Computational Mechanics
Enhanced Civil Engineering Applications (WIND)

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SOFiSTiK AG

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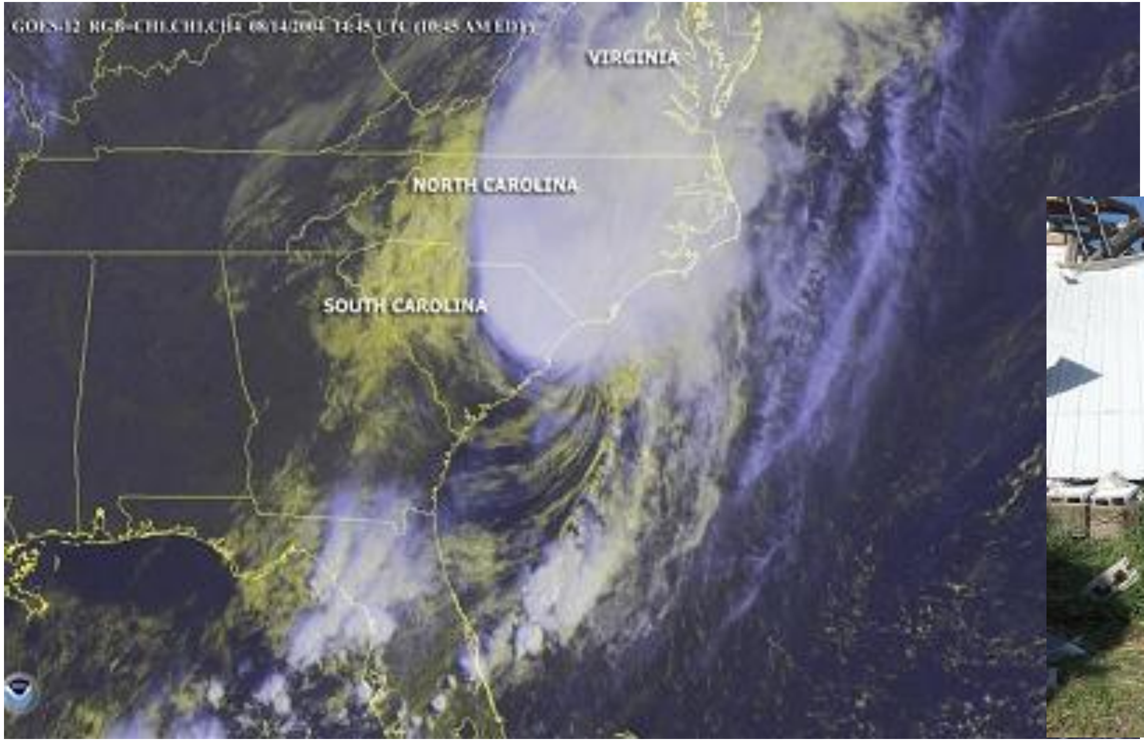
Overview

- Wind
  - Global Wind, local wind
  - Wind spectra, Aerodynamics
  - Design codes
- Some Basic equations for more details (CFD)
  - Navier-Stokes Equation, Turbulence modelling
  - Boundary layers + Detachments
- CFD Examples for Bluff Bodies
- CFD Examples for Bridges
- Dynamic Analysis for Bridges with wind

Wind

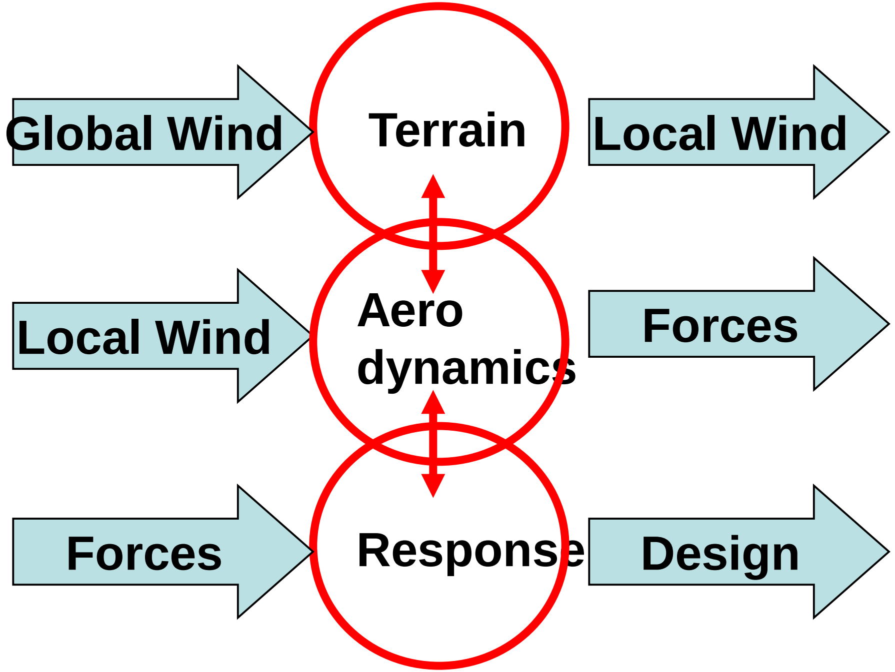


Large Quantities of a light medium with high velocities

Wind

- Random, non deterministic:
  Neither direction nor magnitude nor time history are known in advance.
- Dynamic
  The natural wind is acting dynamically in that way that wind speeds and thus forces vary in time and space.
- Meteorological observations + Statistics + expected life time of structure
  5 sec, 10 min, 1 year, 50 years, 100 years ?

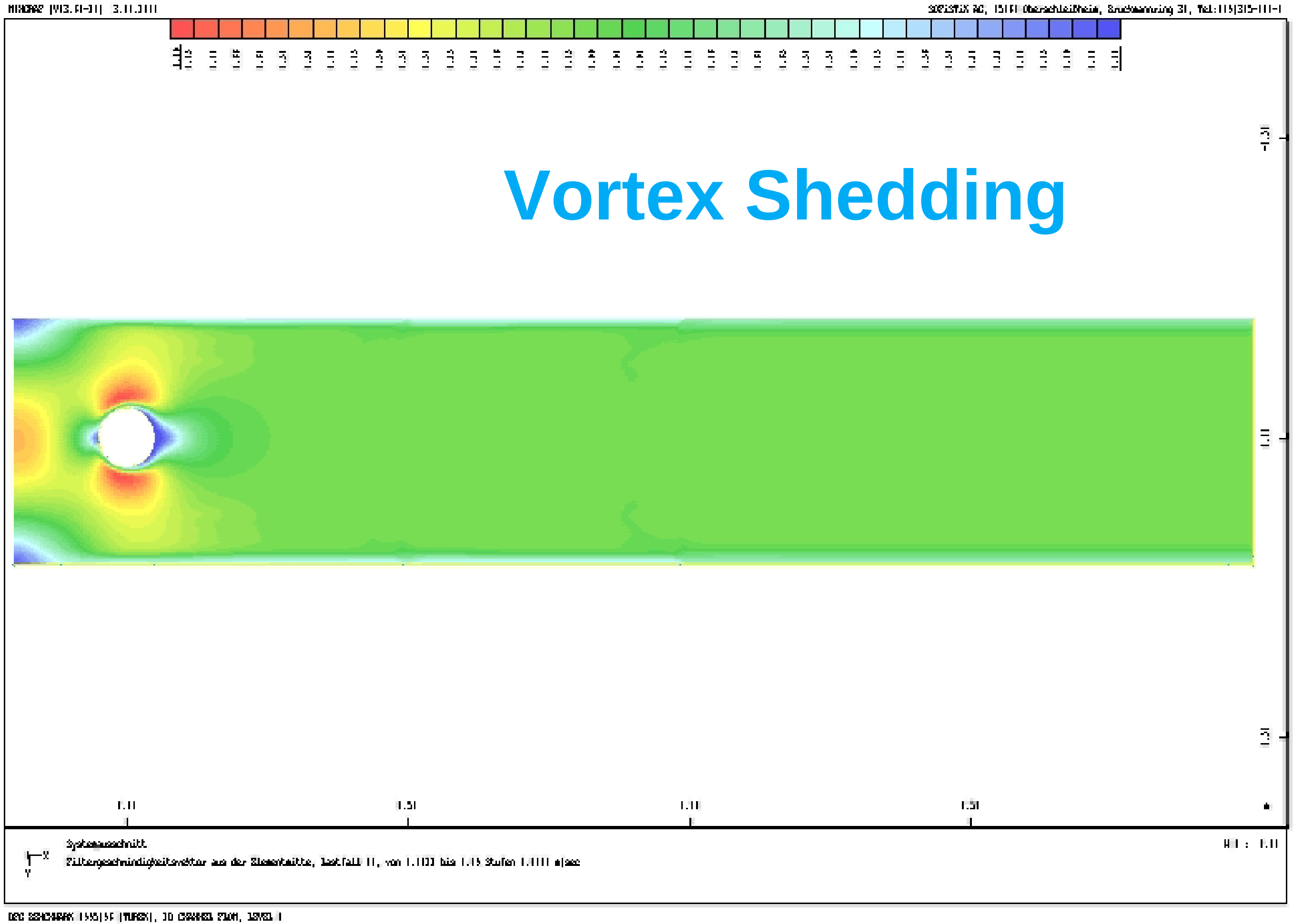
The Davenport wind chain



Dynamic Effects of wind

- Gust (Böen) effects
  (changing wind speed)
- Periodic vortex shedding
  (Karman effect, Rain-Wind induced oscillations)
- Flutter + Interference
  (Tacoma-Bridge)
- Galloping
  (Schlagschwingungen)
- „Theory VIII. Order“
  (Pun, Boundary layer effects)

Vortex Shedding



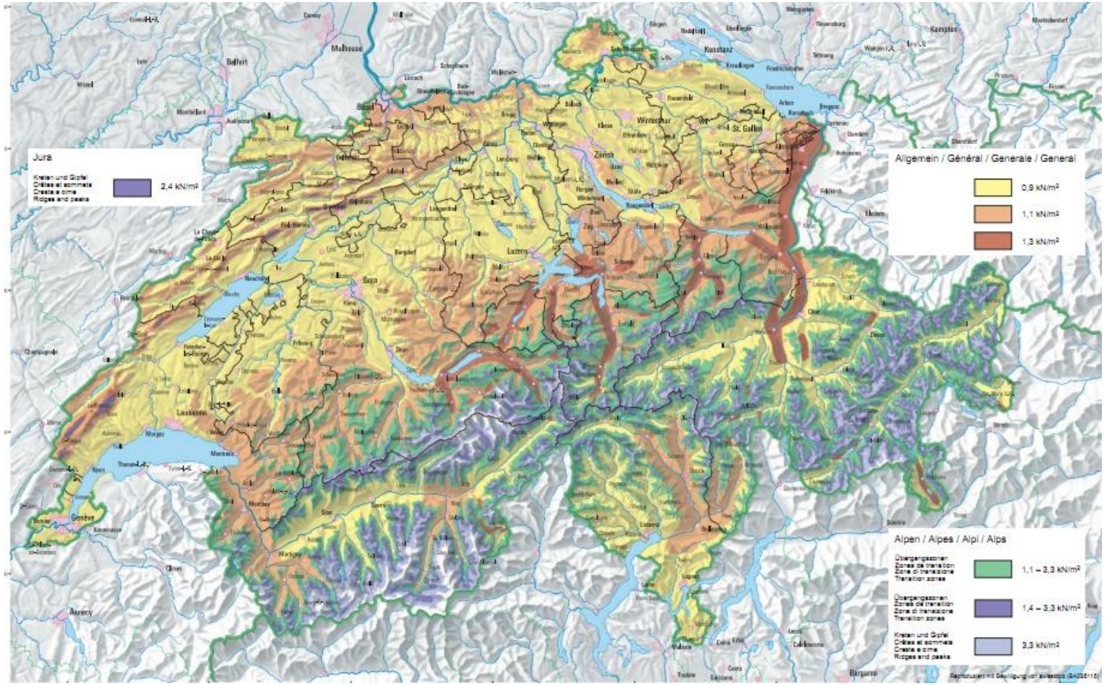
Global Wind

SOFiSTiK

Wind map of Germany

Windzone	$v_{b,0}$	$q_{b,0}$
WZ 1	22,5 m/s	0,32 kN/m²
WZ 2	25,0 m/s	0,39 kN/m²
WZ 3	27,5 m/s	0,47 kN/m²
WZ 4	30,0 m/s	0,56 kN/m²

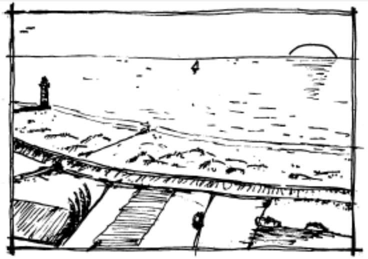
Wind map of Switzerland



Terrain Categories EN 1991-1-4

Terrain category 0

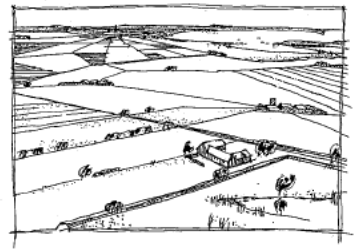
Sea, coastal area exposed to the open sea



