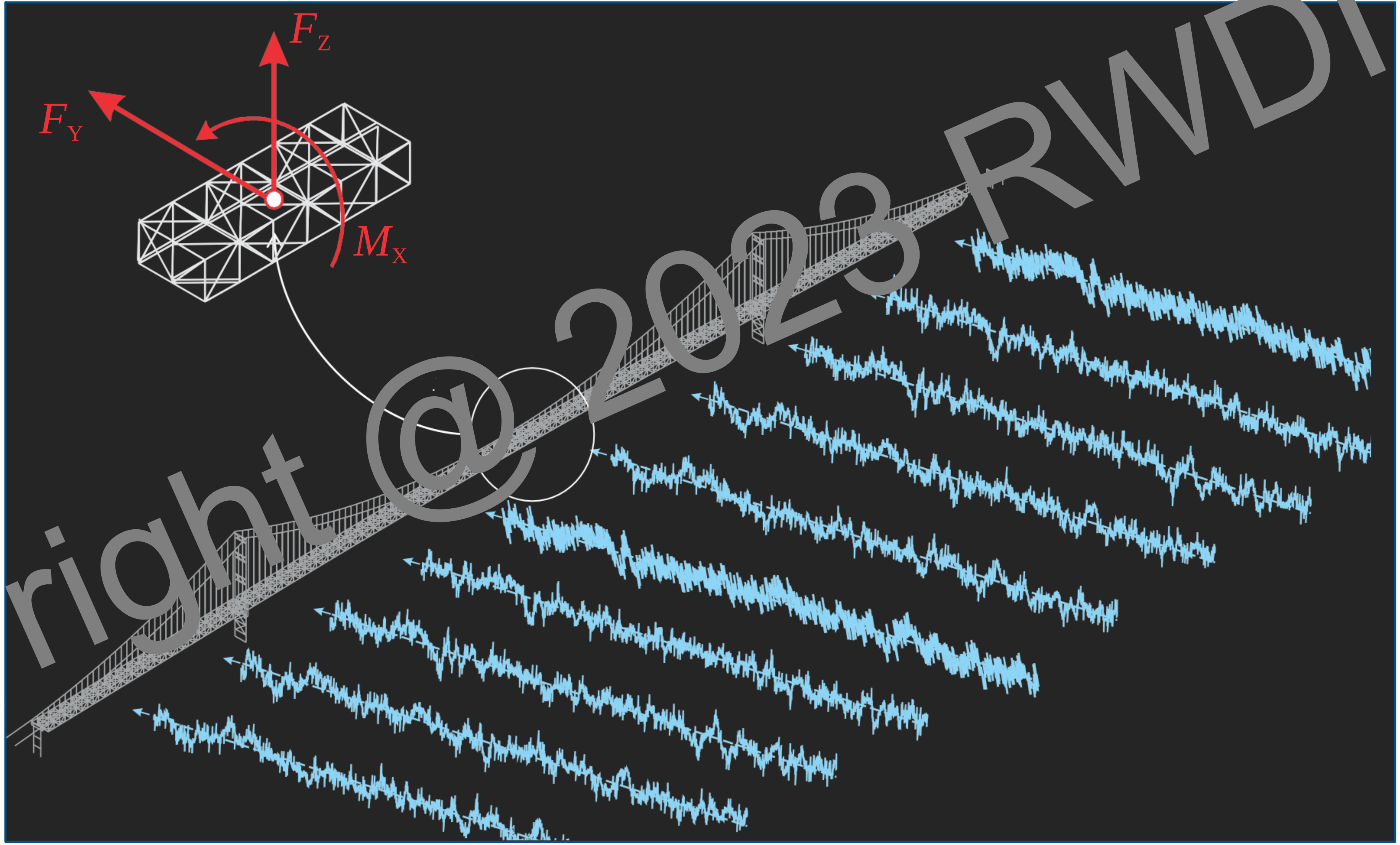
**Vortex Shedding Induced Oscillations**

5% of gravity up to 30 mph (13 m/s) **(1.8% g for tall buildings)**
10% of gravity from 30 to 50 mph (22 m/s).
If above 50 mph - become a strength or fatigue issue, not comfort

