

Wind-induced Vibrations of Long-span Bridges

Prof. Dr. Guido Morgenthal



Motivation: Prediction of Aerodynamic Excitation of Bridges



Tacoma Narrows Bridge, 1940

Lecture Contents

- Principal Concepts of Wind Engineering
- Dynamic Wind Excitation Phenomena
- Case Studies: Sutong Bridge and Stonecutters Bridge
- (Simulation Methods for Wind Effects)

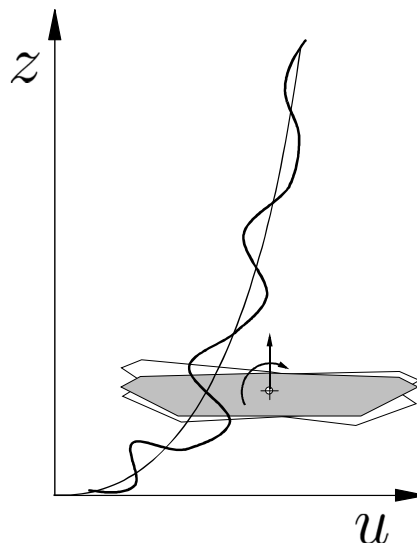
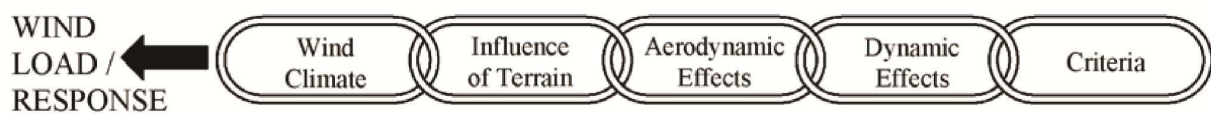


Principal Concepts of Wind Engineering

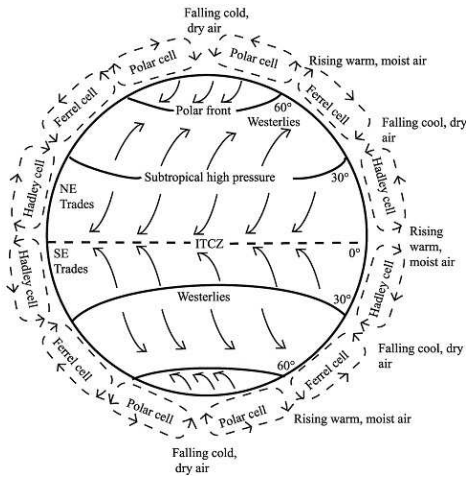


Introduction

The Davenport Wind Chain: Wind Response Analysis



Wind Climate



10-min mean wind speed
at 10m height with
50 year return period
according to DIN EN 1991-1-4:

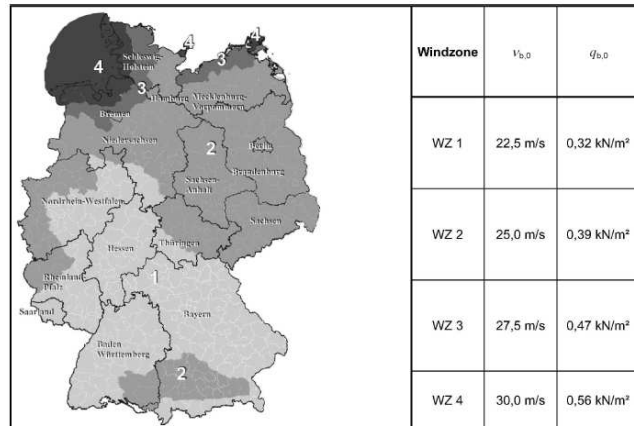


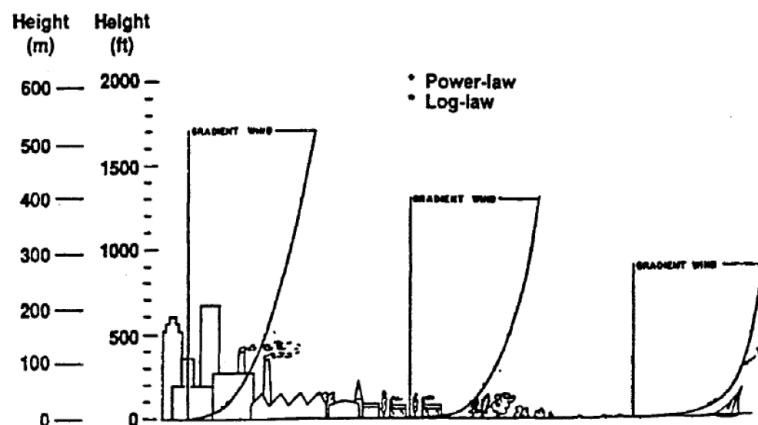
Bild NA.A.1 — Windzonenkarte für das Gebiet der Bundesrepublik Deutschland



Introduction – Terrain

Terrain Effects: Mean Wind Speed Profile

Effect of Roughness on wind speed (atmospheric boundary layer)



Power Law: $U(z) = U_{z_G} \left(\frac{z}{z_G} \right)^\alpha$

z_G is gradient height

U_{z_G} is unobstructed velocity (speed constant above gradient height)

α for mean speed, β for gust speeds

Log Law: $U(z) = 2.5 U_0 \ln \left(\frac{z}{z_0} \right)$

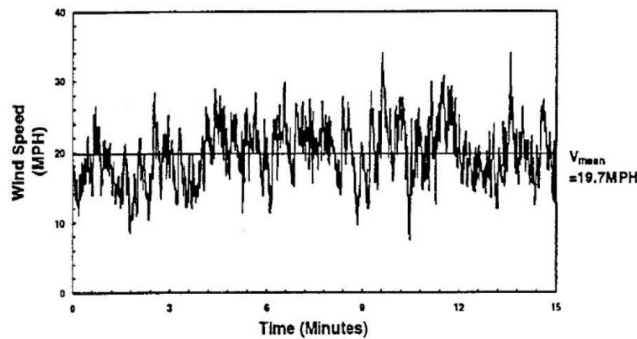
z_0 is roughness length



Terrain Effects: Atmospheric Turbulence

Turbulence intensity:

$$I_u = \frac{\sigma_u}{\bar{u}}$$



Typical Wind Spectra (von Karman):

Along-wind component (u):

$$\frac{f \cdot S_{uu}(f)}{\sigma_u^2} = \frac{4 \frac{L_u \cdot f}{V_{10}(z)}}{\left[1 + 70.8 \cdot \left(\frac{L_u \cdot f}{V_{10}(z)}\right)^2\right]^{5/6}}$$

Cross-wind lateral (v) and vertical (w):

$$\frac{f \cdot S_{vv,ww}(f)}{\sigma_{v,w}^2} = \frac{4 \frac{L_{v,w} \cdot f}{V_{10}(z)} \cdot \left[1 + 755 \cdot \left(\frac{L_{v,w} \cdot f}{V_{10}(z)}\right)^2\right]}{\left[1 + 283 \cdot \left(\frac{L_{v,w} \cdot f}{V_{10}(z)}\right)^2\right]^{11/6}}$$

where the parameters in the expression are:

i	turbulence component (u , v or w)
$S_{ii}(f)$	Wind energy spectrum for turbulence component i
f	Frequency [Hz]
σ_i	Standard deviation of wind speed for turbulence component i
$V_{10}(z)$	10 min. mean wind speed at level z
L_i	$L_i = L_{iso} \cdot \left(\frac{z}{50}\right)^{0.45}$ Length scales, all wind directions : $L_{u50} = 230$ m, $L_{v50} = L_{u50}/3$, $L_{w50} = L_{u50}/9$

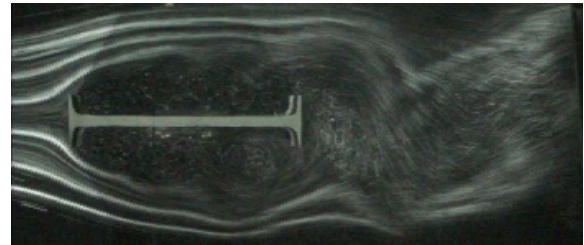


Introduction – Bluff Body Aerodynamics

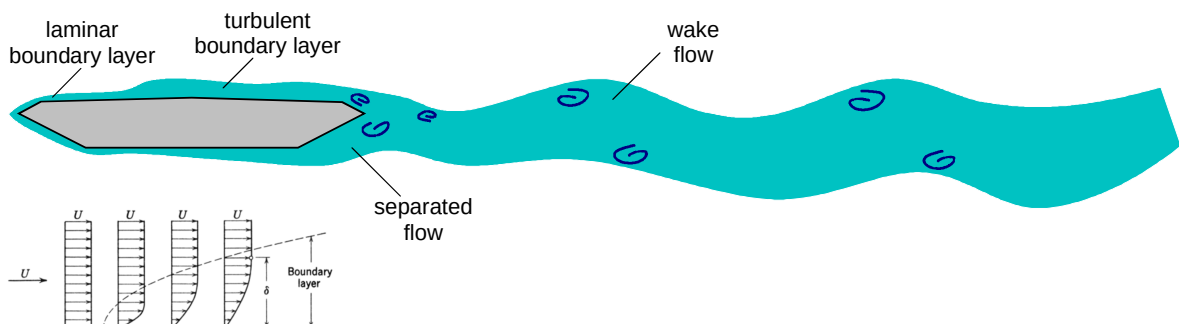
Bluff Body Aerodynamics

Fluid flow at high Reynolds numbers

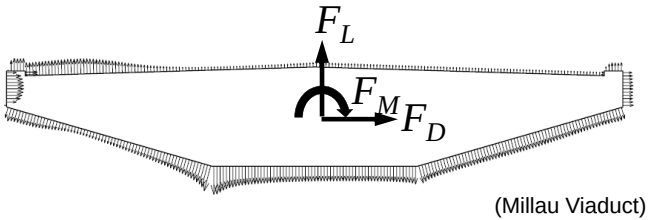
- unsteady
- rotational
- turbulent



Bridge deck



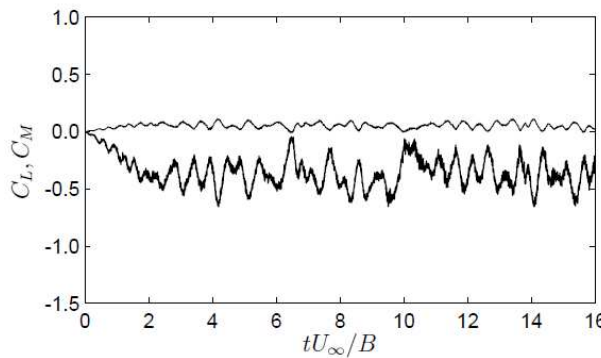
Static Forces



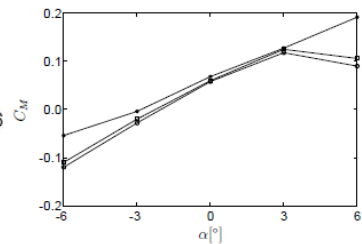
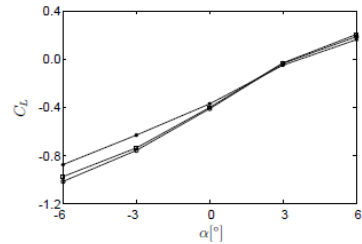
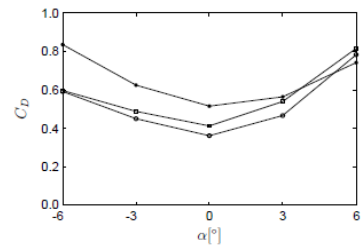
$$C_L = \frac{F_L}{\frac{1}{2}\rho B U_\infty^2},$$

$$C_D = \frac{F_D}{\frac{1}{2}\rho D U_\infty^2},$$

$$C_M = \frac{F_M}{\frac{1}{2}\rho B^2 U_\infty^2},$$



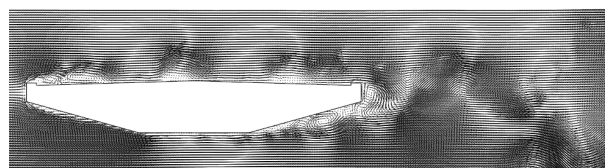
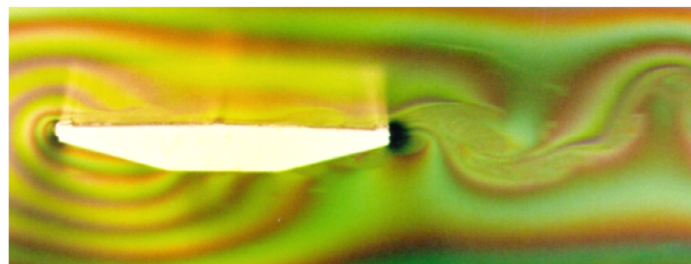
Time-averaged (mean) coefficients vs angle of attack:



Vortex Shedding

- Alternating creation of vortices
- periodic
- Kármán Vortex Street

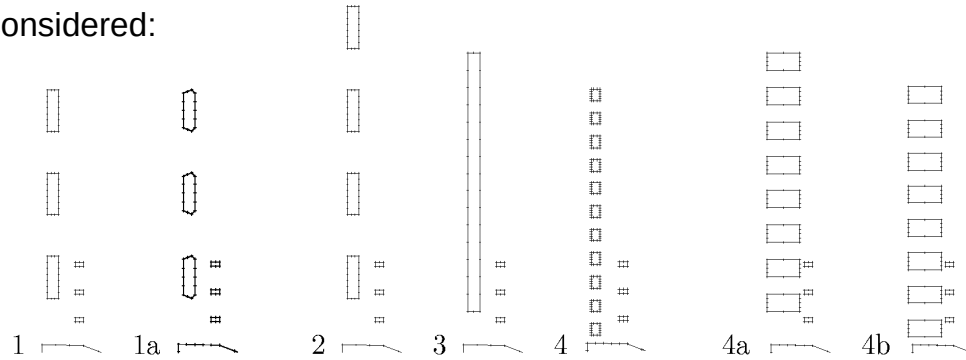
Frequency – Strouhal Number: $St = \frac{f_{shed} D}{U}$



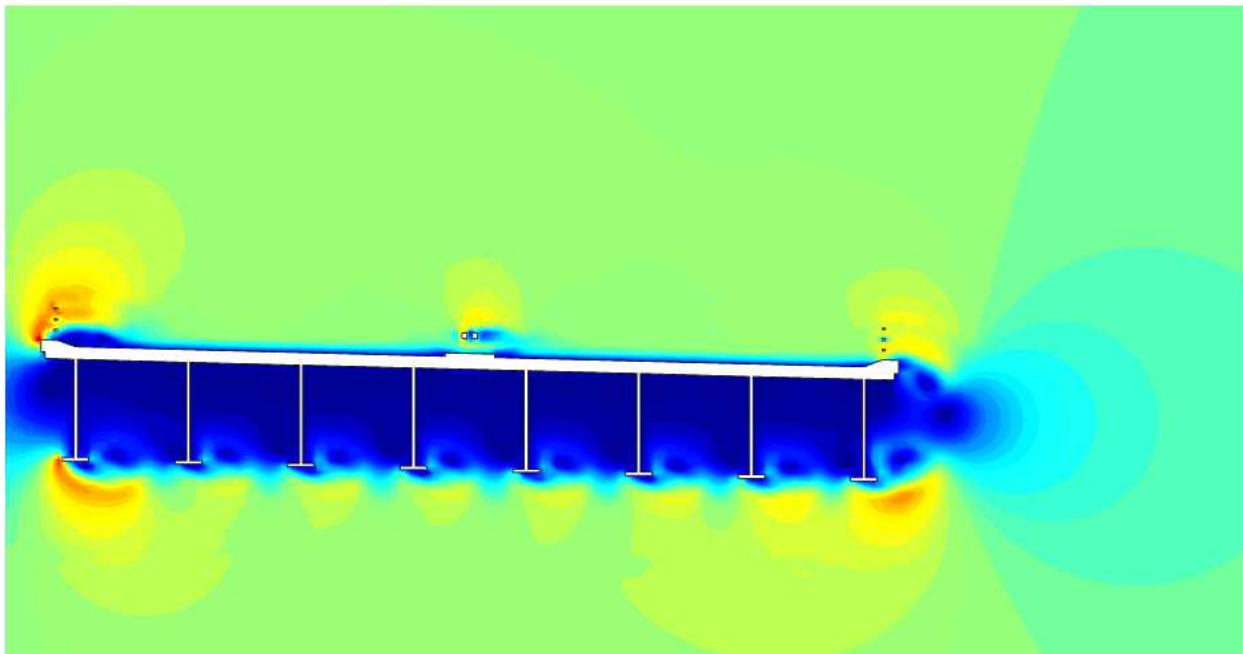
Wind screen simulations: M4 Neath



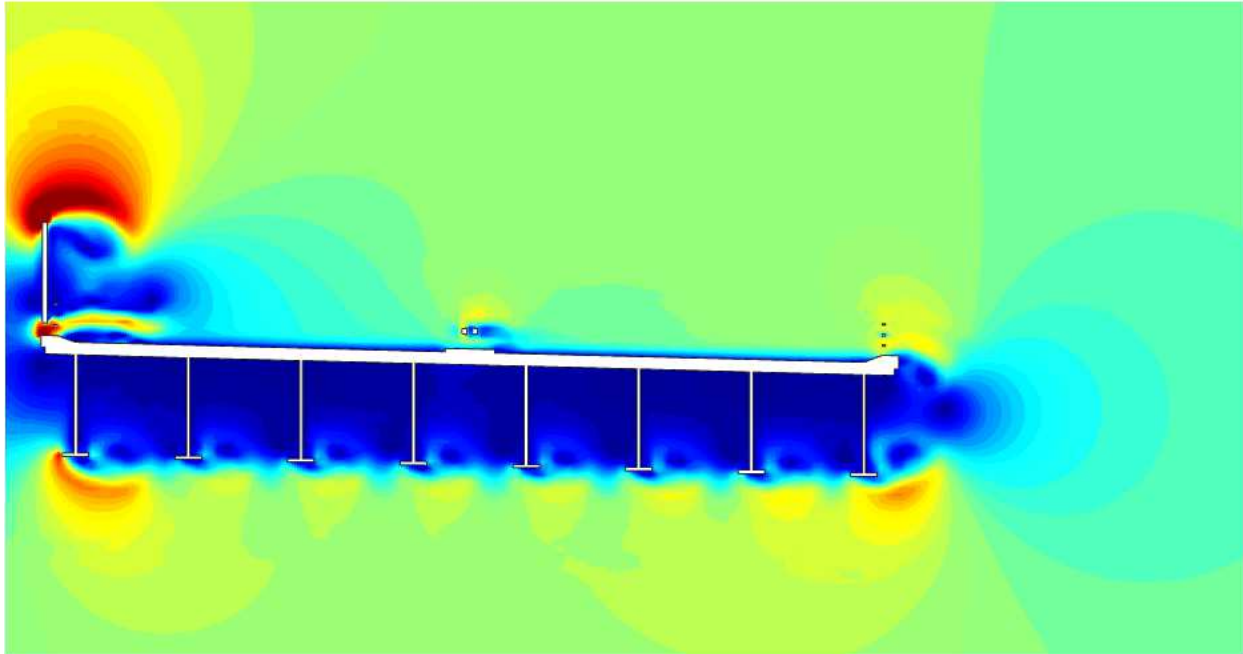
Screens considered:



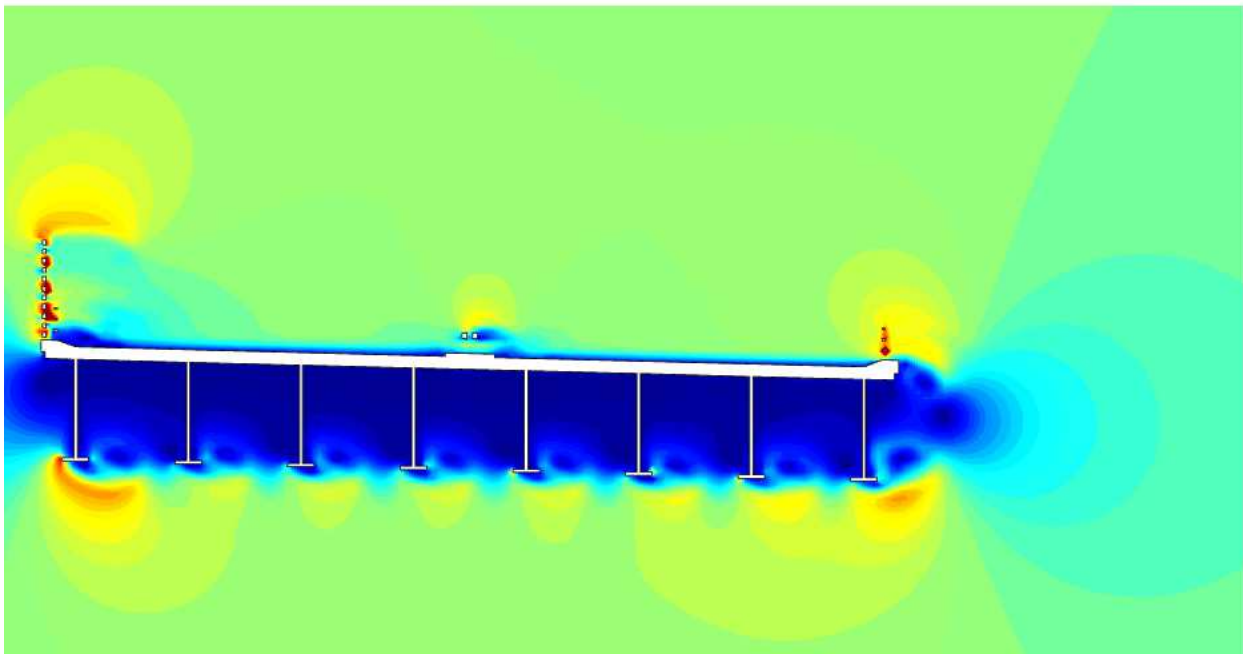
Wind screen simulations: M4 Neath (original section)



Wind screen simulations: M4 Neath (with solid screen)

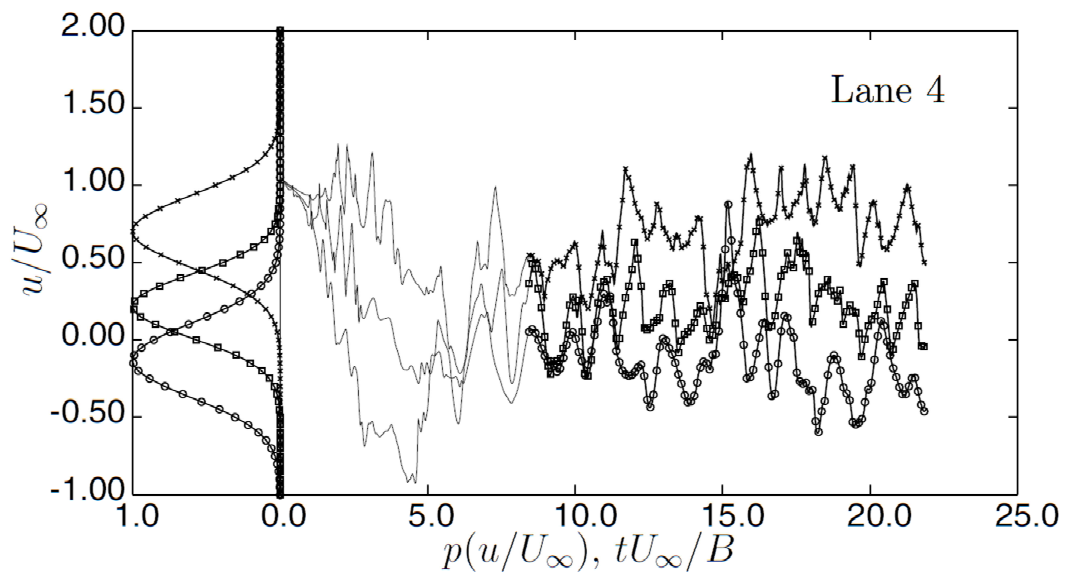


Wind screen simulations: M4 Neath (with perforated screen)



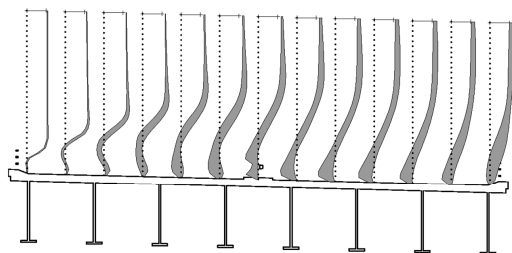
Wind screen simulations: M4 Neath

Velocity time-histories

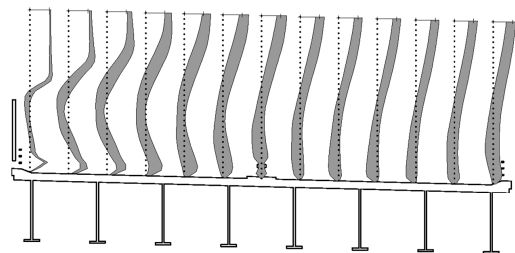


Wind screen simulations: M4 Neath

Velocity profiles (mean $\pm$ 1 std.dev.):



Main span, no screens.

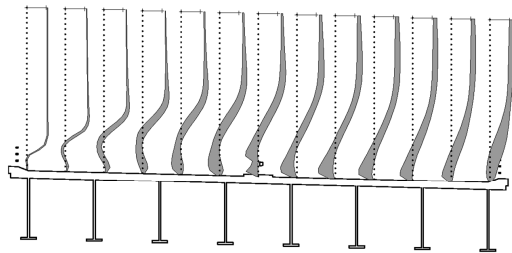


Main span, screen 3.

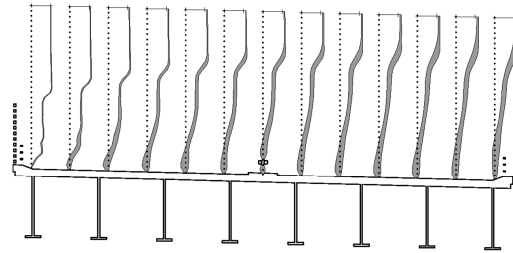


Wind screen simulations: M4 Neath

Velocity profiles (mean $\pm$ 1 std.dev.):



Main span, no screens.



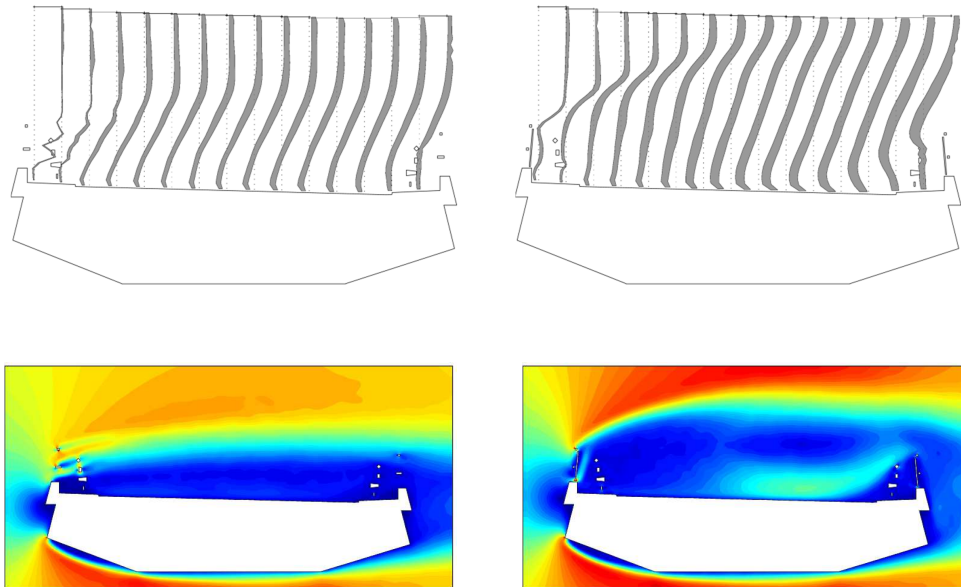
Main span, screen 4.