Terrain category I

Lakes or area with negligible vegetation and without obstacles

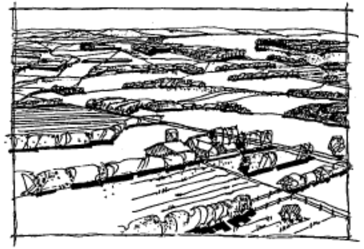
Z_0=0.01 m



Terrain category II

Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights

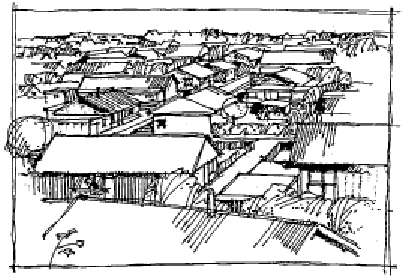
Z_0=0.05 m



Terrain Categories EN 1991-1-4

Terrain category III

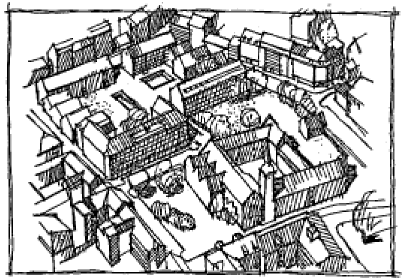
Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)



Z_0=0.30 m

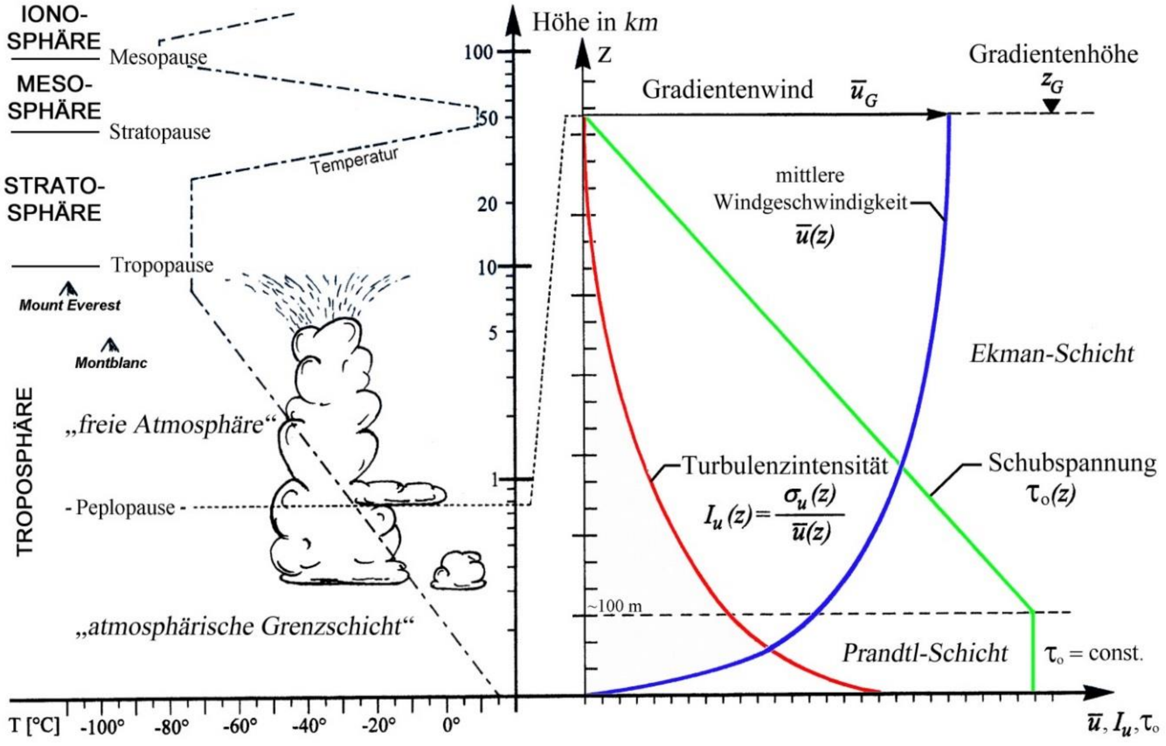
Terrain category IV

Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m



Z_0=1.05 m

Wind layers



IONO-
SPHÄRE
Mesopause
MESO-
SPHÄRE
Stratopause
STRATO-
SPHÄRE
Tropopause
Mount Everest
Montblanc
TROPOSPHÄRE
„freie Atmosphäre"
- Peplopause -
„atmosphärische Grenzschicht"
Temperatur
Höhe in km
100
50
20
10
5
1
T [°C]
-100°
-80°
-60°
-40°
-20°
0°
z
Gradientenwind $\overline{u}_G$
Gradientenhöhe
z_G
mittlere
Windgeschwindigkeit
$\overline{u}(z)$
Ekman-Schicht
Turbulenzintensität
$I_u(z) = \frac{\sigma_u(z)}{\overline{u}(z)}$
Schubspannung
$\tau_o(z)$
~100 m
Prandtl-Schicht
τ_o = const.
$\overline{u}, I_u, \tau_o$

The natural wind

$$\bar{u} = \begin{bmatrix} U(z) + u(x,y,z,t) \\ v(x,y,z,t) \\ w(x,y,z,t) \end{bmatrix} \qquad U(z) = u_* \frac{1}{\kappa} \ln\left[\frac{z-d}{z_0}\right]$$

- Mean wind velocity U(z) as logarithmic profile over the height (exponential in some design codes)
- Three turbulence components

Wind profiles

- Deaves & Harris (ISO)

$$\bar{u}(z) = \frac{u_*}{\kappa}\left[\ln\left(\frac{z-d_0}{z_0}\right) + 5.75\cdot\left(\frac{z-d_0}{z_g}\right) - 1.88\cdot\left(\frac{z-d_0}{z_g}\right)^2 - 1.33\cdot\left(\frac{z-d_0}{z_g}\right)^3 + 0.25\cdot\left(\frac{z-d_0}{z_g}\right)^4\right]$$

- Potential Law

$$\bar{u}(z) = \bar{u}_{ref}\cdot\left(\frac{z-d_0}{z_{ref}-d_0}\right)^{\alpha}$$

Turbulence intensities

(Standard deviation / mean wind speed)

$$I_u(z) = \frac{\sigma_u(z)}{U(z)} \quad I_v(z) = \frac{\sigma_v(z)}{U(z)} \quad I_w(z) = \frac{\sigma_w(z)}{U(z)}$$

- Armitt / Hansen:

$$\sigma_u = A \cdot u_* \quad \sigma_v \approx 0.75 \cdot \sigma_u \quad \sigma_w \approx 0.50 \cdot \sigma_u$$

A ≈ 2.5 for z_0= 0.05 m und A ≈ 1.8 for z_0= 0.30 m

- Panofsky / Dutton:

$$\sigma_u = 2.39 \cdot u_* \quad \sigma_v \approx 0.80 \cdot \sigma_u \quad \sigma_w \approx 0.52 \cdot \sigma_u$$

Turbulence intensities II

- Simiu: $\sigma_u^2 = \beta \cdot u_*^2$

z_0[m]	0.005	0.07	0.30	1.00	2.50	
β	6.5	6.0	5.25	4.85	4.00	
√β	2.55	2.45	2.29	2.20	2.00	

Turbulence intensities in the design code

$$I_v(z) = \frac{\sigma_v}{v_m(z)} = \frac{k_I}{c_0(z) \cdot \ln(z / z_0)}$$

EN 1991-1-4 (4.7)
k_I = 1.0 ≡ A = 2.5

Terrain category	I	II	III	IV
z_0[m]	0.01	0.05	0.30	1.05
σ_u/v_b	0.165	0.19	0.22	0.24
ε	0.13	0.26	0.37	0.46

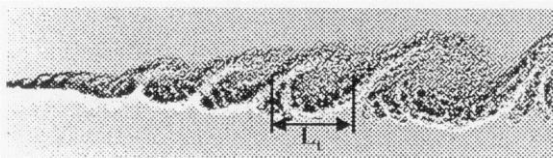
Windprofiles DIN EN 1991-1-4 NA.B/C ⇒ σ_u = const

Integral Length and Time Measures

$$T(z) = \int_0^{\infty} \rho_u^T(z,\tau)\, d\tau$$

$$L_u^x = \int_0^{\infty} \rho_u(z, r_x)\, dr_x$$

$$\rho_u^T(z,\tau) \approx \exp\left(\frac{-\tau}{T(z)}\right)$$



9 different Length measures!

- Counihan:

$$L_u^x = C \cdot z^m \qquad L_u^y \approx 0.33 \cdot L_u^x \qquad L_u^z \approx 0.50 \cdot L_u^x$$

- Simu:

$$L_u^x \approx L_{10} \cdot \left(\frac{z}{z_{10}}\right)^{0.3} \qquad L_u^y \approx 0.30 \cdot L_u^x \qquad L_u^z \approx 0.20 \cdot L_u^x$$

Integral Length Measure in the Design Code

EN 1991-1-4 Appendix B.1

$$L(z) \approx L_t \cdot \left(\frac{z}{z_t} \right)^{\alpha} \qquad L_t = 300\,m\ ;\ z_t = 200\,m \qquad \alpha = 0.67 + 0.05 \cdot \ln(z_0)$$

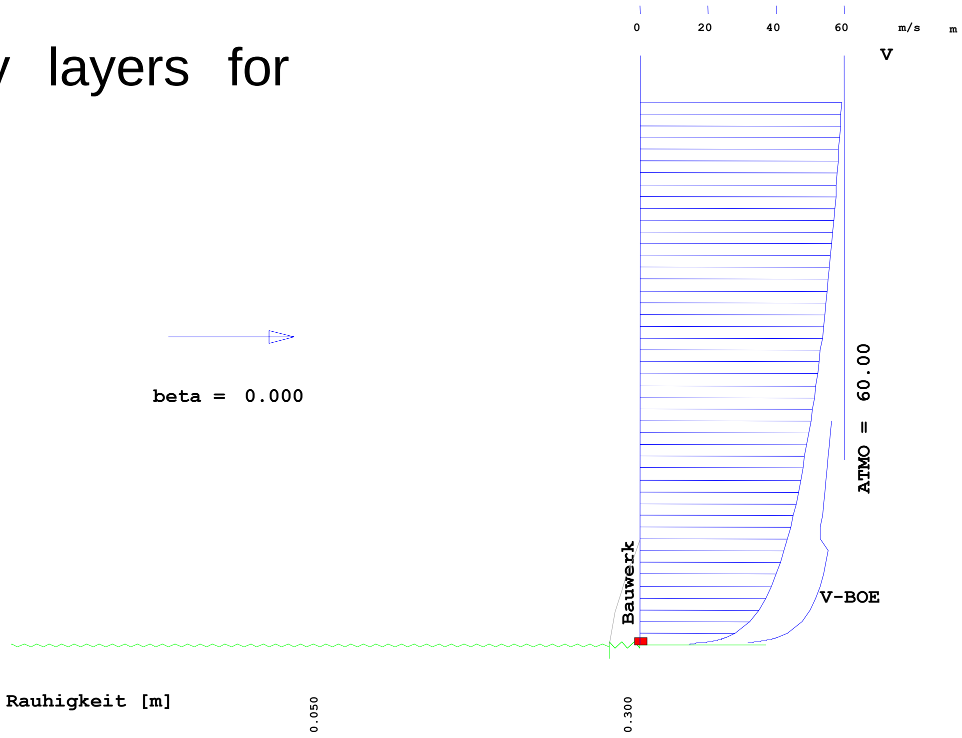
Windprofile DIN EN 1991-1-4 NA/C

$$L(z) = 300 \cdot \left(\frac{z}{300} \right)^{\varepsilon} \qquad \varepsilon = see\,Table 1$$

Local Wind depending on Terrain

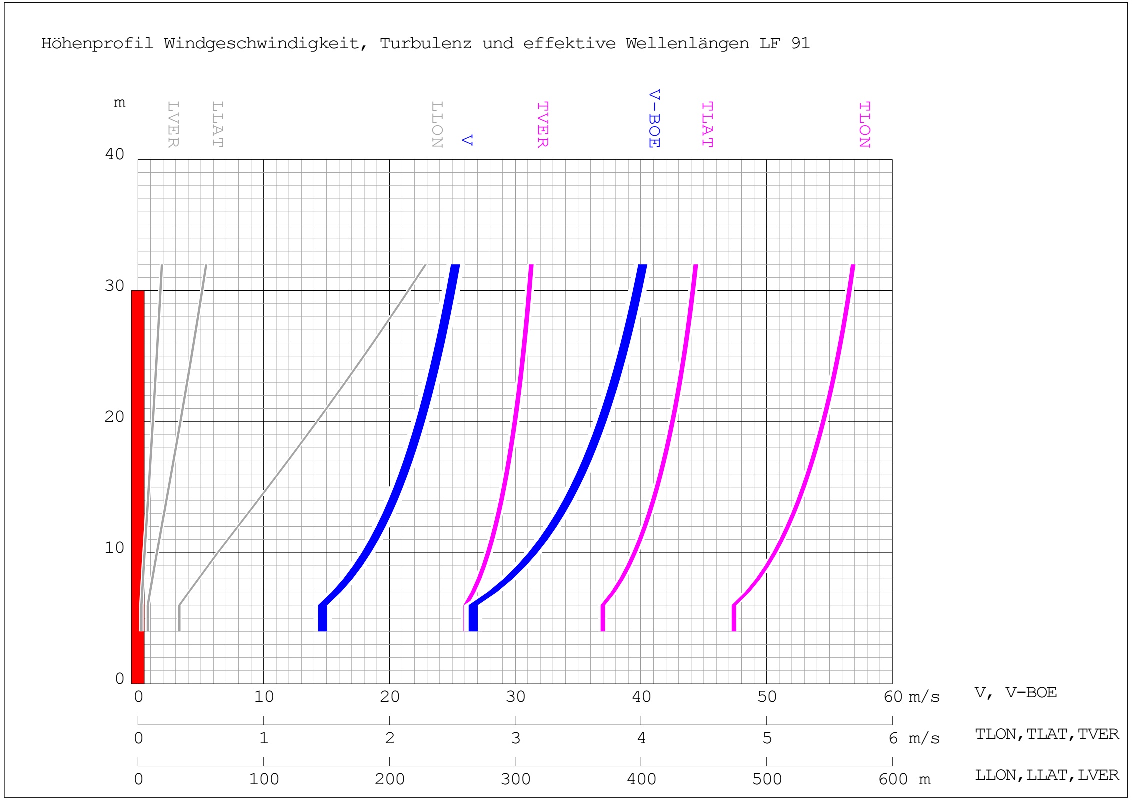
Superposition of Boundary layers for every change of roughness:

- Mean Wind speeds
- 3 sec Gust Peak values



- Turbulence intensities
- Effective Wave length (Integral measures)

Lower Wind profile



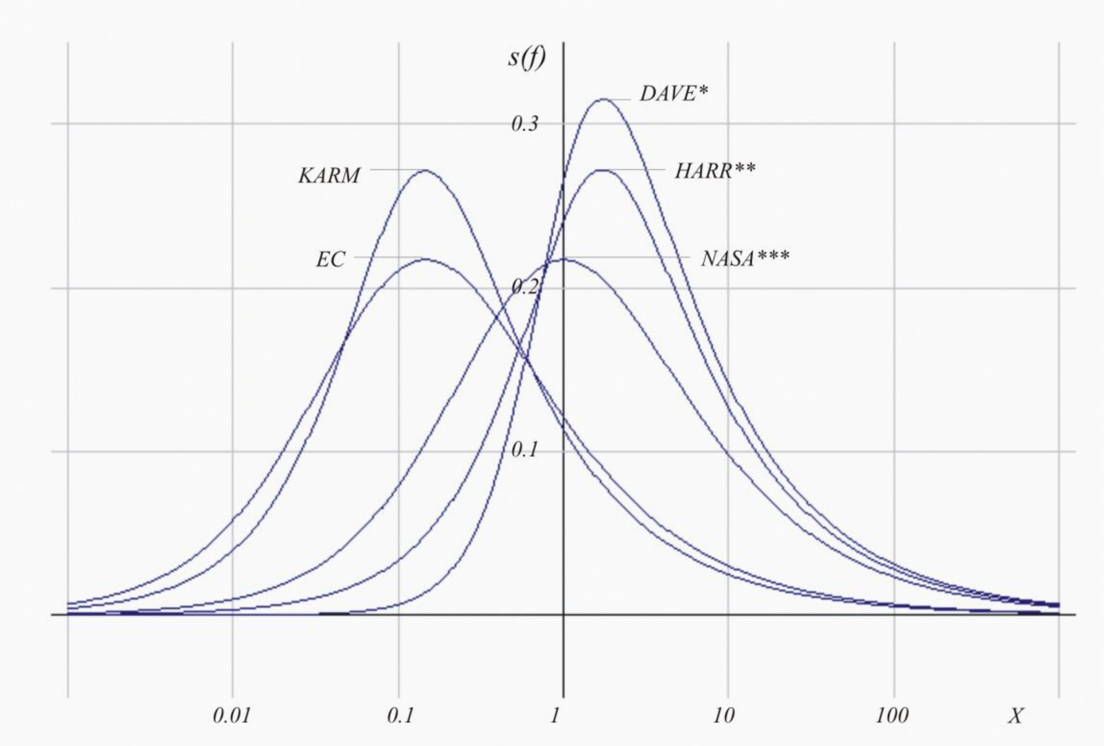
Wind profiles in Design Codes

- Category 0 to IV according to Eurocode
- Mixed profiles for rural and coastal regions in DIN
- Provisions for
  - Wind pressure
  - Mean wind speed
  - Gust Speed = max. Design Pressure
  - Longitudinal Turbulence Intensity
  - Longitudinal Integral Length Scale
- Simplified constant wind loadings on the save side

Wind profiles

- Continuous function of speed and pressure along the height:
- For rural regions the gust wind is given :
  - For $z \leq 7$ m: $q(z) = 1{,}5\ q_{ref}$
  - For $7\ m < z \leq 50$ m: $q(z) = 1{,}7\ q_{ref}\ (z/10)^{0{,}37}$
  - For $50\ m < z \leq 300$ m: $q(z) = 2{,}1\ q_{ref}(z/10)^{0{,}24}$
- For costal regions the gust wind speed is given :
  - For $z \leq 4$ m: $q(z) = 1{,}8\ q_{ref}$
  - For $4\ m < z \leq 50$ m: $q(z) = 2{,}3\ q_{ref}\ (z/10)^{0{,}27}$
  - For $50\ m < z \leq 300$ m: $q(z) = 2{,}6\ q_{ref}(z/10)^{0{,}19}$

Wind-Spectra



Wind-Spectra

$$\frac{f \times S}{\sigma^2} = \frac{a_1 \times X + a_2 \times X^2 + a_3 \times X^3}{\left(1 + b \times X^c\right)^d} \; ; \; X = \frac{f}{f_0} = \frac{f \times L}{V}$$

	a1	a2	a3	b	c	d	X
Karman longitudinal	4.000	0.0	0.0	70.8	2	5/6	$f \cdot L/v$
Karman lateral	4.000	0.0	3021	283.0	2	11/6	$f \cdot L/v$
CEN	6.800	0.0	0.0	10.2	1	5/3	$f \cdot L/v$
Davenport	0.0	0.667	0.0	1.0	2	4/3	$\frac{1200 \cdot f}{v(10)}$
Harris	0.374	0.0	0.0	0.5	2	5/6	$\frac{1800 \cdot f}{v(10)}$
Kaimal	33.33	0.0	0.0	50.0	1	5/3	$f \cdot z/v$
Kaimal lateral	2.50	0.0	0.0	9.5	1	5/3	$f \cdot z/v$
Panofsky Lumely	0.56	0.0	0.0	10.0	5/3	1	$f \cdot z/v$
Fichtl/McVehil	54.38	0.0	0.0	36.5	0.845	5/3c	$f \cdot z/v$
Fichtl/McVehil lat	66.17	0.0	0.0	30.5	0.781	5/3c	$f \cdot z/v$

Spectral Analysis

- Spectra are defined deterministic Energetic quantities for selected frequencies.
- Each frequency of a structure may be exited with a value derived from the spectra

$$S_y(f) = |\alpha_a|^2 \times |\alpha_m|^2 \times S_{`z}(f)$$

$$\alpha_a = aerodynamic\ transfer\ function$$

$$\alpha_m = mechanical\ transfer\ function$$

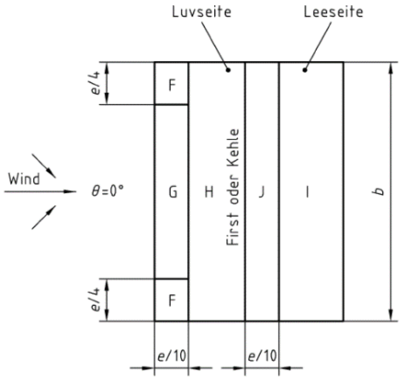
Spectral Analysis

- But for the superposition of the individual modes we have a random effect introduced by the phase of the response.
- Coherencies (Kohärenzen) define how similar are two wind loadings at neighboured locations.
- Mathematics not easy, some key words to search for:
  - Autocorrelation function
  - Normal distribution / Weibull-distribution

Time History Analysis

- From the spectra and coherences we may generate time histories for the wind speed at every point via a Fourier transformation and a random generator.
- This wind is acting on our structure.
- All non linear effects may be accounted for.
- You see what happens (Animated movements)
- „Tuned mass dampers“ (Tilger) are easy to include.
- To assure the safety of the structure several independent transient runs are needed.

Wind pressure coefficients



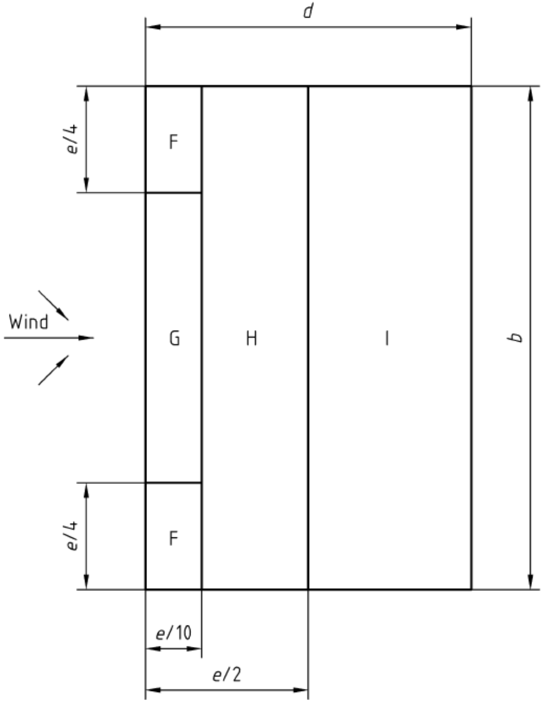
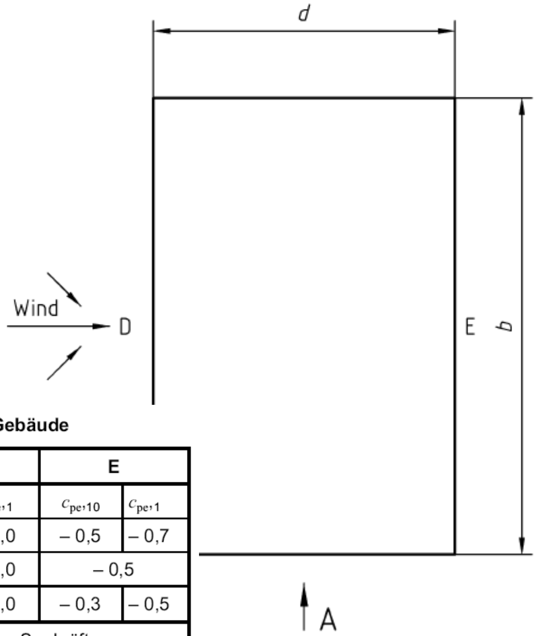


Tabelle 6 — Außendruckbeiwerte für Sattel- und Trogdächer

Anströmrichtung $\theta = 0°$										
Neigungswinkel α	Bereich F		G		H		I		J	
	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
–45°	– 0,6		– 0,6		– 0,8		– 0,7		– 1,0	– 1,5
–30°	– 1,1	– 2,0	– 0,8	– 1,5	– 0,8		– 0,6		– 0,8	– 1,4
– 15°	– 2,5	– 2,8	– 1,3	– 2,0	– 0,9	– 1,2	– 0,5		– 0,7	– 1,2
–5°	– 2,3	– 2,5	– 1,2	– 2,0	– 0,8	– 1,2	– 0,6 / + 0,2		– 0,6 / + 0,2	
5°	– 1,7	– 2,5	– 1,2	– 2,0	– 0,6	– 1,2	– 0,6 / + 0,2		– 0,6 / + 0,2	
10°	– 1,3	– 2,2	– 1,0	– 1,7	– 0,4		– 0,5 / + 0,2		– 0,8	+ 0,2
15°	– 0,9	– 2,0	– 0,8	– 1,5	– 0,3		– 0,4		– 1,0	– 1,5
	+ 0,2		+ 0,2		+ 0,2					
30°	– 0,5	– 1,5	– 0,5	– 1,5	– 0,2		– 0,4		– 0,5	
	+ 0,7		+ 0,7		+ 0,4					
45°	+ 0,7		+ 0,7		+ 0,6		– 0,4		– 0,5	
60°	+ 0,7		+ 0,7		+ 0,7		– 0,4		– 0,5	
75°	+ 0,8		+ 0,8		+ 0,8		– 0,4		– 0,5	

Wind pressure coefficients



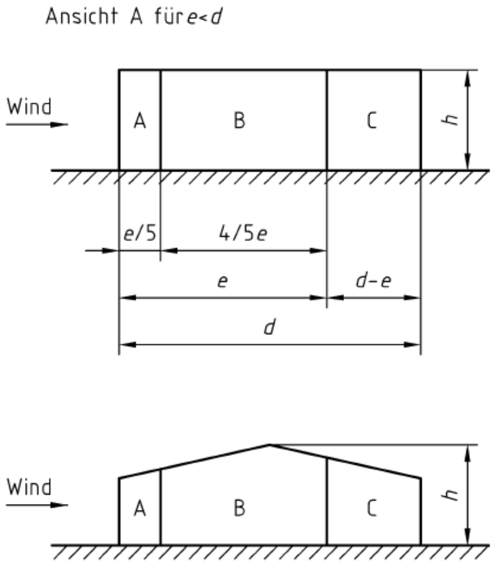


Tabelle 3 — Außendruckbeiwerte für vertikale Wände rechteckiger Gebäude

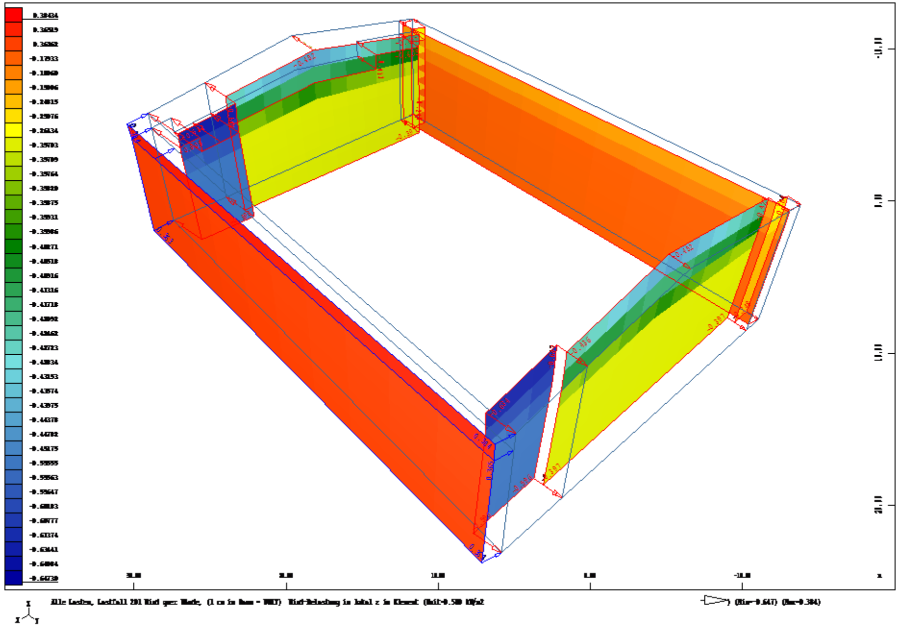
Bereich	A		B		C		D		E	
h/d	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
≥ 5	– 1,4	– 1,7	– 0,8	– 1,1	– 0,5	– 0,7	– 0,8	+1,0	– 0,5	– 0,7
1	– 1,2	– 1,4	– 0,8	– 1,1	– 0,5		– 0,8	+1,0	– 0,5	
≤ 0,25	– 1,2	– 1,4	– 0,8	– 1,1	– 0,5		– 0,7	+1,0	– 0,3	– 0,5