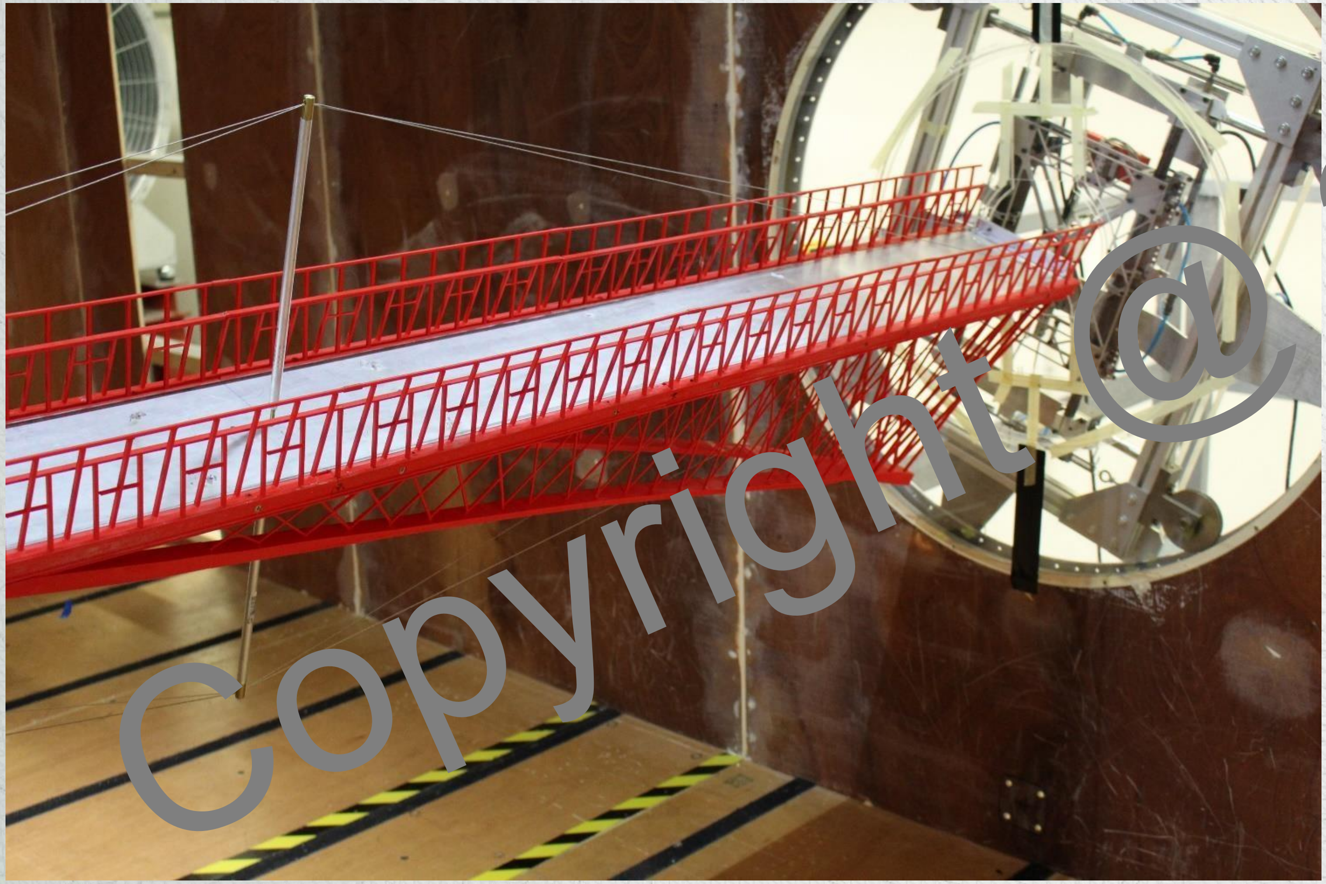
# Sectional Model Test

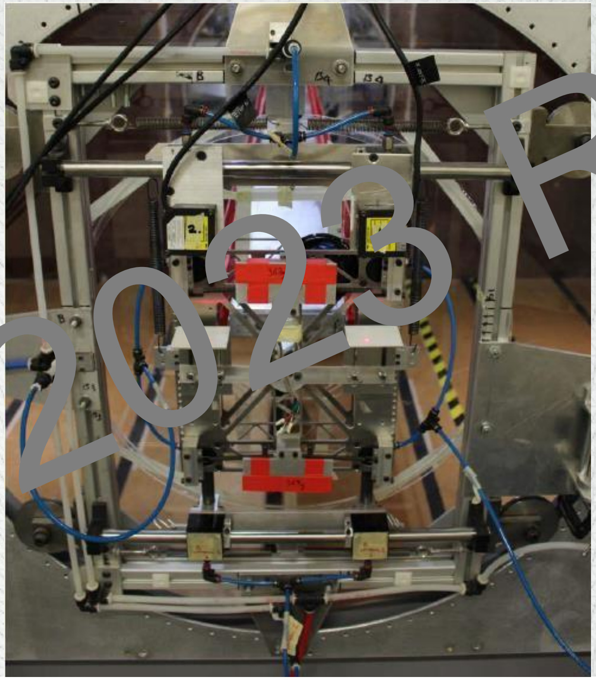
- Pass or Fail Test
- Carried out at the preliminary design stage to assess the aerodynamic stability of the deck section
- Aerodynamic Phenomenon: Flutter, Vortex Shedding, Buffeting
- In case of instability, remedial measures will be suggested and confirmed through wind tunnel tests. The wind tunnel becomes a design tool, providing evidence of the performance of a geometry and a mitigation solution
- Other results once stability confirmed: Static coefficients, aerodynamic derivatives