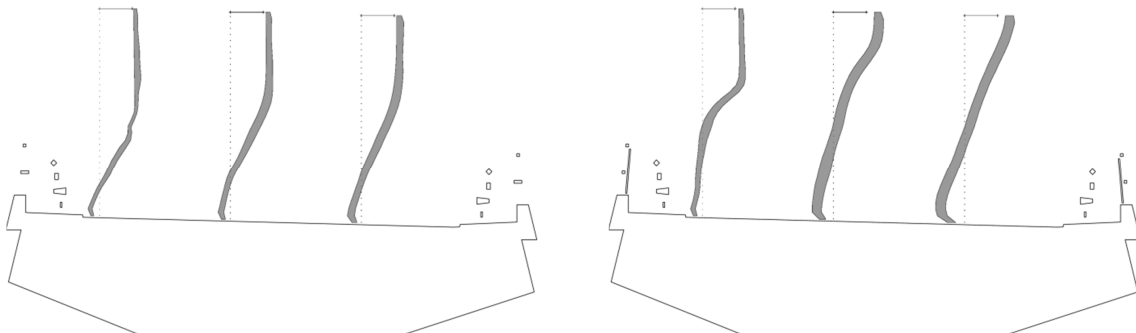
Wind screen simulations: Strelasund Bridge



Wind screen simulations: Strelasund Bridge



Wind screen simulations: Strelasund Bridge



	Original	With Wind Screens
M_v Lane 1	177	61 (-66%)
M_v Lane 3	112	29 (-74%)
$C_{D,design}$ (D=4.01m)	1.11	1.41 (+27%)

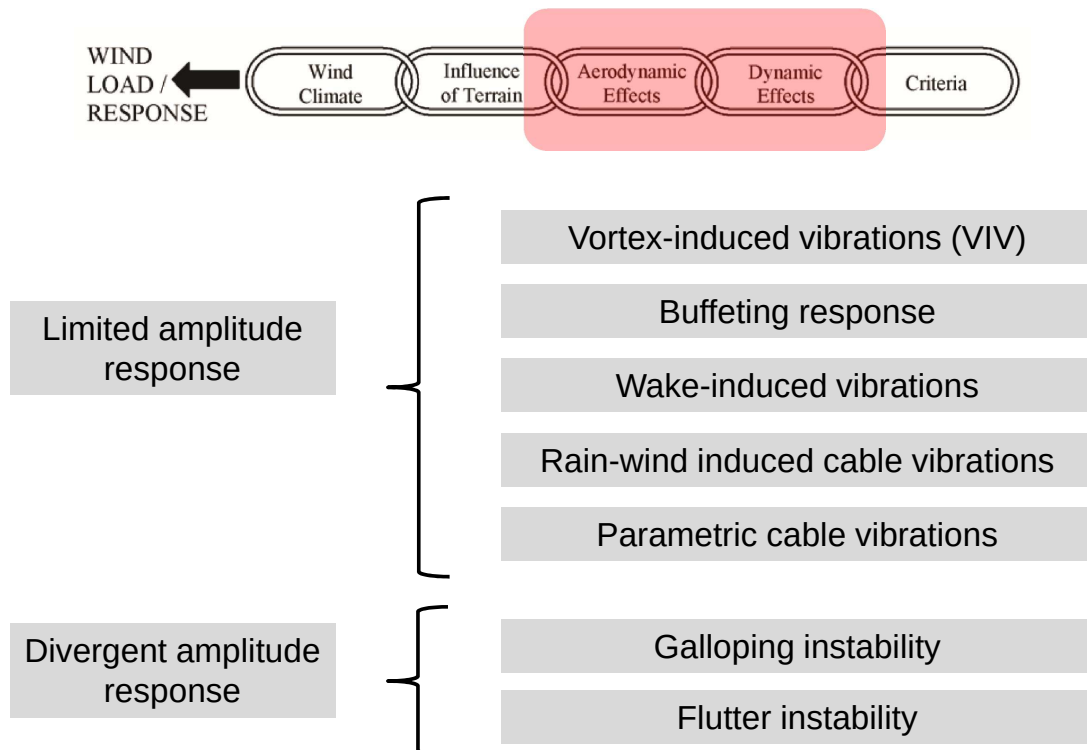


Dynamic Wind Excitation Phenomena

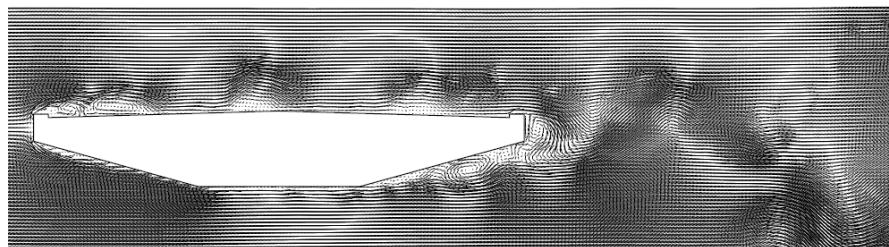
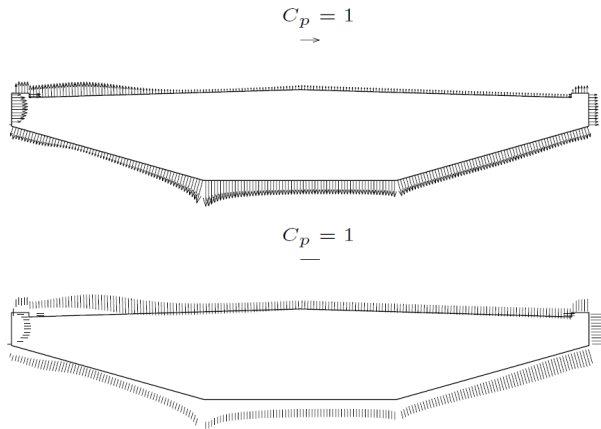


Fluid-Structure Interaction Phenomena

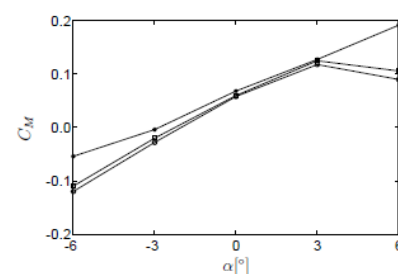
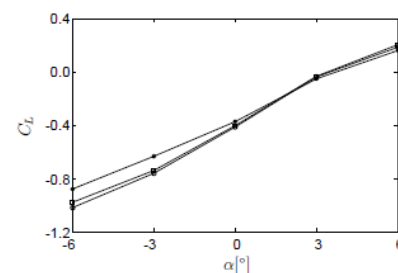
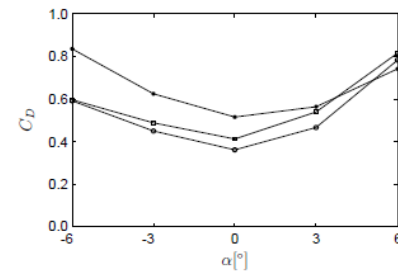
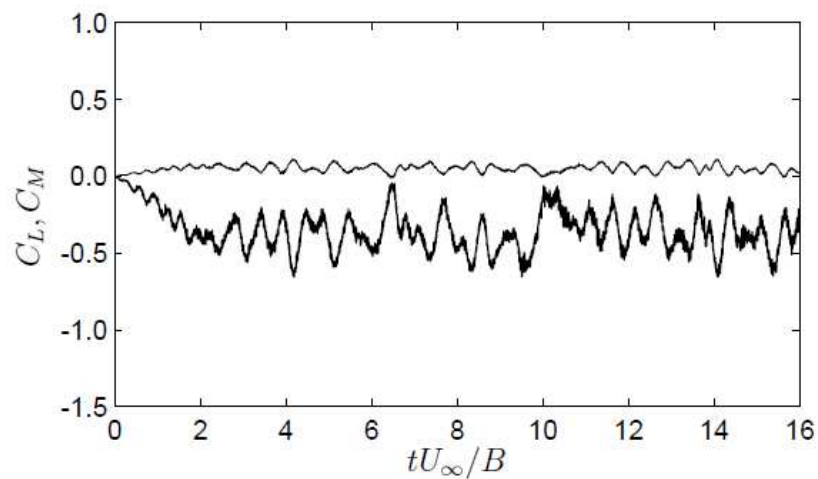
Main Excitation Phenomena in Bridge Aerodynamics



Millau Viaduct: static section



Millau Viaduct: static section

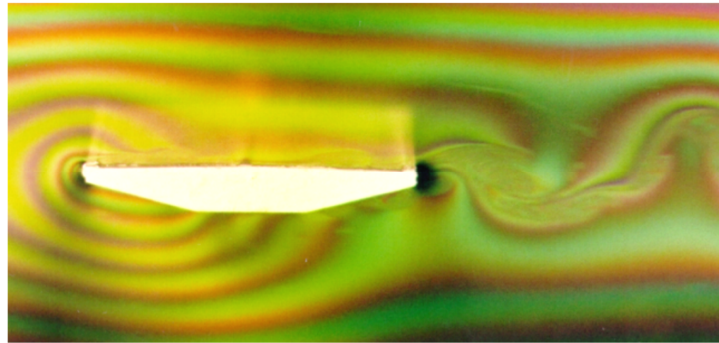


Vortex Shedding

- Alternating creation of vortices
- periodic
- *Kármán* Vortex Street

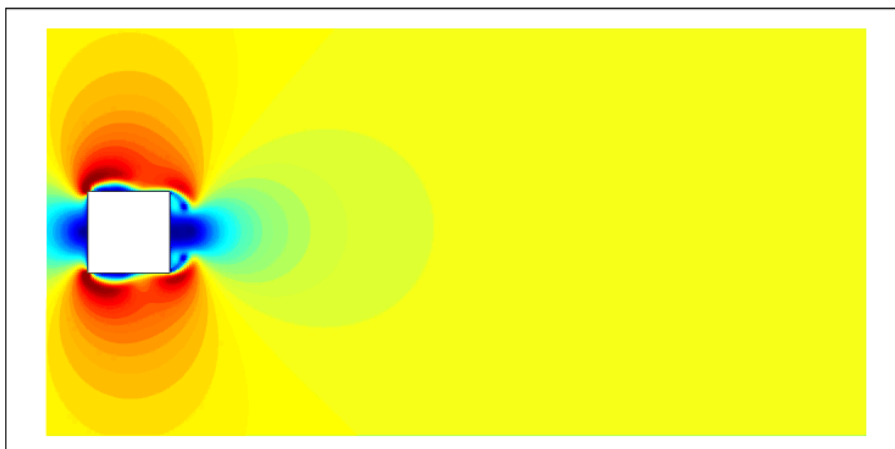
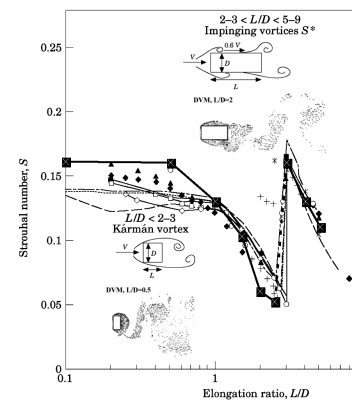
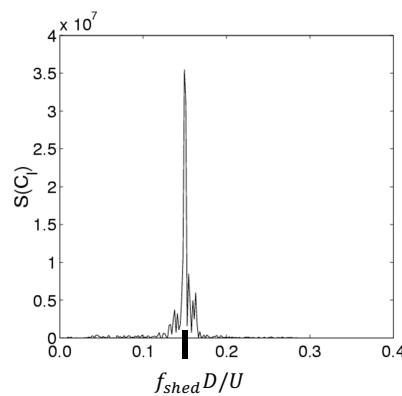
Frequency – *Strouhal Number*: $St = \frac{f_{shed} D}{U}$

Millau Bridge: Flow visualisation



Vortex-Induced Vibrations (VIV)

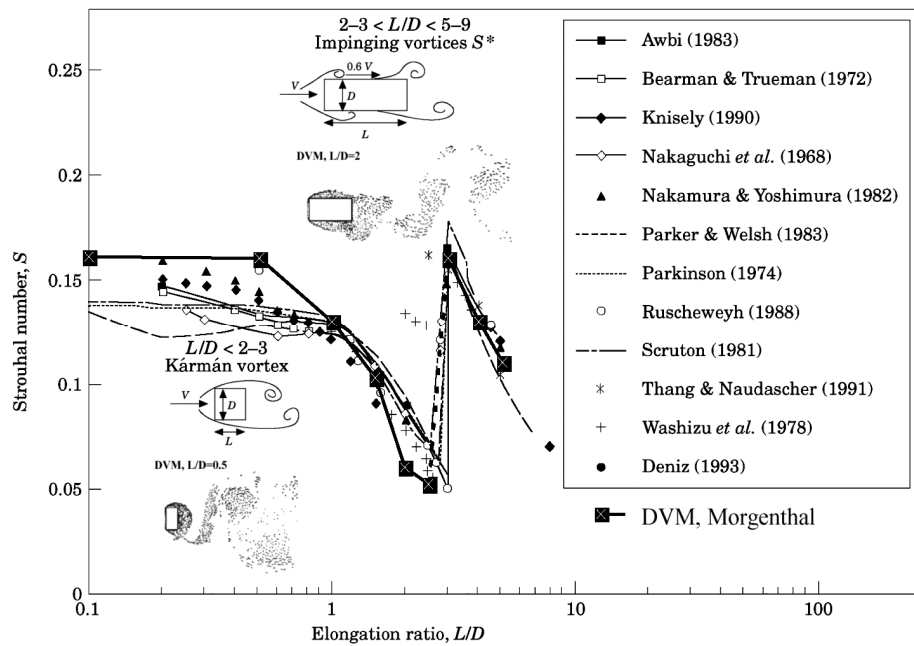
Rectangular Section: Static



(VXflow)



Rectangular Section: Static



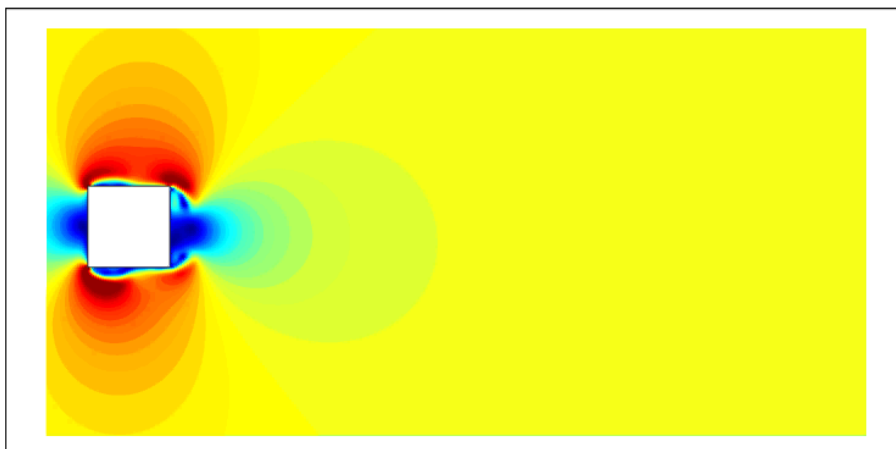
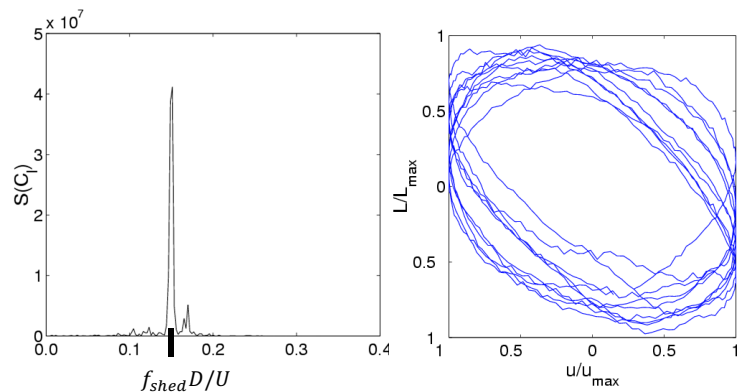
Vortex-Induced Vibrations (VIV)

Rectangular Section: Forced

$$d(t) = d_0 \sin(2\pi f_0 t)$$

$$d_0 = 0.15D$$

$$f_0 = 1.0 f_{\text{shed}}$$

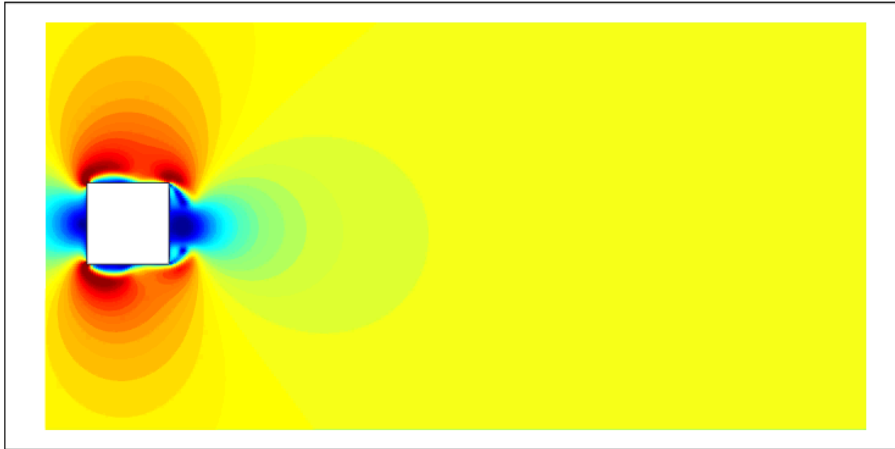
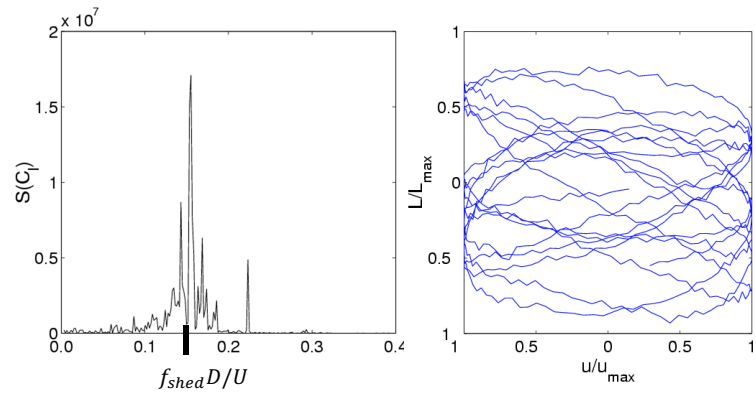


Rectangular Section: Forced

$$d(t) = d_0 \sin(2\pi f_0 t)$$

$$d_0 = 0.05D$$

$$f_0 = 1.5 f_{\text{shed}}$$

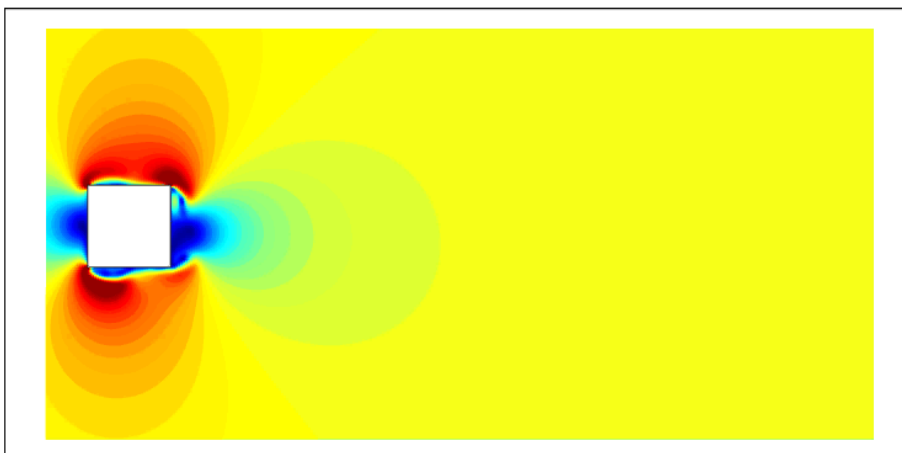
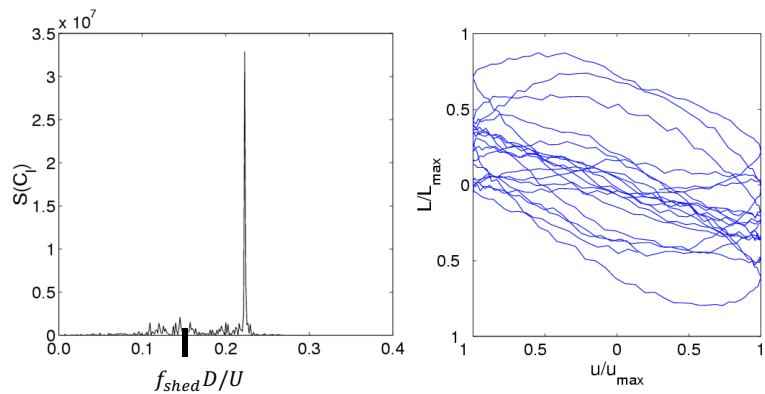


Rectangular Section: Forced

$$d(t) = d_0 \sin(2\pi f_0 t)$$

$$d_0 = 0.15D$$

$$f_0 = 1.5 f_{\text{shed}}$$

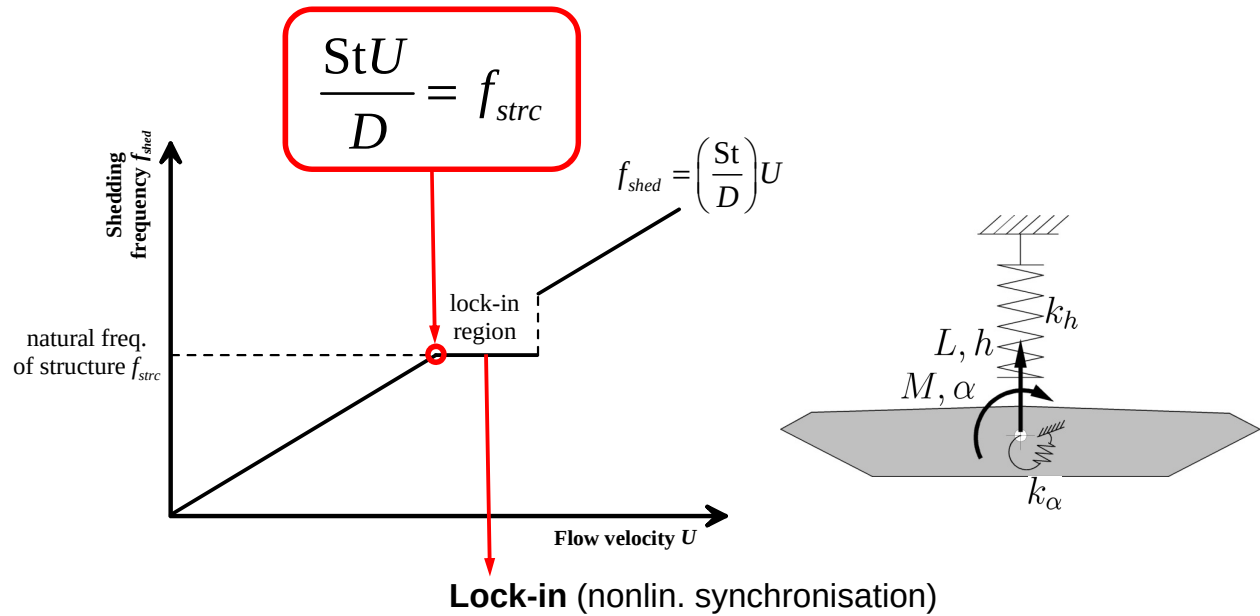


(VXflow)

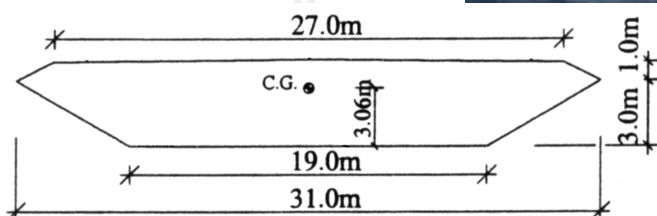


Vortex-induced Vibrations (VIV)

Elastic system → 'resonance' between vortex shedding frequency $f_{shed} = \frac{St U}{D}$ and a natural frequency of the structure f_{strc} :

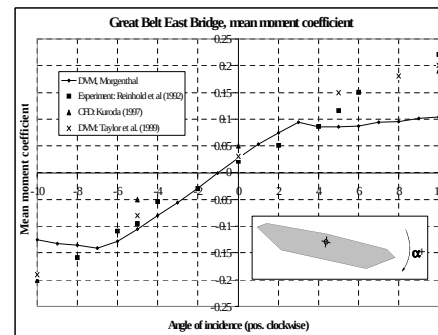
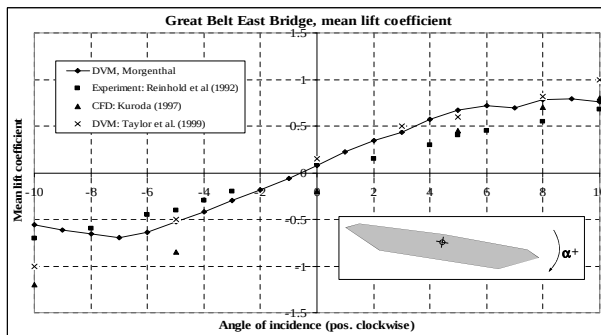


Storebælt Bridge

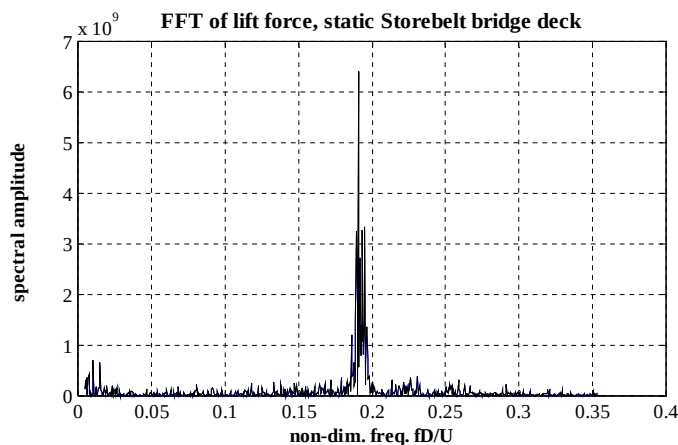


Storebælt Bridge: aerodynamic properties

Source	$C_D = \frac{F_D}{\frac{1}{2} \rho U^2 D}$	$C_L = \frac{F_L}{\frac{1}{2} \rho U^2 B}$	$St = \frac{fD}{U}$
Morgenthal, McRobie, (DVM)	0.42	0.08	0.19
Jenssen and Kvelmsdal (1999), (FV)	0.45	0.04	0.16
Enevoldsen et al. (1999), (FV)	0.51	0.08	0.17
Larsen and Walther (1998), (DVM)	0.56	0.07	0.17
DMI and SINTEF (1993), (section model)	0.54	0.01	0.11-0.15
Larose (1992), (Taut strip model)	0.72	-0.08	0.11
Morgenthal, (smoke tunnel)			0.19
Jang, Morgenthal (soap film channel)			0.19