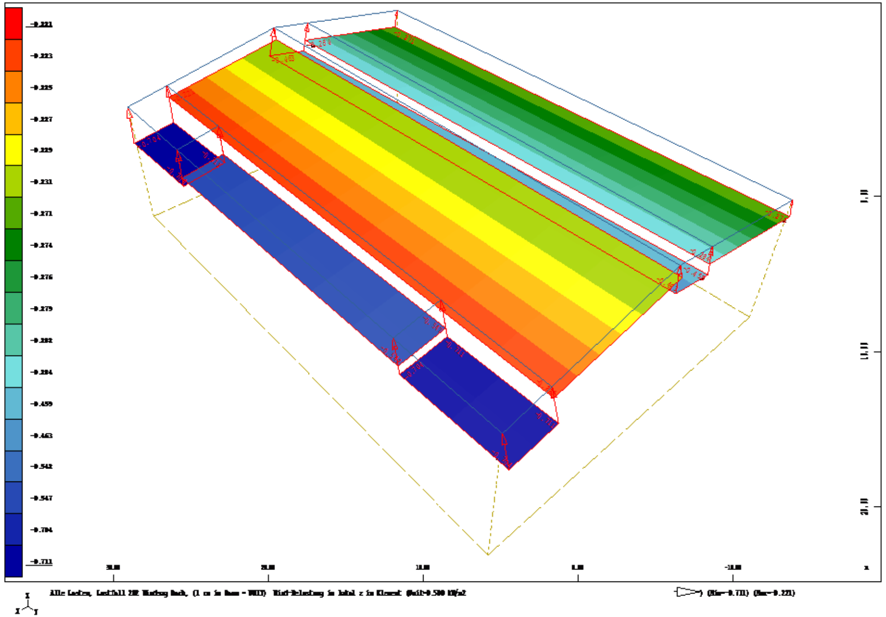
Für einzeln in offenem Gelände stehende Gebäude können im Sogbereich auch größere Sogkräfte auftreten.

Zwischenwerte dürfen linear interpoliert werden.

Für Gebäude mit $h/d > 5$ ist die Gesamtwindlast anhand der Kraftbeiwerte aus 12.4 bis 12.6 und 12.7.1 zu ermitteln.

Wind on walls and roofs like this ?





Wind pressure coefficients
The missing link !

- Current Steps for a wind analysis:
  - Profile of wind along the height and Spectra
  - Pressure coefficients from literature or wind tunnel (transient in general)
  - Instability effects (Buffeting, Flutter etc.)
- A CFD analysis could model the last two steps.
- However this requires considerable effort and experts argue, that they are not reliable at all.
- Robust methods should yield “acceptable” results even for coarse meshes!

Motivation for CFD

Area	Computational Method	Experimental Method
Capability	Software used for all flow types, Turbulences rarely resolved, Enables physical situation to be modeled, Allows quick geometry variation	Experiments seen as being the „real thing“ Exact simulation only at „full-scale“ Scale effects can lead to experimental situation also being a model of the desired flow situation
Accuracy	Depends on algorithms used, Depends on mesh density	Should be correct within the limits of experimental error if geometry and scale effects are realistic and equipment is appropriate designed and calibrated
Detail	All variables calculated at every mesh or point; Variables can be integrated to find overall properties	Easy to find overall properties such as pressure drops and forces and moments, Difficult and expensive to instrument for more than only crude data production
Cost	Requires relatively cheap hardware but expensive software, Time and care needed to get good results, Specialist required to achieve good results	Instrumentation expensive in many cases Raw experiments cheap to carry out but data achieved is very limited, Time and care needed to get good results
Time	Solution may take long iteration time, Dependency is the problem being solved and the computer speed	Time needed for set-up and calibrate Results usually quick to obtain once this is done

From: CFD Round Table Madrid 2007

A Bad Example for a Wind Tunnel Test

Vela Hotel
M.O.Cornejo
F.M. Mato
IDEAM S.A.
IABSE 2010

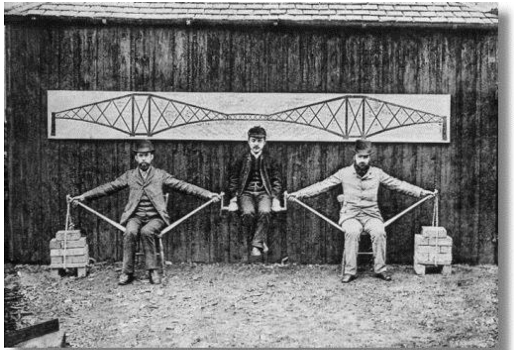
No boundary layer
Blockage to high
CFD used instead

Firth of Tay
Insufficient Design and Workmanship

(28.12.1879, after train passing at 11-12 Bft)

Bridge over Firth of Forth

Consequence:
The bridge over the Firth of Forth has been designed on the safe side (i.e. 5-times) Wind loading.



Basic Equations for Fluid Dynamics

- Fluid Dynamics = Many Formulas !?
- Mass, Density (also buoyancy for thermal problems)
- Compressibility (may be neglected in many cases)
- Conservation of mass, energy and momentum
- e.g. law of Bernoulli derived from conservation of energy:

$$p + \frac{\rho}{2} \cdot u^2 + \rho \cdot g \cdot z = const$$

Scales of Forces of Fluids on Bodies

- Inertial force

$$F_i \approx 1/2 \cdot \rho \cdot A \cdot U^2 \approx \rho \cdot l^2 \cdot U^2$$

- Viscous force

$$F_v \approx \mu \cdot S \cdot dU/dH \approx \mu \cdot l \cdot U$$

- Gravitational force

$$F_g \approx \rho \cdot g \cdot V \approx \rho \cdot g \cdot l^3$$

- Froude Number $F^2 = F_i / F_g = U^2/(gl)$
- Reynolds Number $Re = F_i / F_v = \rho \cdot U \cdot l / \mu$

Viscosity - Reynolds number

$$\mathrm{Re} = \frac{d \cdot u}{\nu} = \frac{d \cdot \rho \cdot u}{\mu}$$

$$\nu = kinematic\,Viscosity$$

$$\mu = dynamic\,Viscosity$$

$$Air \quad \nu = 15 \cdot 10^{-6}\,\frac{m^2}{\sec} \quad ; \quad Water \quad \nu = 1.31 \cdot 10^{-6}\,\frac{m^2}{\sec}$$

Ground water:

d = 0.001 ; u = 0.01 Re = 10

Aerodynamics:

d = 10 ; u = 15 Re = 10^7

Navier-Stokes-Equation

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_j u_i)}{\partial x_j} = \frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial}{\partial x_i}\left(p + \frac{2}{3}\mu\frac{\partial u_j}{\partial x_j}\right) + \rho g_i$$

u = Velocity

ρ = Density

τ = Reynold Shear stress => turbulent viscosity

p = Pressure

μ = dynamic Viscosity

Overview

- RANS
  Reynolds Averaged Navier Stokes
  - Complete Model of Turbulence, very effective
- LES
  Large Eddy Simulation
  - Model small scales, calculate large scales
- DNS
  Direct Solution of Navier Stokes-Equations
  - Calculate all effects, limited to low Reynold numbers < 20000

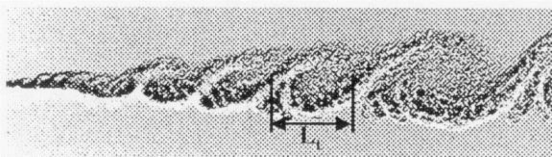
Turbulence modelling

$$u(t) = \overline{u_i} + u_x^{'}(t)$$

- **Kinetic Energy of turbulence k [m²/sec²]**

$$k = \frac{1}{2}\overline{u_i^{'}u_i^{'}} = \frac{1}{2}\left[(U \cdot I_x)^2 + (U \cdot I_y)^2 + (U \cdot I_z)^2\right] \approx 0.9 \cdot (U \cdot I_x)^2$$

- Length Scale L_t



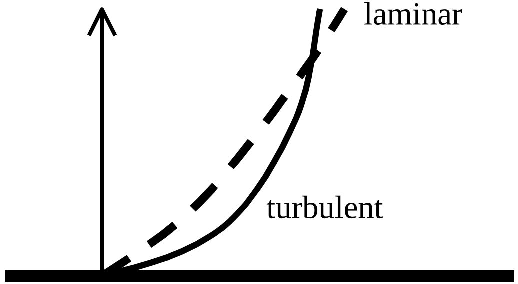
- **Dissipation rate ε [m²/sec³] or Frequency [1/sec]**

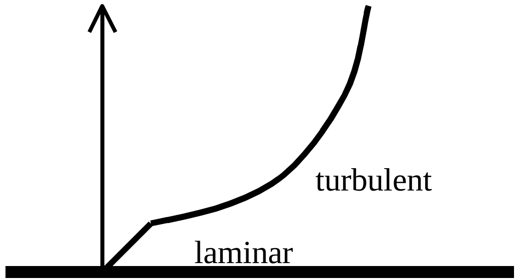
$$\varepsilon \approx 0.168 \cdot \frac{k^{3/2}}{L_t} \qquad \omega = \frac{k^{1/2}}{L_t}$$

Boundary Conditions

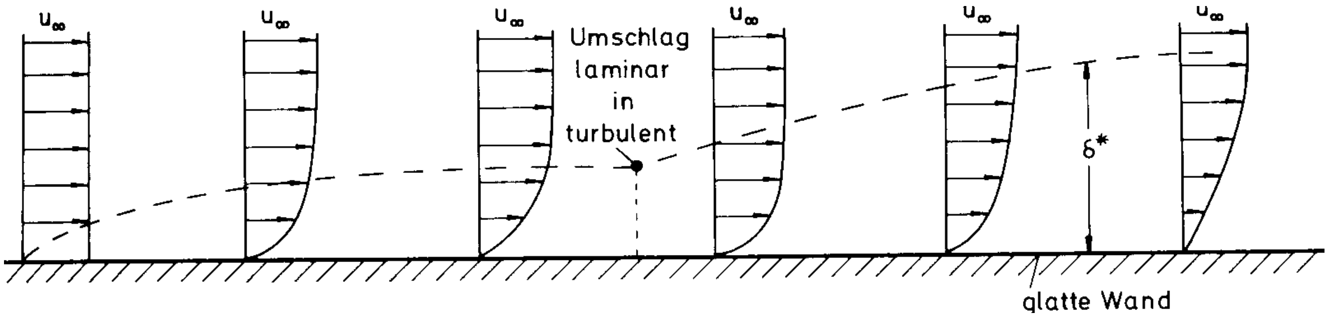
- Inflow u (= supported Edge in statics)
- Smooth Boundary Rand ∂u/∂n (= free edge in statics)
- Wall with friction

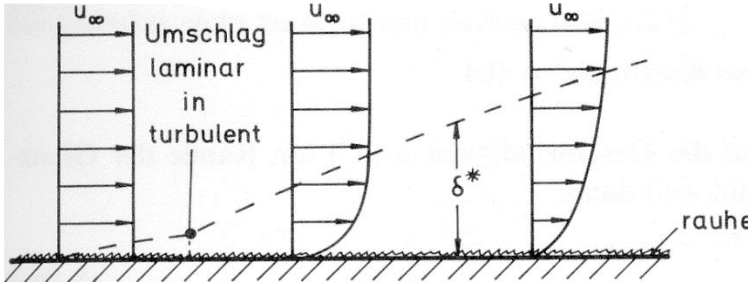
$$\frac{du}{dz} = \frac{\tau}{\eta} = \frac{\tau}{\nu \cdot \rho} = \frac{Shearstress}{Viscosity}$$