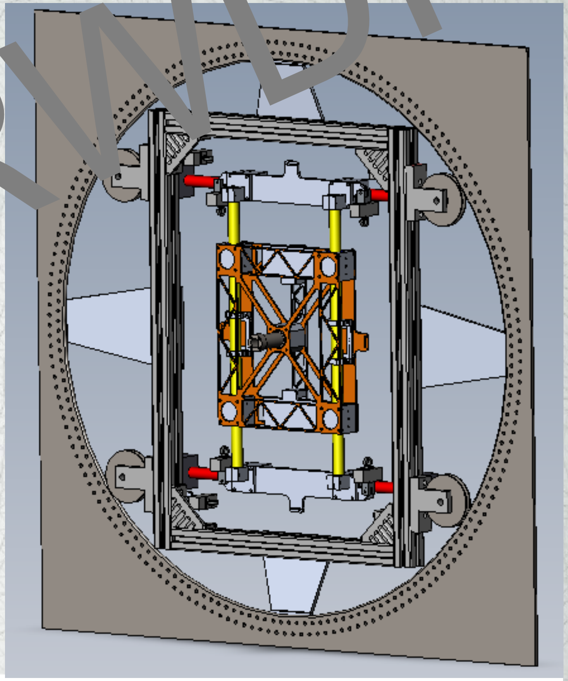
# Sectional Model Test

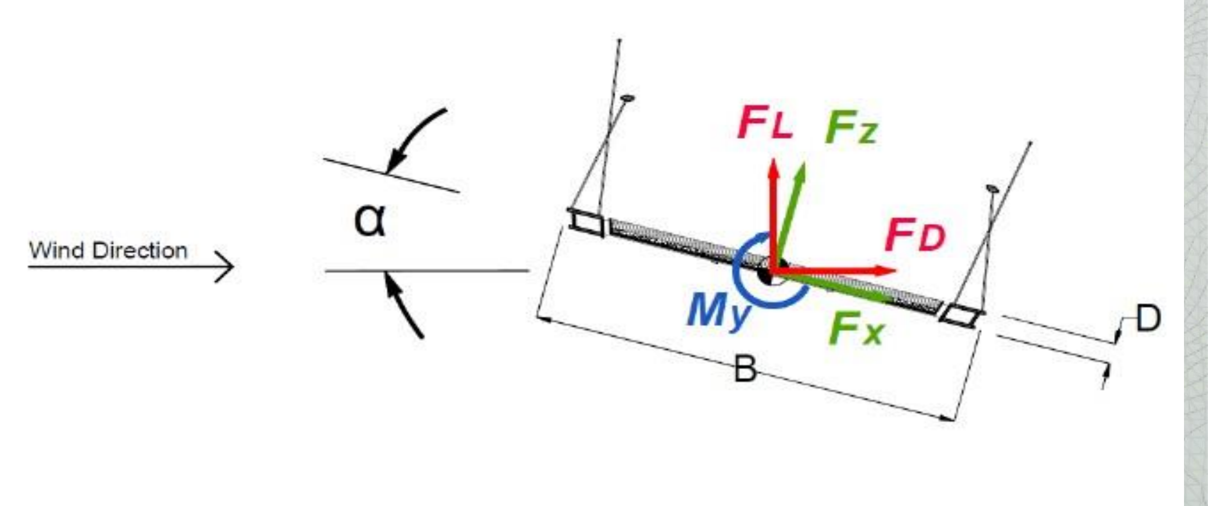


# Sectional Modal Test



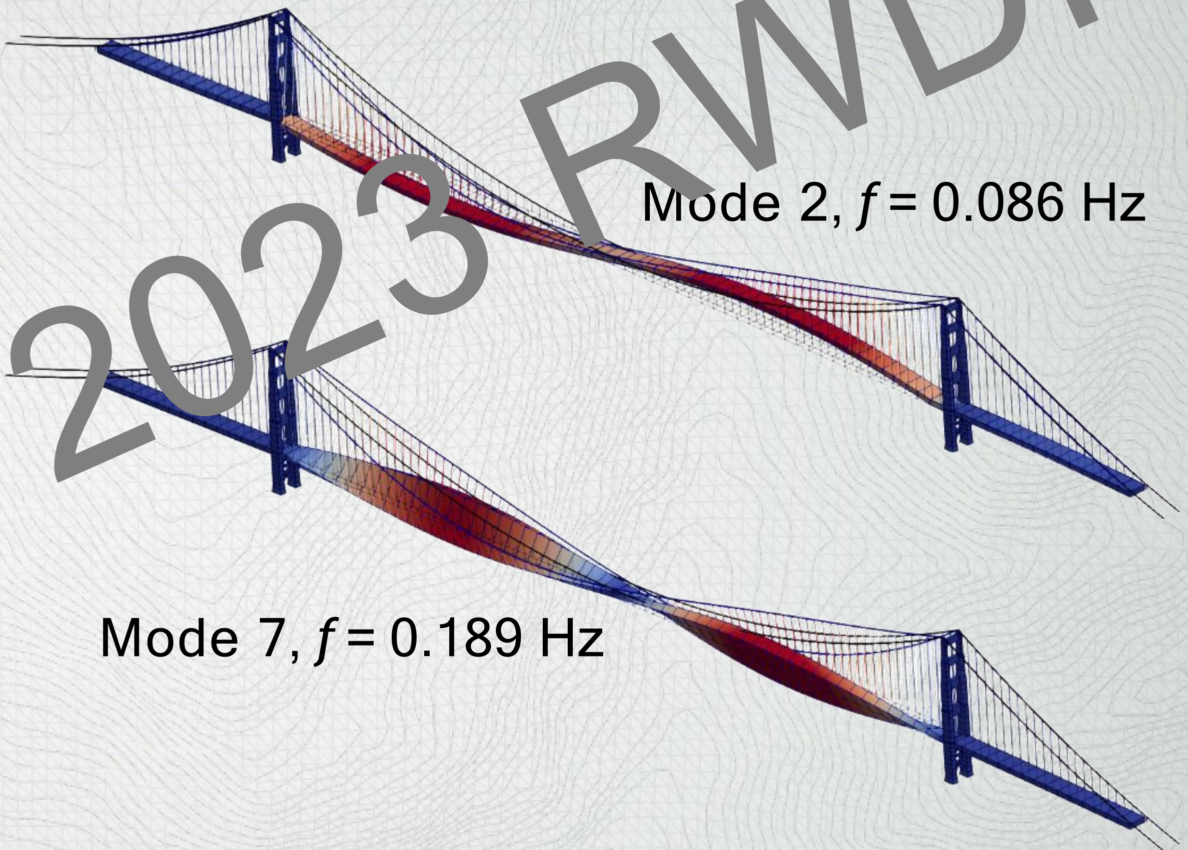






# Sectional model test

# Wind Tunnel Study – Sectional Model – Golden Gate Bridge



- Sectional model tests at scale in Guelph or the UK wind tunnels
- Model on springs free-to-respond to investigate aerodynamic stability
- Measurements of static aerodynamic force and aeroelastic coefficients

# Sectional model test, twin bridges

Interference effects between bridges

Effects of traffic on aerodynamic stability

# Twin deck sectional model tests

# Sectional Model Test

- Sectional models - rigid and geometrically represent a segment of the full-scale deck
- Typical geometrical scales are in the range of 1:30 ~ 1:80
- Materials used for construction: Brass, Aluminum, Wood, Plexiglass
- Non-dimensional parameters

# Sectional Model Test

- **Geometric Similarity**
- **Kinematic Similarity** (Partial turbulence simulation)
- **Dynamic Similarity**

$$\left(\frac{Mass}{Length}\right)_M = \left(\frac{Mass}{Length}\right)_P \left(\frac{1}{Length\ Scale}\right)^2$$

$$\left(\frac{MMI}{Length}\right)_M = \left(\frac{MMI}{Length}\right)_P \left(\frac{1}{Length\ Scale}\right)^4$$

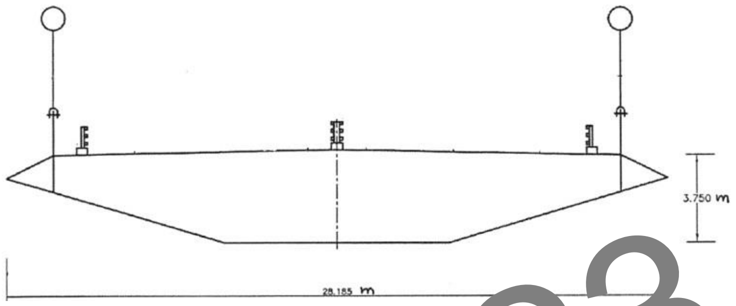
$$Speed_M = Speed_P \left(\frac{f_M}{f_P}\right)\left(\frac{1}{Length\ Scale}\right)$$

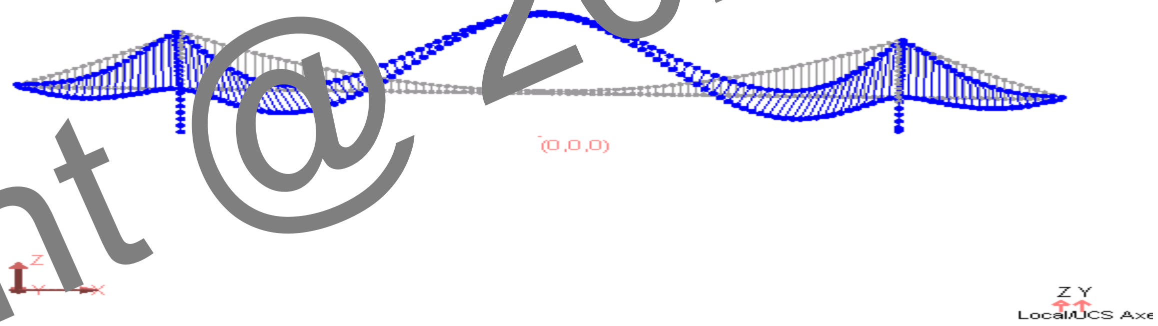
$$\left(\frac{f_T}{f_V}\right)_M = \left(\frac{f_T}{f_V}\right)_P$$

