Wind effects on multispan suspension bridge
20.10.2016

Ketil Aas-Jakobsen / kaa@aaj.no

Topics for today

Stability limit for multispan suspension bridge – multimodal flutter analysis

Initial thoughts on effects of wind shielding on vehicles

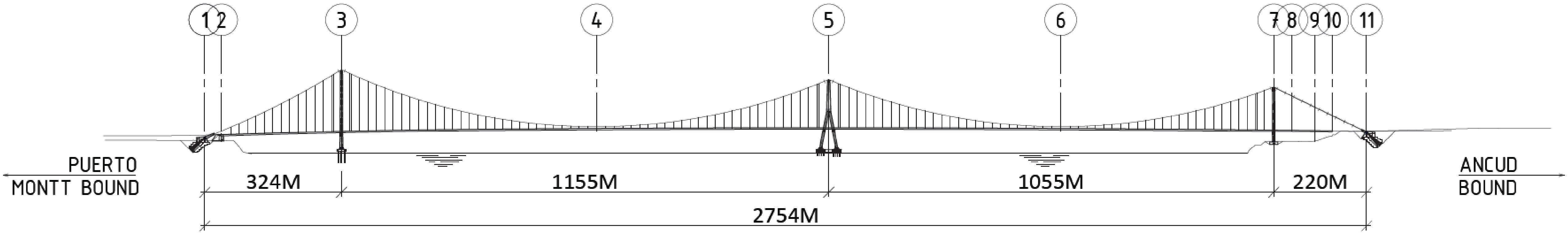
AAS-JAKOBSEN

Stability phenomena for long span bridges

- Stability phenomena
  - **Static divergence**
  - **Galloping**
  - **Dynamic torsion instability**
  - **Flutter**
- Other effects
  - **Vortex shedding (Bridge deck, cables, pylons)**

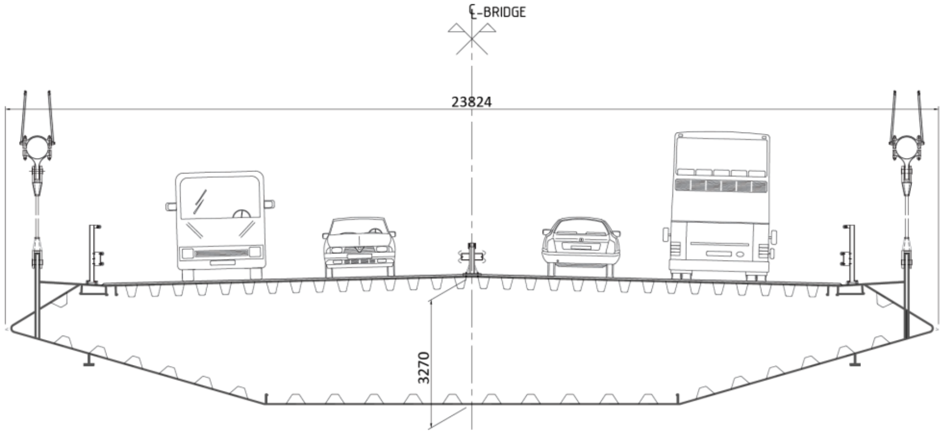
AAS-JAKOBSEN

Multimode flutter analysis of Chacao bridge



- Location: Chile
- Spans: 1155m + 1055m
- Pylon height: 157m-199 m
- Girder Dimension: 23.8m x 3.27m.
- Deck elevation: 50m
- U_10min_100y = 42.5 m/s

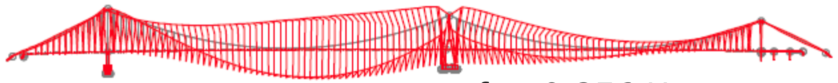
- Flutter criteria: 63.5 m/s



AAS-JAKOBSEN

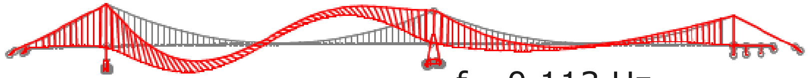
Selbergs formula - Choice of modes

Chacao - two span suspension bridge



f_{29}=0.356 Hz

f_{32}=0.372 Hz



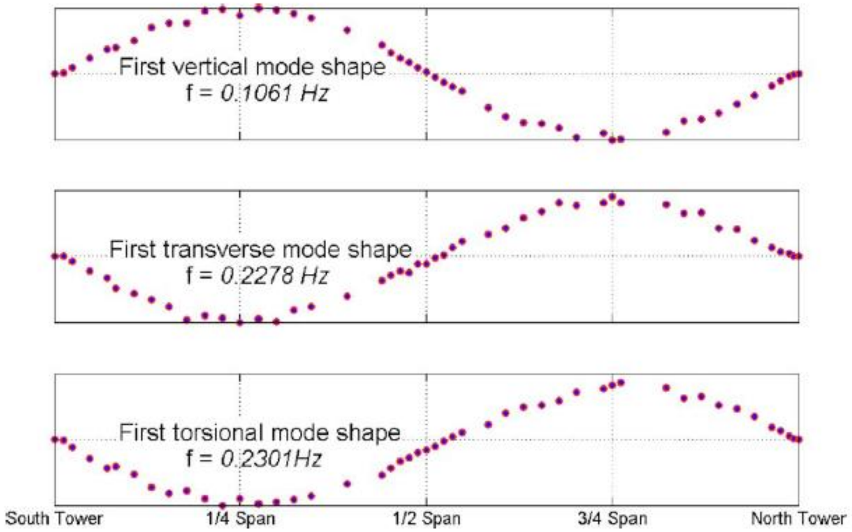
f_3=0.113 Hz

f_4=0.121 Hz

f_5=0.123 Hz

f_6=0.149 Hz

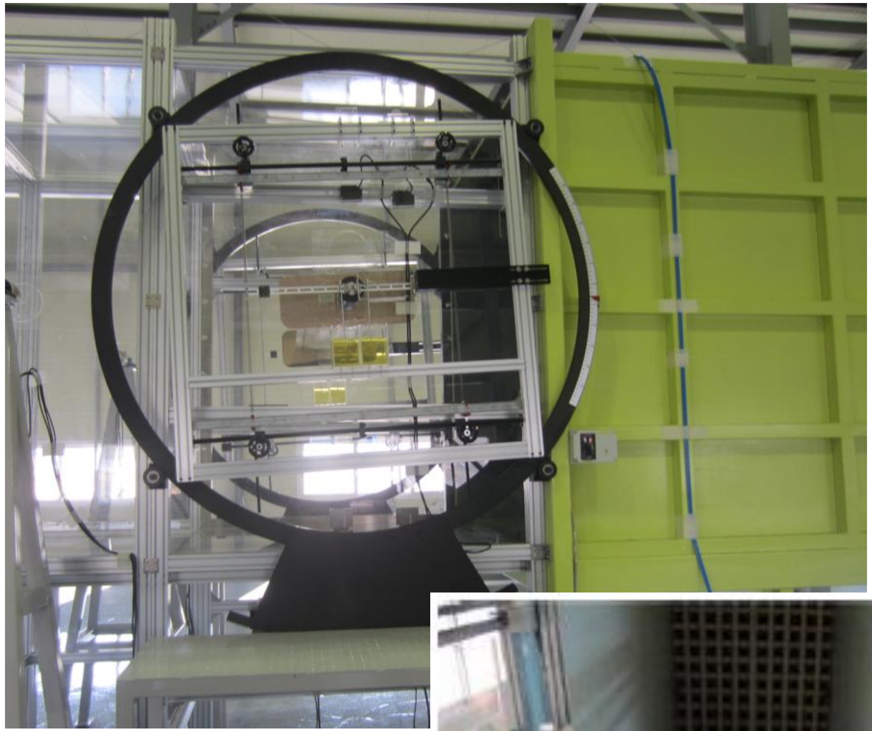
One span suspension bridge

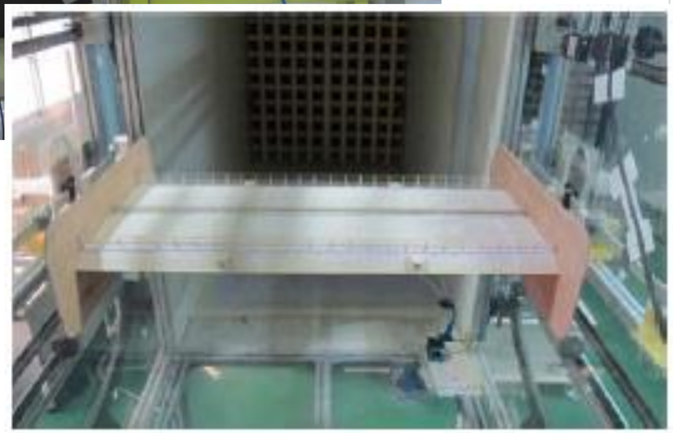


Mode No	Shape sim. [-]	Freq. ratio. [1/s]	V_{cr} [m/s]
5(V) / 29(T)	0,28	2,90	80,04
5(V) / 32(T)	0,46	3,03	80,44