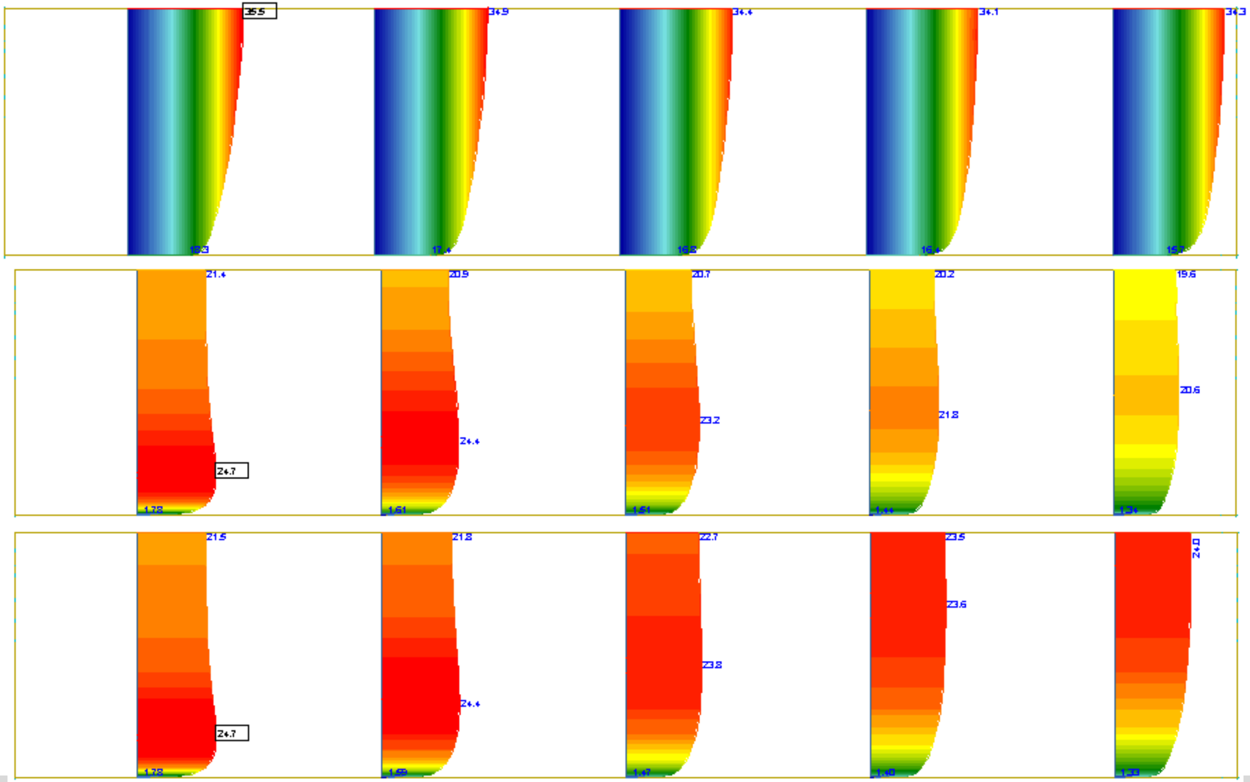


Boundary Layer





Boundary Layer is not easy !



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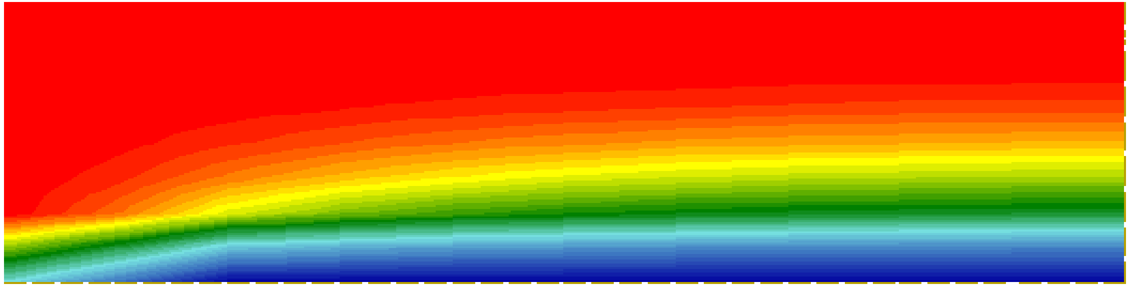
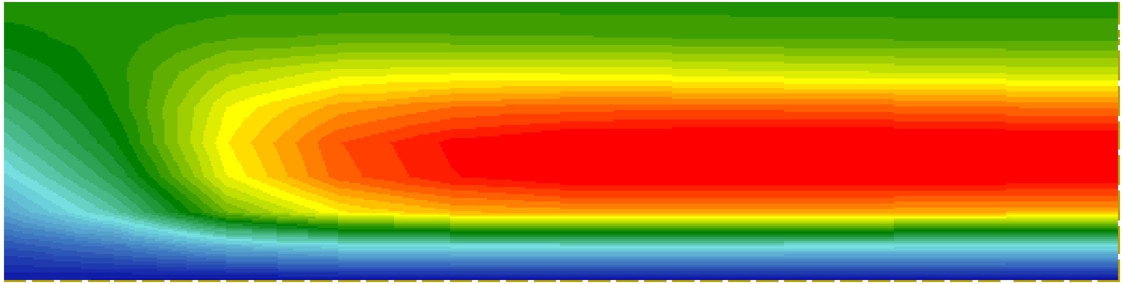
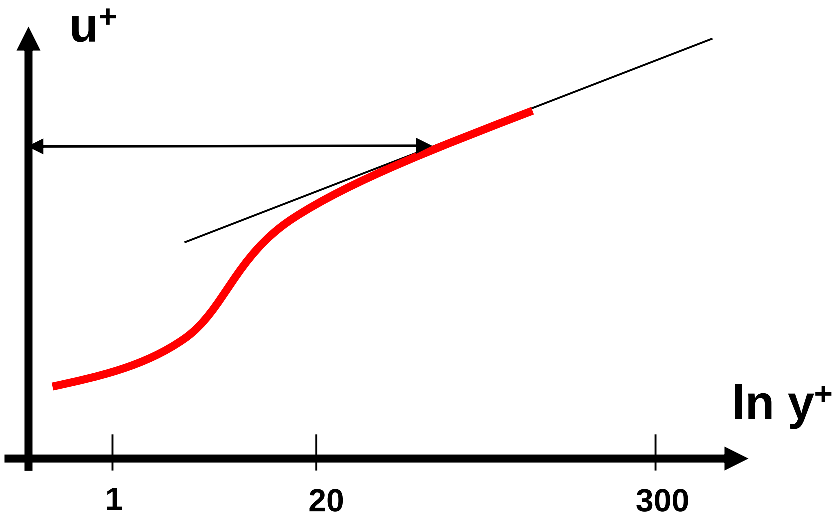
Modelling errors with a boundary layer

- Turbulent energy for same input velocity but different turbulent parameters:





Logarithmic Wall Law



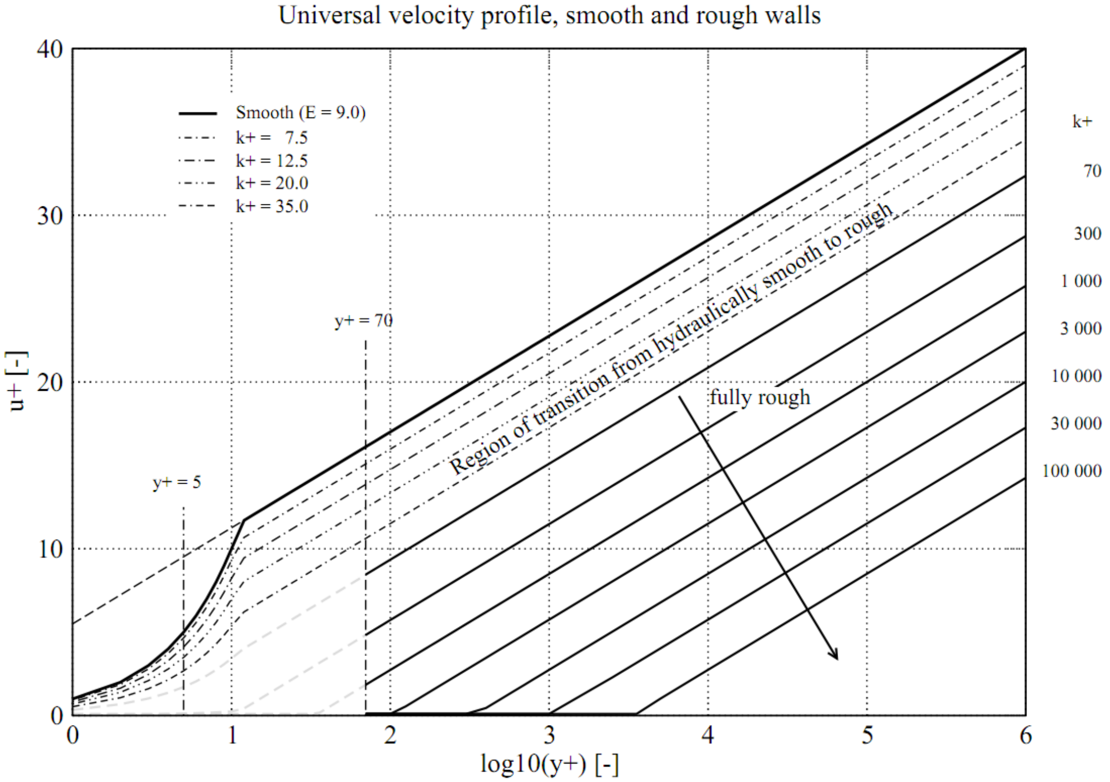
$$\frac{u(z)}{u^*} = \frac{1}{k}\ln\left(Ey^+\right)$$

$$u^* = \sqrt{\tau / \rho}$$

$$y^+ = \frac{y}{\delta} = \frac{y}{u^* \cdot \nu}$$

- Near Wall models $y^+<1$ (k-ω)
- Far Wall models $y^+>20$ (k-ε)
- Mixed models

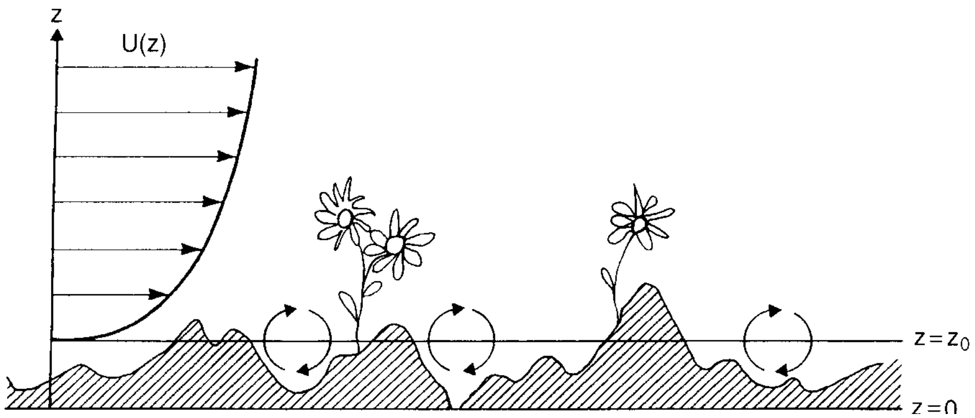
The full picture



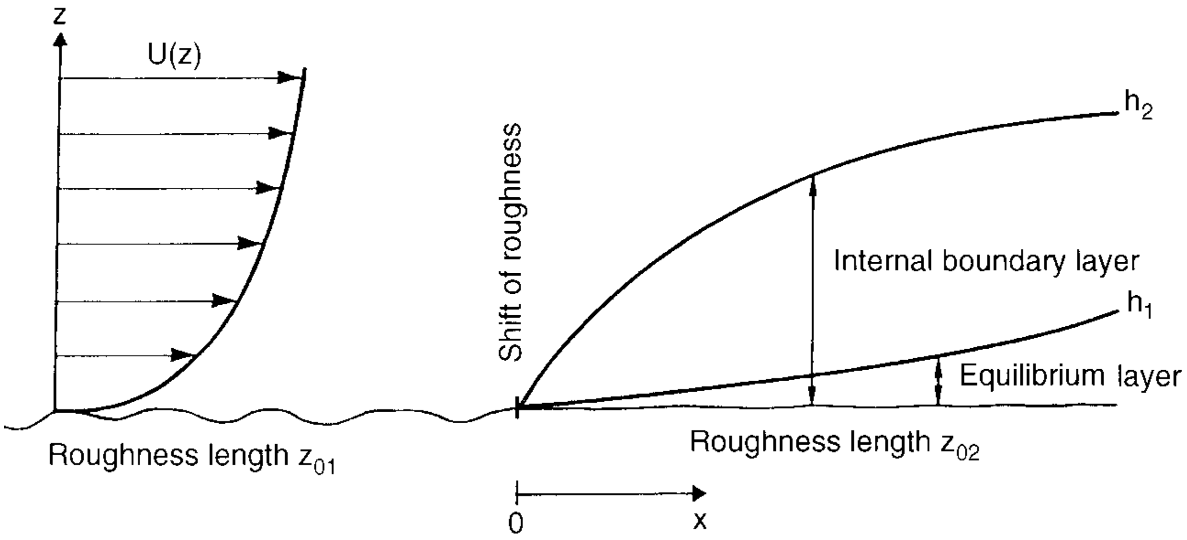
Logarithmic wall law versus wind profiles

$$\frac{u(z)}{u^*} = \frac{1}{k}\ln\left(\frac{z}{z_0}\right) = \frac{1}{k}\ln\left(Ey^+\right)$$

$$u^* = \sqrt{\tau / \rho}$$



Boundary Layer and change of roughness



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Problem of the atmospheric boundary layer

- There are two common velocity distributions
  - Exponential $v = v_{ref} * (z/z_0)^{\alpha}$
  - Logarithmic $v = v_{ref} * \ln (z/z_0)$
- We need sound values for turbulent k and ε
- There is an analytic solution for k-ε !