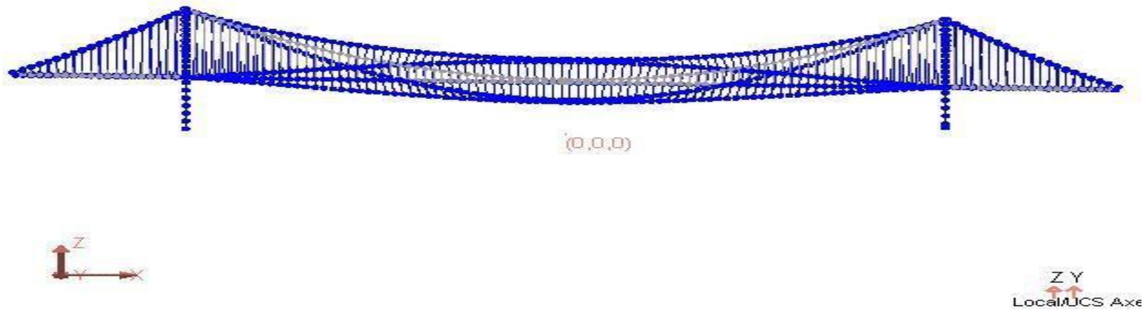
$$\beta_M = \beta_P$$

# Sectional Model Test

## Modeling



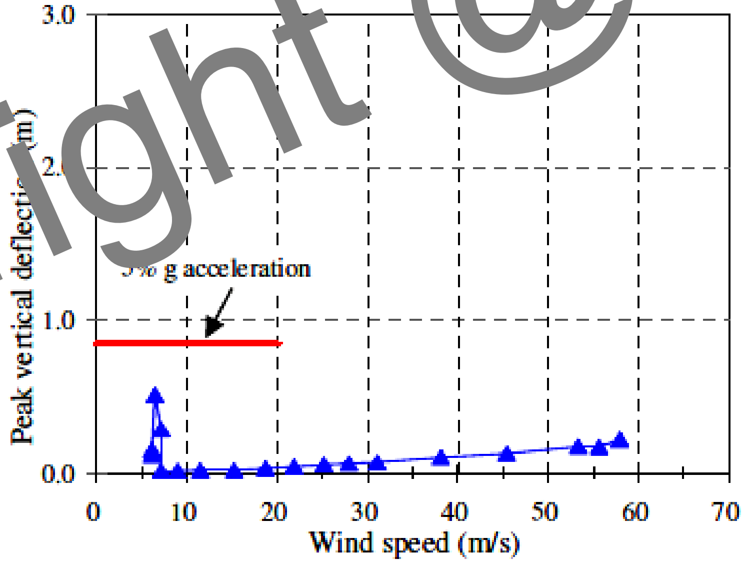


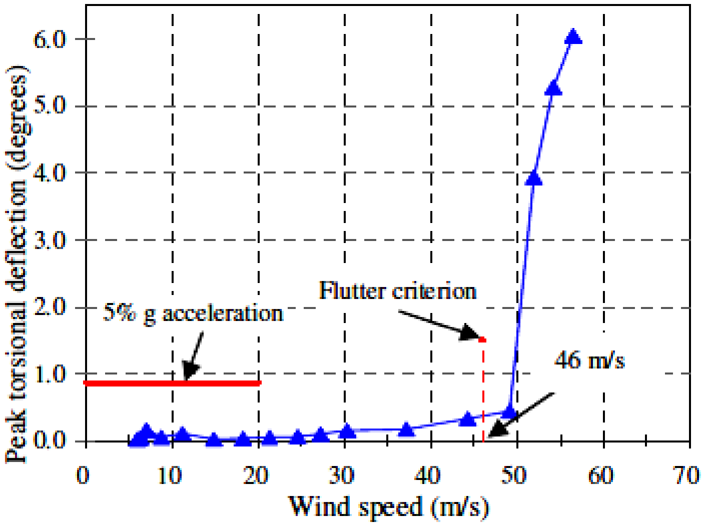


# Key parameters of the sectional model

| Key Parameter | Full Scale | Model Scale 1:60 | |
|---|---|---|---|
| | | Target | Actual |
| **Vertical frequency** | 0.121 Hz | -- | 1.53 |
| **Torsional frequency** | 0.347 Hz | -- | 4.5 |
| **Frequency ratio** | 2.87 | 2.87 | 2.94 |
| **Deck mass + 2x Cables** | 17,600+2x 2800 kg/m | 15.47 kg | 15.4 kg |
| **Deck mass moment of inertia (mmi)** | 1,041,000 kg.m$^2$/m | 0.193 kg.m$^2$ | 0.240 kg.m$^2$ |
| **Equivalent mmi, Mode 19** | 2,067,000 kg.m$^2$/m | 0.383 kg.m$^2$ | |
| **Vertical damping** | 0.2 ~0.3 % | 0.2~0.3 % | 0.25 % |
| **Torsional damping** | 0.2~0.3 % | 0.2~0.3 % | 0.30 % |