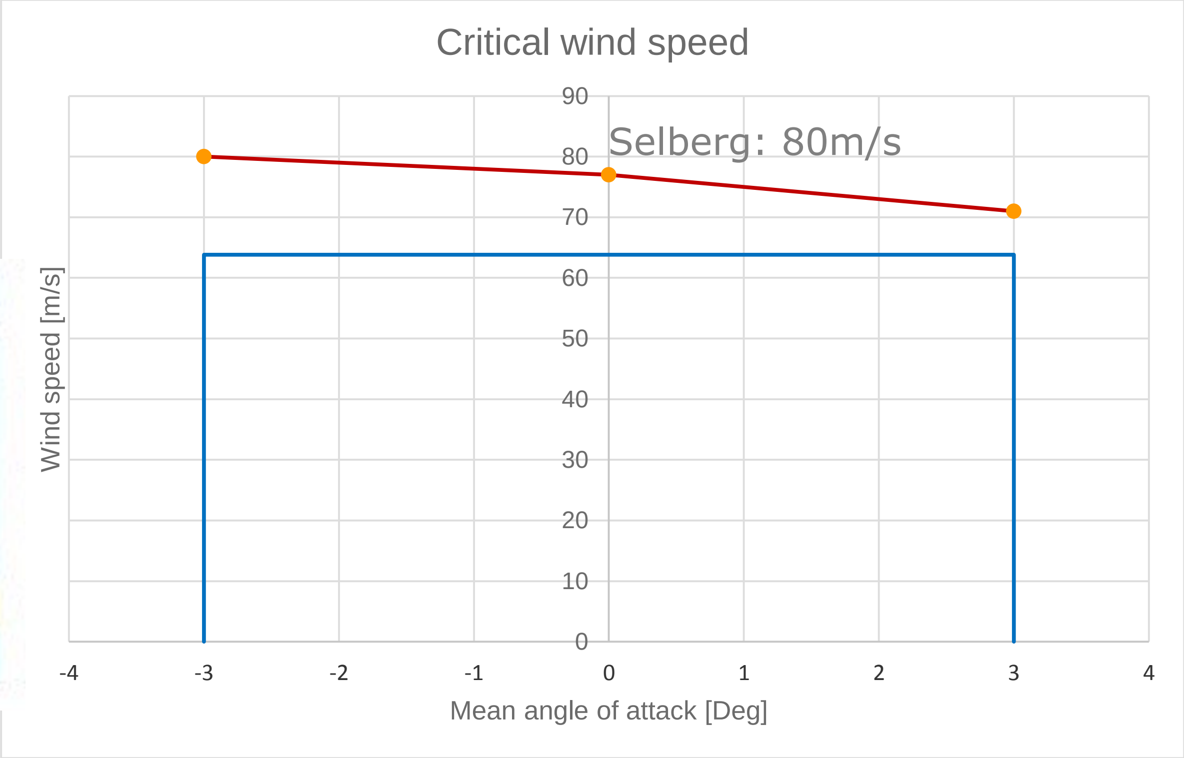
AAS-JAKOBSEN

Flutter speed from section model WTT



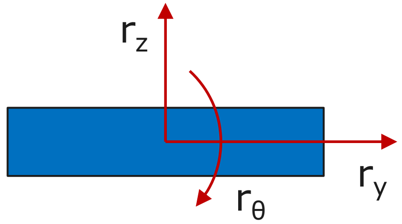


Flow	Flutter Onset Speed 1)			Critical speed
	-3°	0°	+3°	
Smooth Flow	higher than 80m/s	77 m/s	71 m/s	63.8m/s
Turbulent Flow	higher than 77 m/s	higher than 77 m/s	72 m/s	



AAS-JAKOBSEN

Multimodal approach



$$M_0\ddot{r}(t)+C_0\dot{r}(t)+K_0r(t)=Q_{se}(t) \qquad Q_{se}(t)=C_{ae}\dot{r}(t)+K_{ae}r(t)$$

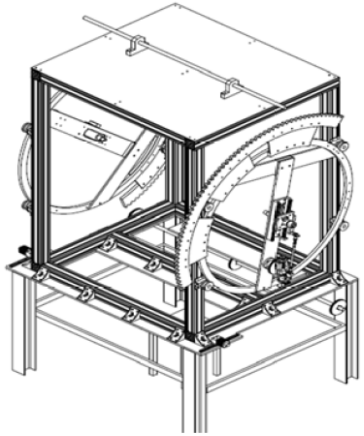
$$q_{y,se}=\frac{\rho V^2B}{2}\left(KP_1^*\frac{\dot{r}_y}{V}+KP_2^*\frac{B\dot{r}_\theta}{V}+K^2P_3^*r_\theta+K^2P_4^*\frac{r_y}{B}+KP_5^*\frac{\dot{r}_z}{V}+K^2P_6^*\frac{r_z}{B}\right)$$

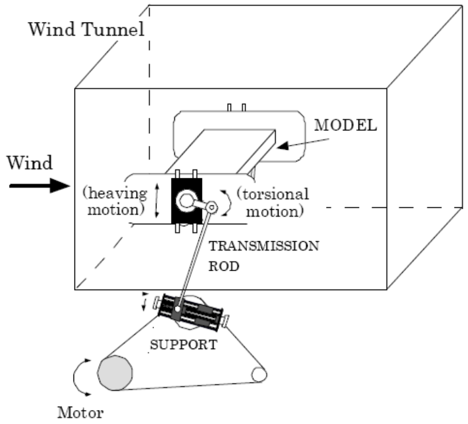
$$q_{z,se}=\frac{\rho V^2B}{2}\left(KH_1^*\frac{\dot{r}_z}{V}+KH_2^*\frac{B\dot{r}_\theta}{V}+K^2H_3^*r_\theta+K^2H_4^*\frac{r_z}{B}+KH_5^*\frac{\dot{r}_y}{V}+K^2H_6^*\frac{r_y}{B}\right)$$

$$q_{\theta,se}=\frac{\rho V^2B^2}{2}\left(KA_1^*\frac{\dot{r}_z}{V}+KA_2^*\frac{B\dot{r}_\theta}{V}+K^2A_3^*r_\theta+K^2A_4^*\frac{r_z}{B}+KA_5^*\frac{\dot{r}_y}{V}+K^2A_6^*\frac{r_y}{B}\right)$$

- Re-arranging terms => aerodynamic damping and stiffness matrix

$$\mathbf{C}_{ae}=\frac{\rho B^2}{2}\omega\begin{bmatrix} P_1^* & P_5^* & \cancel{BP_2^*} \\ H_5^* & H_1^* & BH_2^* \\ BA_5^* & BA_1^* & B^2A_2^* \end{bmatrix},\mathbf{K}_{ae}=\frac{\rho B^2}{2}\omega^2\begin{bmatrix} \cancel{P_4^*} & \cancel{P_6^*} & BP_3^* \\ \cancel{H_6^*} & H_4^* & BH_3^* \\ \cancel{BA_6^*} & BA_4^* & B^2A_3^* \end{bmatrix}$$