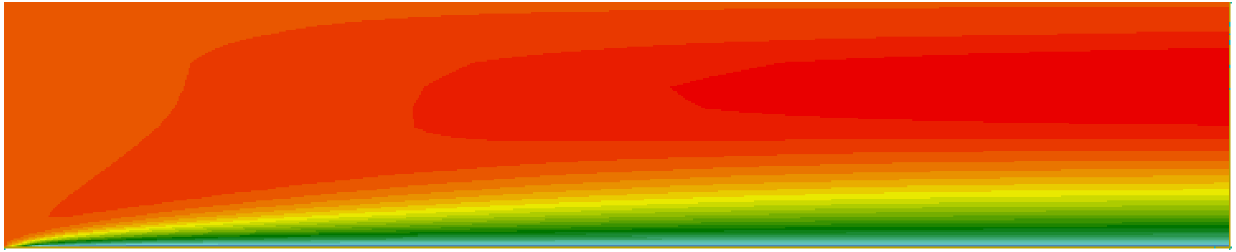
$$u(z) = \frac{u^*_{ABL}}{\kappa} \ln\left(\frac{z + z_0}{z_0}\right)$$

$$k(z) = \frac{u^{*2}_{ABL}}{\sqrt{C_\mu}}$$

$$\varepsilon(z) = \frac{u^{*3}_{ABL}}{\kappa\left(z + z_0\right)}$$

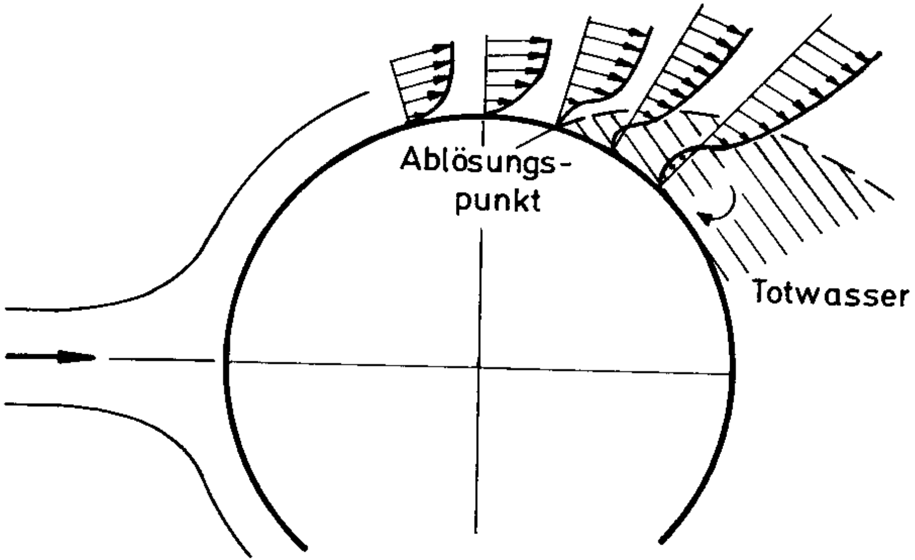
Modelling with the analytic solution

- Boundary condition at top required
- There is a new boundary layer for small elements

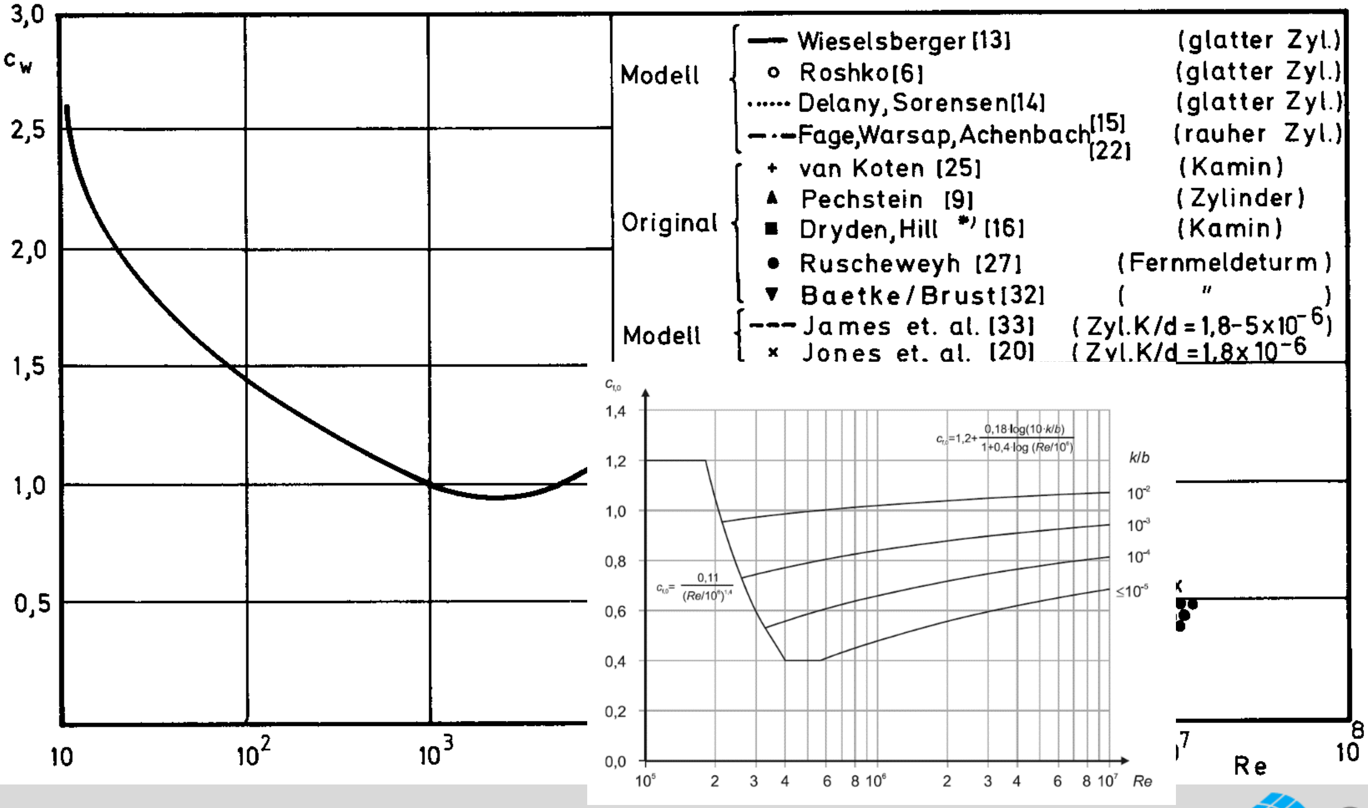


Detachment

- Stall point
- Accelerated Flow
- Retarded Flow
- Pressure increase
- Detachment
- Reattachment



Drag coefficients for Cylinder



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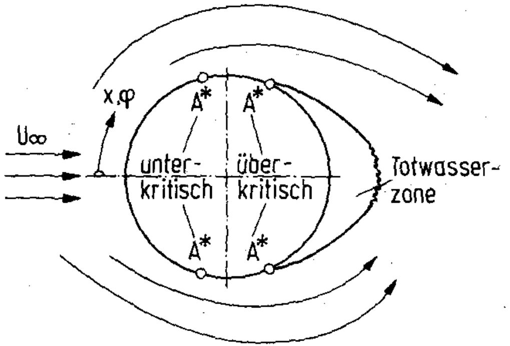
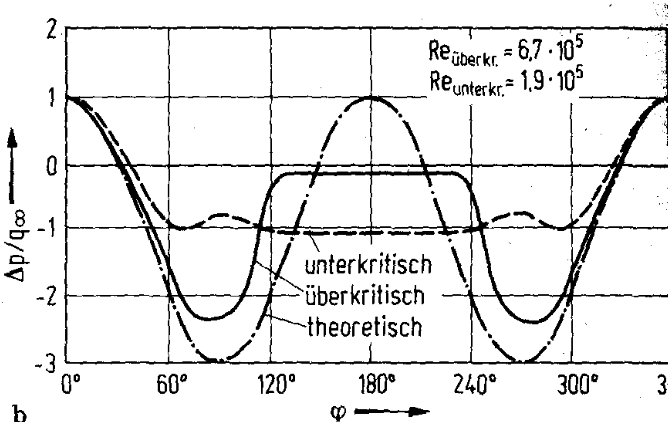
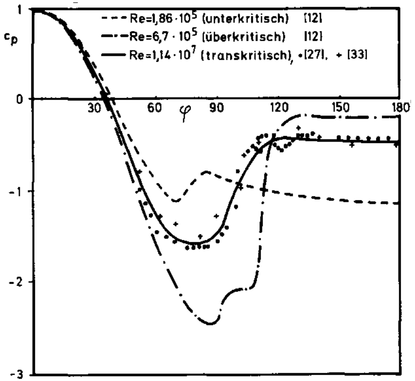
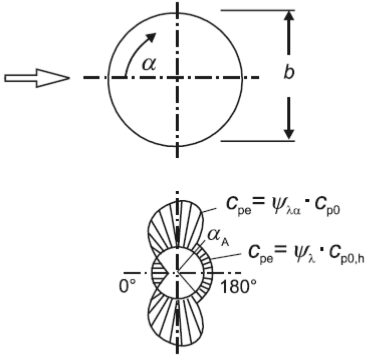
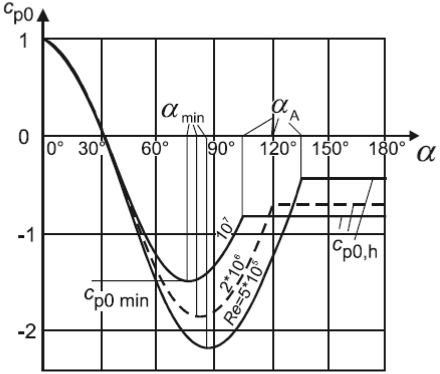
Flow + Pressures











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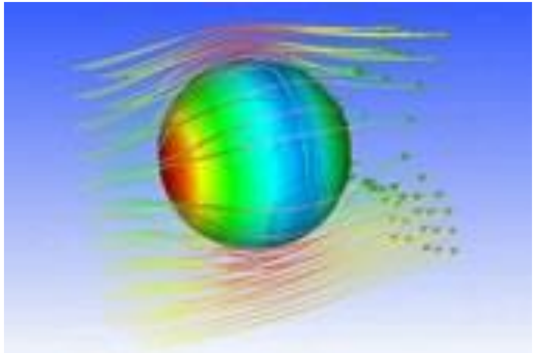
Mesh sensitivity (Reynolds Number = 100)

Level	Volume element	Time steps	Cd	Cl	S	D-p	CPU
2	552	500	2.28	-0.002	-	1.566	9
3	2208	500	2.96	-0.020	0.210	2.122	1205
4	8832	1000	3.12	0.877	0.261	2.610	20443
4	8832	500	2.97	0.558	0.263	2.331	32324
4	8832	200	2.96	-0.014	-	2.278	11982
Refer.			3.23	1.100	0.300	2.480	

Cylinder Crisis

- Low Reynolds Flow
  Pressure before equals approximately pressure behind: drag mainly caused by friction
- With increasing Reynolds numbers, shear forces become less
- Detachment
  we have a suction at the end of the cylinder
  thus a resulting force from pressure
- Reattachment
  A positive pressure reduces the drag coefficient

Teamgeist

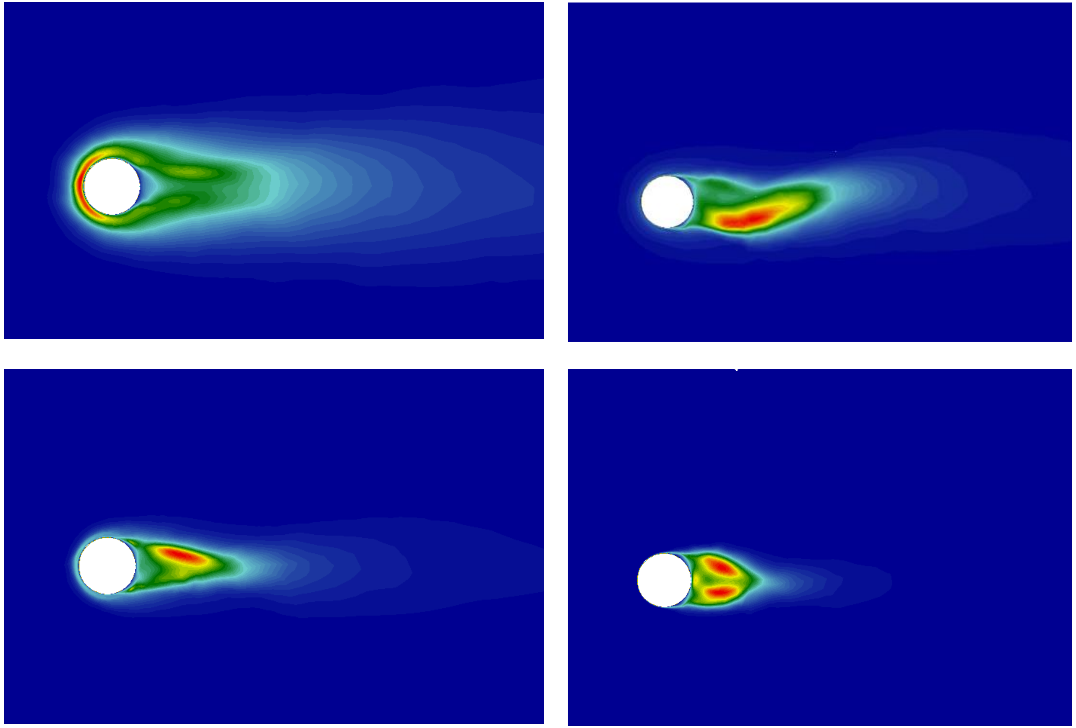


- Analogue for spheres
- A foot ball will be shot in the trans critical region
- If it becomes slower the drag coefficient will raise quite suddenly, the ball will drop down.
- The optimisation of the roughness of the ball to achieve the best curve for a goal keeper shot is a really difficult task.