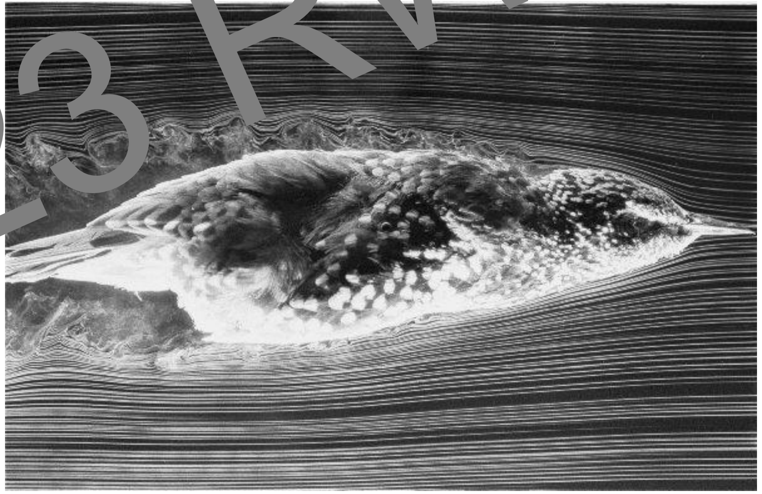
# Sectional Model Test

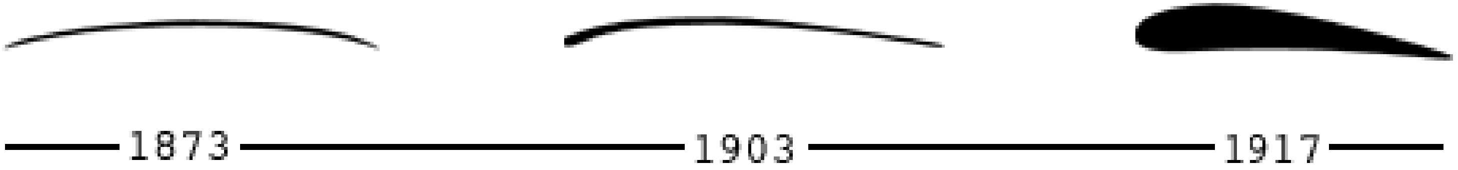




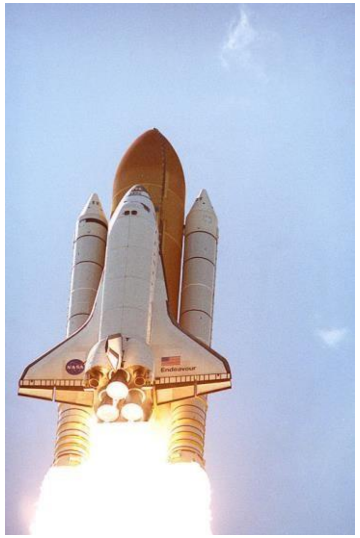
## Sectional Model Test

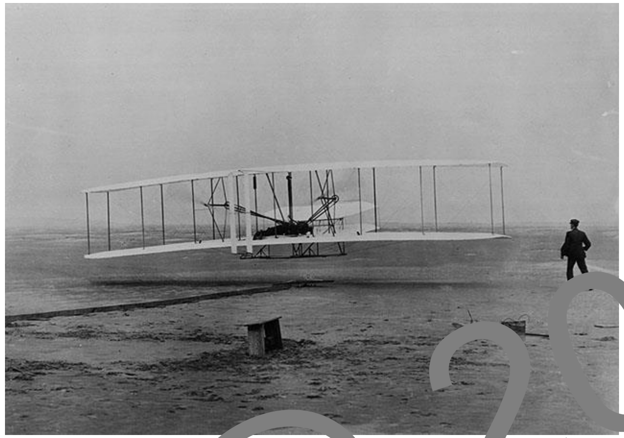
# Aerodynamics

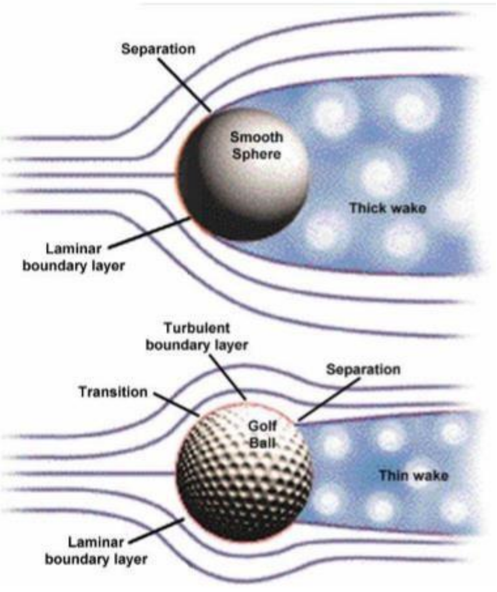




# Sectional Model Test

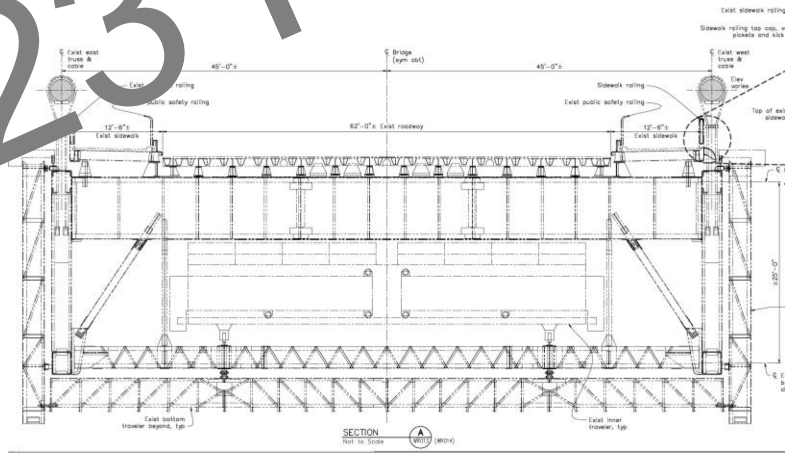






# Sectional Model Test

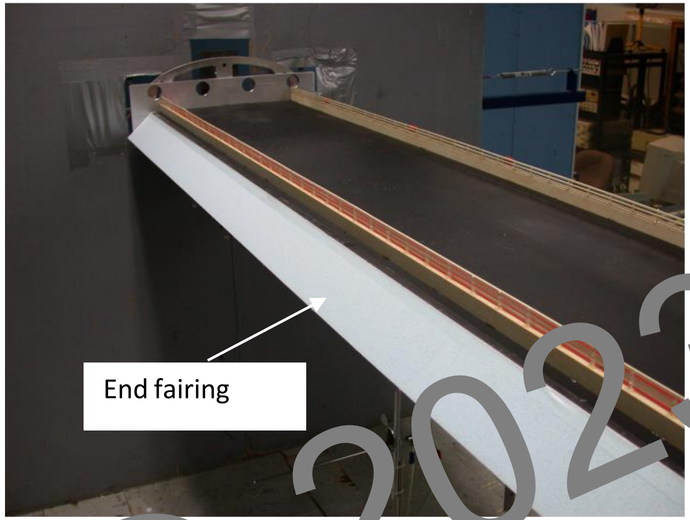
**Cd = .045**
**Airfoil**

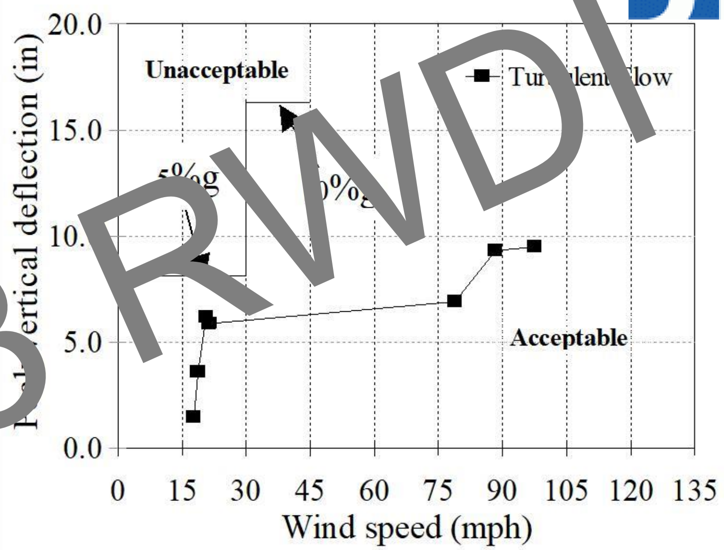


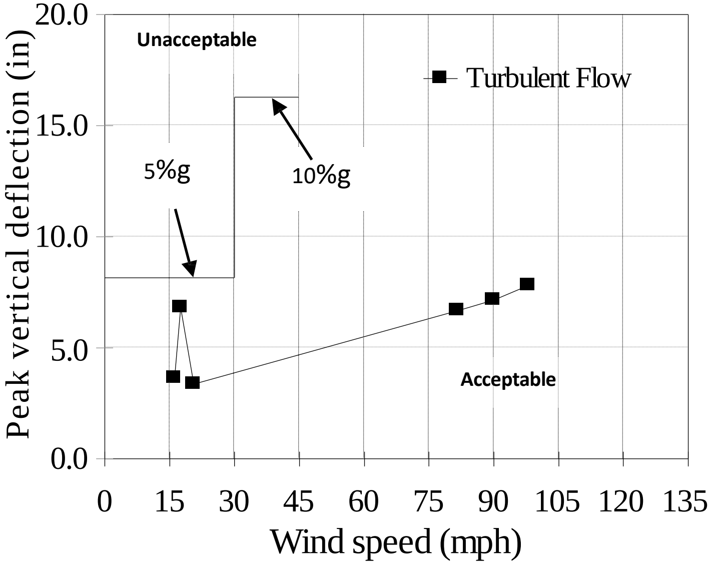
**Cd = 1.3, Golden Gate Bridge**

# Sectional Model Test

# Aerodynamic Mitigation Measures

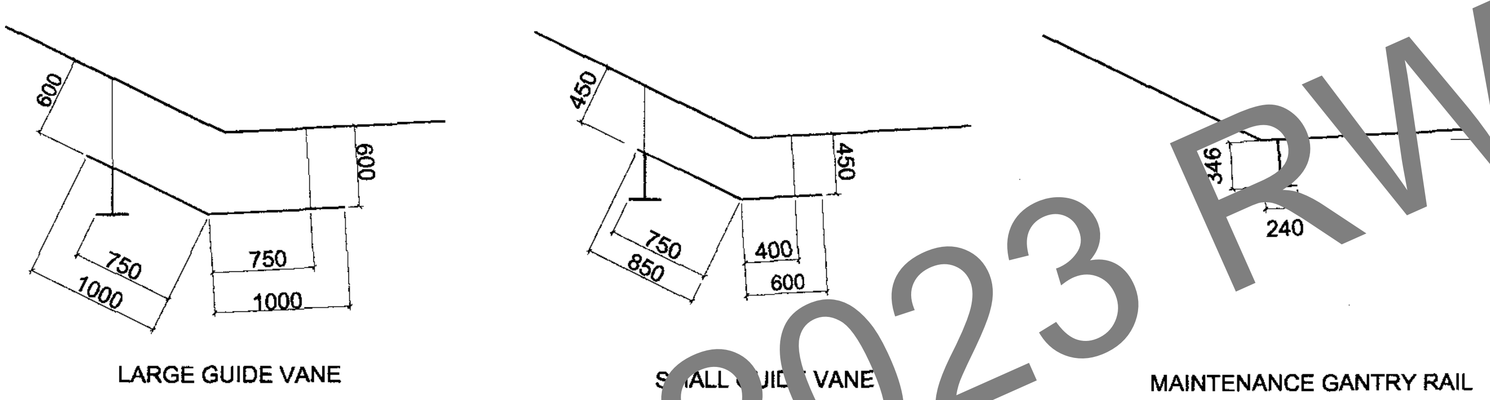