: Quasistatic

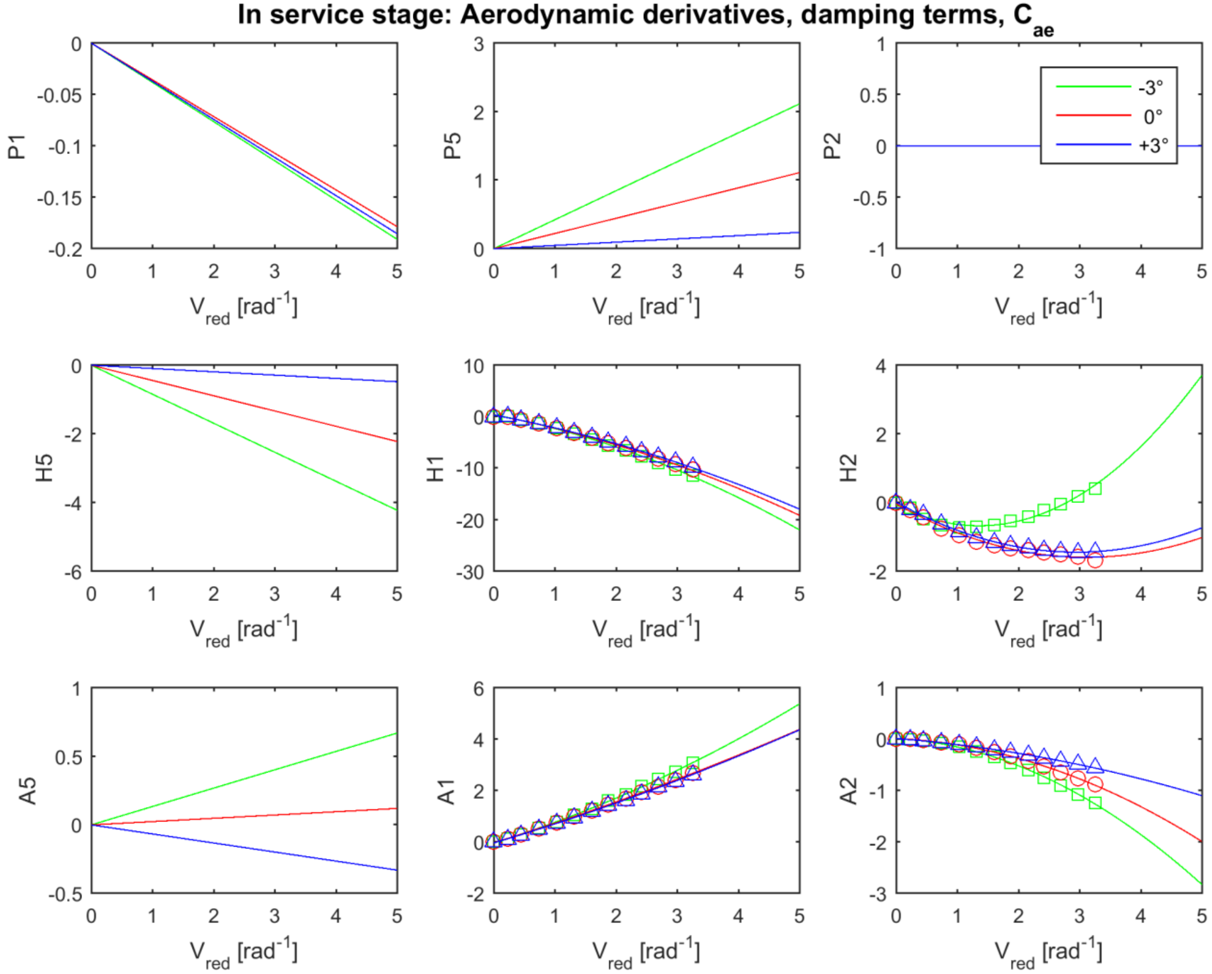
X : Zero

AAS-JAKOBSEN

Results - damping

$$M \cdot \ddot{r} + (C_0 - C_{ae}) \cdot \dot{r} + (K_0 - K_{ae}) \cdot r = F(t)$$

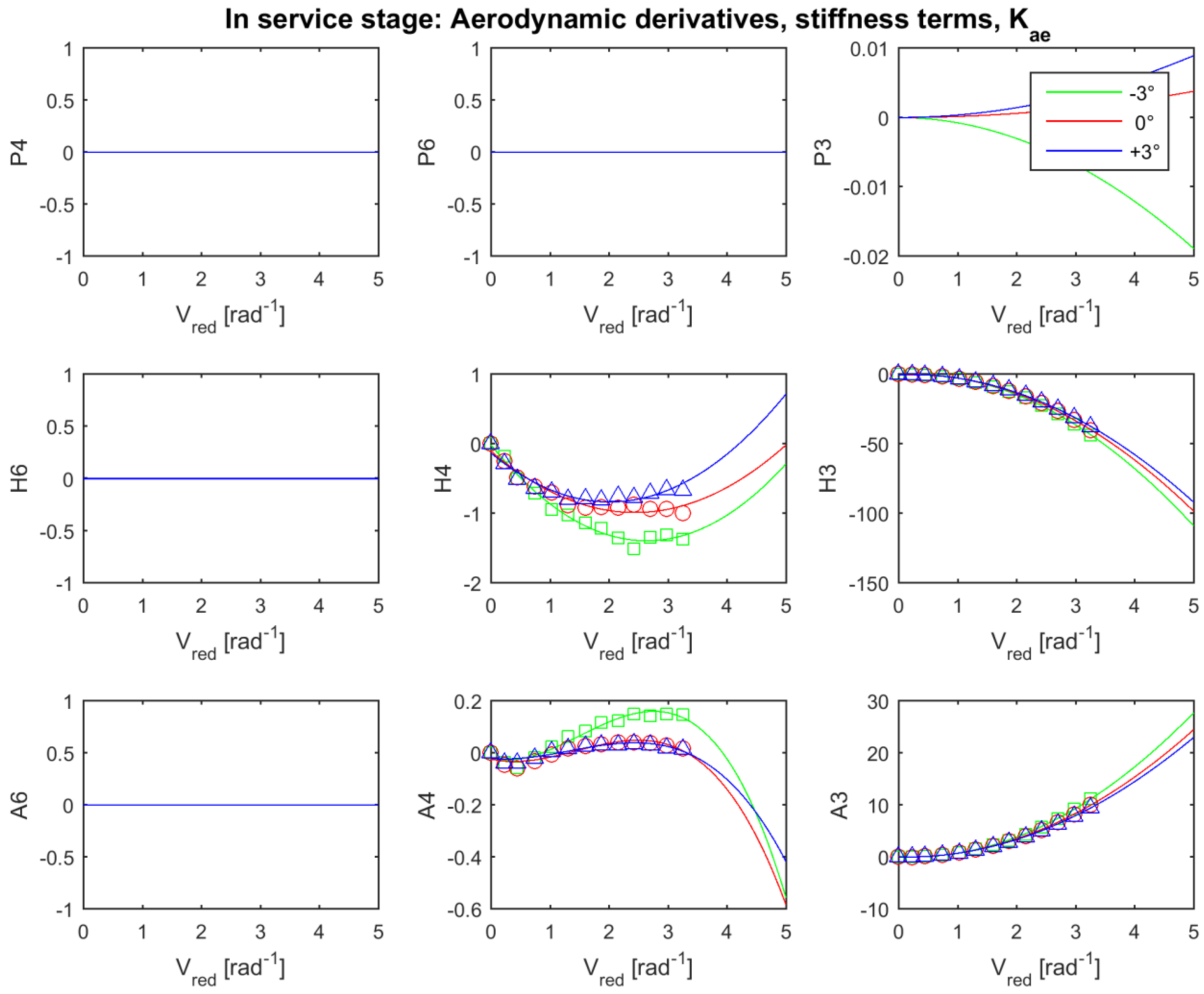
$$\begin{bmatrix} P_1^* & P_5^* & BP_2^* \\ H_5^* & H_1^* & BH_2^* \\ BA_5^* & BA_1^* & B^2A_2^* \end{bmatrix}$$



Results - stiffness

$$M \cdot \ddot{r} + (C_0 - C_{ae}) \cdot \dot{r} + (K_0 - K_{ae}) \cdot r = F(t)$$

$$\begin{bmatrix} P_4^* & P_6^* & BP_3^* \\ H_6^* & H_4^* & BH_3^* \\ BA_6^* & BA_4^* & B^2A_3^* \end{bmatrix}$$