Turbulence models RANS

- Variants
  - Standard k-ε Model
  - ReNormalisation Group k-ε Model (RNG)
  - k-ε Model according Murakami, Mochida and Kondo (MMK)
  - Standard k-ω model
  - SST model (Mixture from k-ε model and k-ω model)
- Remarks
  - For the k-ε model the boundary layer is described by a wall law $y^+ > 30$
  - For the k-ω model the boundary layer is resolved $y^+ < 1$ (the finer the better)
  - Meshes are sensitive to the geometric shape, hybrid meshes are strongly recommended

Comparison Turbulence model
Standard - RNG



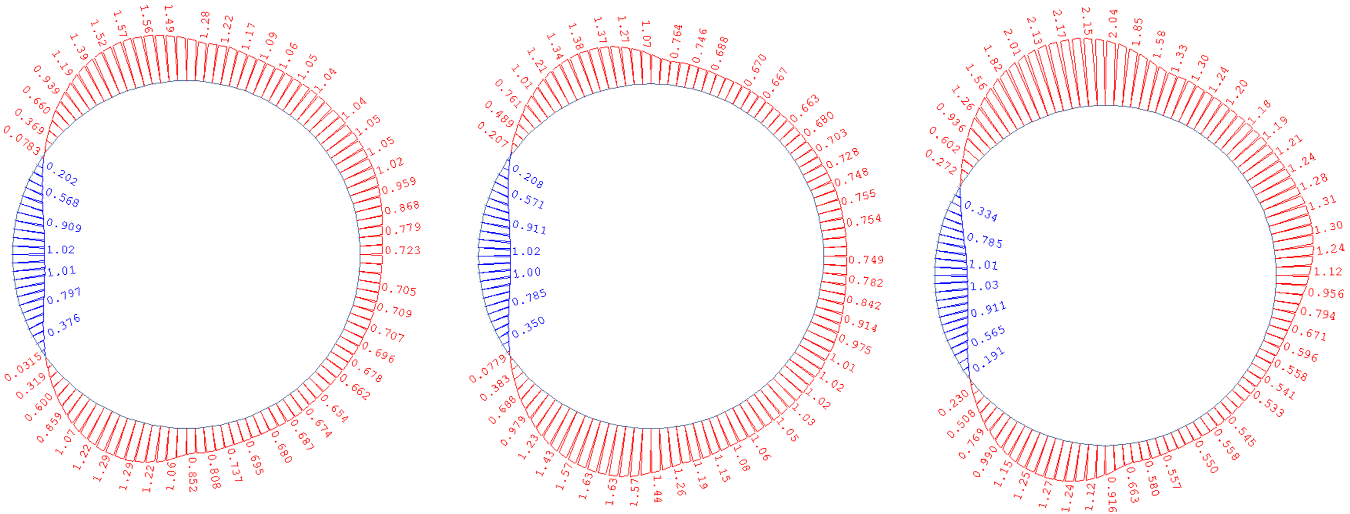
Turb. Energy

Re = 186000

Turb. Energy

Re = 670000

Pressures
Re = 0.186 / 0.670 / 11.400 • 10^6



Results Re = 46 500

Pressures for cylinder								
	4 % blockage				**1 % blockage**			
	Cd	cp-luv	cp-min	cp-lee	Cd	cp-luv	cp-min	cp-lee
Reference	1,200	-1,00	1,29	1,25				
k-ε standard	0,720	-1,03	1,66	0,60	0,673	-1,05	1,54	0,51
k-ε RNG	0,916	-1,02	1,16	0,77	0,839	-1,02	1,25	0,63
k-ε MMK	0,791	-1,01	1,50	0,66	0,735	-1,02	1,40	0,57
k-ω	0,424	-1,02	2,31	0,42				

Results Re = 186 000

Pressures for cylinder								
	4 % blockage				1 % blockage			
	Cd	cp-luv	cp-min	cp-lee	Cd	cp-luv	cp-min	cp-lee
Reference	1,200	-1,00	1,10	1,20				
k-ε standard	0,590	-1,08	1,96	0,46	0,563	-1,09	1,87	0,40
k-ε RNG	0,895	-1,02	1,57	0,72	0,796	-1,03	1,25	0,60
k-ε MMK	0,745	-1,02	1,61	0,64	0,701	-1,03	1,45	0,55
k-ω	0,429	-1,09	2,30	0,32				

Results Re = 670 000

Pressures for cylinder								
	4 % blockage				1 % blockage			
	Cd	cp-luv	cp-min	cp-lee	Cd	cp-luv	cp-min	cp-lee
Reference	0,42-1,00	-1,00	2,45	0,20				
k-ε standard	0,540	-1,08	2,08	0,39	0,517	-1,10	2,00	0,34
k-ε RNG	0,878	-1,02	1,63	0,75	0,779	-1,03	1,39	0,60
k-ε MMK	0,724	-1,02	1,69	0,62	0,675	-1,03	1,52	0,53
k-ω	0,391	-1,10	2,40	0,22				

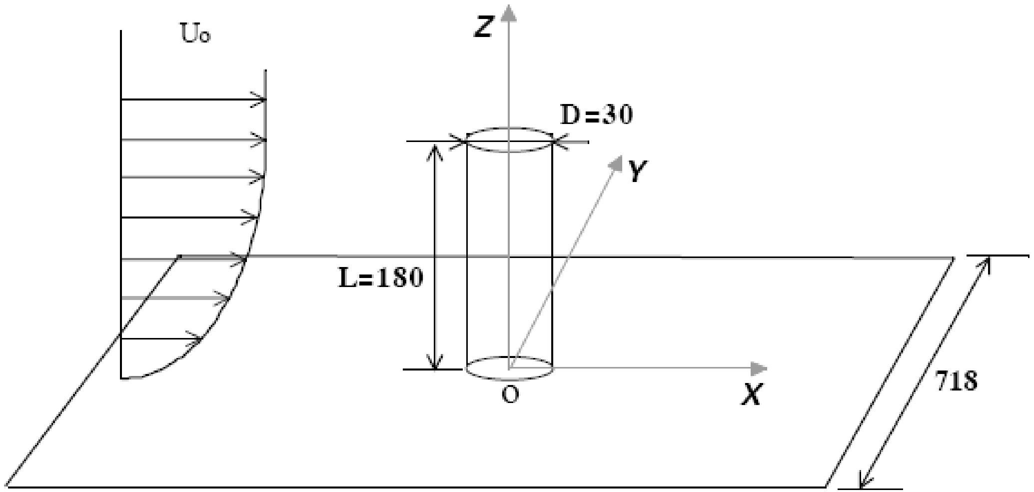
Results Re = 11 400 000

Pressures for cylinder								
	4 % blockage				**1 % blockage**			
	Cd	cp-luv	cp-min	cp-lee	Cd	cp-luv	cp-min	cp-lee
Reference	0,63-1,04	-1,00	1,55	0,50				
k-ε standard	0,474	-1,08	2,24	0,27	0,458	-1,10	2,15	0,21
k-ε RNG	0,933	-1,02	1,72	0,96	0,725	-1,03	1,55	0,55
k-ε MMK	0,650	-1,02	1,82	0,58	0,622	-1,02	1,66	0,51
k-ω	0,336	-1,10	2,67	-0,18				

First Remarks

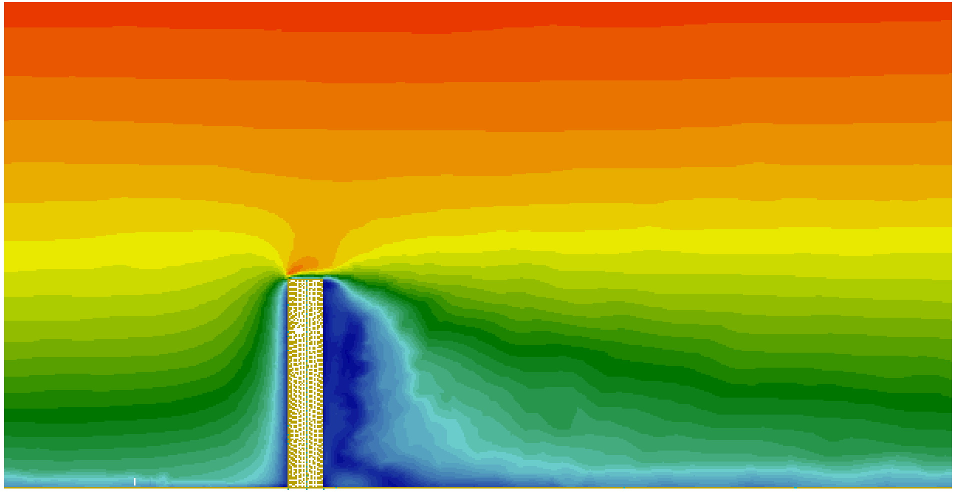
- There are some problems for CFD
  (It is nearly impossible to calculate the problem of a cylinder for 200 000 < Re < 600 000)
- Time step and mesh size are critical
- Where is the detachment / reattachment ?
- Rotating Flow is also known to be very difficult
- Wall law – Roughness – Formulations ?

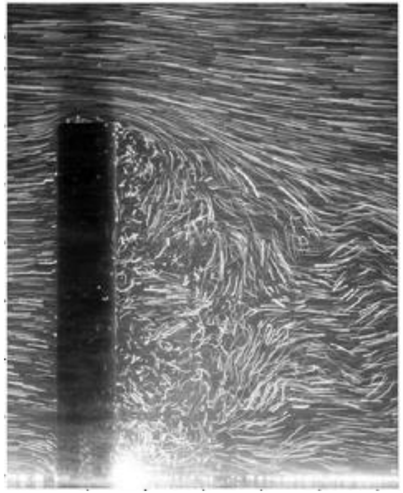
Cylinder in boundary layer



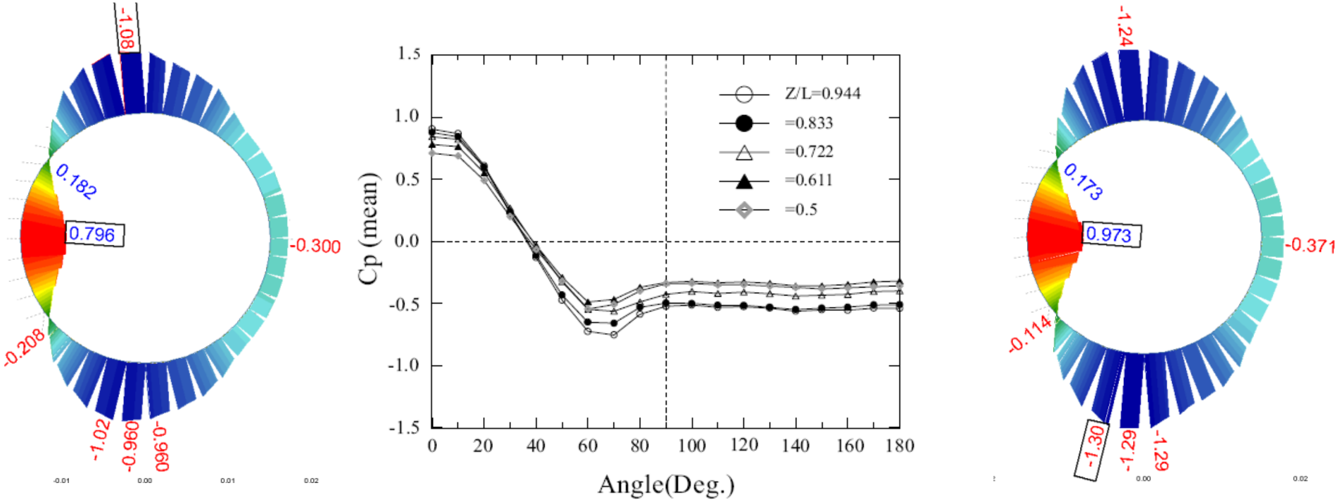
- Reynolds number 20000
- Profile exponent 0.14 / 0.22
- Blockage 1.3 %

Longitudinal section





Pressures



- Pressures very well
- Suction at sides to large by a factor of 1.7
- Suction at tail to small by 30 %