# Sectional Model Test

## Aerodynamic Mitigation Measures



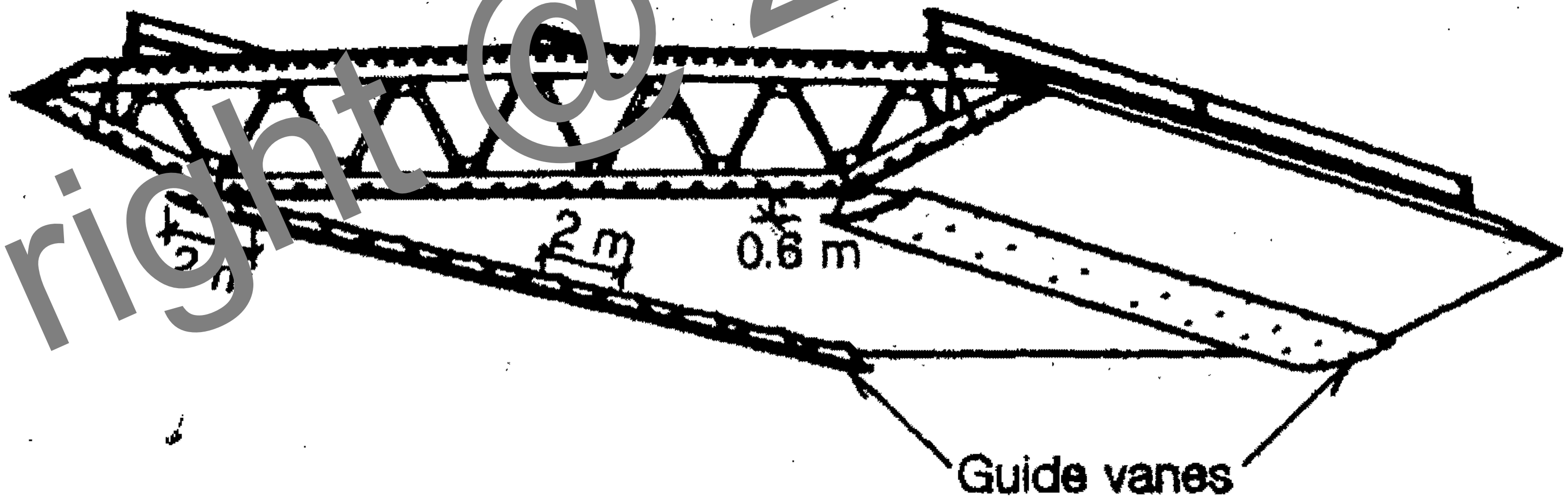
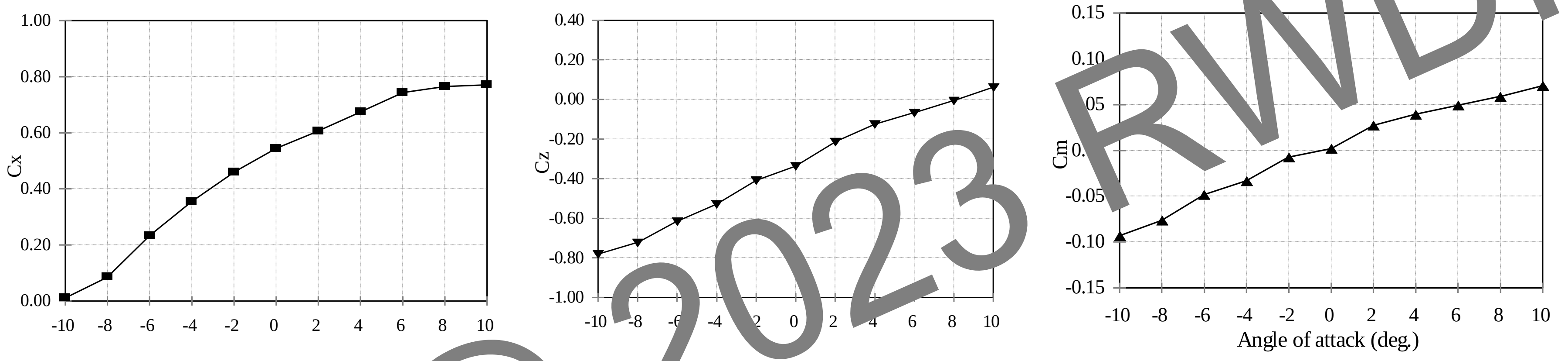
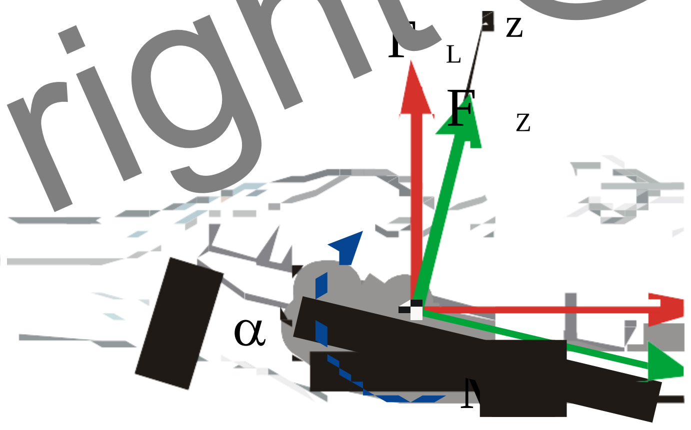


Figure 10. Lay-out and arrangement of guide vanes along the Great Belt East Bridge main span.

# Force and Moment Coefficients





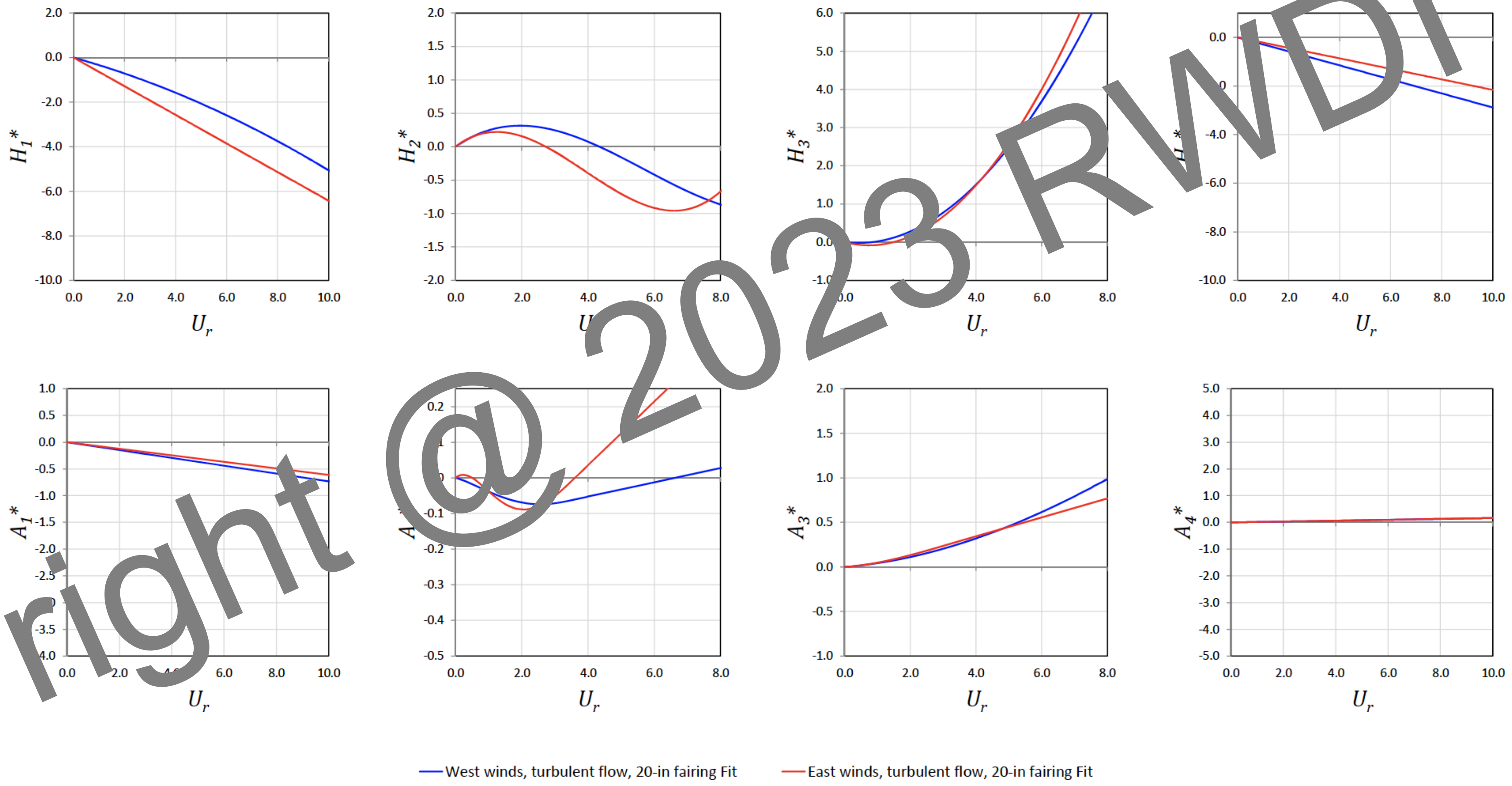
**Drag:** $F_X = ½ \rho\, d\ U^2 C_X$

**Lift:** $F_Z = ½ \rho\, b\ U^2 C_Z$

**Moment:** $M = ½ \rho\, b^2 U^2 C_M$

# Sectional Model Test

## Aerodynamic Derivatives



$$m\left(\ddot{h} + \varsigma_h\ \omega_h\ \dot{h} + \omega_h^2\ h\right) = L_{ae}$$