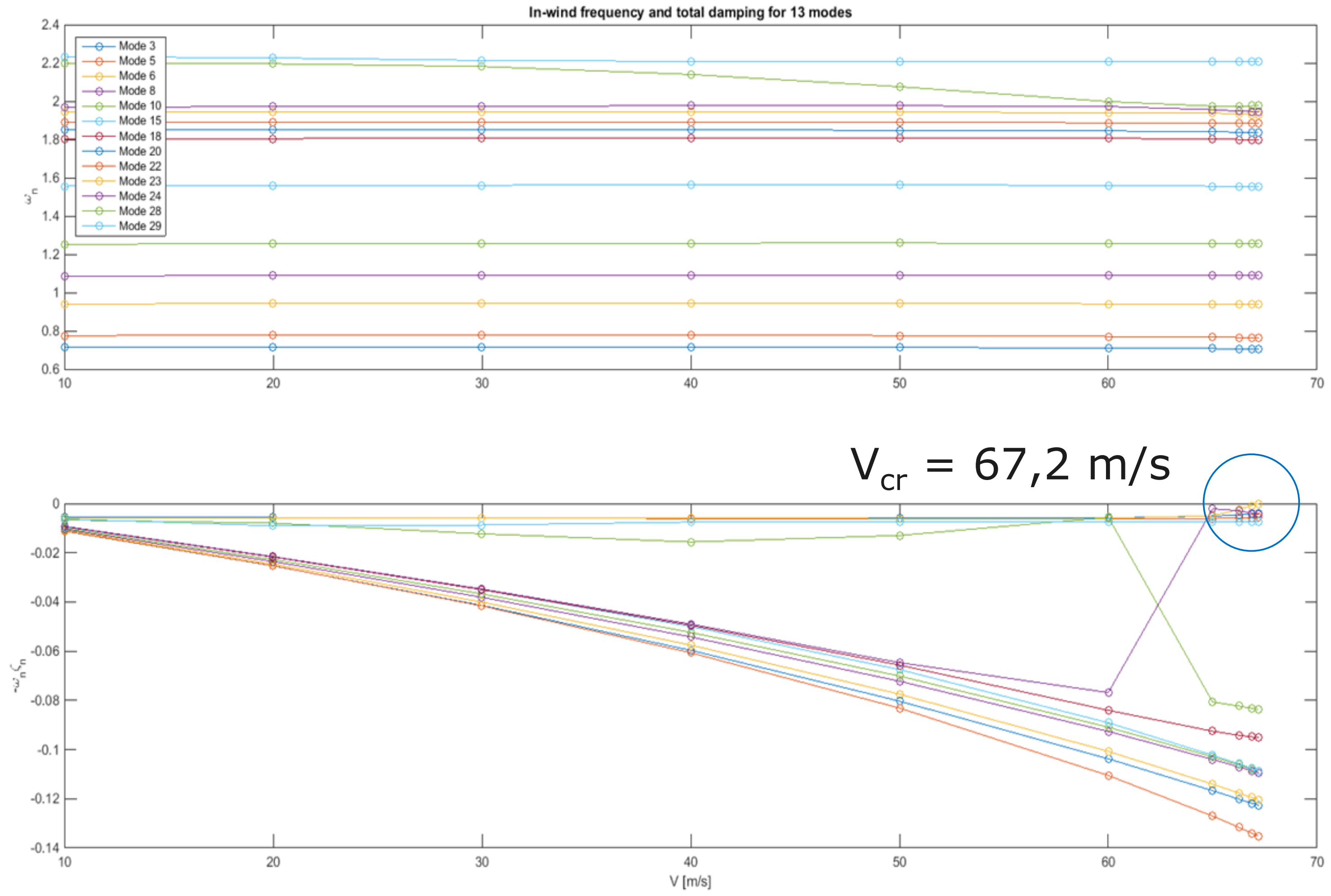


AAS-JAKOBSEN

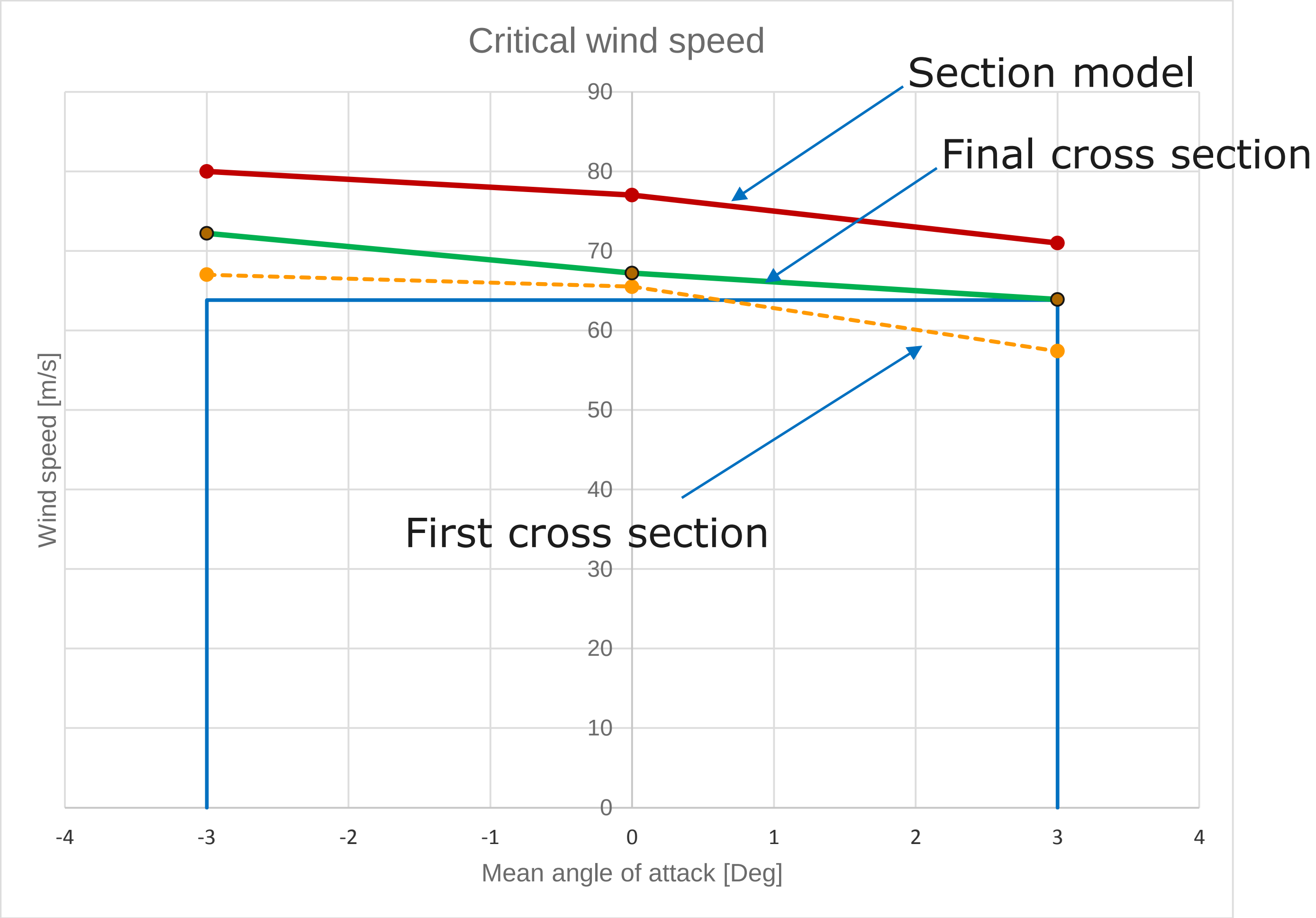
Calculation method

Numerical analysis:

- Chose modes to be included
- Incrementally increase wind speed
- Look for zero-damping => flutter