Storebælt Bridge: Vortex shedding frequency



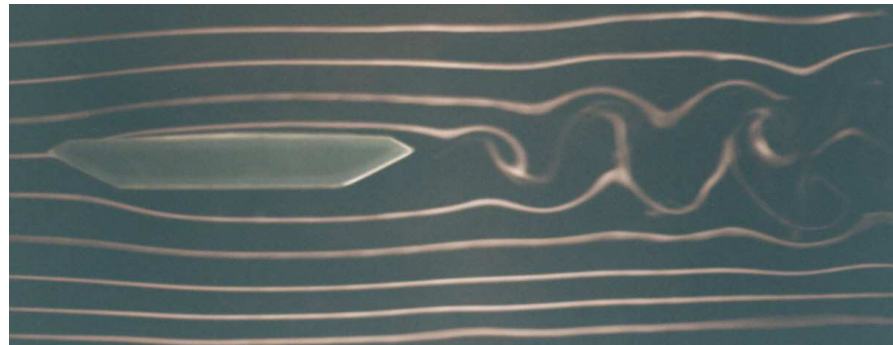
FFT of lift force →
 $St(D) = 0.19$



Storebælt Bridge: flow visualisation

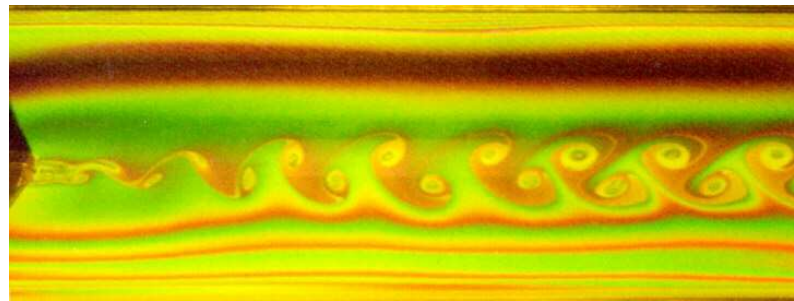
Smoke tunnel:

St=0.19

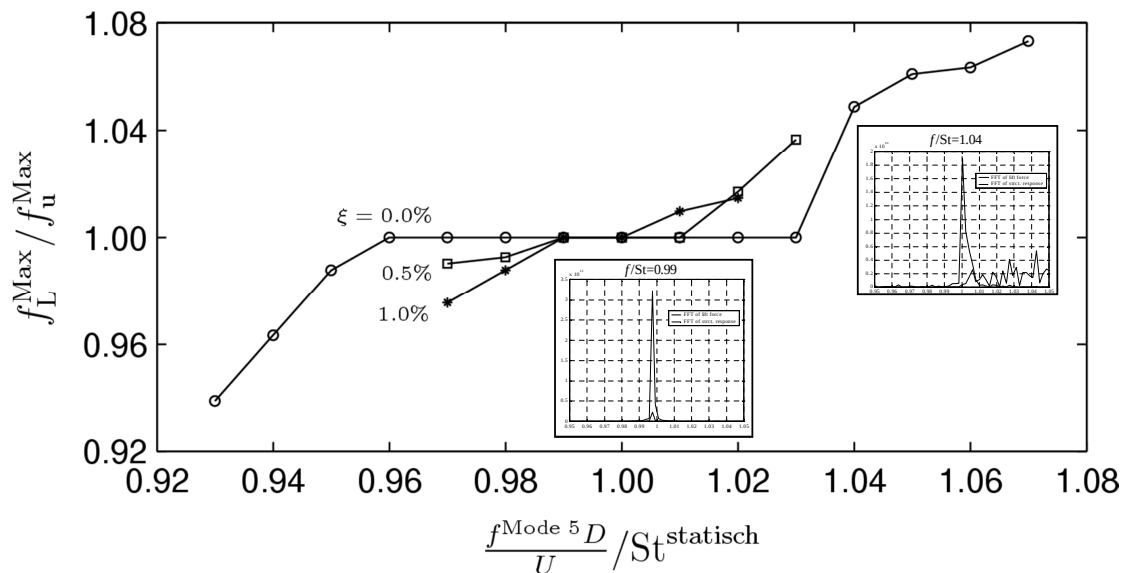
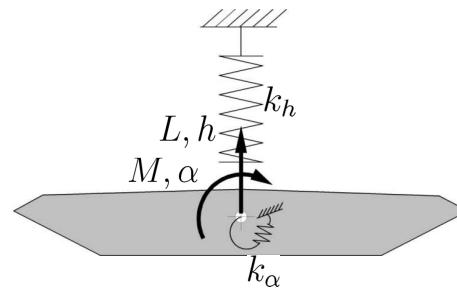


Soap film channel:

St=0.19



Storebælt Bridge: Lock-in



Multi-slice CFD Formulation: Niteroi Bridge (main span $l=300\text{m}$)

Vertical modes: $f_1=0.32\text{Hz}$, $f_2=0.55\text{Hz}$, $f_3=0.70\text{Hz}$

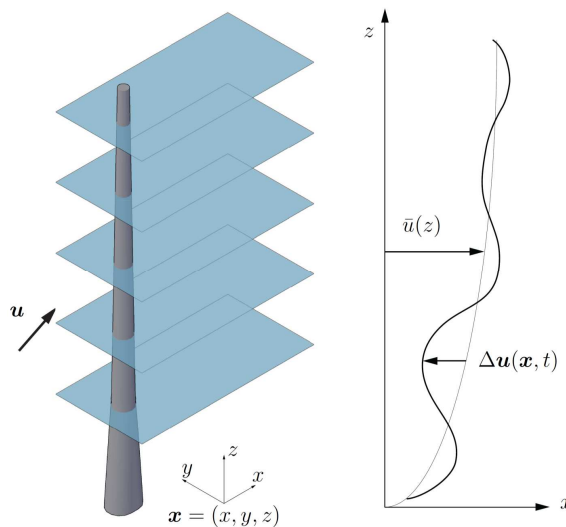


Source of estimation		Y_B (cm)
Original bridge — theoretical	Full correlation	± 34
	Partial correlation	± 26
Estimated from video images		$\pm 25 (\pm 5)$
Bridge with eight TMDs-theoretical		± 2.1
Bridge with active control		~ 0

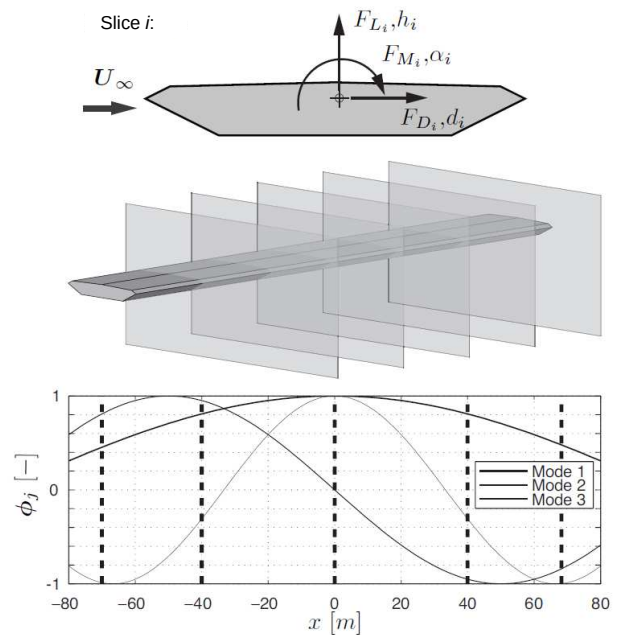


Multi-slice CFD Formulation: Concept

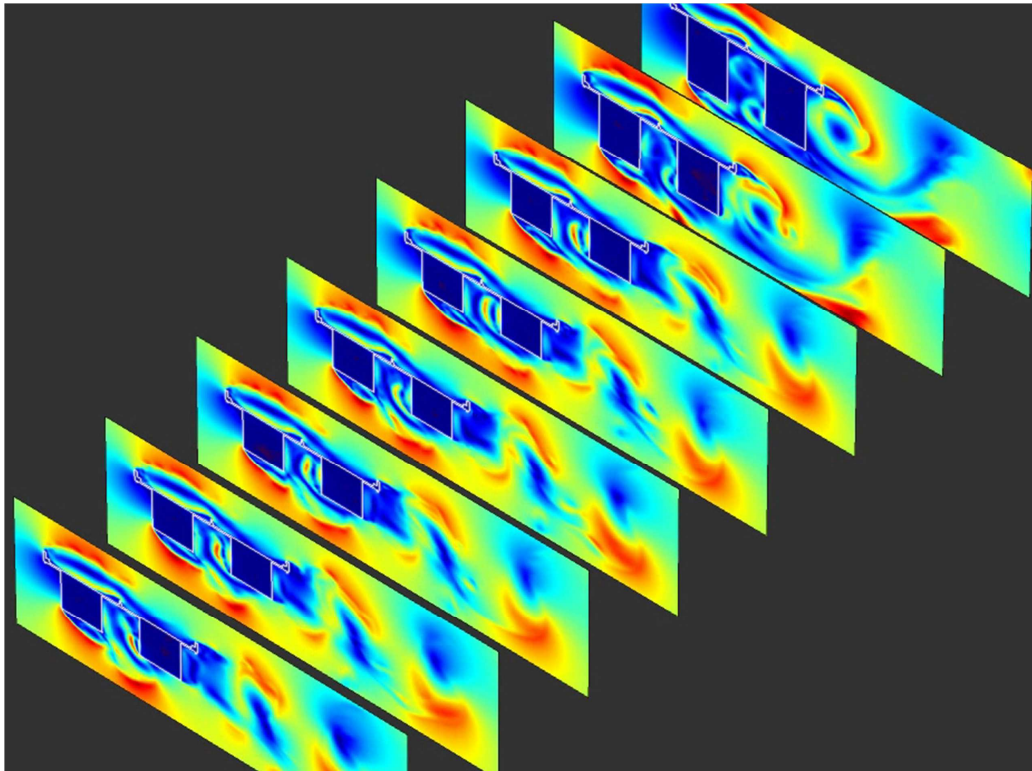
Vertical structure:



Horizontal structure:



Multi-slice CFD Formulation: Example Niteroi Bridge (main span $l=300\text{m}$)



Aerodynamic Instability

Aerodynamic Instability

[Aircraft Flutter](#)

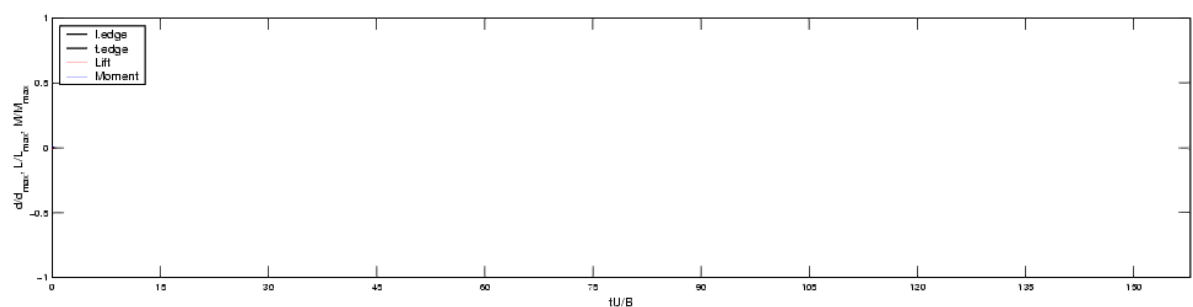
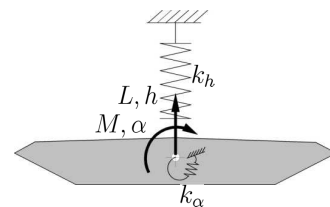


Aerodynamic Instability

(CSTB)



Aerodynamic Instability



(VXflow)



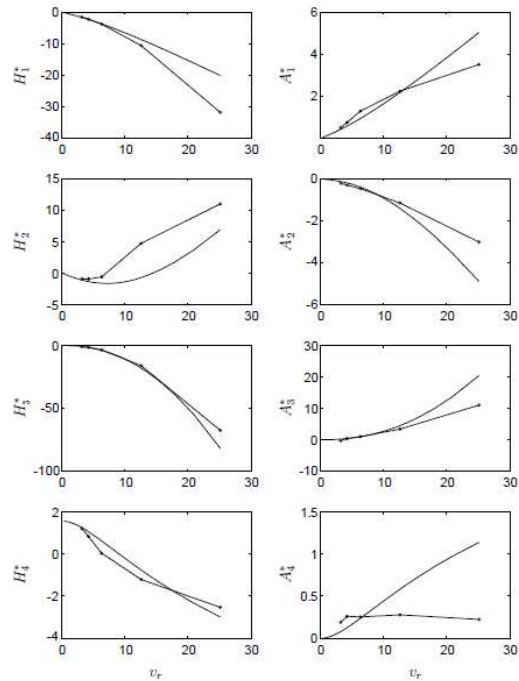
Aerodynamic Instability (2 DOF)

Expressing motion-induced forces:

- flat plate (*Theodorsen*)
- using aerodynamic derivatives
(typ. determined from section model tests)

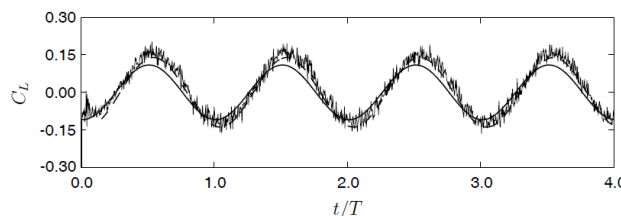
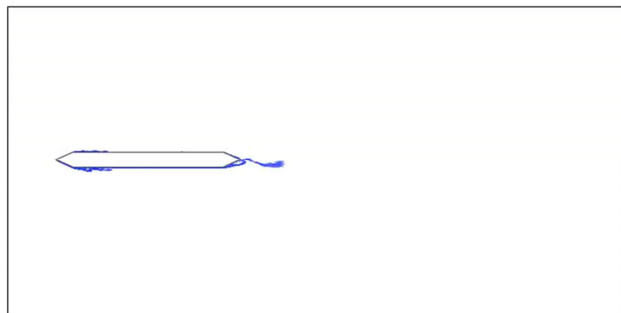
$$F_L = \frac{1}{2}\rho U_\infty^2 B \left[KH_1^*(K) \frac{\dot{h}}{U_\infty} + KH_2^*(K) \frac{B\dot{\alpha}}{U_\infty} + K^2 H_3^*(K) \alpha + K^2 H_4^*(K) \frac{h}{B} \right]$$

$$F_M = \frac{1}{2}\rho U_\infty^2 B^2 \left[KA_1^*(K) \frac{\dot{h}}{U_\infty} + KA_2^*(K) \frac{B\dot{\alpha}}{U_\infty} + K^2 A_3^*(K) \alpha + K^2 A_4^*(K) \frac{h}{B} \right]$$

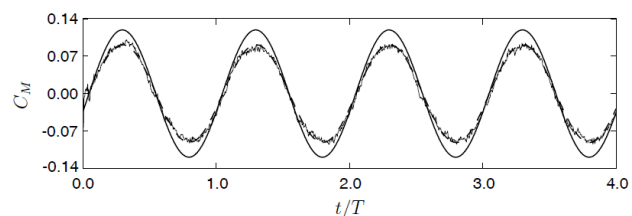
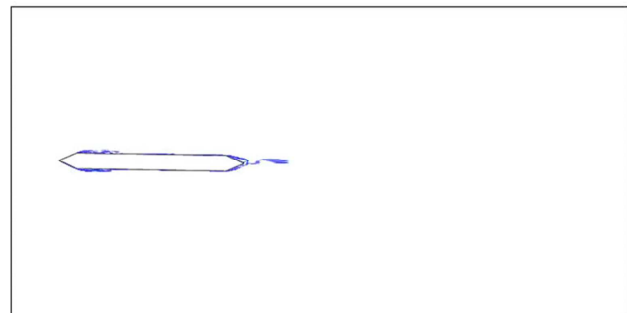


Aerodynamic Instability

- Forced oscillation test to identify Scanlan derivatives



→ H_1^*, H_4^*



→ A_2^*, A_3^*

(—) present results, (— —) RMS fit of present results (—) Theodorsen prediction



Aerodynamic Instability (1 DOF)

Pure Heave: $m\ddot{h} + 2m\xi_h\omega_h\dot{h} + m\omega_h^2h = \frac{1}{2}\rho U^2 B \left(KH_1^* \frac{\dot{h}}{U} + K^2 H_4^* \frac{h}{B} \right)$

$$\rightarrow m\ddot{h} + \underbrace{\left(2m\xi_h\omega_h - \frac{1}{2}\rho UBKH_1^* \right)}_{\text{Aerodynamic damping}} \dot{h} + \underbrace{\left(m\omega_h^2 - \frac{1}{2}\rho U^2 K^2 H_4^* \right)}_{\text{Aerodynamic stiffness}} h = 0$$

effective damping: $c_{eff} = 2m\xi_h\omega_h - \frac{1}{2}\rho U^2 B \frac{KH_1^*}{U}$

$\rightarrow$ if $2m\xi_h\omega_h < \frac{1}{2}\rho UBKH_1^*$, then $c_{eff} < 0$, i.e. unstable: Galloping

$$4m\xi_h < \rho B^2 H_1^*$$



Aerodynamic Instability (1 DOF)

Pure Pitch: $I\ddot{\alpha} + 2I\xi_\alpha\omega_\alpha\dot{\alpha} + I\omega_\alpha^2\alpha = \frac{1}{2}\rho U^2 B^2 \left(KA_2^* \frac{B\dot{\alpha}}{U} + K^2 A_3^* \alpha \right)$

$$\rightarrow I\ddot{\alpha} + \underbrace{\left(2I\xi_\alpha\omega_\alpha - \frac{1}{2}\rho UB^3 KA_2^* \right)}_{\text{Aerodynamic damping}} \dot{\alpha} + \underbrace{\left(I\omega_\alpha^2 - \frac{1}{2}\rho U^2 K^2 A_3^* \right)}_{\text{Aerodynamic stiffness}} \alpha = 0$$

effective damping: $c_{eff} = 2I\xi_\alpha\omega_\alpha - \frac{1}{2}\rho UB^3 KA_2^*$

$\rightarrow$ if $2I\xi_\alpha\omega_\alpha < \frac{1}{2}\rho UB^3 KA_2^*$, then $c_{eff} < 0$, i.e. unstable: Torsional Flutter

$$4I\xi_\alpha < \rho B^4 A_2^*$$

$$0 < \frac{4I\xi_\alpha}{\rho B^4} < A_2^*$$



Aerodynamic Instability (1 DOF)

Pure Pitch:

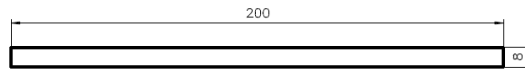


Bild B.43: Modell des Ebene Platte Profils

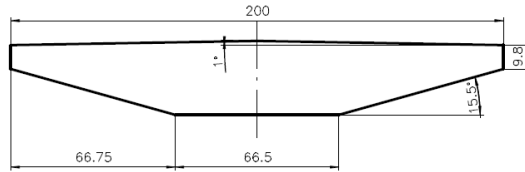


Bild B.7: Modell des Millau Viaduct Profils

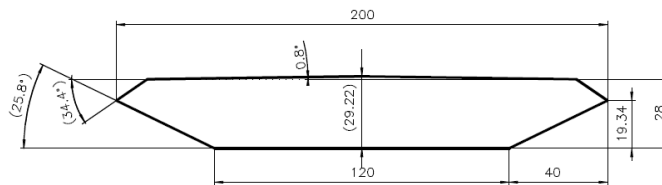
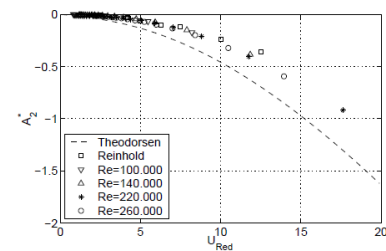
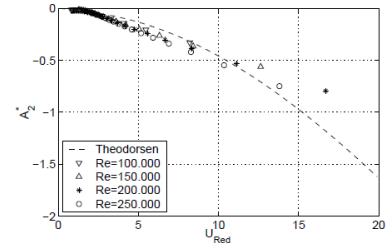
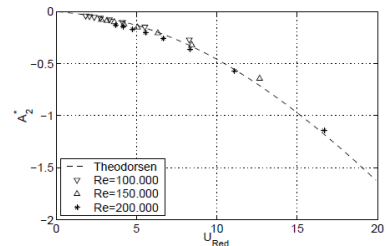


Bild B.13: Modell des Great Belt Profils



Aerodynamic Instability (1 DOF)

Pure Pitch:

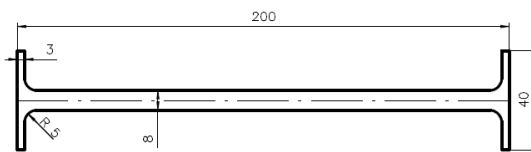


Bild B.31: Modell des Tacoma Narrows Bridge Profils

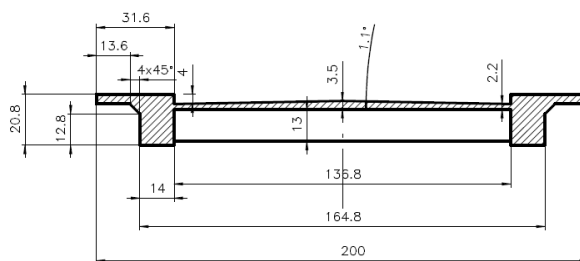
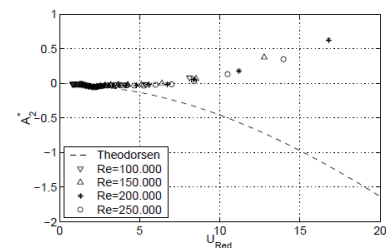
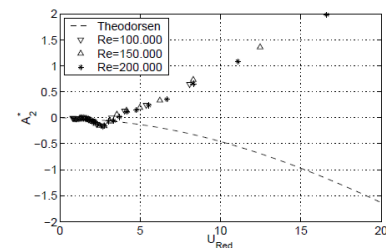
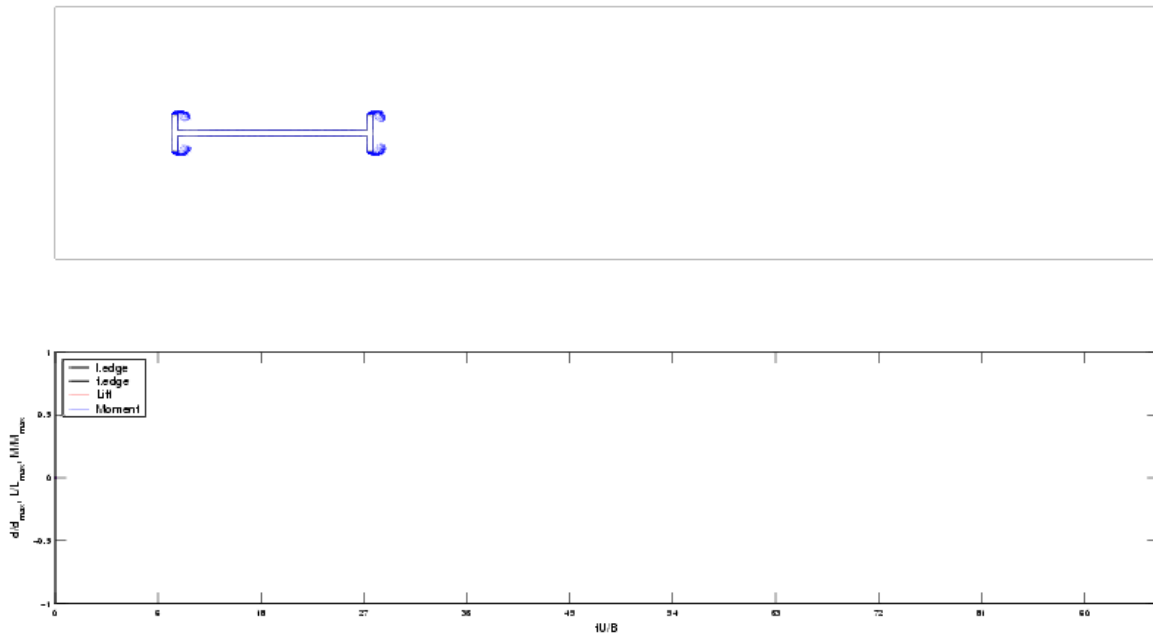


Bild B.37: Modell des Chongqing Bridge Profils

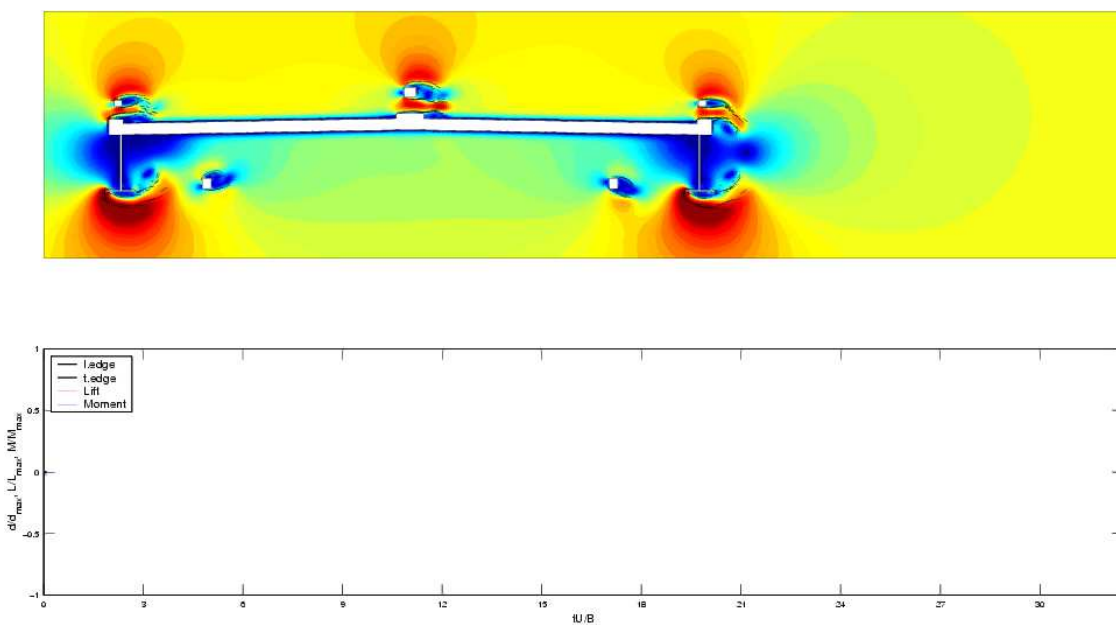


Tacoma Narrows Bridge



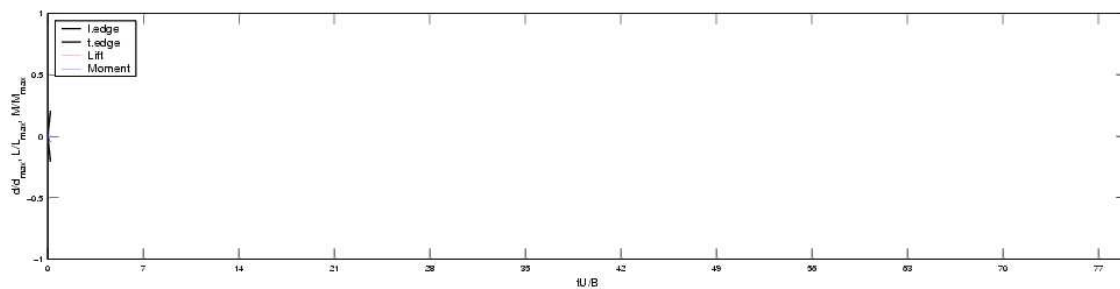
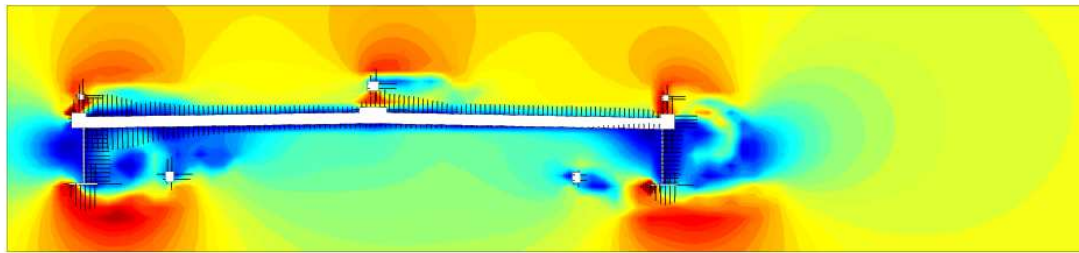
MaChang Bridge Wind Nose Optimisation