$$I_\alpha\ \left(\ddot{\alpha} + \varsigma_\alpha\ \omega_\alpha\ \dot{\alpha} + \omega_\alpha^2\ \alpha\right) = M_{ae}$$

$$L_{ae} = \frac{1}{2}\rho U^2 B\, L\left(KH_1^* \frac{\dot{h}}{U} + KH_2^* \frac{B\dot{\alpha}}{U} + K^2 H_3^* \alpha\ + K^2 H_4^* \frac{h}{B}\right)$$

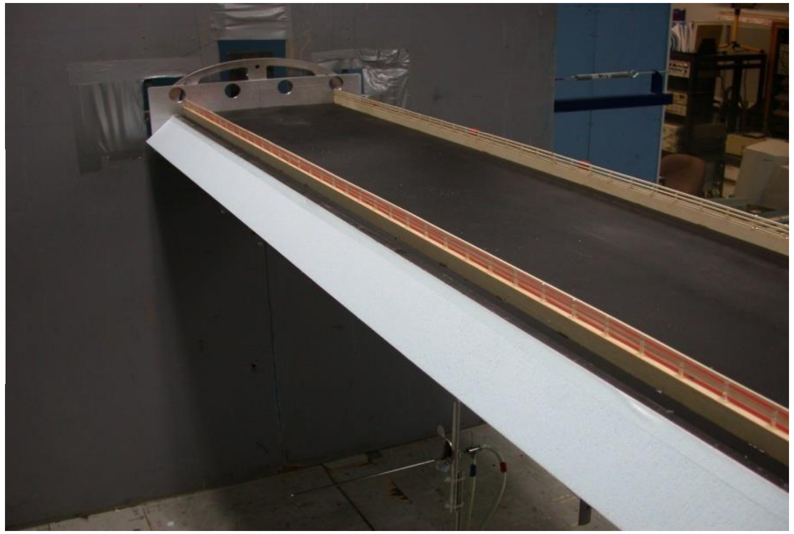
$$M_{ae} = \frac{1}{2}\rho U^2 B^2\ L\left(KA_1^* \frac{\dot{h}}{U} + KA_2^* \frac{B\dot{\alpha}}{U} + K^2 A_3^* \alpha\ + K^2 A_4^* \frac{h}{B}\right)$$

# 3D Buffeting Analysis

# 3D Buffeting Analysis

- **Statistical predictions of peak responses**
  - Direct integration of dynamic equations of motion in time domain

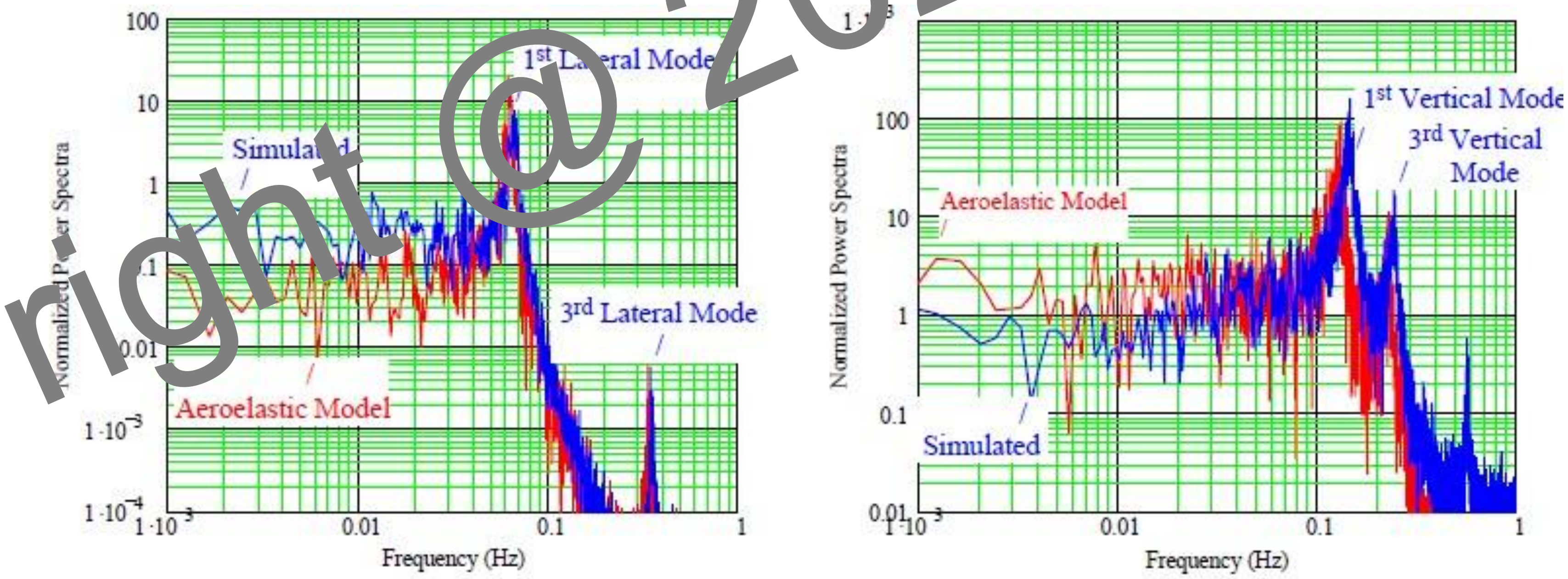
- **Inputs**
  - Static aerodynamic force & moment coefficients
  - Mass and MMI
  - Bridge dimensions
  - Mode shape & frequencies
  - Structural damping
  - Wind turbulence properties
  - Aerodynamic derivatives



# 3D Buffeting Analysis

- **Time domain approach involves two steps**
  - Numerical simulation of turbulence velocity histories and wind loads
  - Evaluation of structural response due to these loads