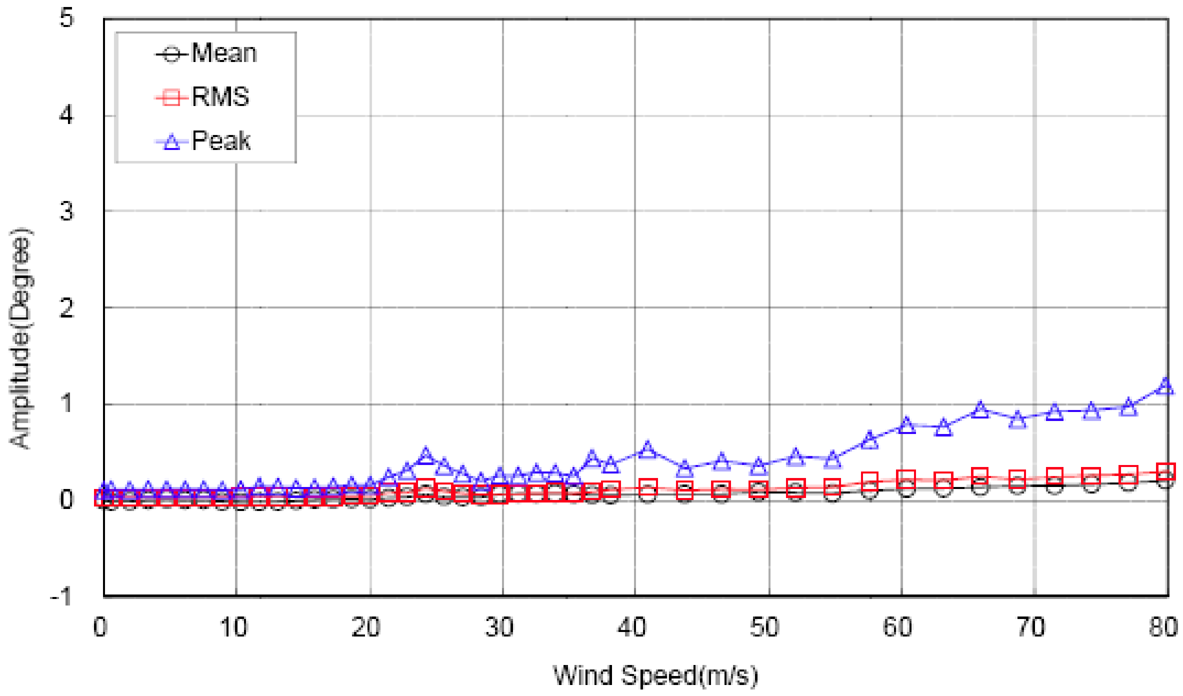
Analysis of final cross section

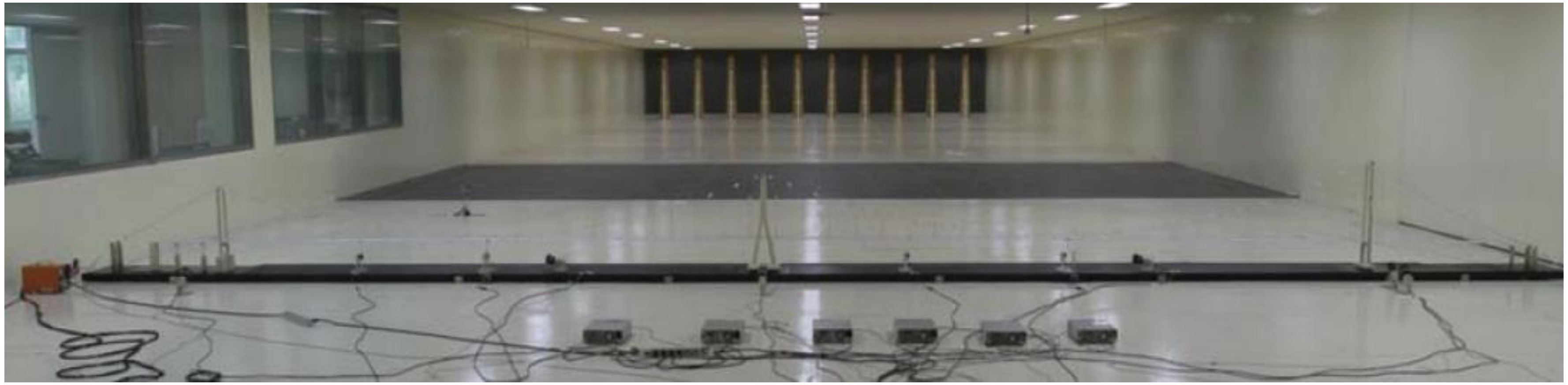


AAS-JAKOBSEN

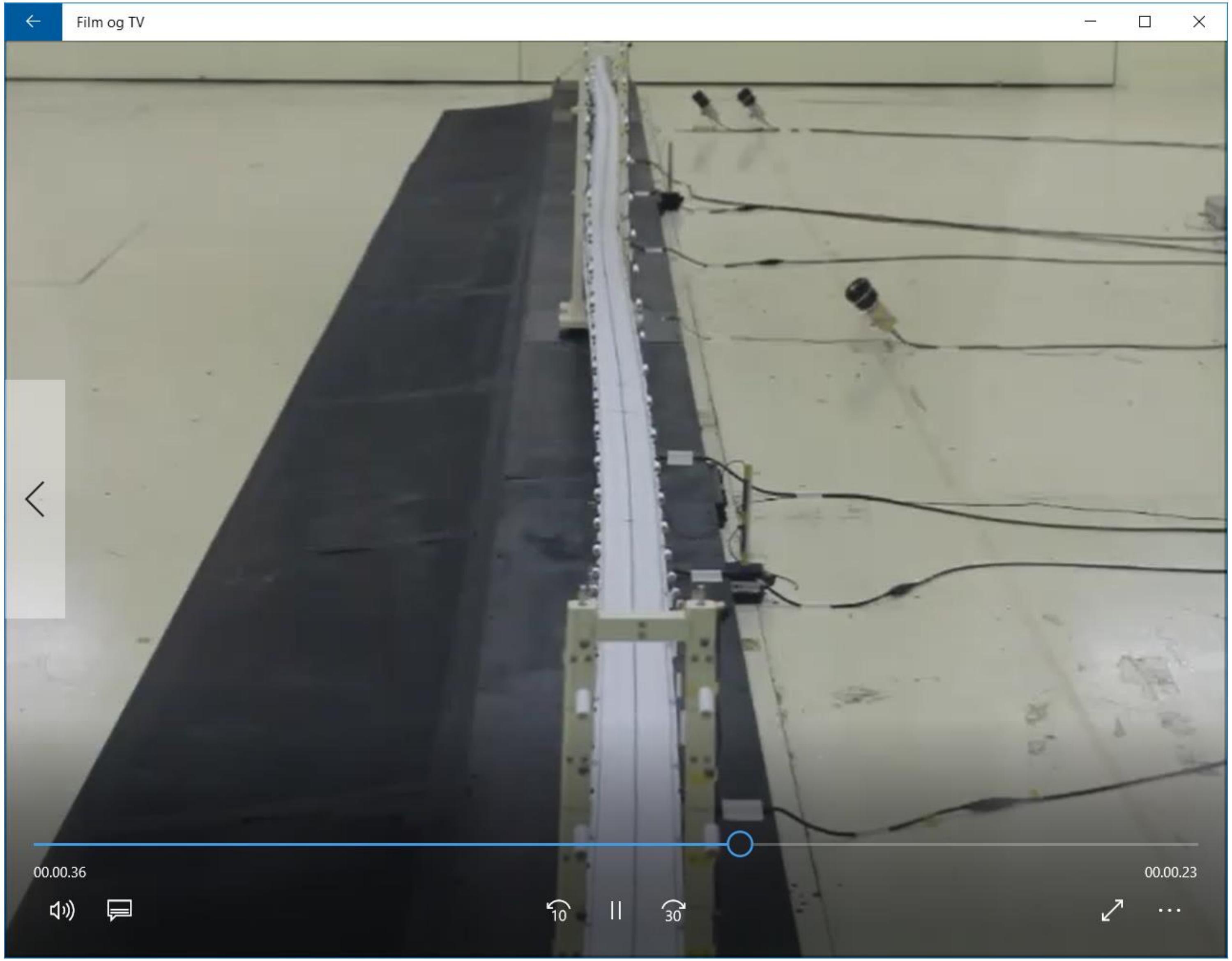
Verification wind tunnel test – full bridge

- Scale: 1:250
- Smooth and turbulent wind.
- Wind direction: Perpendicular and 30º
- Tolerance on vibration modes: 5%
- Actual damping: typically 0.5% of critical.