- Aerodynamic behaviour of the static deck



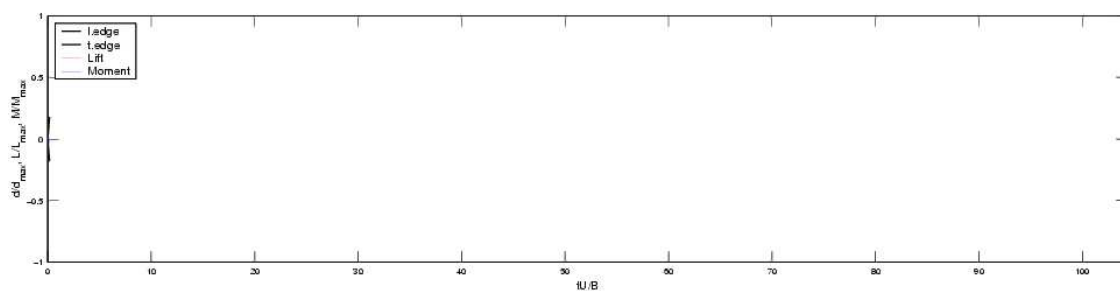
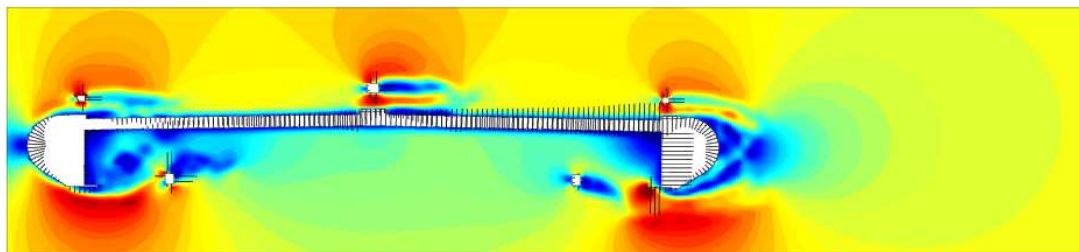
MaChang Bridge Wind Nose Optimisation

- Motion-induced forces – Scanlan flutter derivatives



MaChang Bridge Wind Nose Optimisation

- Motion-induced forces – Scanlan flutter derivatives

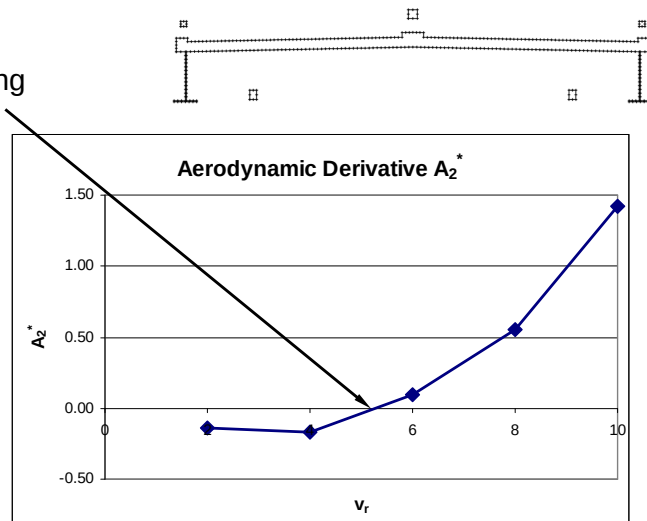


MaChang Bridge Wind Nose Optimisation

- Motion-induced forces – Scanlan flutter derivatives

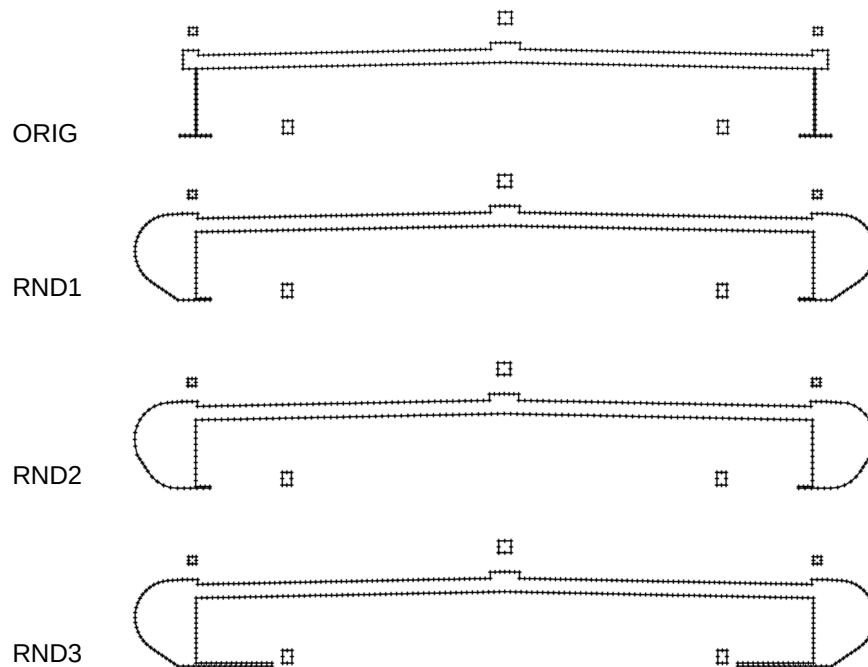
Instability point (torsional flutter):

Instability point at zero damping



MaChang Bridge Wind Nose Optimisation

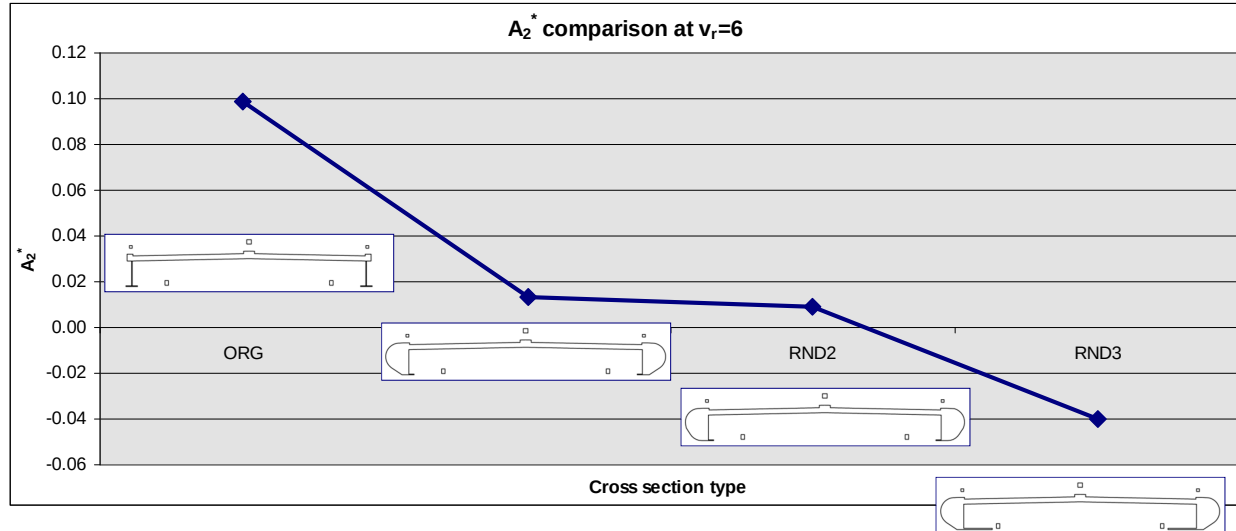
- Motion-induced forces – Scanlan flutter derivatives



MaChang Bridge Wind Nose Optimisation

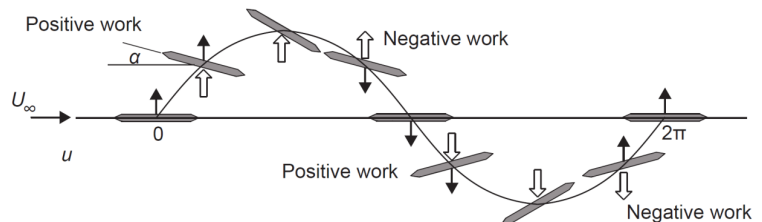
- Motion-induced forces – Scanlan flutter derivatives

Instability point (torsional flutter):



Aerodynamic Instability (2 DOF)

- Two modes (vertical/torsional) couple to a flow-driven unstable oscillation
- negative effective damping due to neg. aerodynamic damping
- mode coupling due to aerodynamic stiffness (frequency shift)
- motion-induced aerodynamic forces feed energy into the system
- classical flutter: two modes couple
- flutter boundary: U_{crit}
- Ultimate Limit State



Equations of motion:

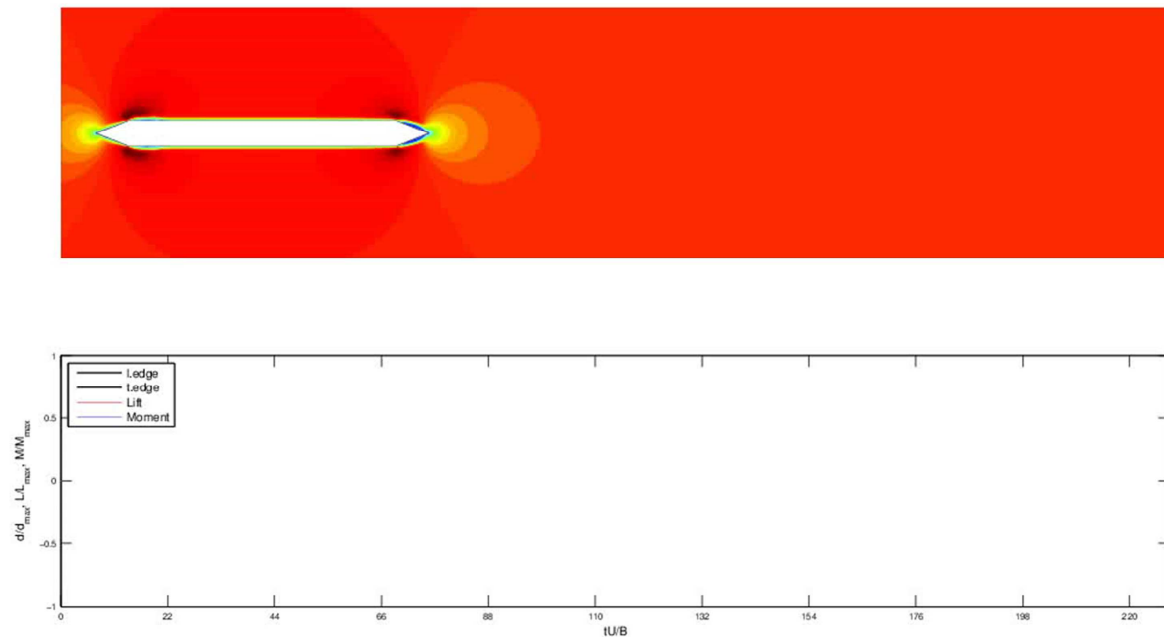
$$m\ddot{h} + 2m\zeta_h\omega_h\dot{h} + m\omega_h^2h = F_h(K, \rho, h, \dot{h}, \alpha, \dot{\alpha}, \dots)$$

$$I\ddot{\alpha} + 2I\zeta_\alpha\omega_\alpha\dot{\alpha} + I\omega_\alpha^2\alpha = F_\alpha(K, \rho, h, \dot{h}, \alpha, \dot{\alpha}, \dots) \quad \left(K = \frac{b\omega}{U} \right)$$



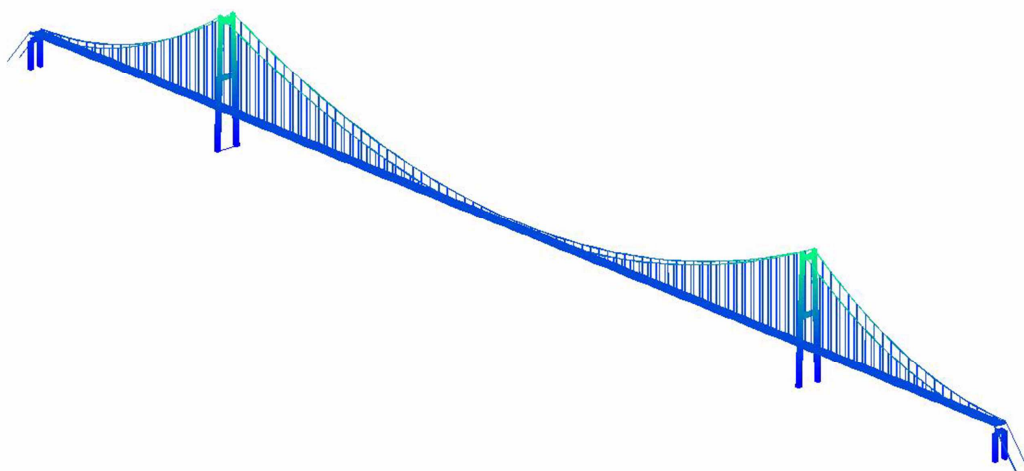
Aerodynamic Instability (2 DOF)

- Fully coupled flutter analysis:

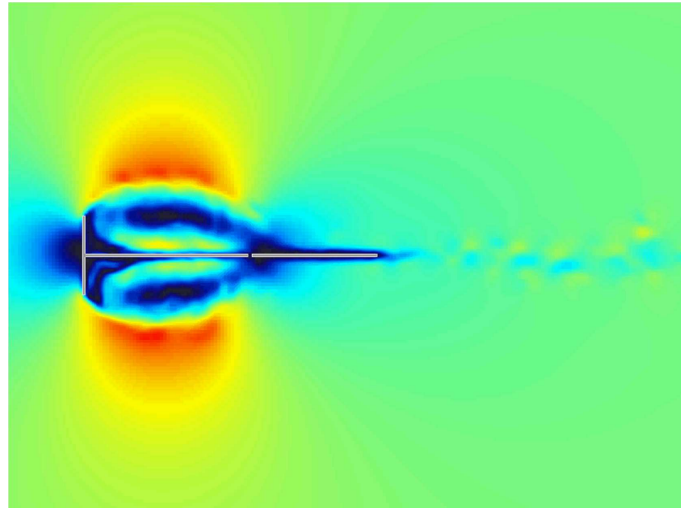
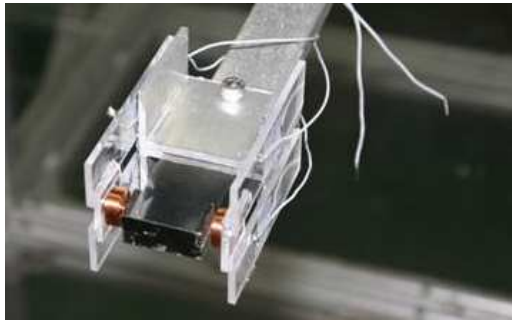


Aerodynamic Instability (2 DOF)

Simulation with aerodynamic section properties (static coefficients and aerodynamic derivatives) coupled to 3D structural model:



Exploiting Unstable Behaviour: Energy Harvesting



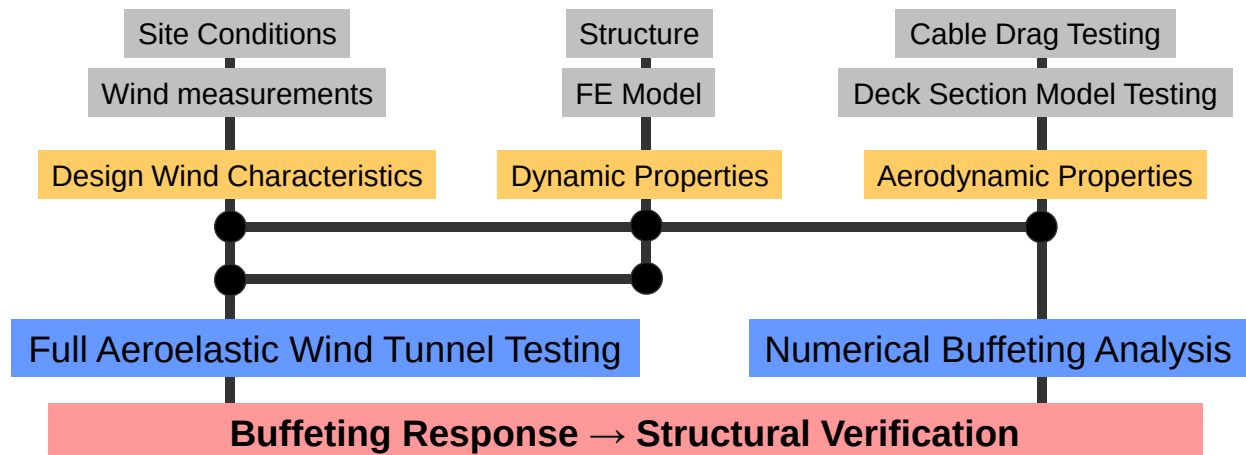
Energy harvester (with Prof. Law, Stanford)



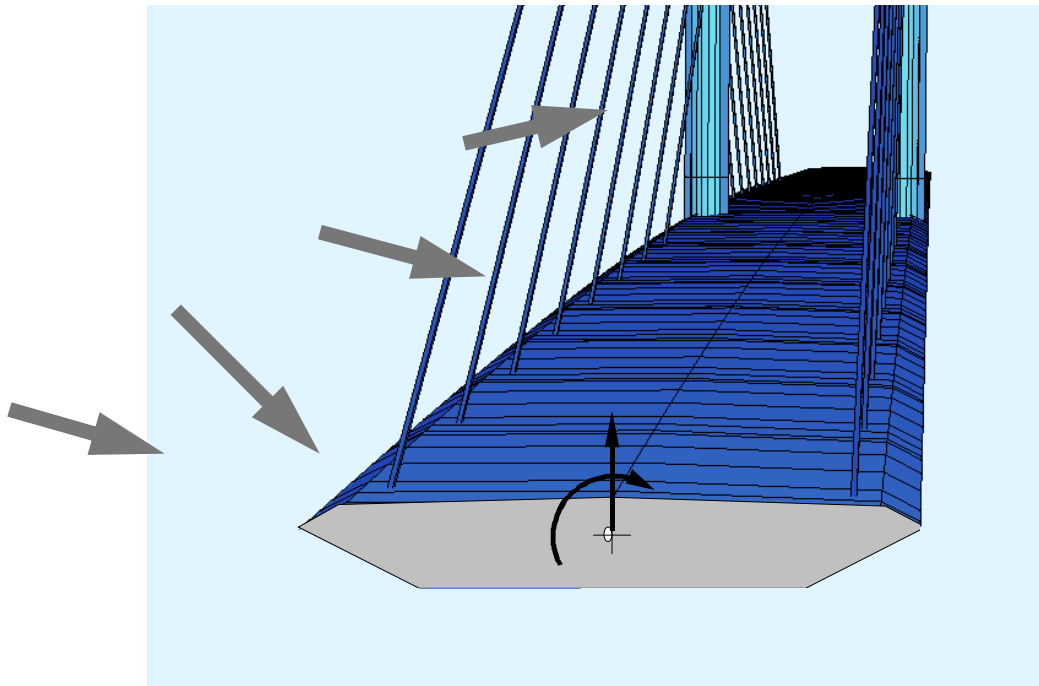
Buffeting

Buffeting

- Turbulent atmospheric boundary layer
- Wind velocity field variable in time and space
- Fluctuating aerodynamic forces on the structure
- Dynamic response of the structure

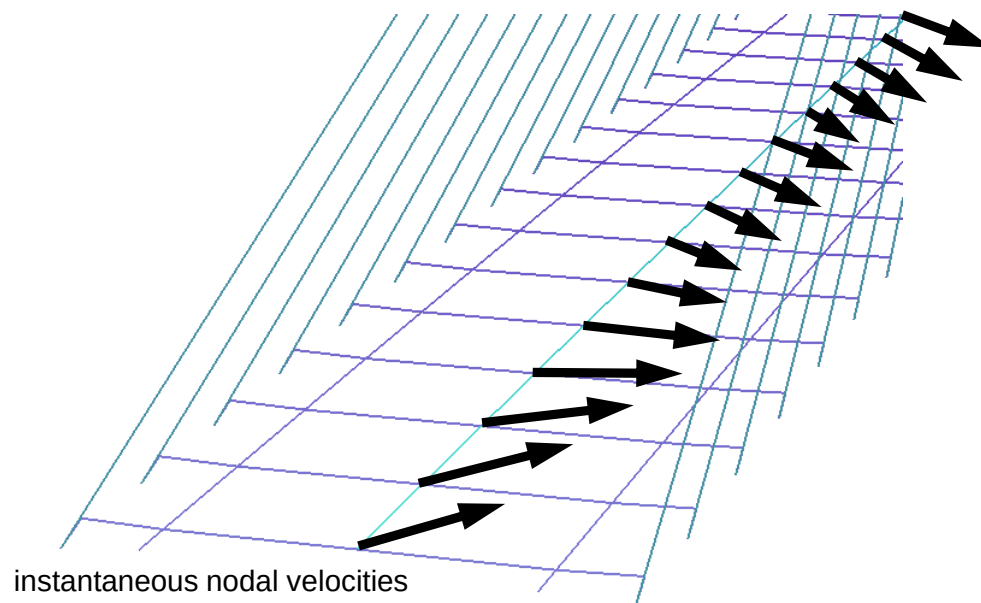


Simulations on full 3D system model



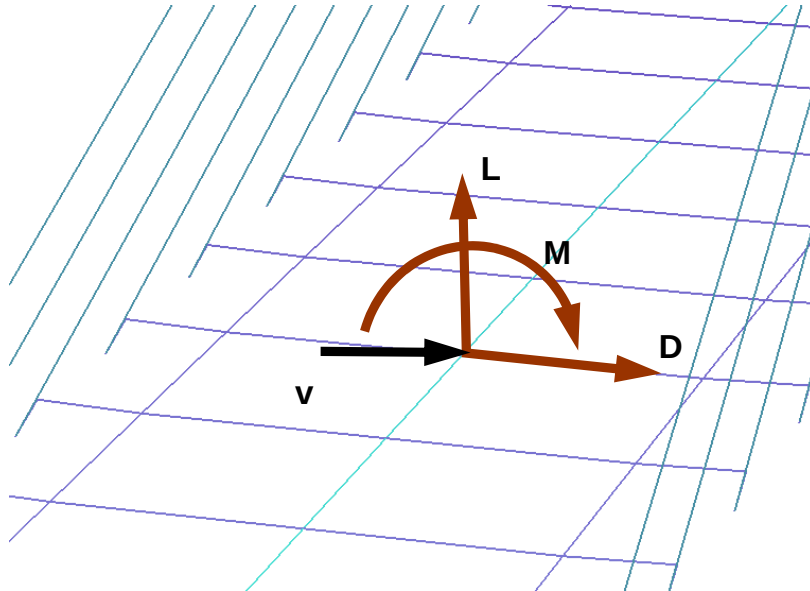
Simulations on full 3D system model

Local velocities due to **simulated wind field**



Simulations on full 3D system model

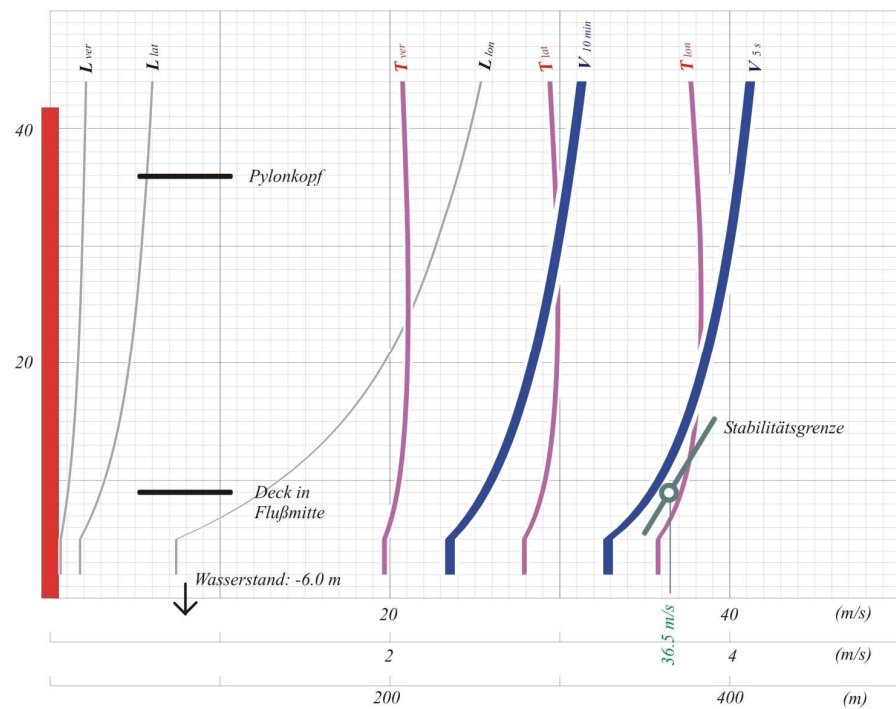
Nodal aerodynamic forces due to local velocities (quasi-static + motion-induced)



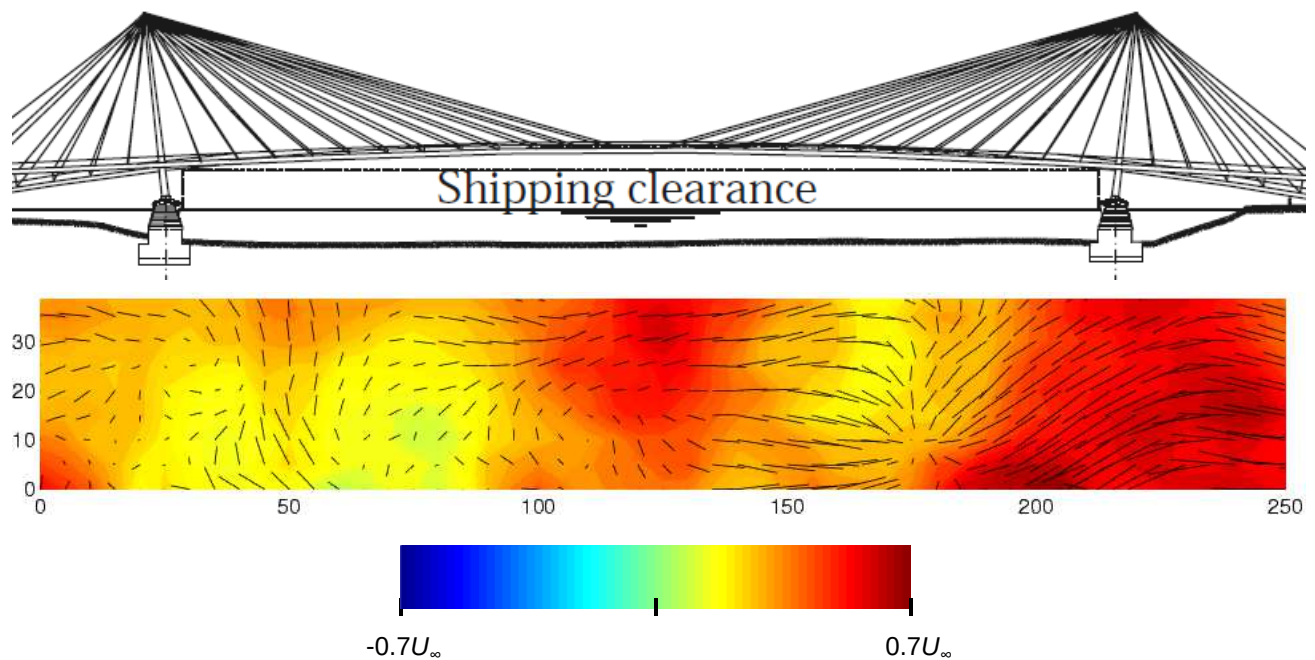
Footbridge Kehl-Strasbourg: Structure



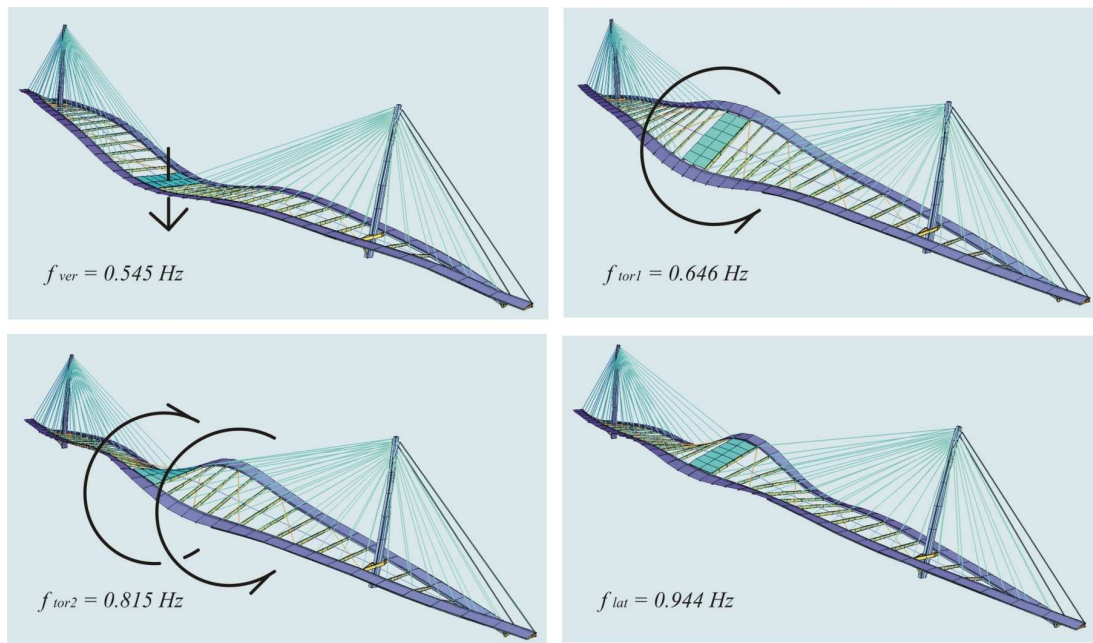
Footbridge Kehl-Strasbourg: Wind profile