Tacoma Narrows Bridge – Response power spectra at the middle span



a) power spectra of lateral deflections

b) power spectra of vertical deflections

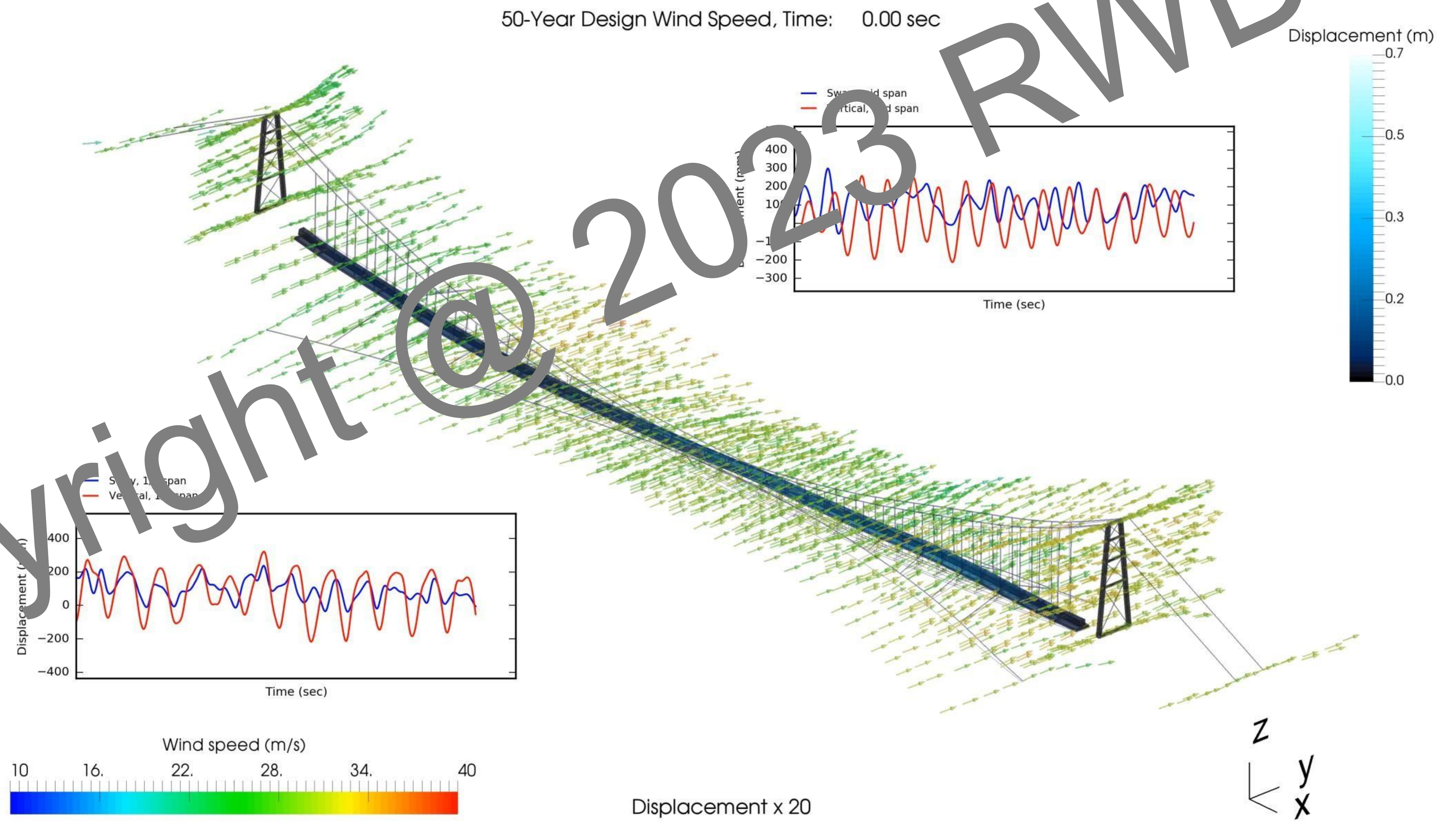
# Evaluating the buffeting motion to derive wind loads

Dynamic information from design team (frequencies, modes, mass distribution)

Local wind-climate parameters (wind speed, turbulence, wind profile)

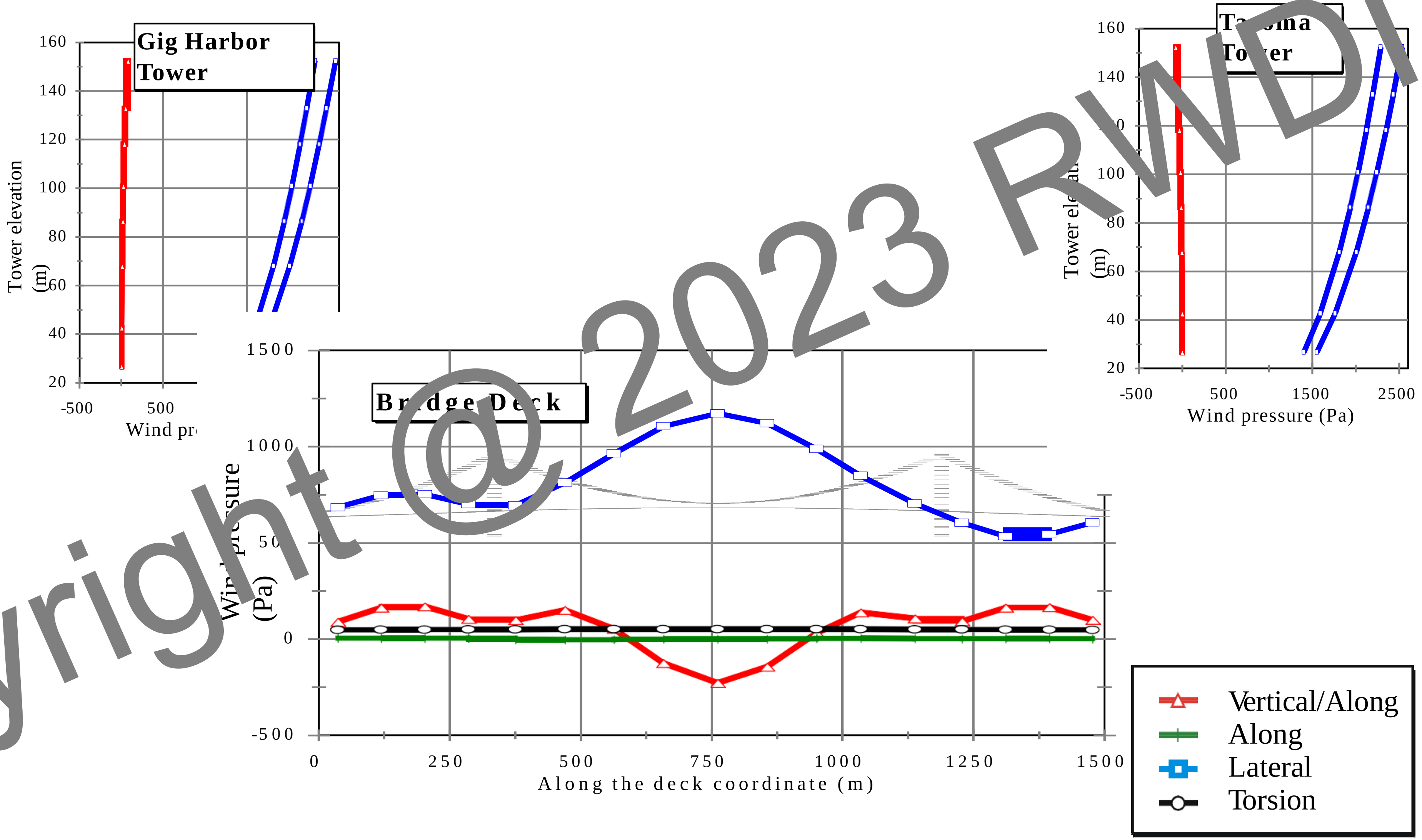
Final cross-section aerodynamic properties (shape, mean forces)

Compute numerically the structural response to fluctuating wind forces



# 3D Buffeting Analysis

## Equivalent static design wind loads



# Equivalent Static Wind Loads

Cases are developed to capture the envelope of peak displacements

Displacement x 30

# Concluding Remarks

# Concluding Remarks

- Wind effects on bridges are quite different from traditional high-rise buildings
- Stability issues are a serious concern at completed and construction stages; wind tunnel tests are required
- Mitigation measures for stability purposes requires wind tunnel testing
- Static force and moment coefficients are also unknown for many cross sections
- Minimum studies are to be conducted for design
- Wind climate study, desktop stability assessment, sectional model study, 3D buffeting analysis

Redefining possible

# THANK YOU

# QUESTIONS ?

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**Email: Suresh.Kumar@rwdi.com**