AAS-JAKOBSEN



AAS-JAKOBSEN

Summary of flutter analysis

The Chacao bridge has sufficient safety towards flutter

Wind shielding of vehicles

Linking stability analysis (which is a very unlikely event) with user comfort.

Initial thoughts on effects of wind shielding on vehicles

- What’s important for a bridge:
  - **Safety**
  - **Accessibility (i.e. uptime)**

Typical thresholds:

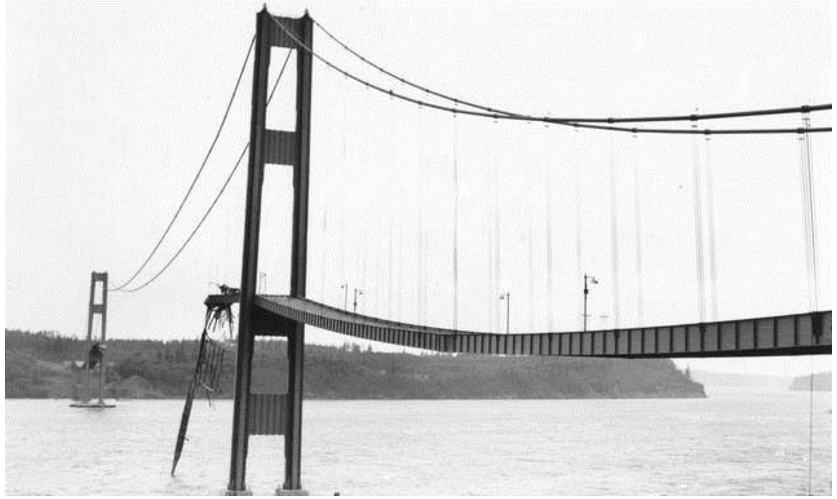
10 m/s: High wind warning

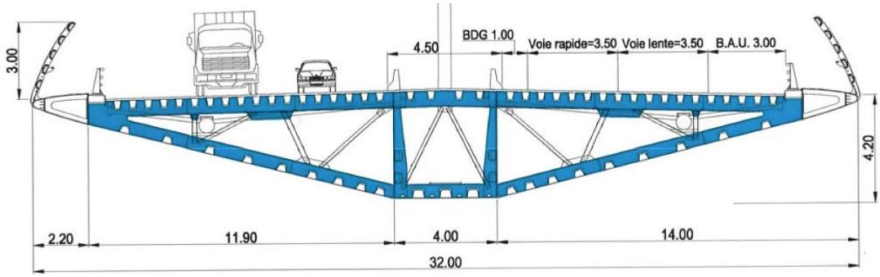
15 m/s: Wind-sensitive vehicles stopped (caravans, motorcycles). Speed limited to 80 kph.

20 m/s: Speed limited to 50kph

25 m/s: Closed for all traffic

Bjørnafjorden – completely closed: 15.5h a year.



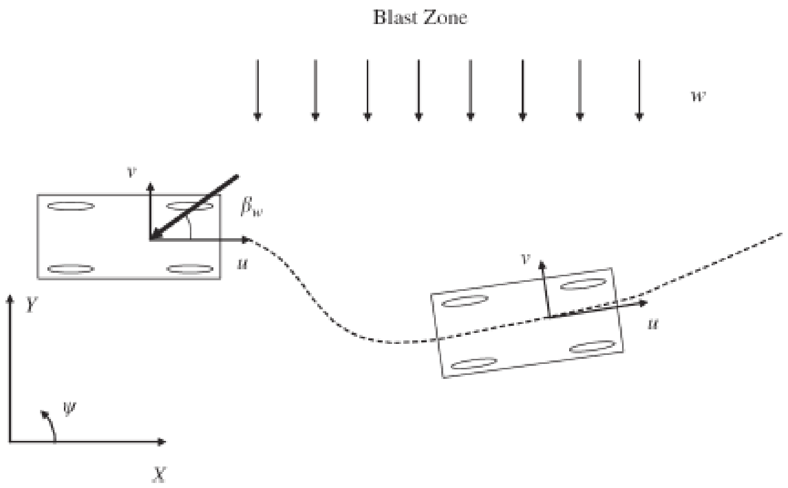


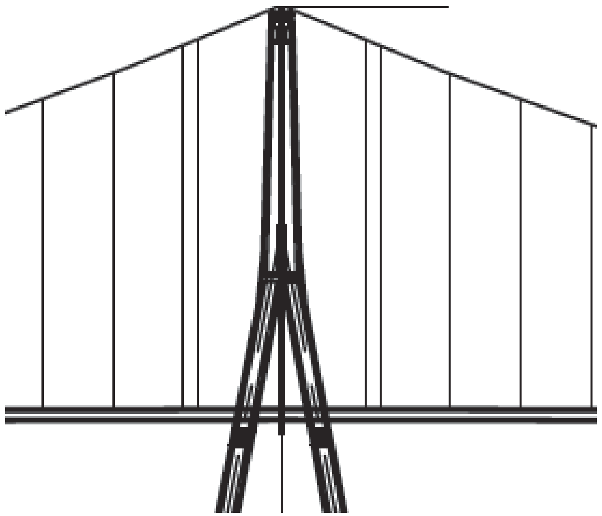
Cross wind effects on vehicles

- Cross wind variation
- Forces on vehicle
- Human response
- Dynamic response of vehicle

- Acceptance criteria:
  - **Lane: 3.5m**
  - **Car: 2.0m**
  - **Wiggle room: +/-0.75m**
  - **Wind: +/- 0.5m**