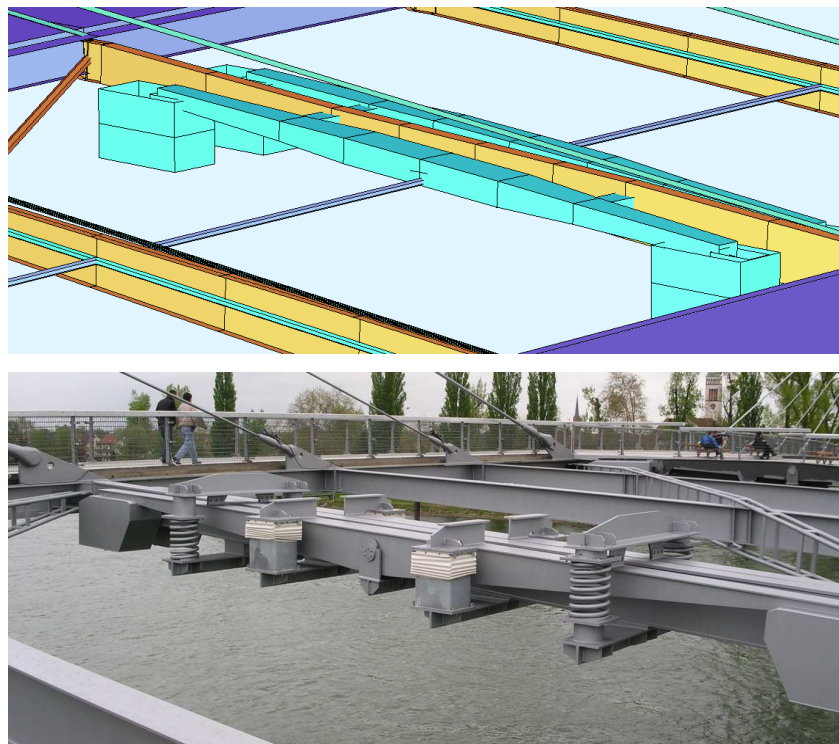
Example: Footbridge Kehl-Strasbourg: Wind velocity field (turbulent component)



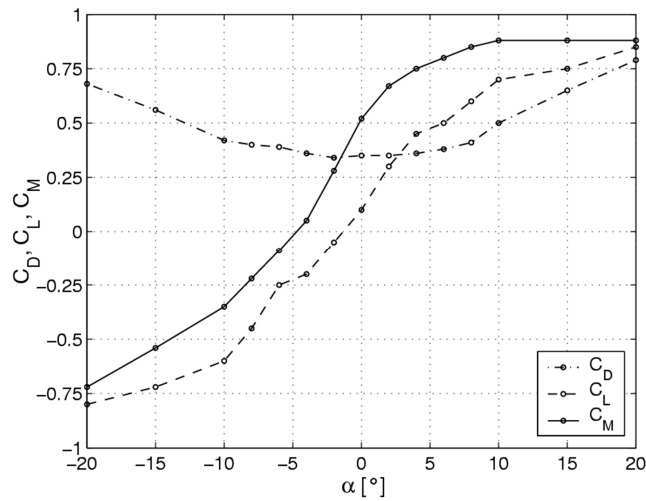
Footbridge Kehl-Strasbourg: Natural frequencies / mode shapes



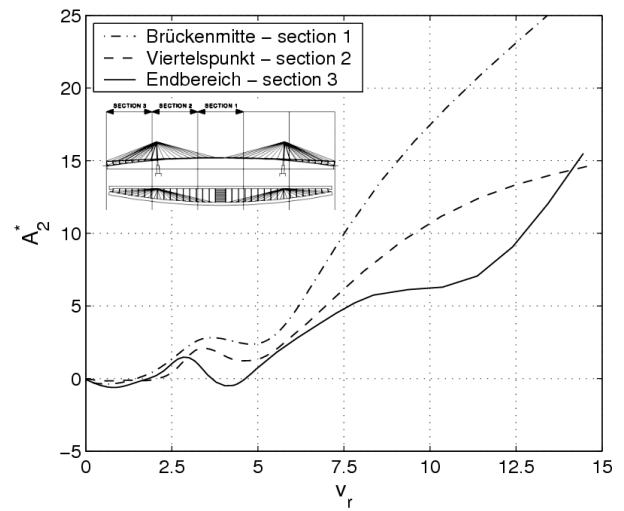
Footbridge Kehl-Strasbourg: TMD



Footbridge Kehl-Strasbourg: Aerodynamic properties



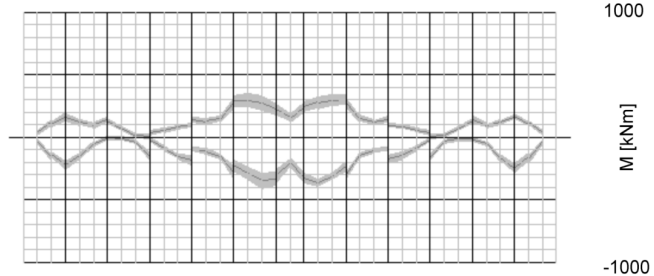
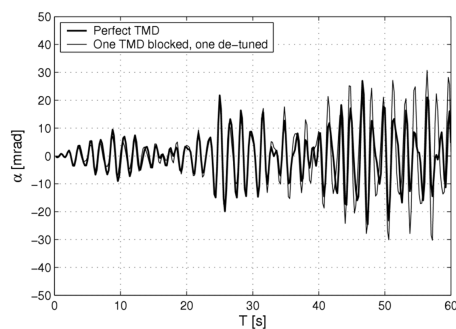
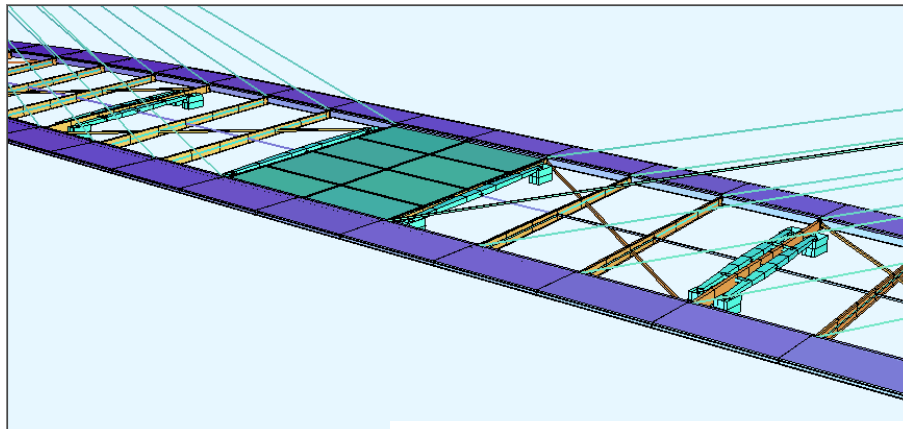
static forces



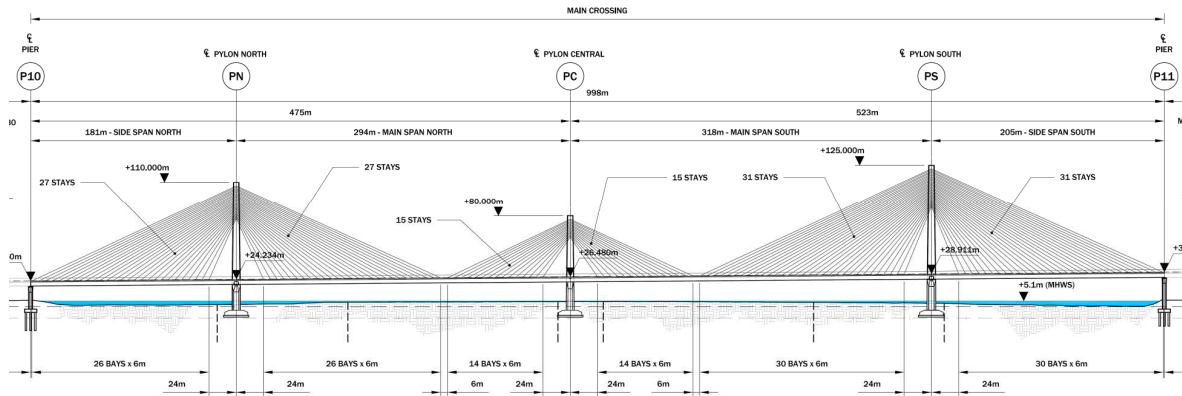
Aerod. Derivative $A_2^* \sim M(\dot{\alpha})$



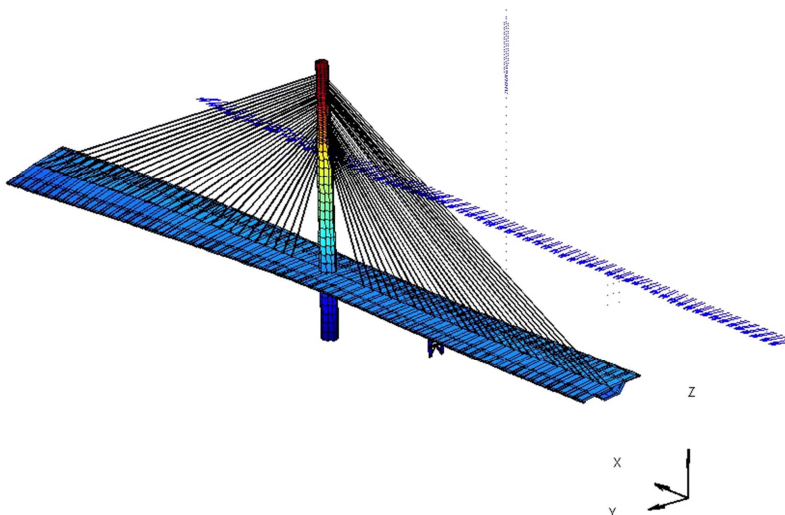
Footbridge Kehl-Strasbourg: Buffeting simulation



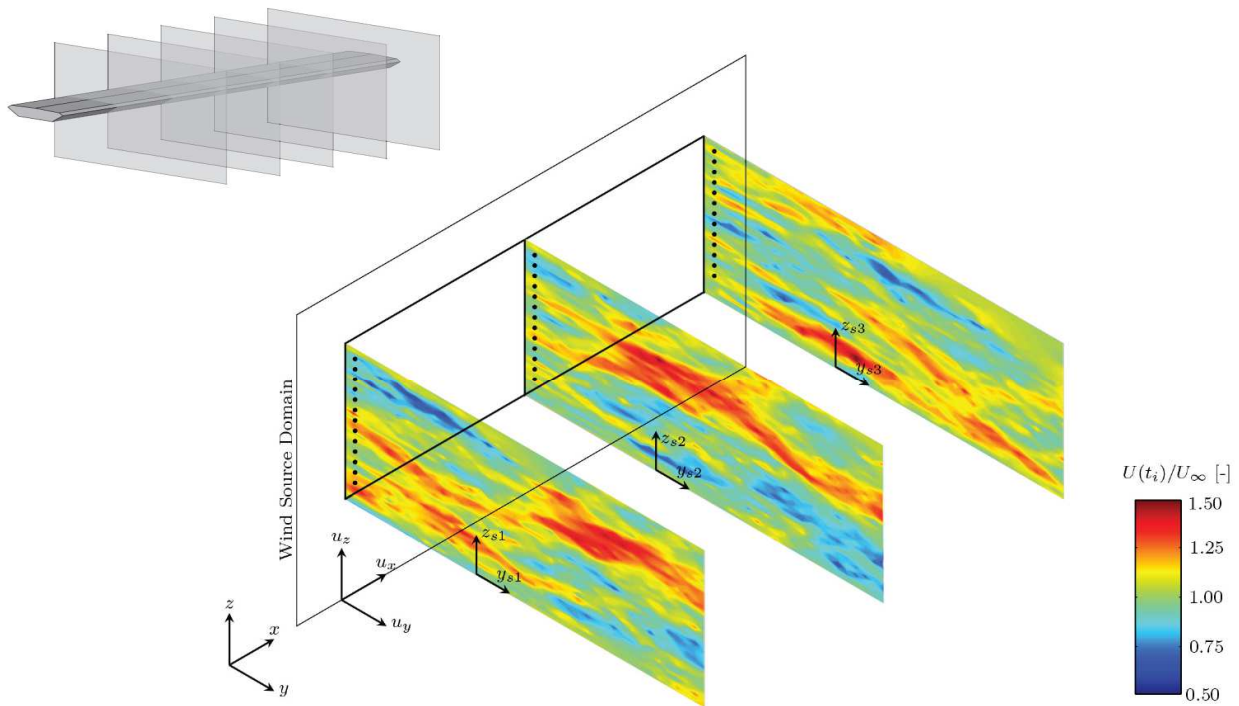
Mersey Gateway Crossing



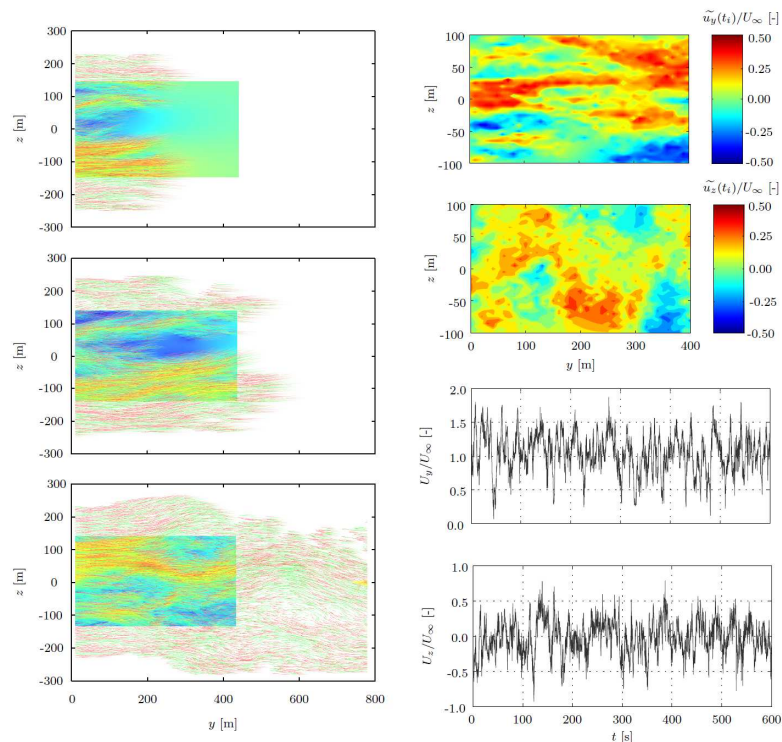
Mersey Gateway Crossing



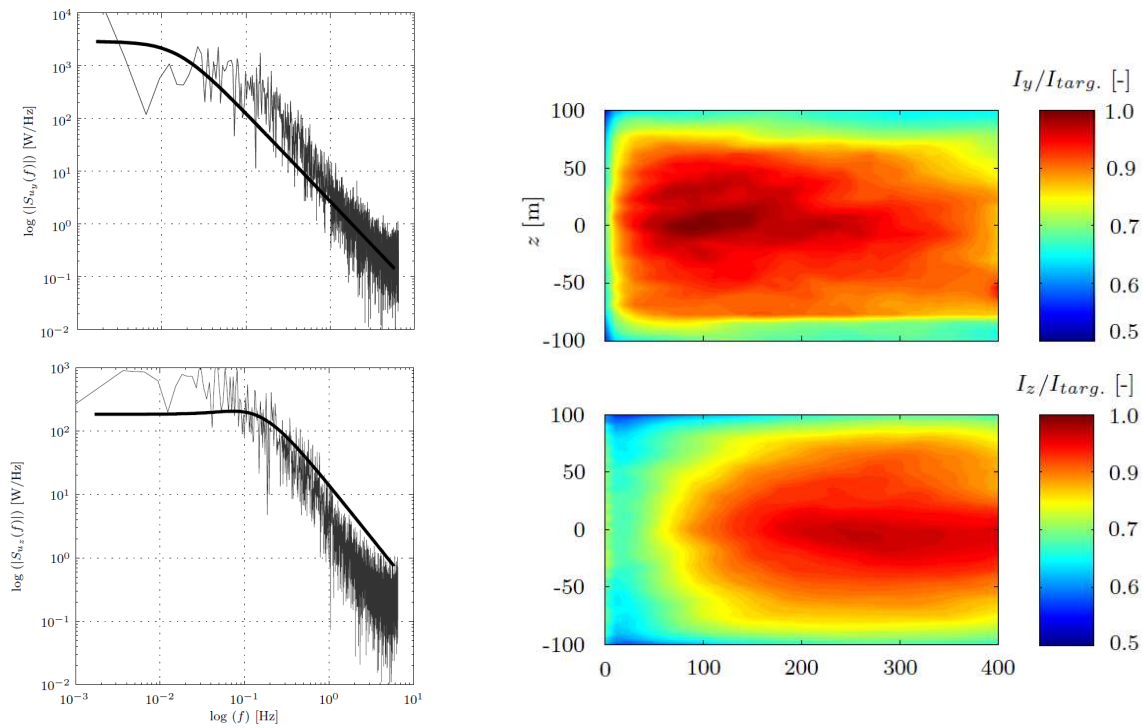
Pseudo-3D CFD Buffeting Simulations



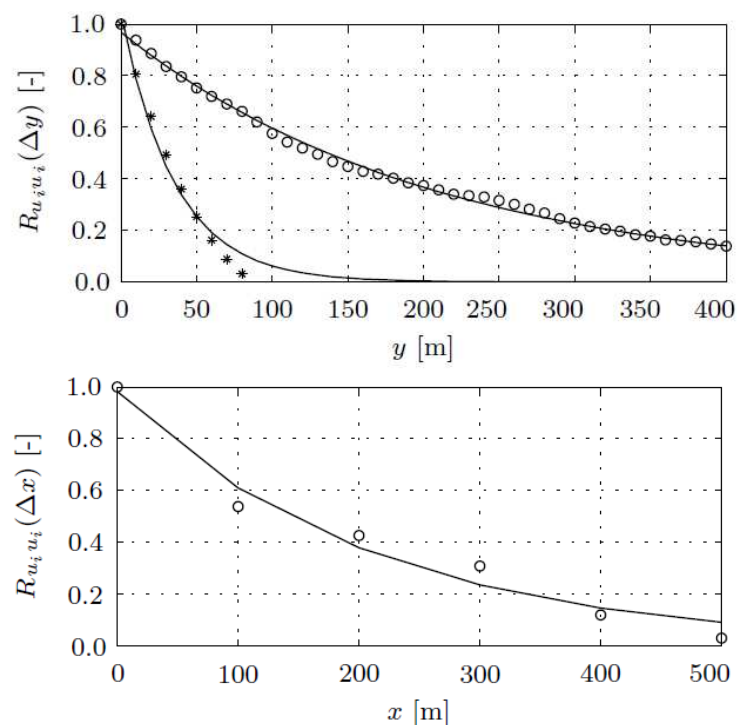
Pseudo-3D CFD Buffeting Simulations



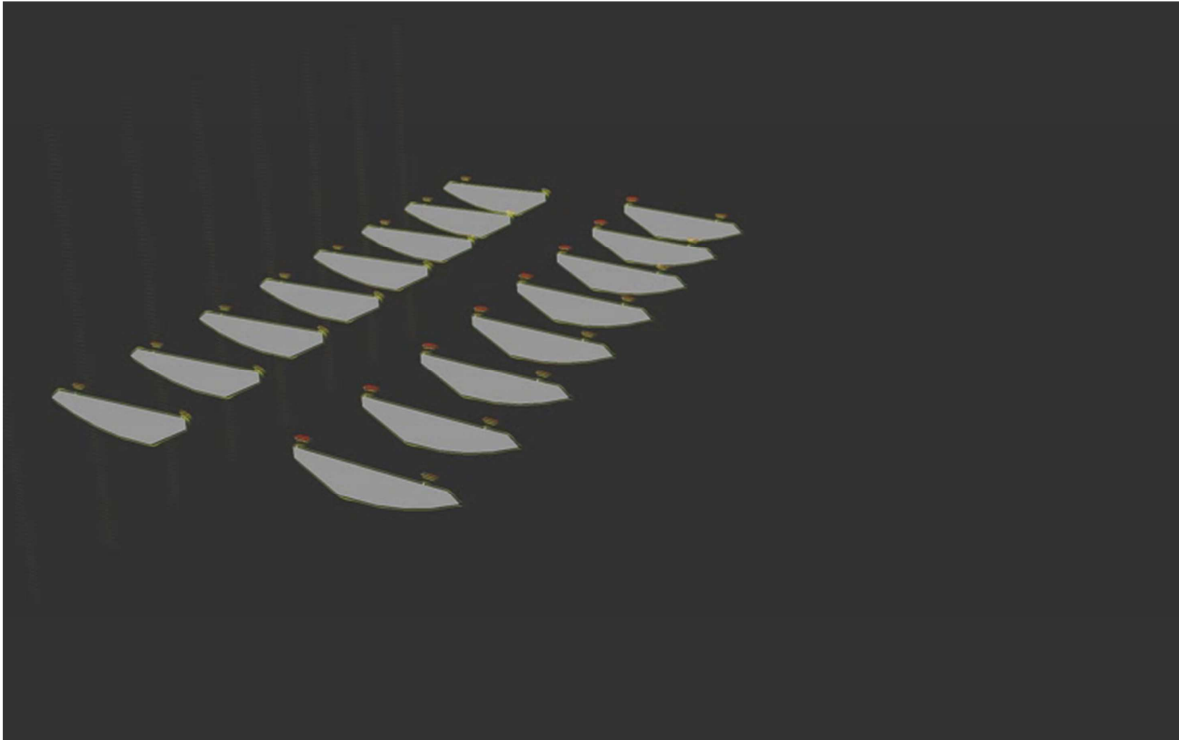
Pseudo-3D CFD Buffeting Simulations



Pseudo-3D CFD Buffeting Simulations

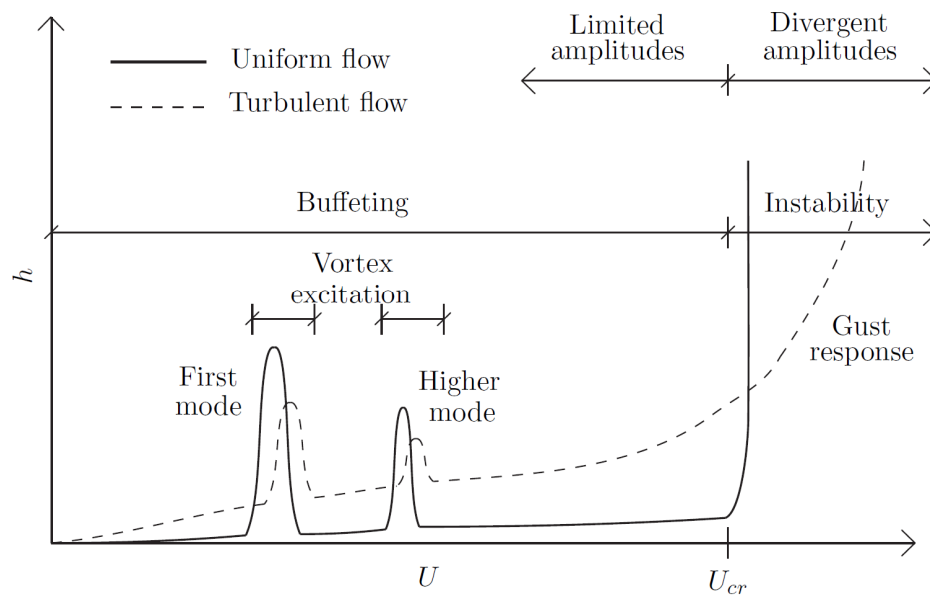


Pseudo-3D CFD Buffeting Simulations



Summary

Summary: Phenomena in Bridge Aerodynamics (Aeroelasticity)



Case Studies: Sutong Bridge and Stonecutters Bridge

Prof. Dr. Guido Morgenthal

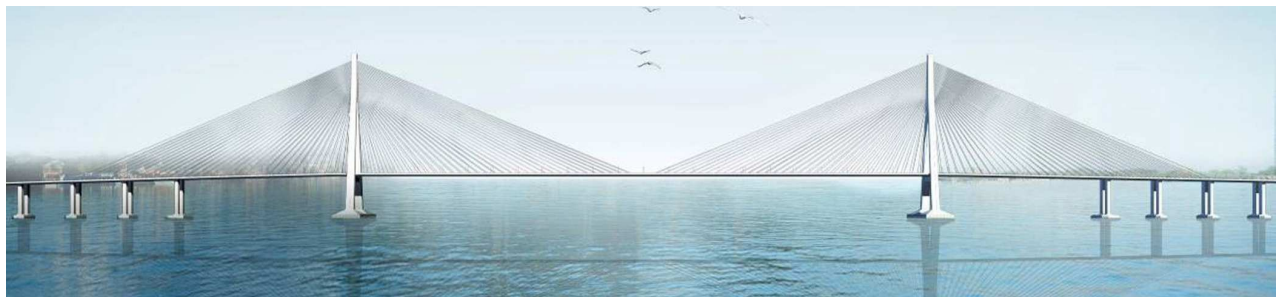
Bauhaus University Weimar
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Stonecutters/Sutong: Overview