- Need WT input





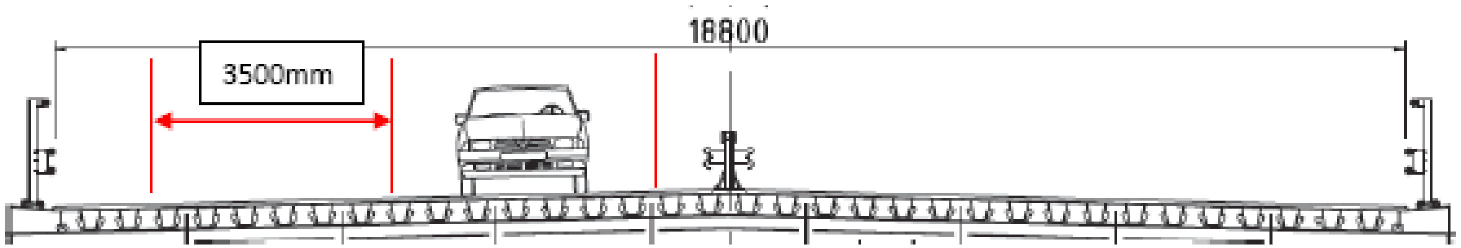
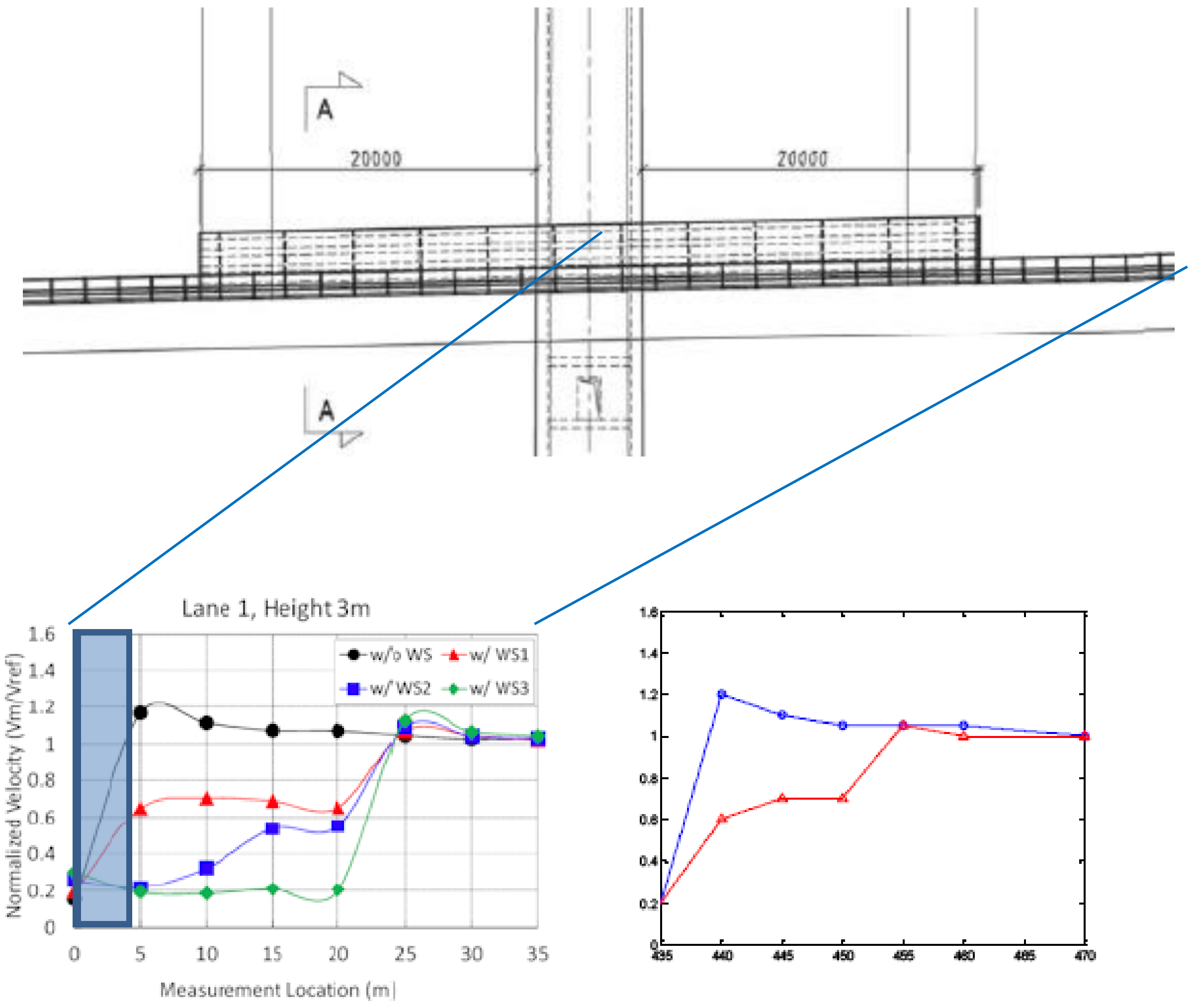
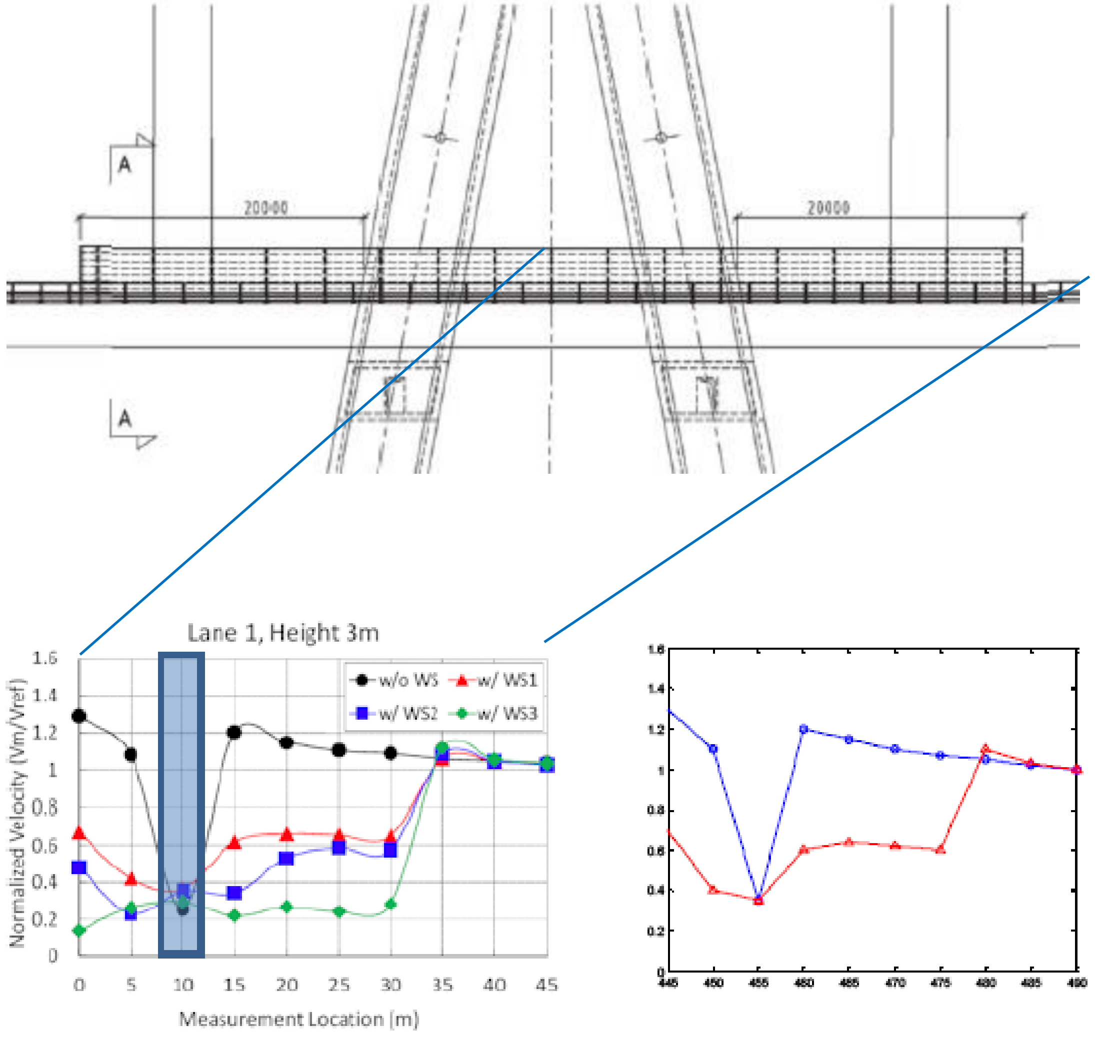


Figure 7 Bridge girder. Lanes indicated

Shielding effects. Wind tunnel tests.



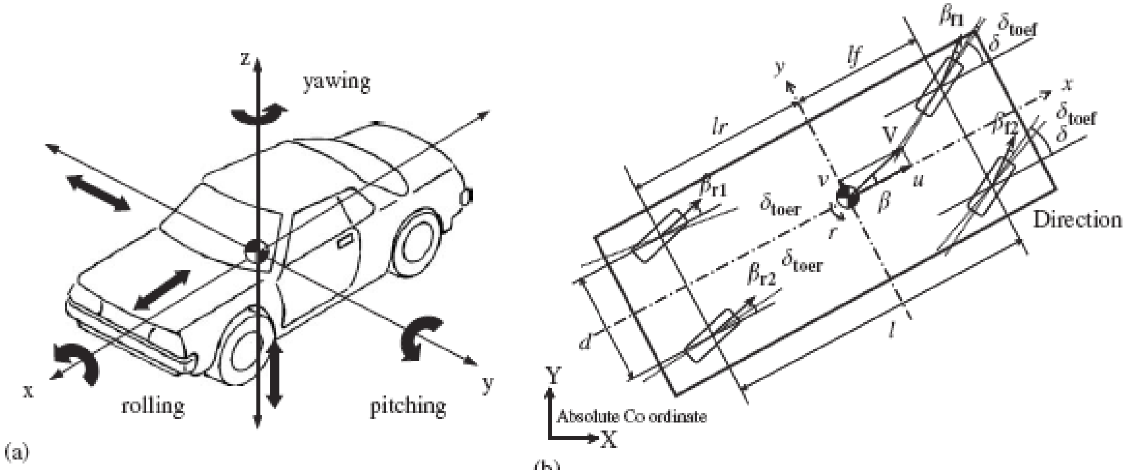


Calculation model

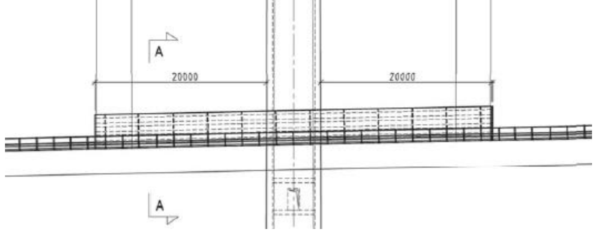
- Vehicle data
  - **Aerodynamic properties**
  - **Dynamic**