Stonecutters Bridge

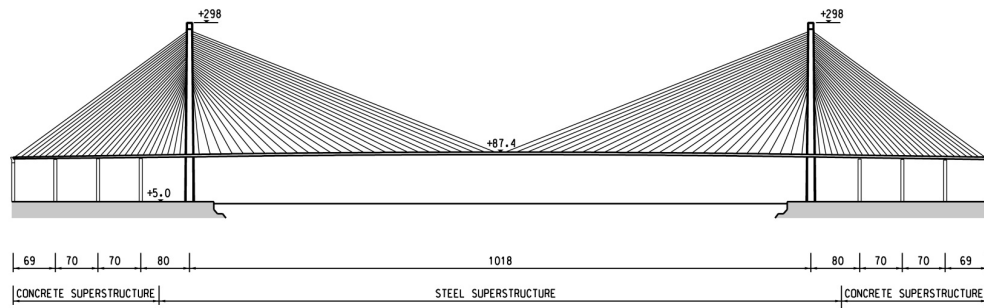


Sutong Bridge

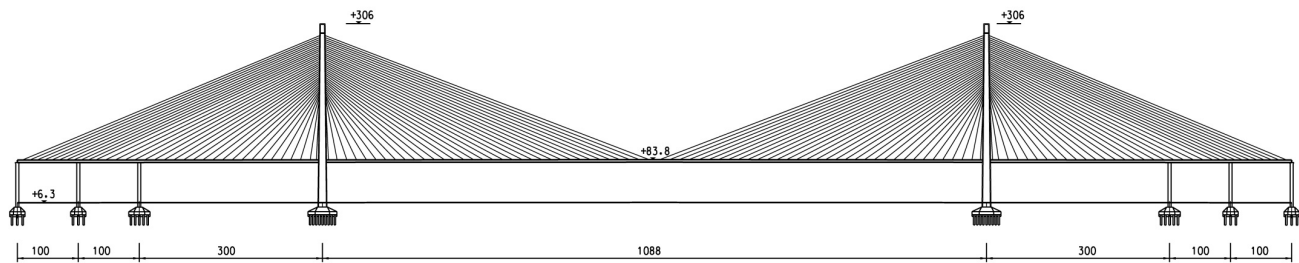
Prof. Dr. Guido Morgenthal

Bauhaus University Weimar
Modelling and Simulation of Structures





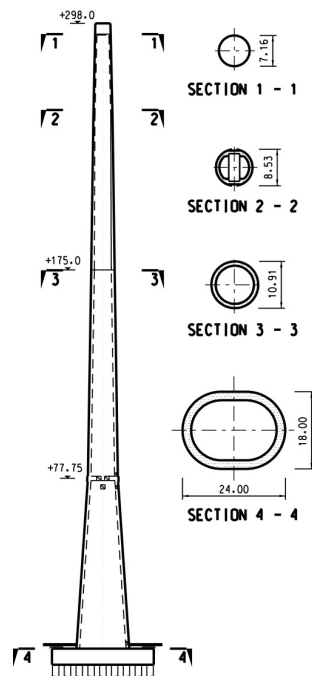
Stonecutters Bridge



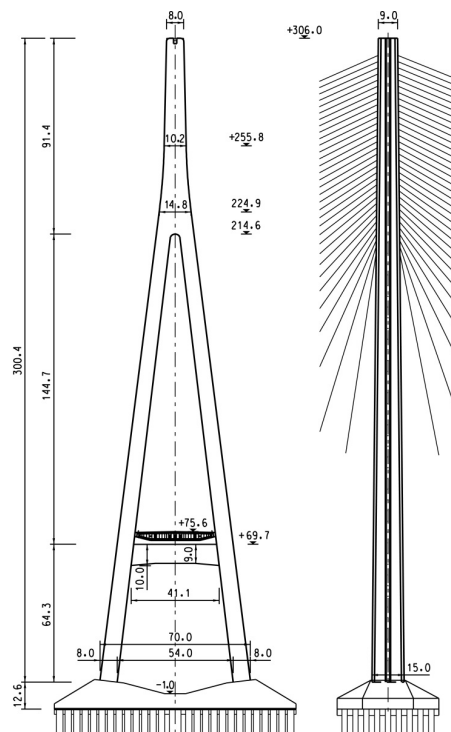
Sutong Bridge



Bridge Towers



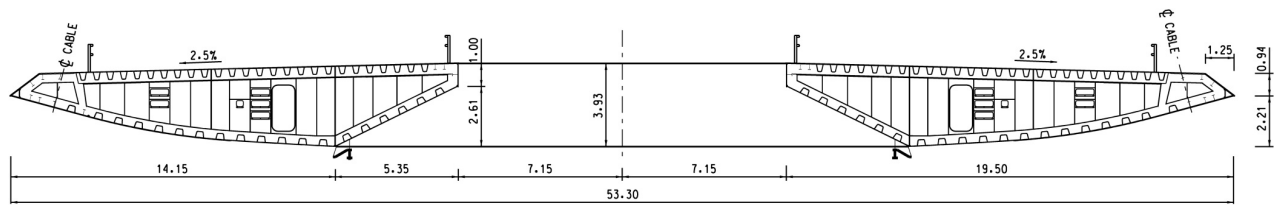
STONECUTTERS BRIDGE



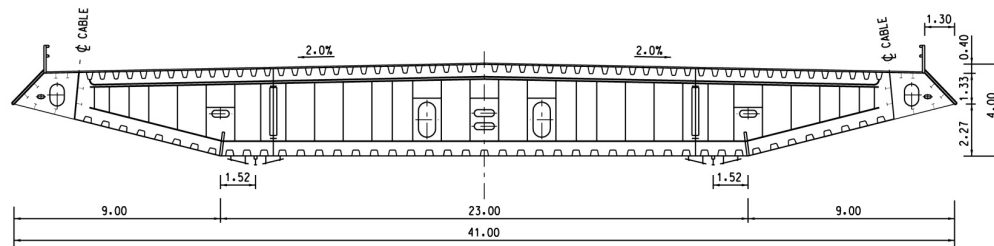
SUTONG BRIDGE



Bridge Decks (Main Span)



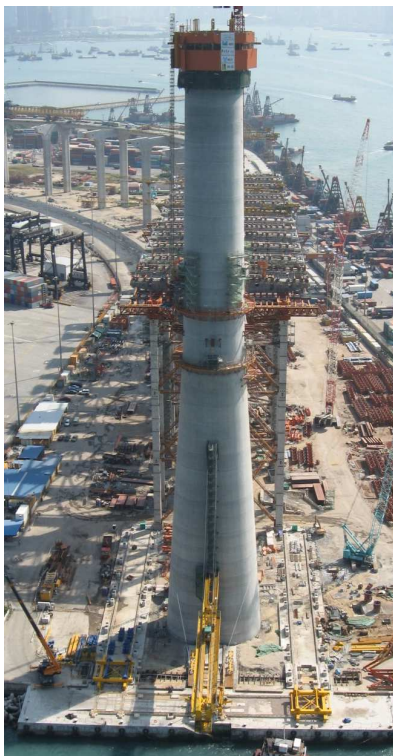
STONECUTTERS BRIDGE



SUTONG BRIDGE



SCB Erection: Tower



View of the Stonecutters Bridge tower under construction. The image shows the barge and surrounding construction site, with the tower being erected on the barge in the water.



SCB Erection: Tower



SCB Erection: Deck Pre-assembly



SCB Erection: Heavy lift



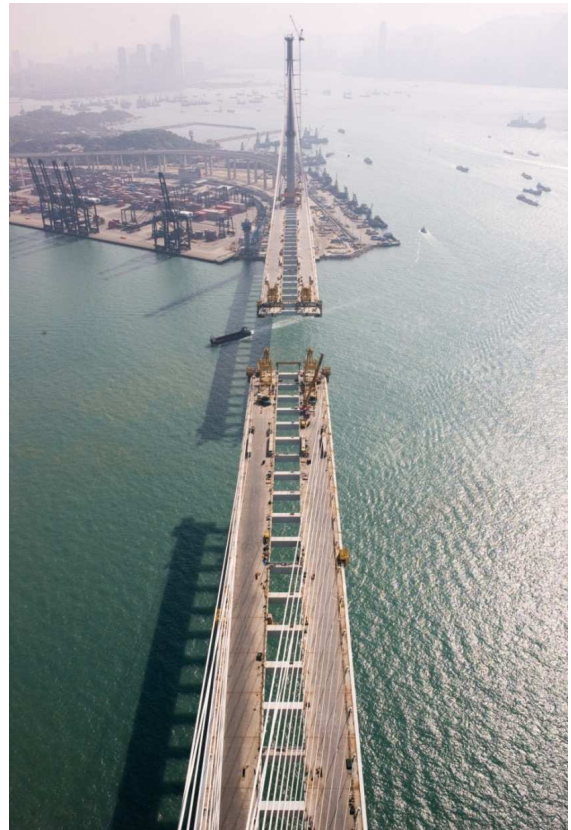
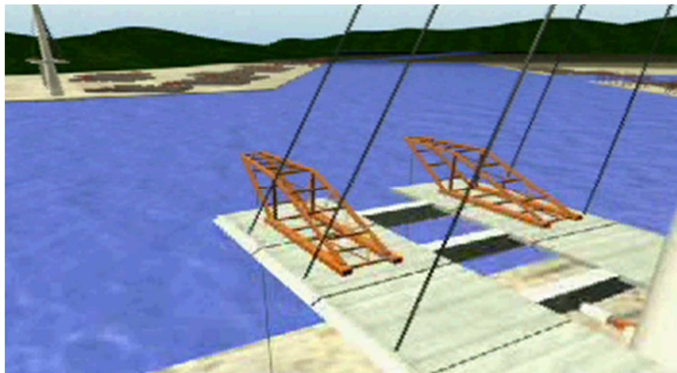
SCB Erection: Heavy lift



SCB Erection: Mainspan cantilevering



SCB Erection: Mainspan cantilevering

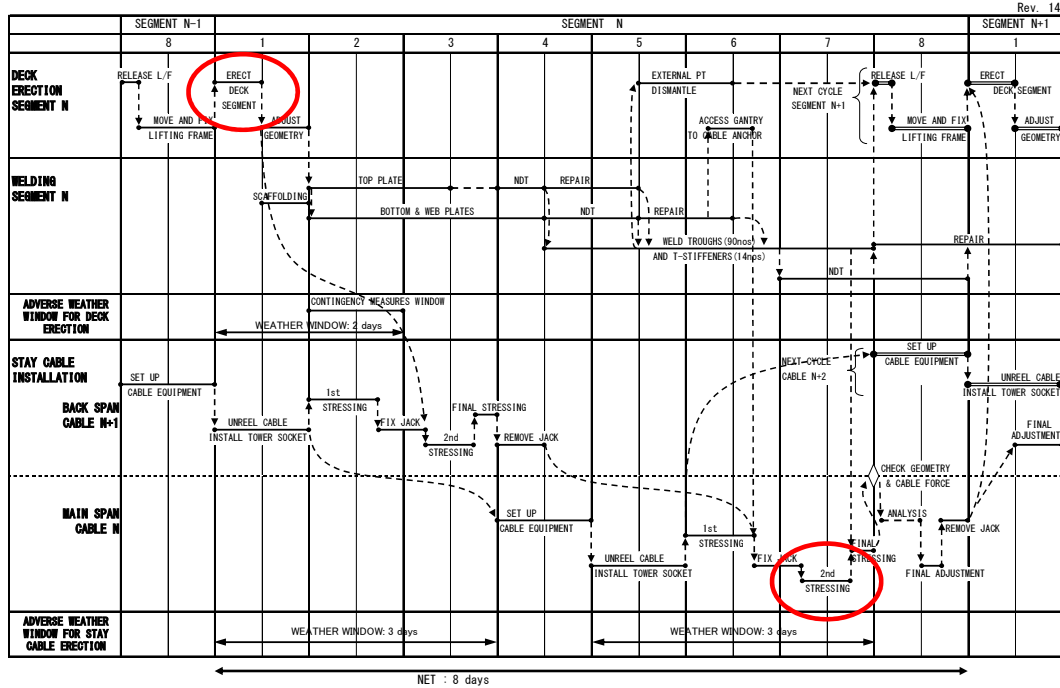


SCB Erection: Mainspan cantilevering - cycle programme

CONTRACT NO. HY/2002/26
STONECUTTERS BRIDGE

22.11.07
MHYH-JV

TYPICAL MAIN SPAN 8 DAY CYCLE PROGRAMME



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STB Erection: Tower and backspan construction



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STB Erection: Mainspan cantilevering (balanced)



STB Erection: Mainspan cantilevering (closure)



Principal Erection Stage Performance Requirements Relating to Wind

SLS:

- Workers (sea-sickness, welding - typ. $a < 3\%g$)
- Surveyability
- Dynamic interaction with erection equipment (ULS?)

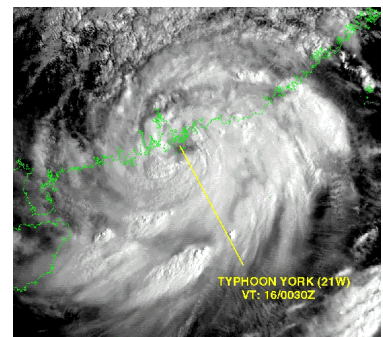
ULS:

- Stability
- Capacity checks (foundations, tower, deck, cables, temporary works)

FLS



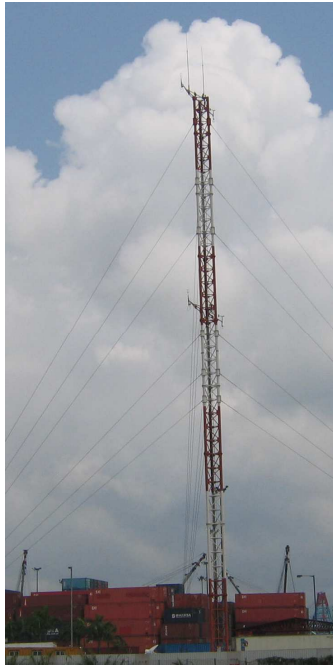
SCB Wind Conditions: Bridge Location



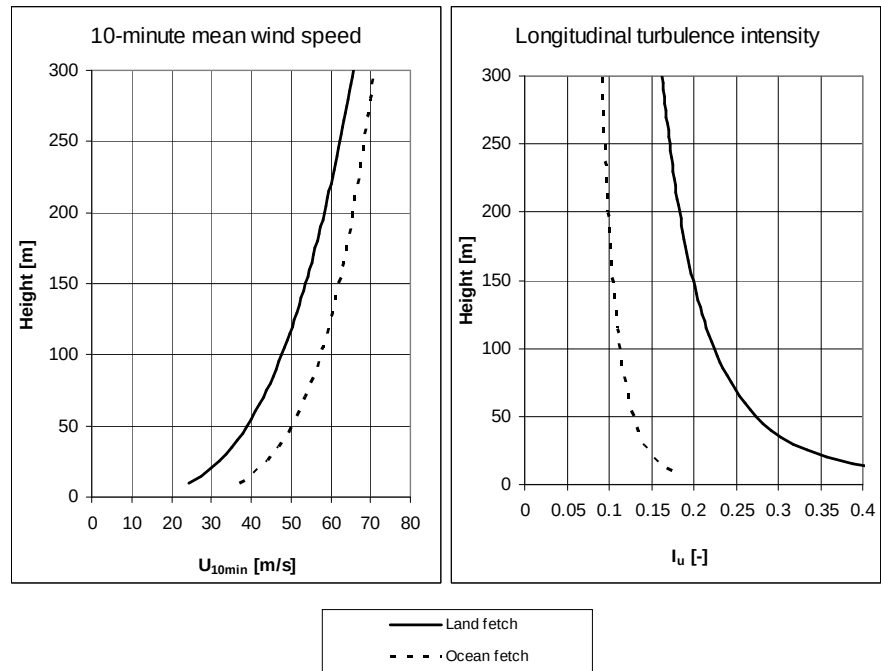
Typhoon York, 1999



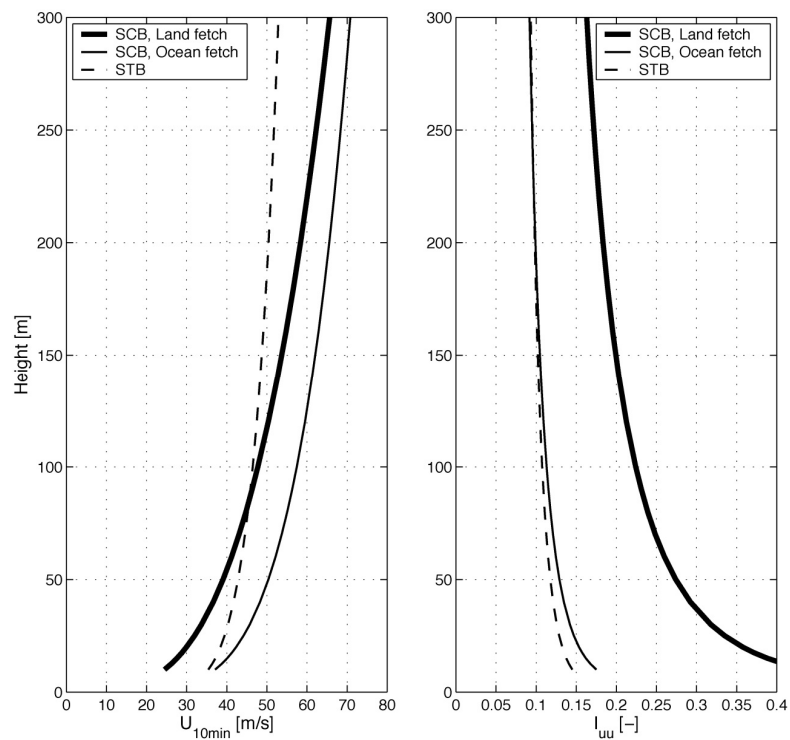
SCB Wind Conditions



WTIFM mast



Wind Conditions: SCB-STB Comparison

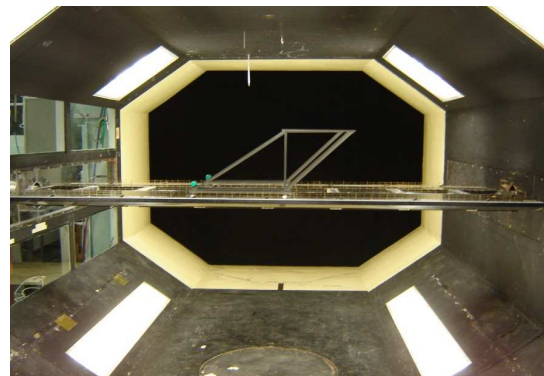
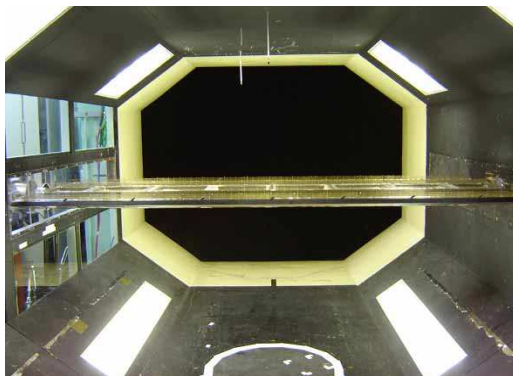
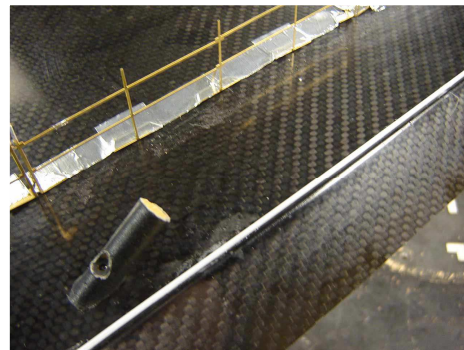


Wind Tunnel Tests: Overview

Type of test	Stonecutters Bridge	Sutong Bridge
Section model	Scale 1:50	Scale 1:50
Static	With different variations (rand rail configuration, lifting gantry and other erection equipment, guide vanes), Re=5E5 and Re=18E5	With and without lifting gantry, Turbulence I_w : 0 and 0.055 Angles -10° to $+10^\circ$
Forced oscillation	<i>No testing undertaken</i>	Smooth flow Angles -3° , 0 , $+3^\circ$
Aeroelastic	Smooth flow, turbulent flow Damping: 0.15% of crit. Angles -5° to $+5^\circ$	<i>No testing undertaken</i>
Tower aeroelastic	Scale 1:200 2 construction stages With/without erection equipment Various orientations Damping: 0.16% and 0.5% of crit.	Scale 1:100 2 construction stages With/without erection equipment various orientations Damping: 0.5, 0.8 and 1.6% of crit.
Full-bridge aeroelastic	Scale 1:200, 2 stages Various orientations With/without opposite cantilever Turbulence/ speed as per Ocean and Land Fetch conditions (cf. Section 2) Damping: 0.4, 1.3, 1.6, 3.2 and 4.0% of crit.	Scale 1:125, 2 stages Various orientations Turbulence I_w : 0, 0.055 and 0.11 Damping: 0.5, 0.8 and 1.3% of crit.
Cable drag testing	Scale 1:1 Different surface patters (smooth and with dimples of different depths)	<i>Testing undertaken at design stage but not at construction stage of the project</i>
Cable rain/wind testing	Scale 1:1 Different cable diameters Different cable angles Rain intensity 80mm/h Damping: 0.6% log dec	<i>Testing undertaken at design stage but not at construction stage of the project</i>



SCB Section Model Tests (Scale 1:50): models



STB Section Model Tests (Scale 1:50): Models

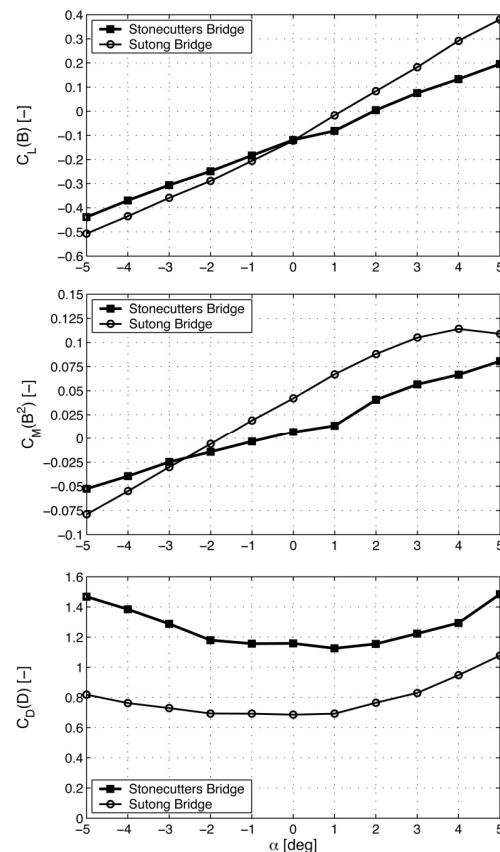


Stonecutters/Sutong: Aerodynamic Assessment

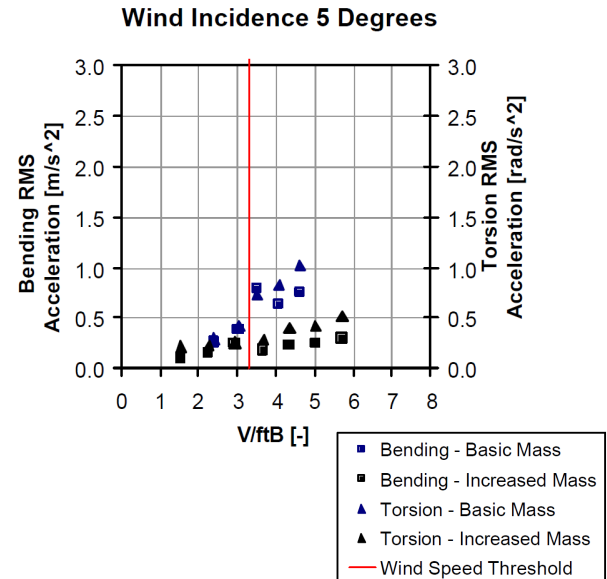
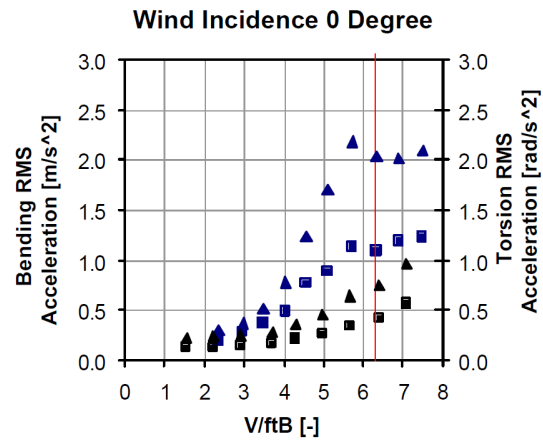
Section Properties

	$dC_L/d\alpha$	$dC_M/d\alpha$
Stonecutters Bridge	3.0	0.5
Sutong Bridge	5.4	1.4

	Increase in drag compared to smooth flow [%]
Stonecutters Bridge, $I_v=0.12$	15
Stonecutters Bridge, $I_v=0.24$	30
Sutong Bridge, $I_v=0.055$	8



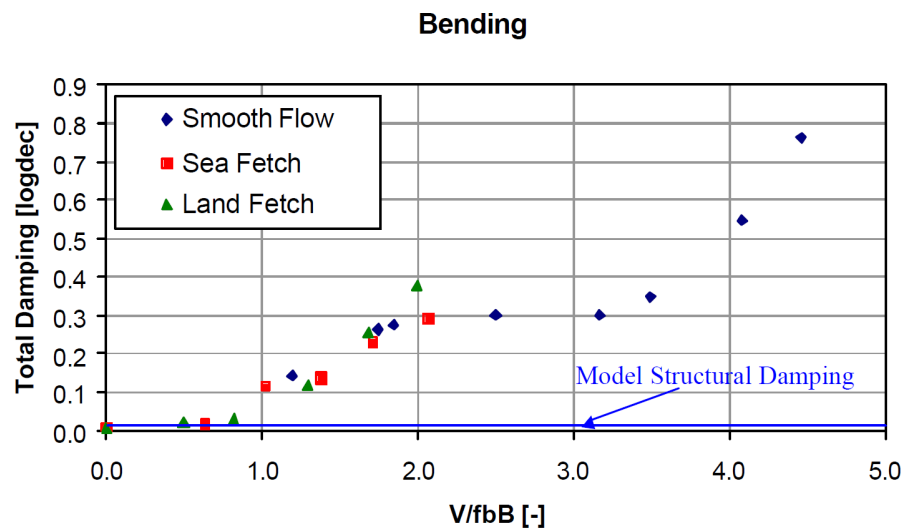
SCB Section Model Tests (Scale 1:50): Divergent amplitude tests

 $\delta=0.9\%$ log dec, $f_T/f_V=1.2$


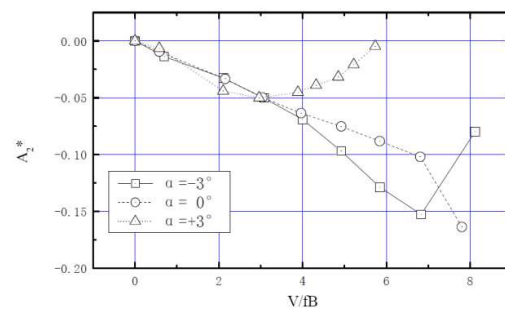
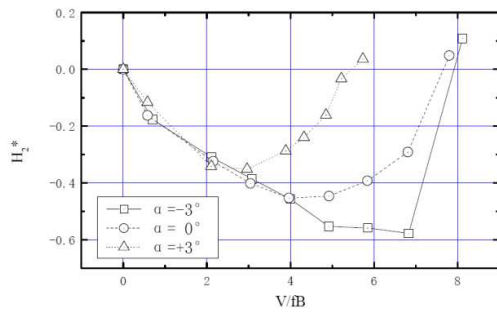
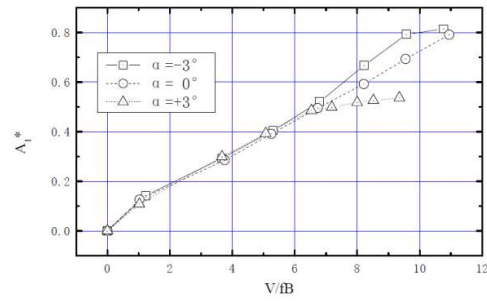
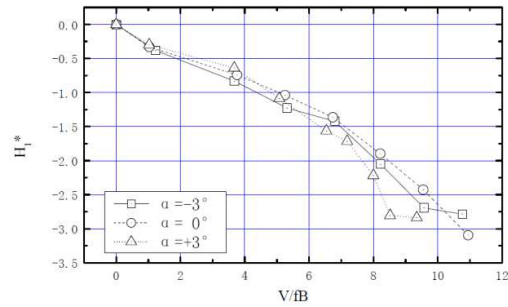
Wind Incidence [deg]	Wind Speed Threshold Full Scale [m/s]	FR = 1.2	FR = 1.6	FR = 2.06
		Reduced Wind Speed [-]	Reduced Wind Speed [-]	Reduced Wind Speed [-]
0	95	6.27	4.70	3.65
2.5, -2.5	75	4.95	3.71	2.88
5, -5	50	3.30	2.47	1.92