- Human response

Maruyama and Yamazaki. *Dynamic response of a vehicle model with six degrees of freedom under seismic motion*

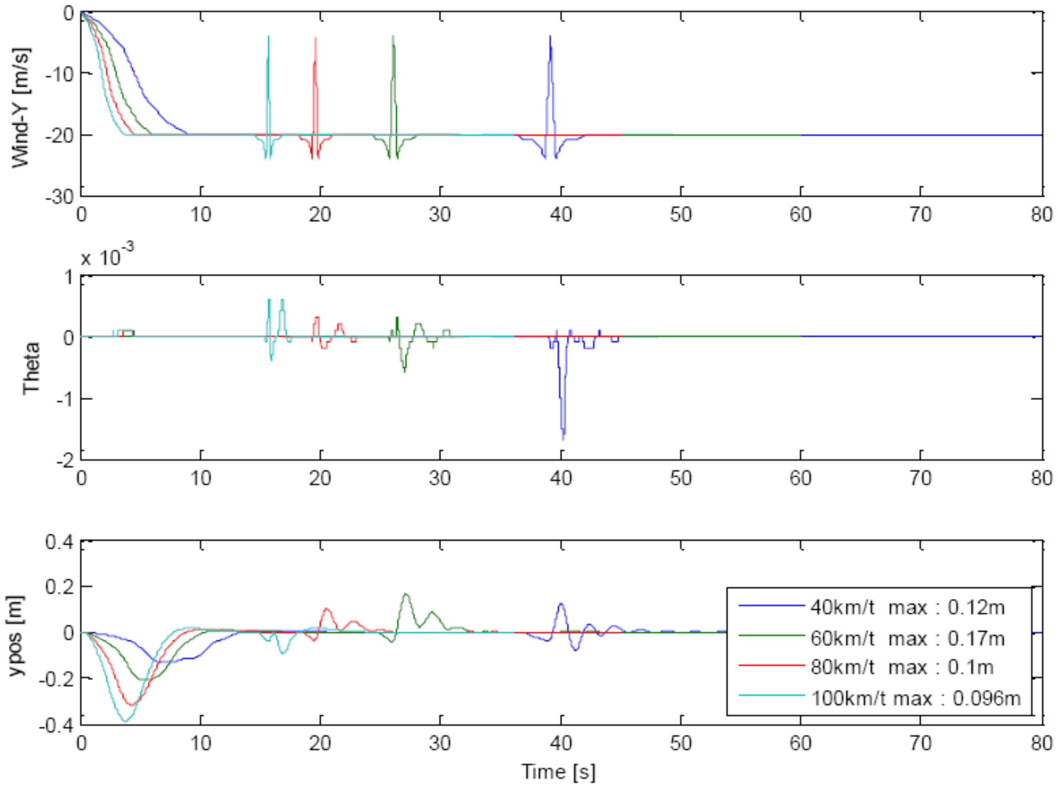


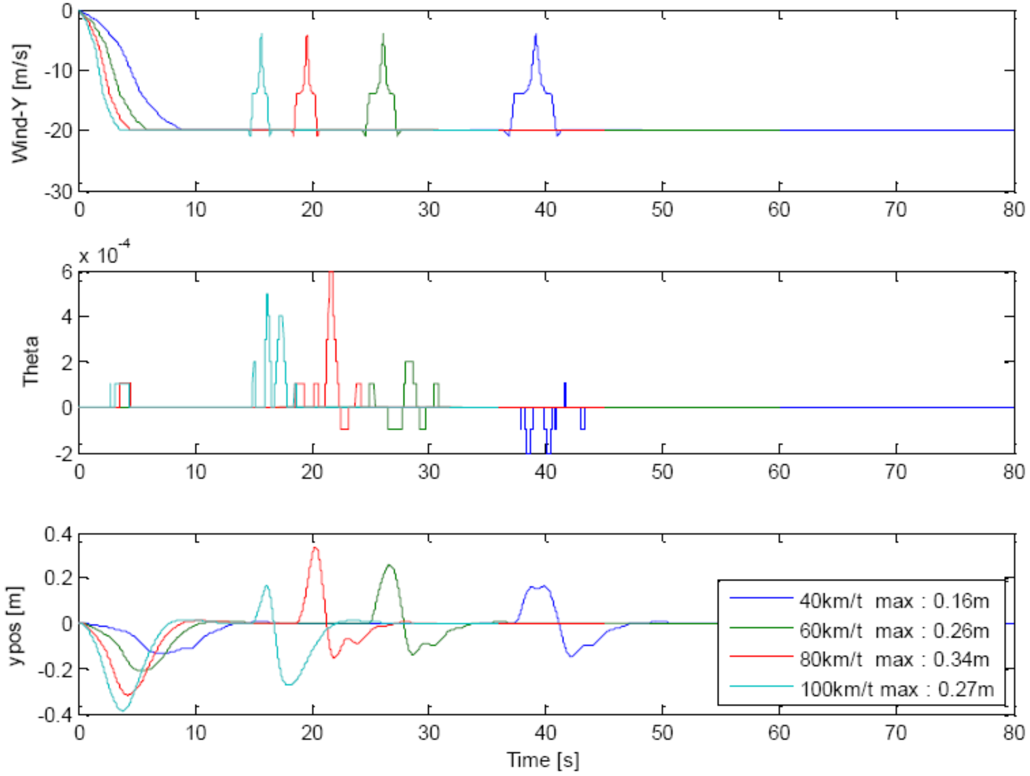
North pylon analysis



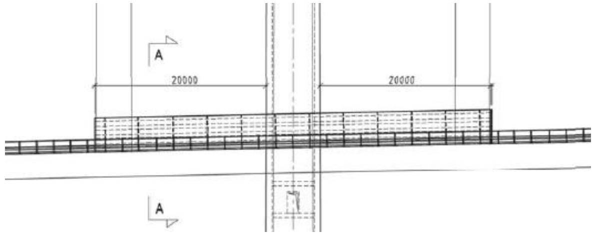
North pylon wo/screens. Compact car. V=20 m/s

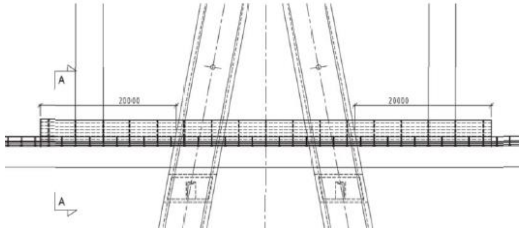
North pylon w/screens. Compact car. V=20 m/s





Results





	North Pylon		Central pylon	
Wind shield:	Without [m]	With [m]	Without [m]	With [m]
40 km/h	0.12	0.16	0.15	0.21
60 km/h	0.17	0.26	0.12	0.27
80 km/h	0.10	0.34	0.15	0.34
100 km/h	0.10	0.27	0.35	0.16

General trend: These wind screens give larger sidways deflection than no-screen case.

Sensitivity analysis:

Lower speed: less response

Increasing mass: response equal or reduced

Increased aerodynamic area: increased response

Further work on cross wind effects on vehicles

- Review acceptance criteria
- Better database for input to analysis
- More vehicles
  - **Aero and dynamic properties**
  - **High sided vehicles**
- Improve human response algorithm
- Local effects near pylon
  - **More wind screen types**
  - **Local «shaping» of pylons?**
  - **Bridge girder effects?**

Summary

The multimodal flutter analysis of Chacao bridge showed that it has sufficient safety towards flutter.

Local wind shielding might not be beneficial for vehicles, but more comprehensive work is needed.
(Different vehicles, identify differences in bridges if any, is optimizing of local shielding possible, interaction with human response)

We would like to thank the following which has contributed during the process:

Associate professor Ole Øiseth, NTNU has let us use some of his Matlab scripts., Professor Einar Strømmen of NTNU, Professor Maruyama for collaborating on the vehicle response calculations.

AAS-JAKOBSEN