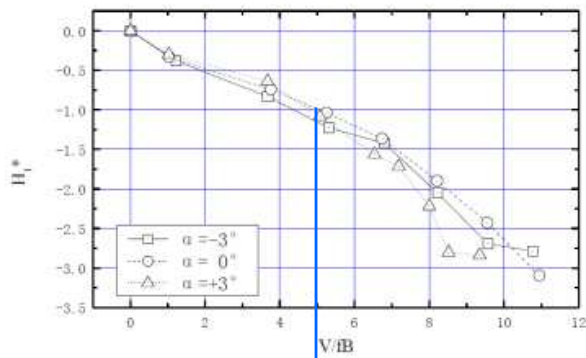
SCB Section Model Tests (Scale 1:50): Aerodynamic damping



STB Section Model Tests (Scale 1:50): Derivatives



STB Section Model Tests (Scale 1:50): Derivatives (aerodynamic damping)



$\delta \approx 1.0 \log \text{dec}$

$$F_L = \frac{1}{2} \rho U_\infty^2 B \left[KH_1^*(K) \frac{\dot{h}}{U_\infty} + KH_2^*(K) \frac{B \dot{\alpha}}{U_\infty} + K^2 H_3^*(K) \alpha + K^2 H_4^*(K) \frac{h}{B} \right]$$



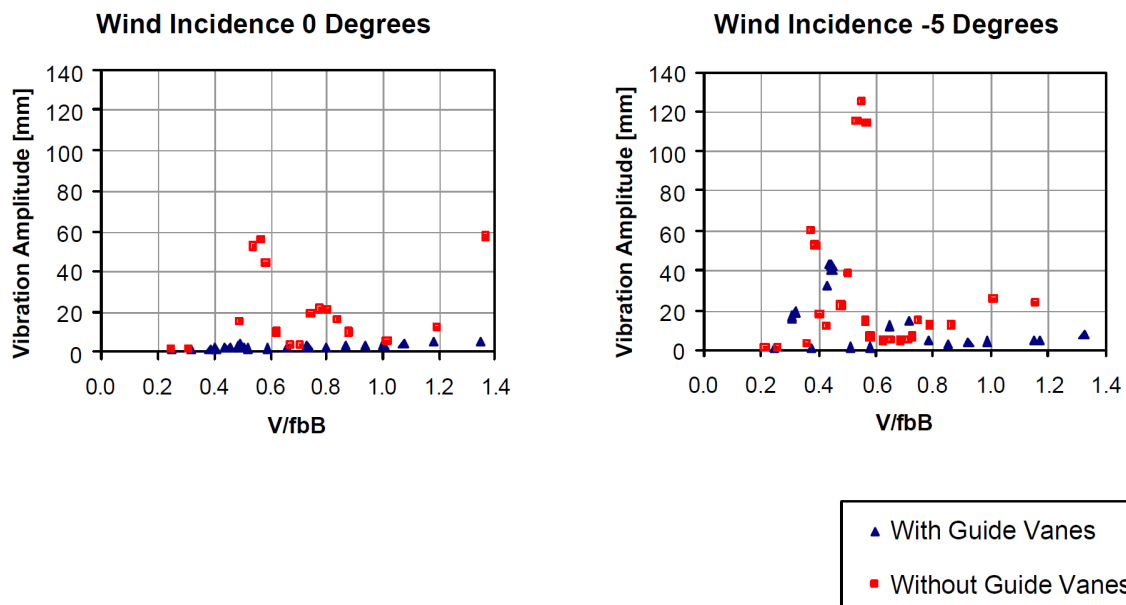
SCB & STB Section Model Tests: Aerodynamic stability summary

Design Flutter Boundaries Confirmed:

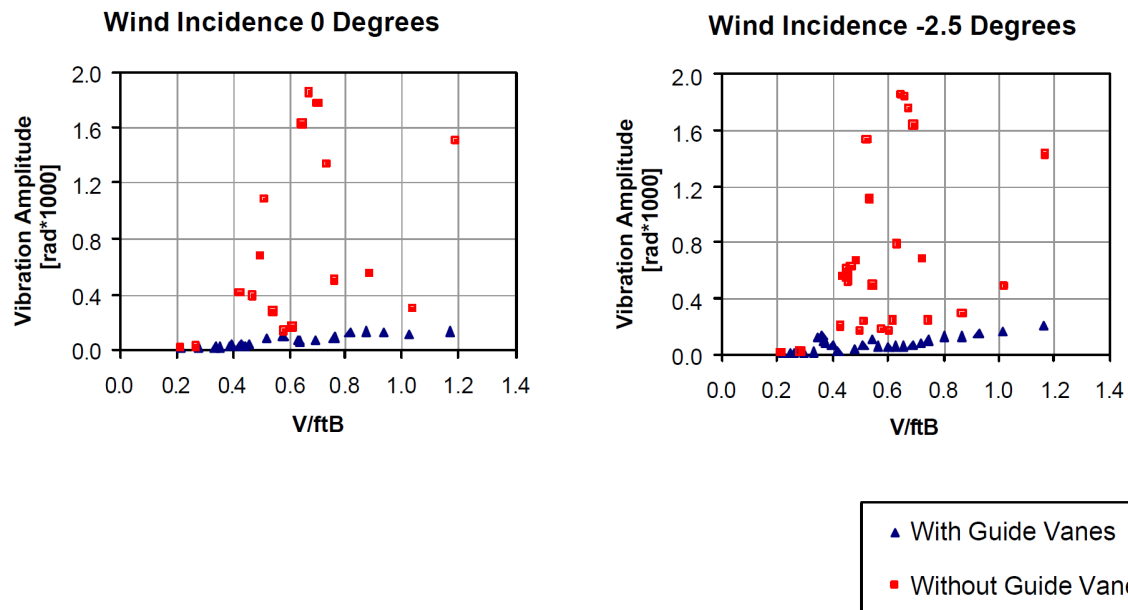
	Tested f_v/f_v	Tested damping [% of crit.]	Wind angle of attack [°]	Confirmed full-scale min. crit. wind speed [m/s]
Stonecutters Bridge	1.20, 1.60, 2.06	0.15	0 +/- 2.5 +/- 5.0	95 75 50
Sutong Bridge	2.21, 2.61	0.3, 0.5, 0.8	-3, 0, 3	64



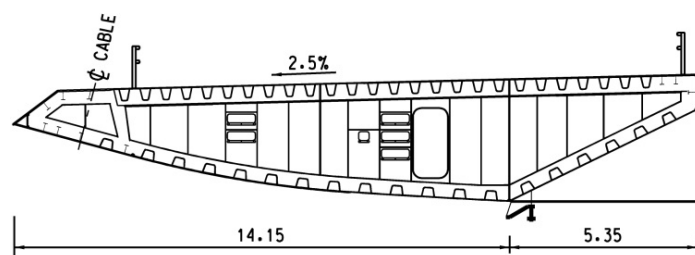
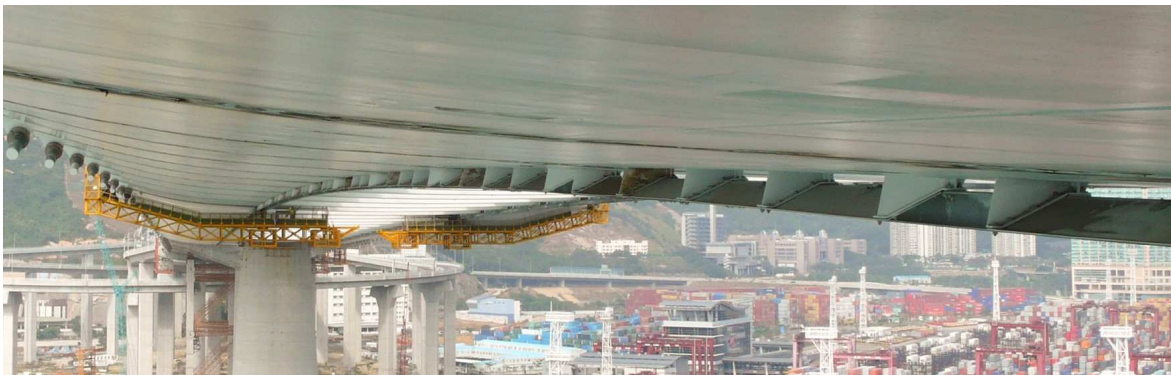
SCB Section Model Tests (Scale 1:50): VIV tests, vertical response



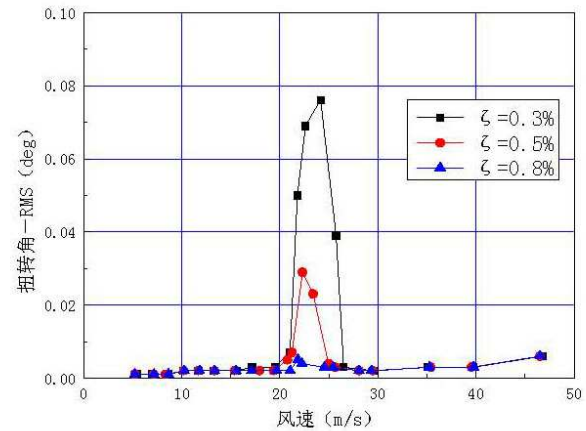
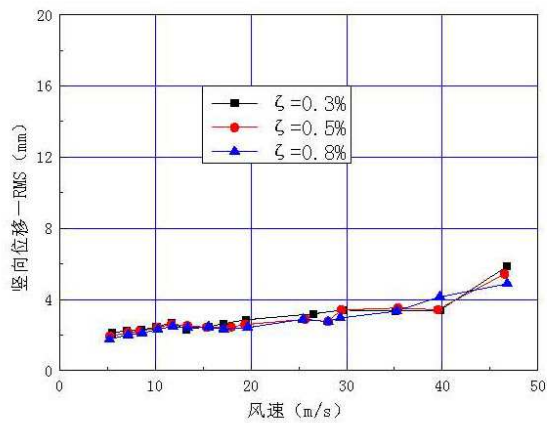
SCB Section Model Tests (Scale 1:50): VIV tests, torsional response



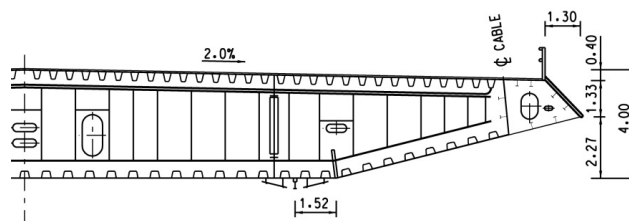
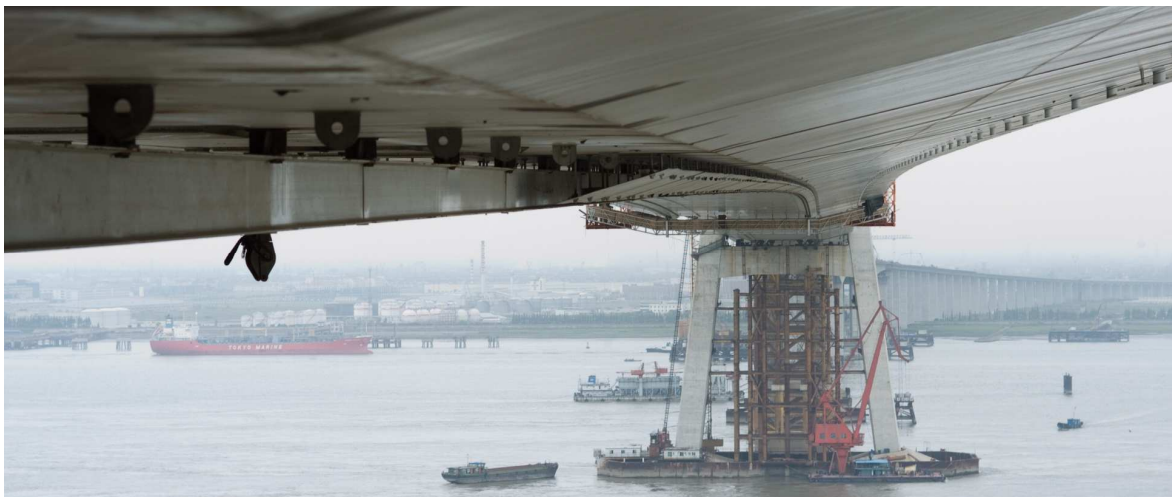
SCB Guide Vanes



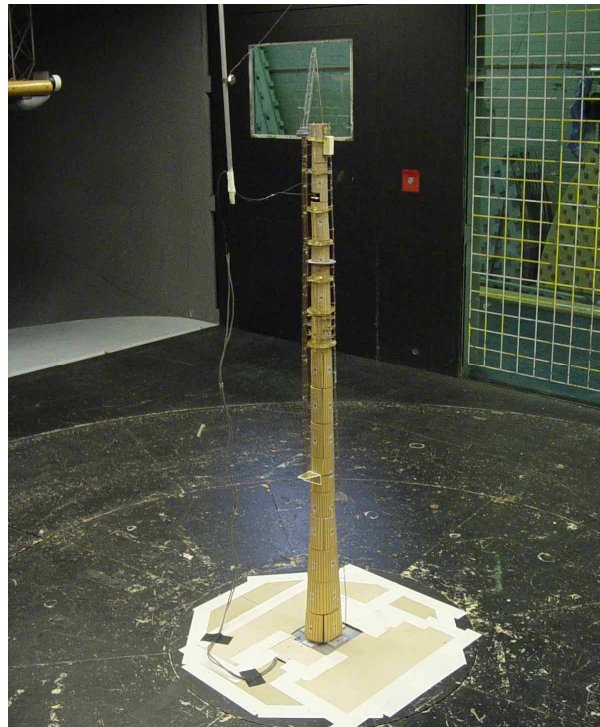
STB Section Model Tests (Scale 1:50): VIV tests, vertical response (with guide vanes)



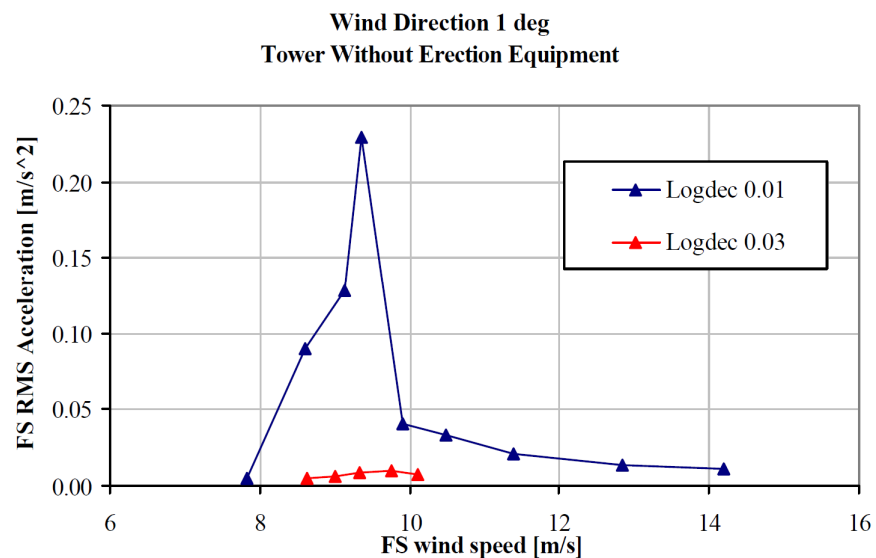
STB Guide Vanes



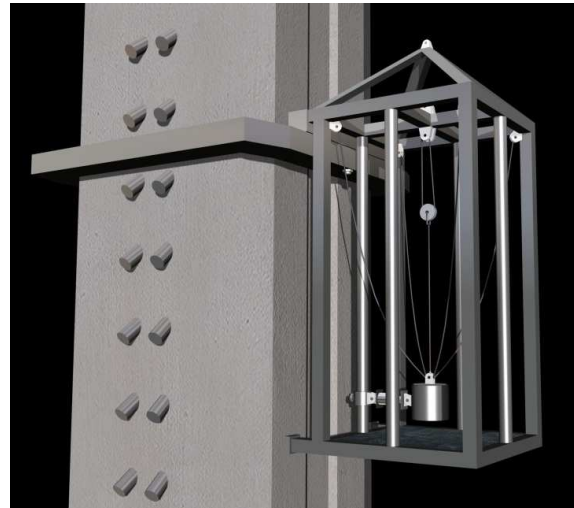
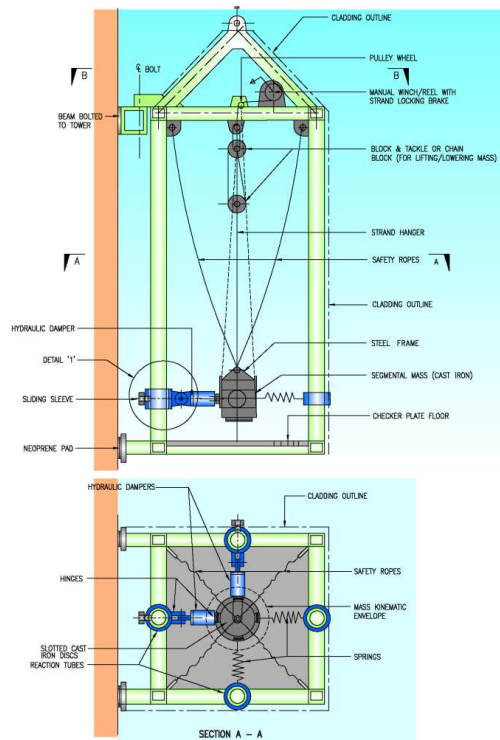
SCB Aeroelastic Tower Tests (Scale 1:200): Full height freestanding condition



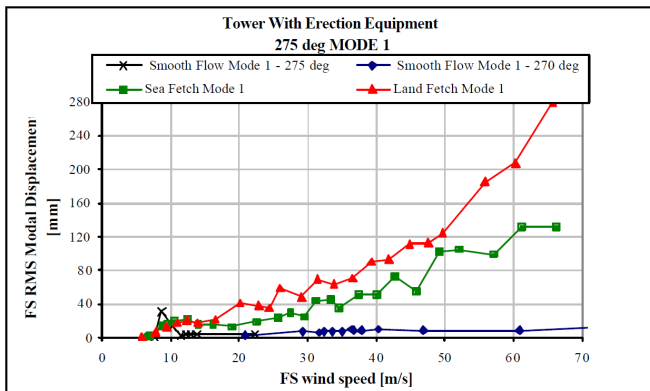
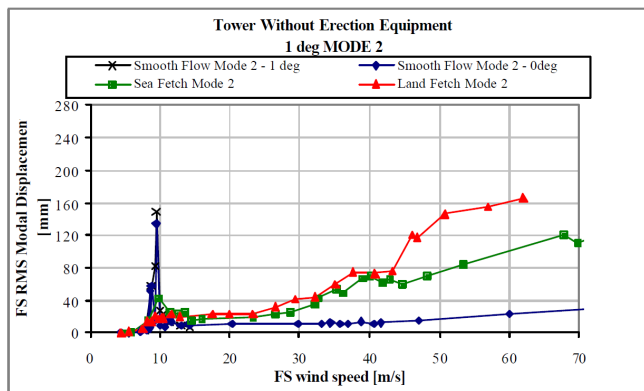
SCB Aeroelastic Tower Tests (Scale 1:200): Full height freestanding condition



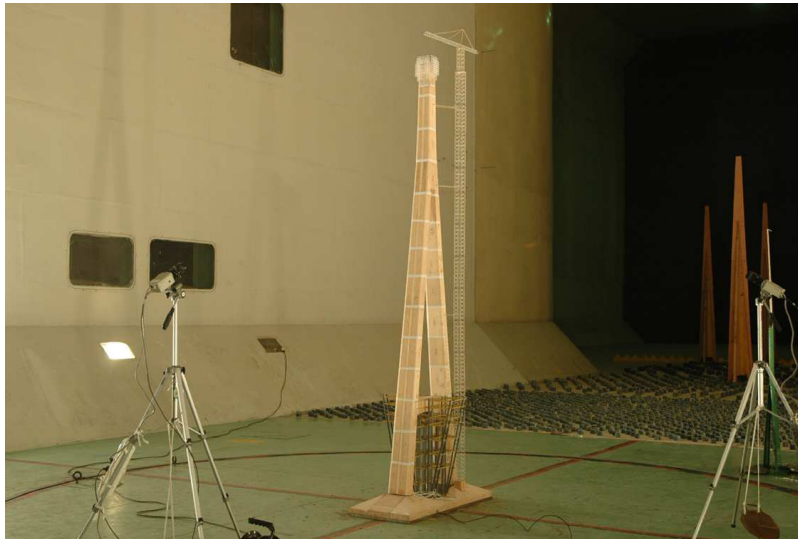
Tower TMD schemes (not implemented)



SCB Aeroelastic Tower Tests (Scale 1:200): Full height freestanding condition



STB Aeroelastic Tower Tests (Scale 1:100): Full height freestanding condition



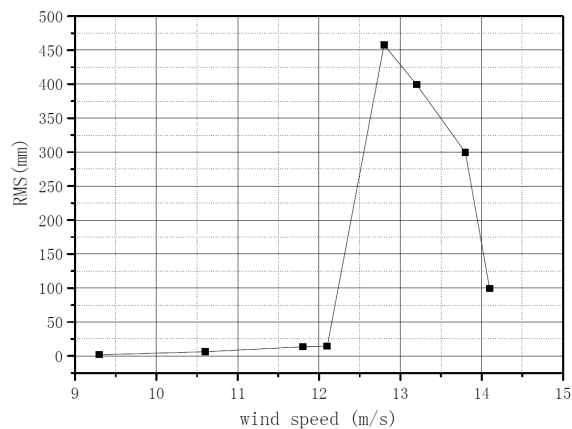
(unit : Hz)

Mode	Full Height Lift 68	212m High Lift 47	154m High Lift 34
Longitudinal (1st)	0.1332	0.2543	0.4586
Transverse (1st)	0.3433	0.2780	0.4887
Torsional (1st)		0.6250	0.7978
Longitudinal (2nd)	0.5671		

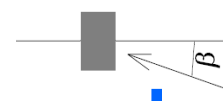
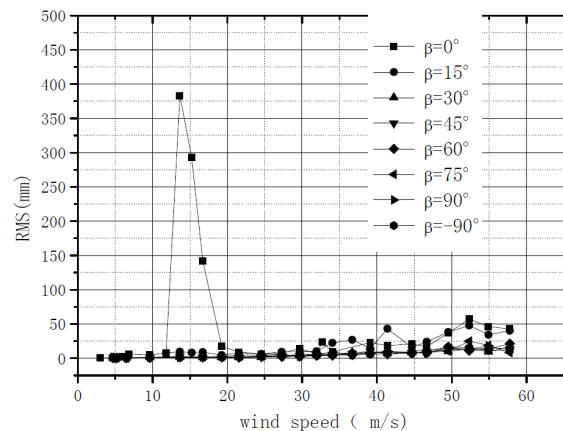


STB Aeroelastic Tower Tests (Scale 1:100): Full height freestanding condition

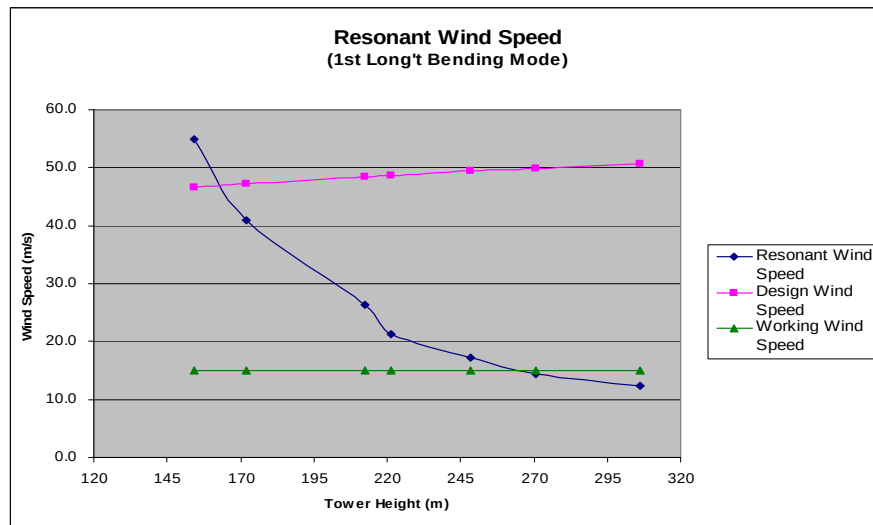
No erection equipment



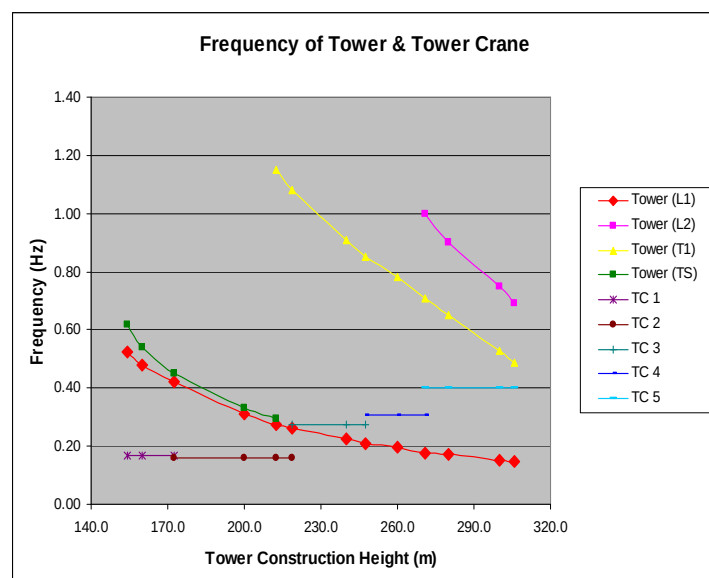
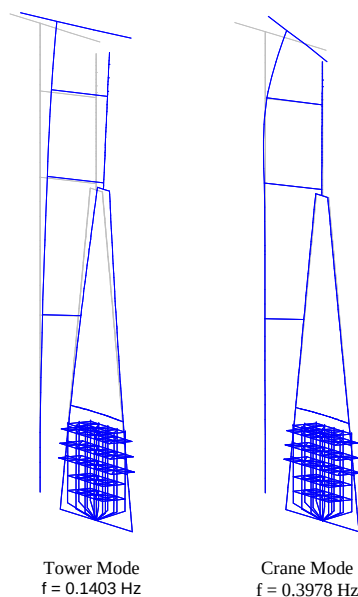
With equipment



STB Aeroelastic Tower Tests (Scale 1:100): Resonant wind speeds



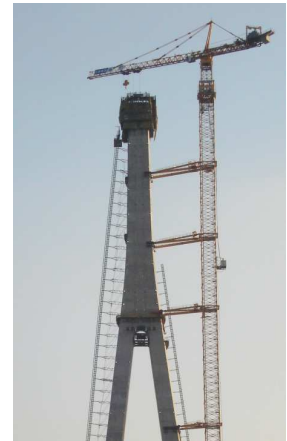
STB Full Height Freestanding Tower Condition - Cranes



Tower Erection – Vortex Induced Vibrations

Stonecutters (0.16% of crit):

Tower Height	Frequency of 1st longitudinal mode [Hz]	Sc Number	Resonant RMS Amplitude [mm]	
			Without Erection Equipment	With Erection Equipment
293m	0.17	12	150	35
246m	0.22	11	30	~0
174m	0.40	10	30	~0
119m	0.72	10	~0	~0

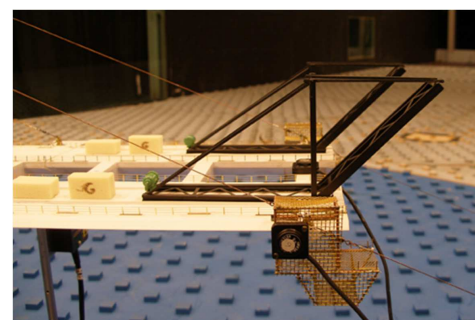
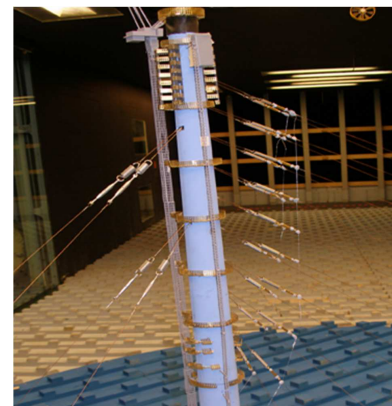
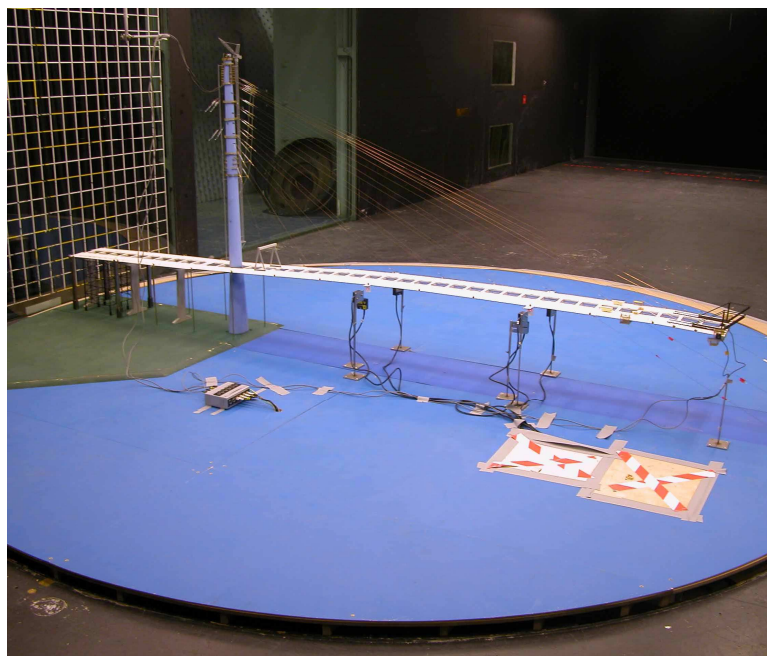


Sutong (0.5% of crit):

Tower Height	Frequency of 1st longitudinal mode [Hz]	Sc Number [-]	Resonant RMS Amplitude [mm]	
			Without Erection Equipment	With Erection Equipment
306	0.13	39	457	394
212	0.25	42	not measured	52



SCB Aerolastic Full Bridge Tests (1:200): Max. cantilever condition



STB Aerolastic Full Bridge Tests (1:125)

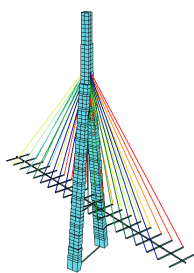
Max. balanced



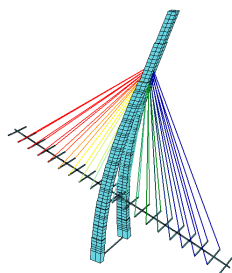
Maximum cantilever



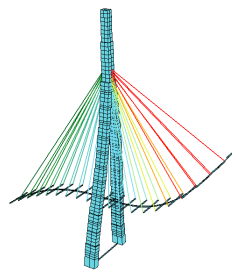
STB Maximum Balanced Cantilever Erection Stage: Dynamic properties



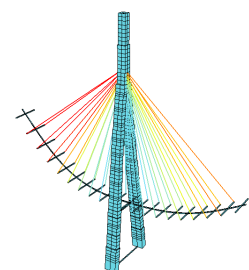
DL, 0.12Hz



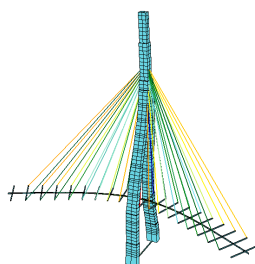
DV/TL, 0.13Hz



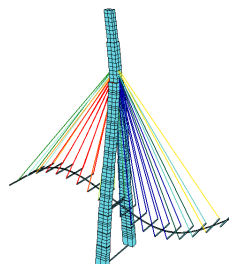
DV, 0.47Hz



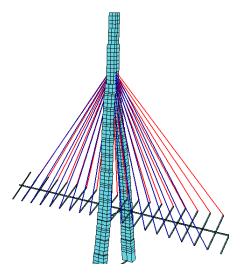
DV, 0.49Hz



DL, 0.94Hz



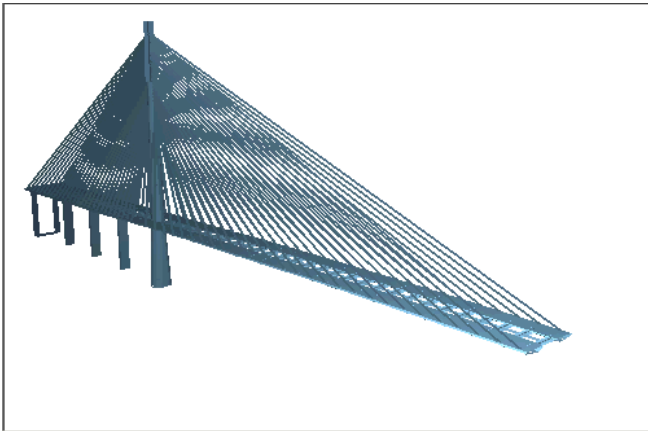
DV, 0.98Hz



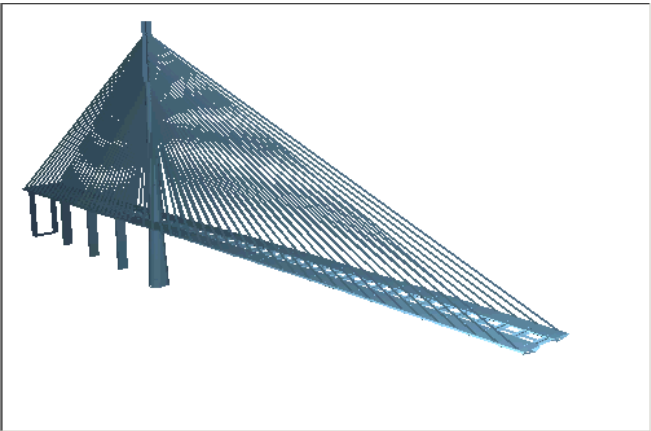
DT, 1.36Hz



SCB Maximum Cantilever Erection Stage: Dynamic properties



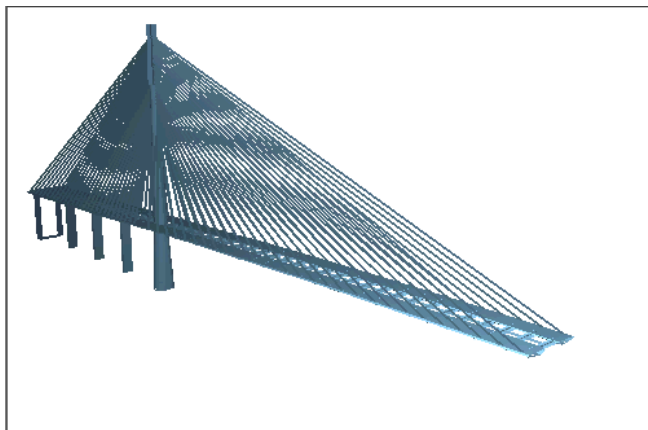
Deck Lateral 1, $f = 0.12\text{Hz}$



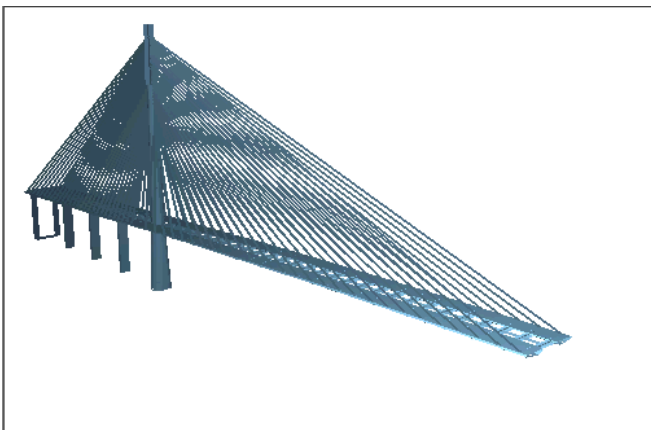
Tower Lateral 1, $f = 0.19\text{Hz}$



SCB Maximum Cantilever Erection Stage: Dynamic properties



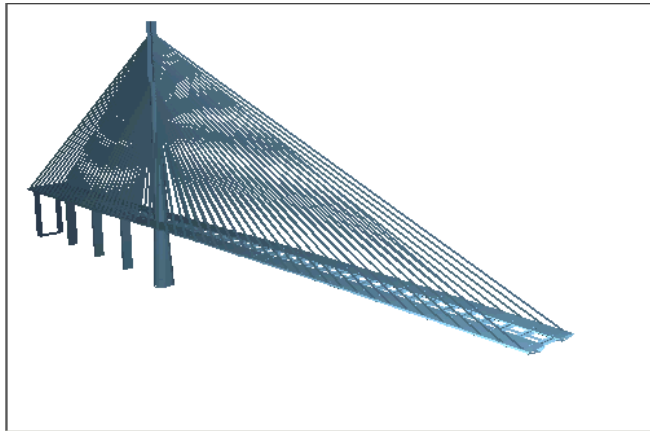
Deck Vertical 1, $f = 0.20\text{Hz}$



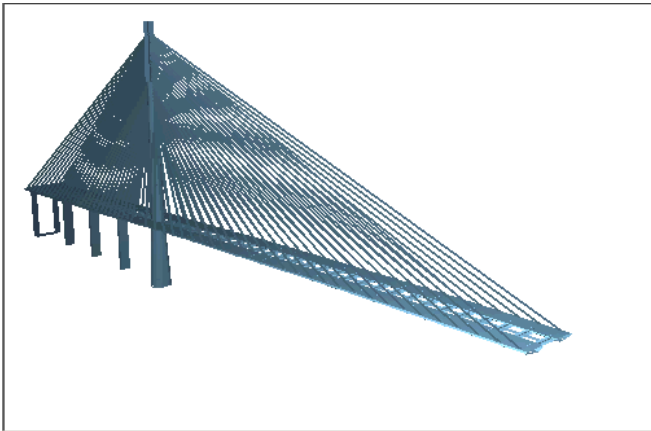
Deck Vertical 2, $f = 0.30\text{Hz}$



SCB Maximum Cantilever Erection Stage: Dynamic properties



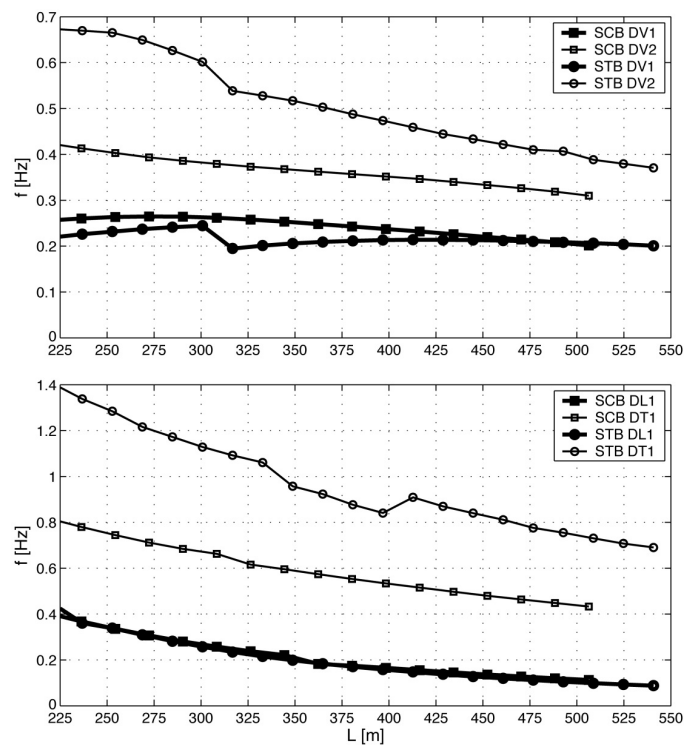
Deck Vertical 3, $f = 0.40\text{Hz}$



Deck Torsional 1, $f = 0.44\text{Hz}$



Summary of Natural Frequencies During Deck Erection (L = cantilever length)



SCB Buffeting Response



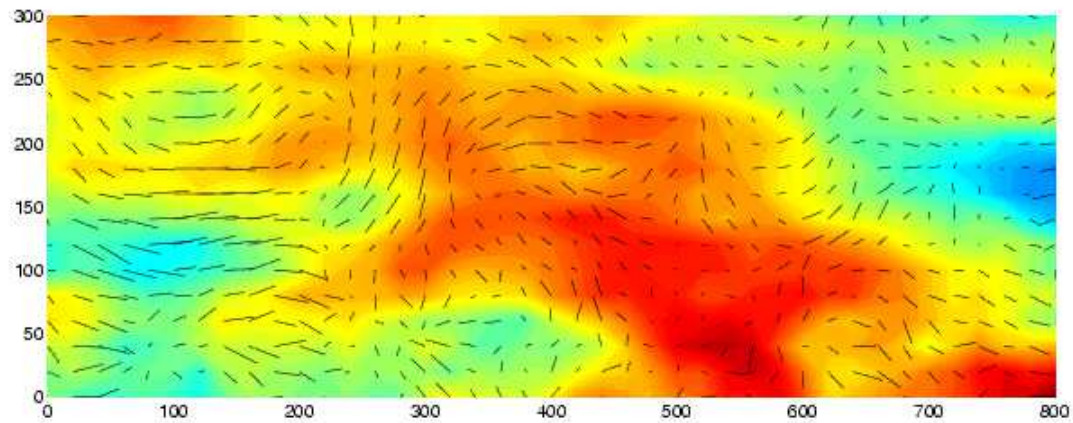
SCB Numerical Buffeting Analysis

Time and space (3D) dependent wind field



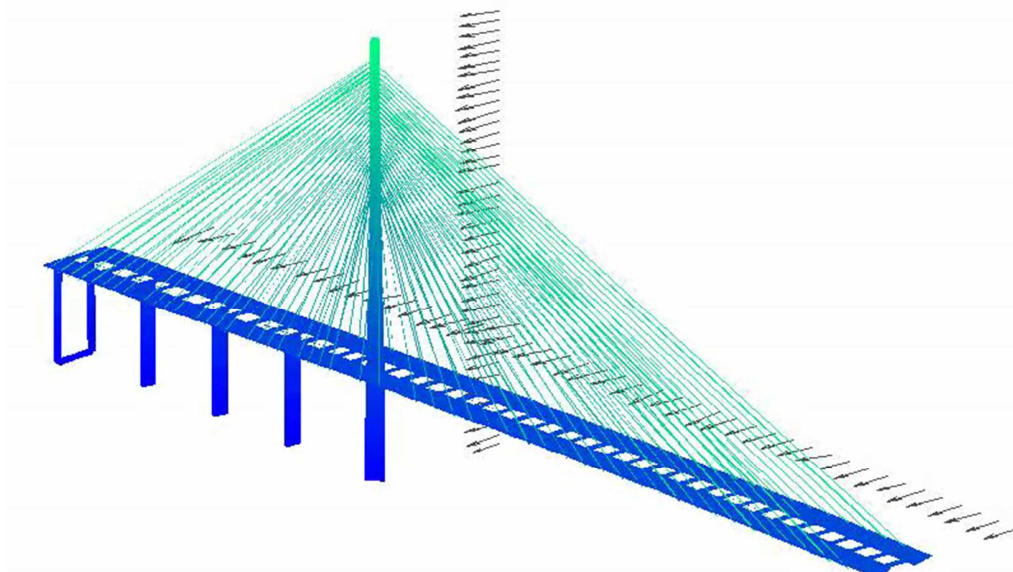
SCB Numerical Buffeting Analysis

Time and space (3D) dependent wind field



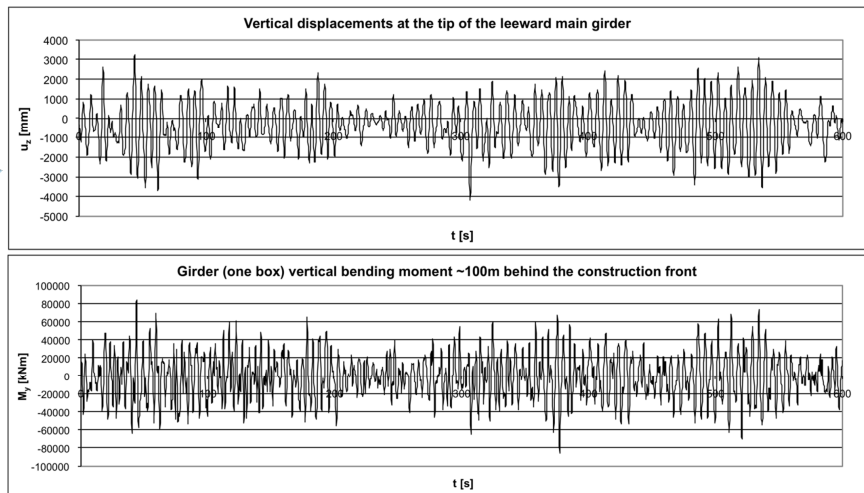
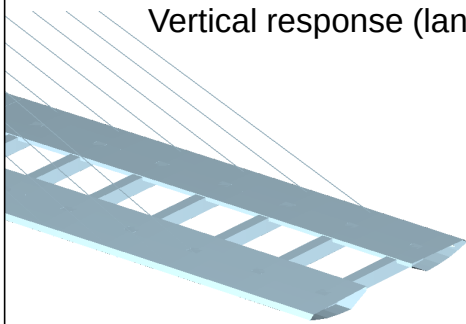
SCB Numerical Buffeting Analysis

Dynamic response (land fetch)



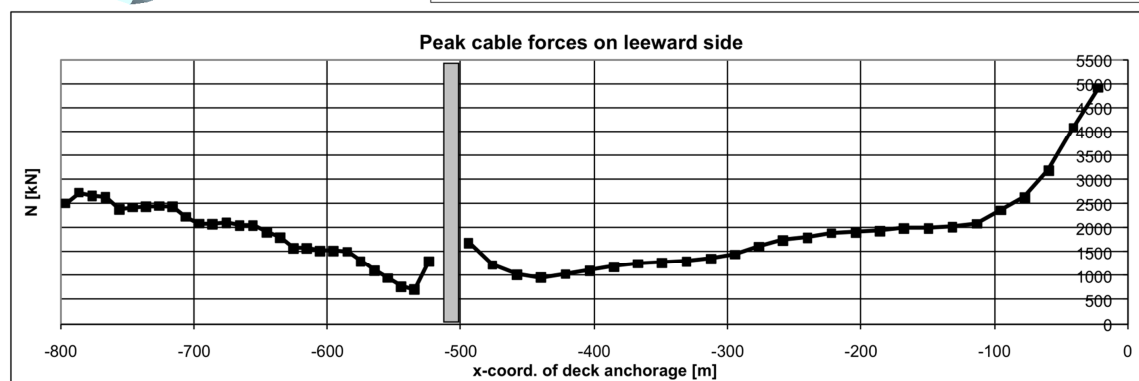
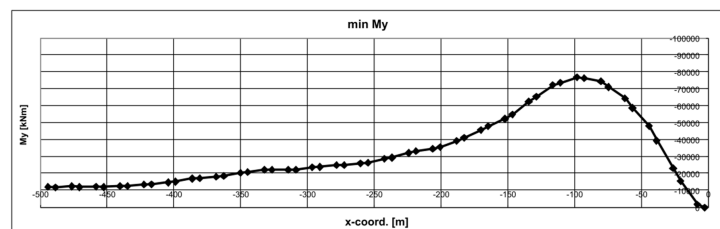
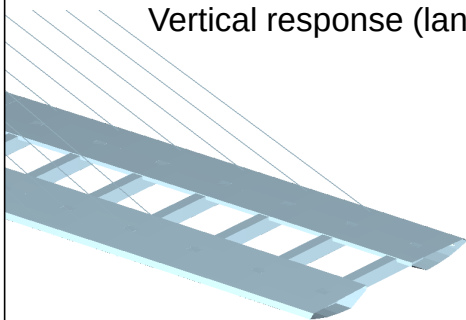
SCB Numerical Buffeting Analysis

Vertical response (land fetch)

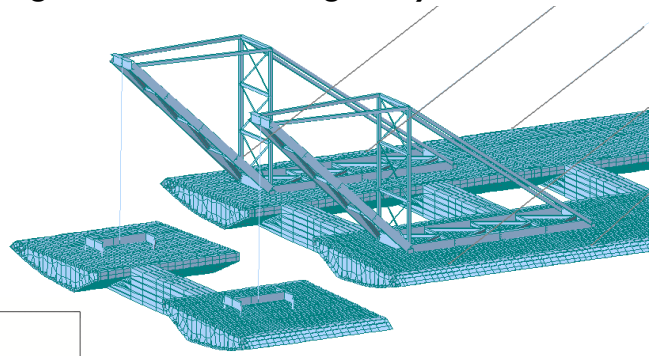
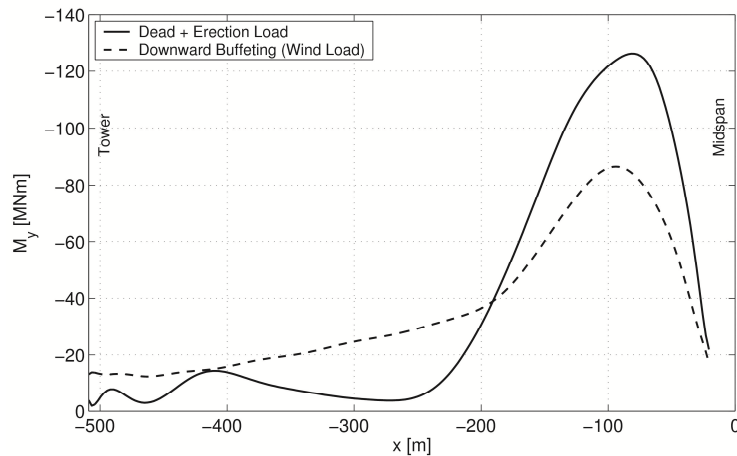


SCB Numerical Buffeting Analysis

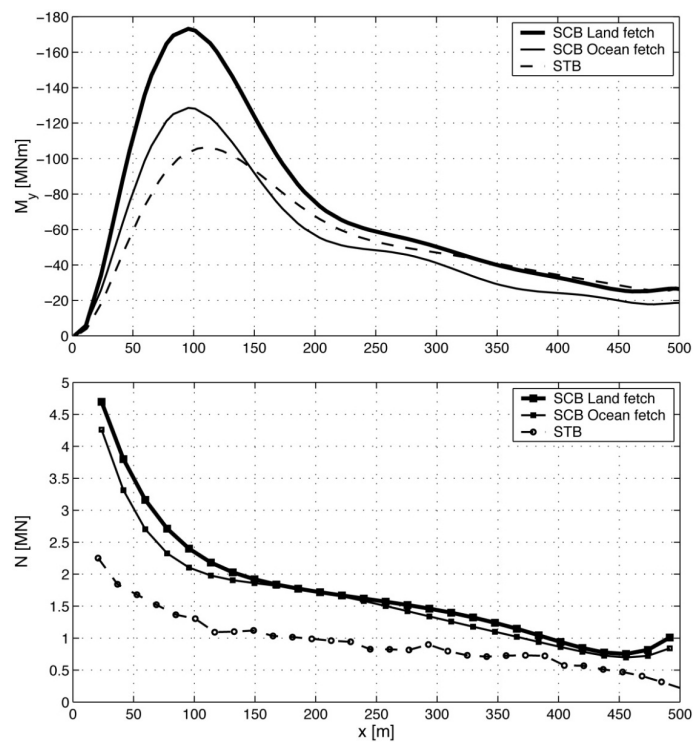
Vertical response (land fetch)



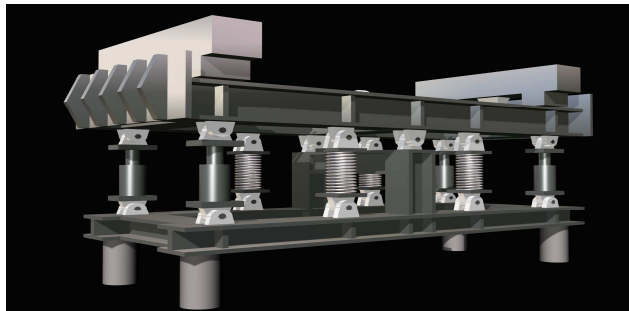
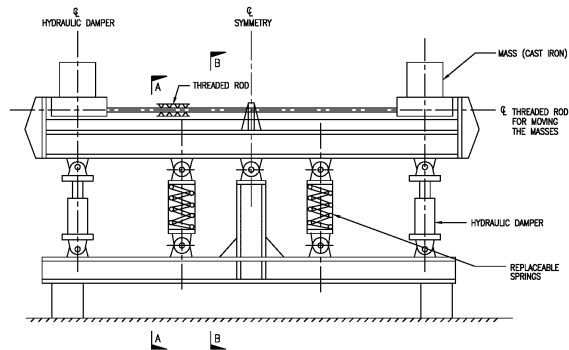
Critical Erection Condition: SCB (bending moments in one girder)



Critical Erection Condition: Summary (total buffeting deck bending moments)

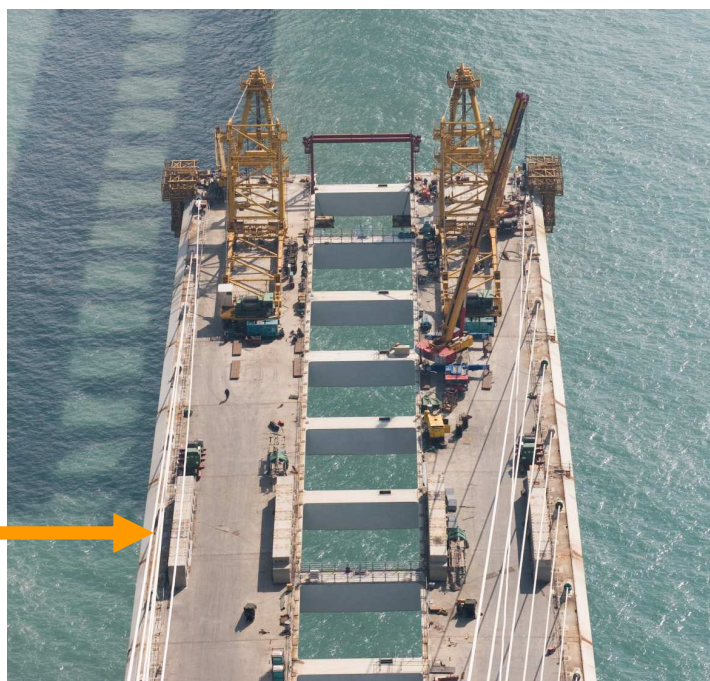


Countermeasure: Rocker-type deck TMD (not implemented)



Countermeasure: Ballasting (SCB)

Ballast: ~800t

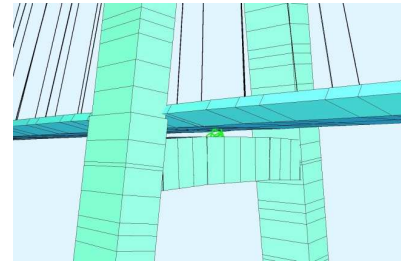


STB: Temporary Deck-Tower Connection



Equivalent Stiffness:

K-PX [kN/m]	38×10^4
K-PY [kN/m]	10^{10}
K-PZ [kN/m]	12×10^6
K-MX [kNm/rad]	10^7
K-MZ [kNm/rad]	45×10^6



Peak buffeting forces in connection:

Forces in deck/tower connection		
$\pm$ PXmax	[MN]	9.4
$\pm$ PYmax	[MN]	3.4
min PZ	[MN]	-3.1
max PZ	[MN]	1.7
$\pm$ MXmax	[MNm]	78
$\pm$ MZmax	[MNm]	209

max. balanced

Forces in deck/tower connection		
$\pm$ PXmax	[MN]	22.4
$\pm$ PYmax	[MN]	16.5
min PZ	[MN]	-3.0
max PZ	[MN]	1.4
$\pm$ MXmax	[MNm]	26.4
$\pm$ MZmax	[MNm]	140.2

max. total



Thank you for your attention.