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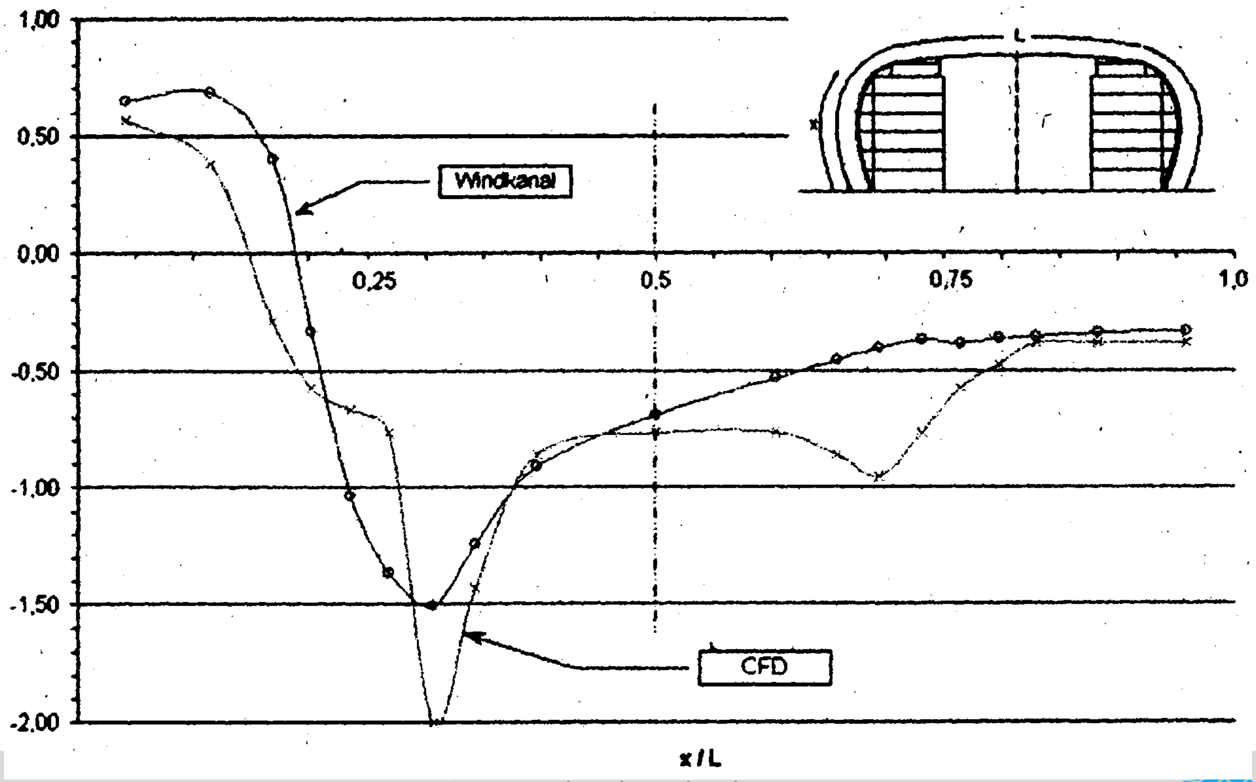
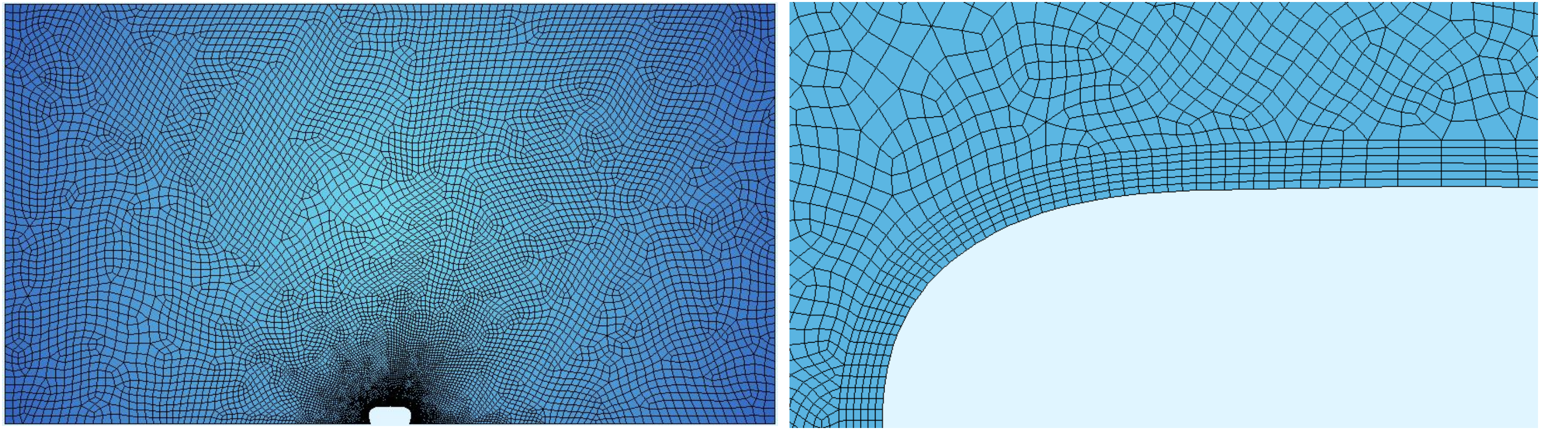
Problematic Building

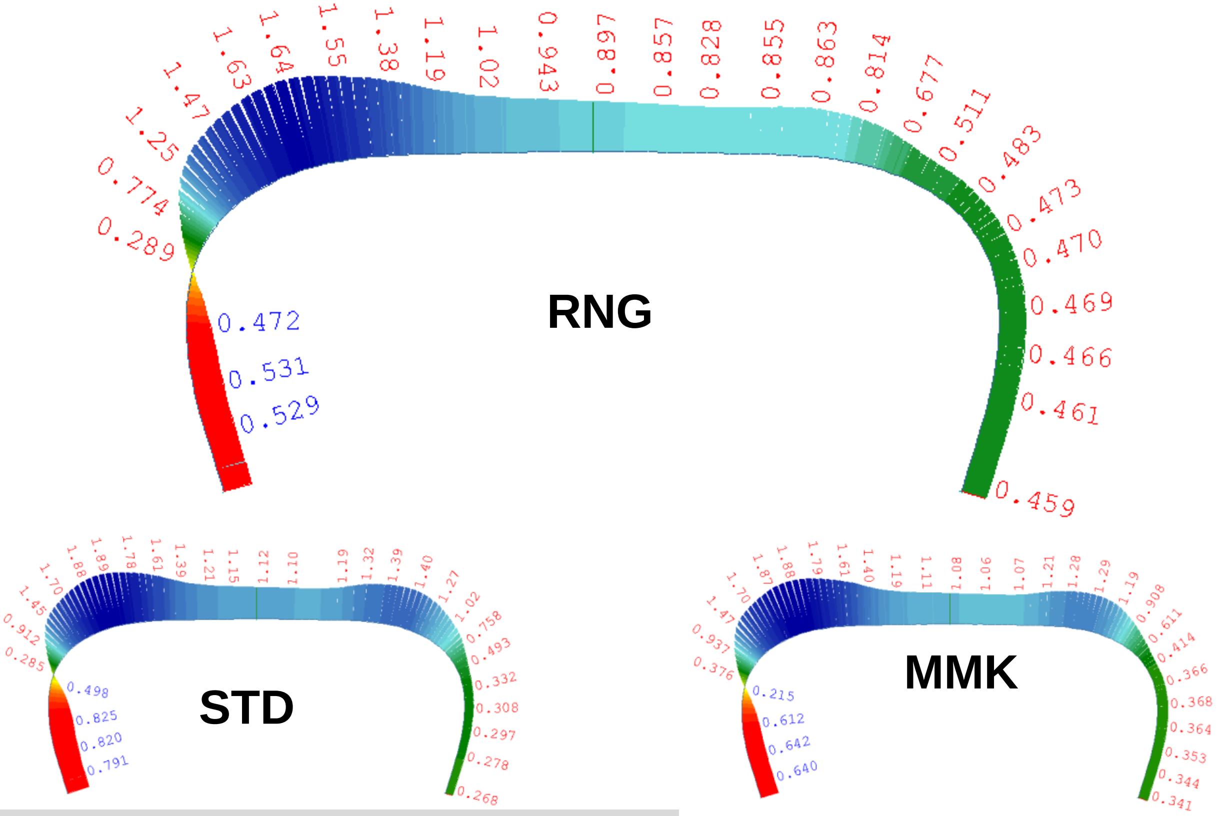


Parameter / mesh generation

- Re = $4 \cdot 10^7$, profile exponent 0.25
- Dimension B/H=55/25 m
- Mesh density with 0.25 cm (30 y+) => 12500 volumes

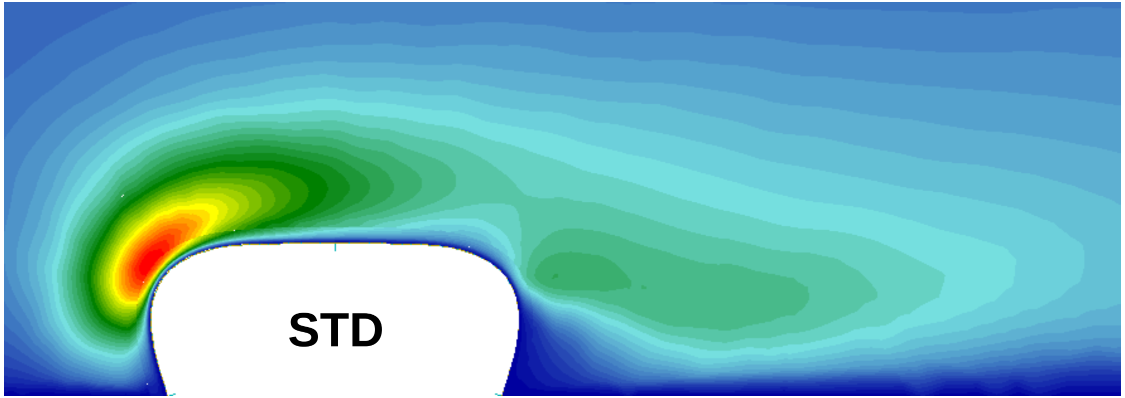


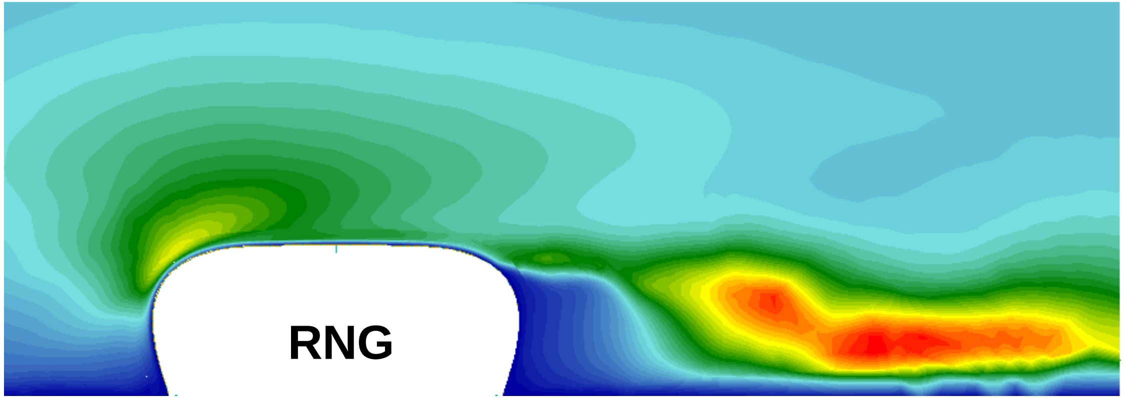
Pressures



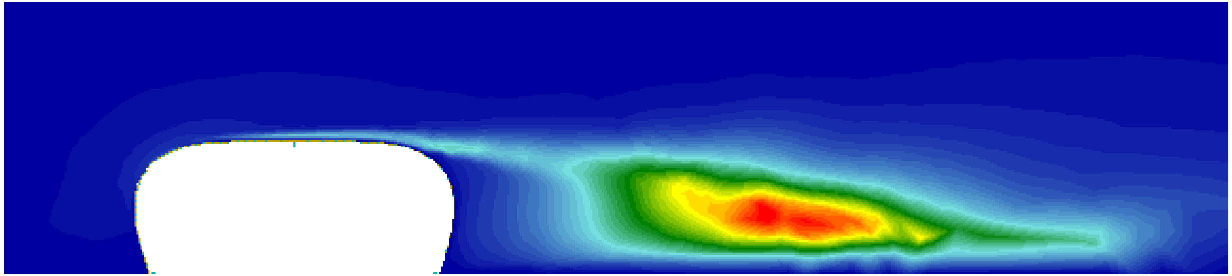
RNG
0.289
0.774
1.25
1.47
1.63
1.64
1.55
1.38
1.19
1.02
0.943
0.897
0.857
0.828
0.855
0.863
0.814
0.677
0.511
0.483
0.473
0.470
0.469
0.466
0.461
0.459
0.472
0.531
0.529
STD
MMK

Turbulent Energy

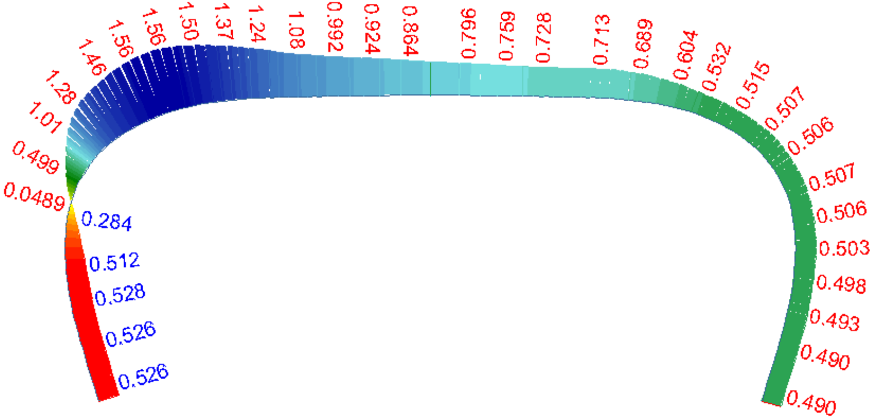




Reduction of viscosity for inflow



RNG

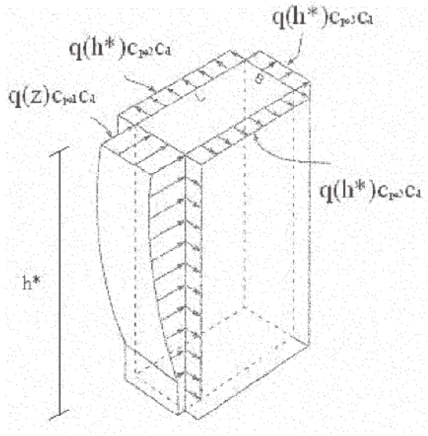


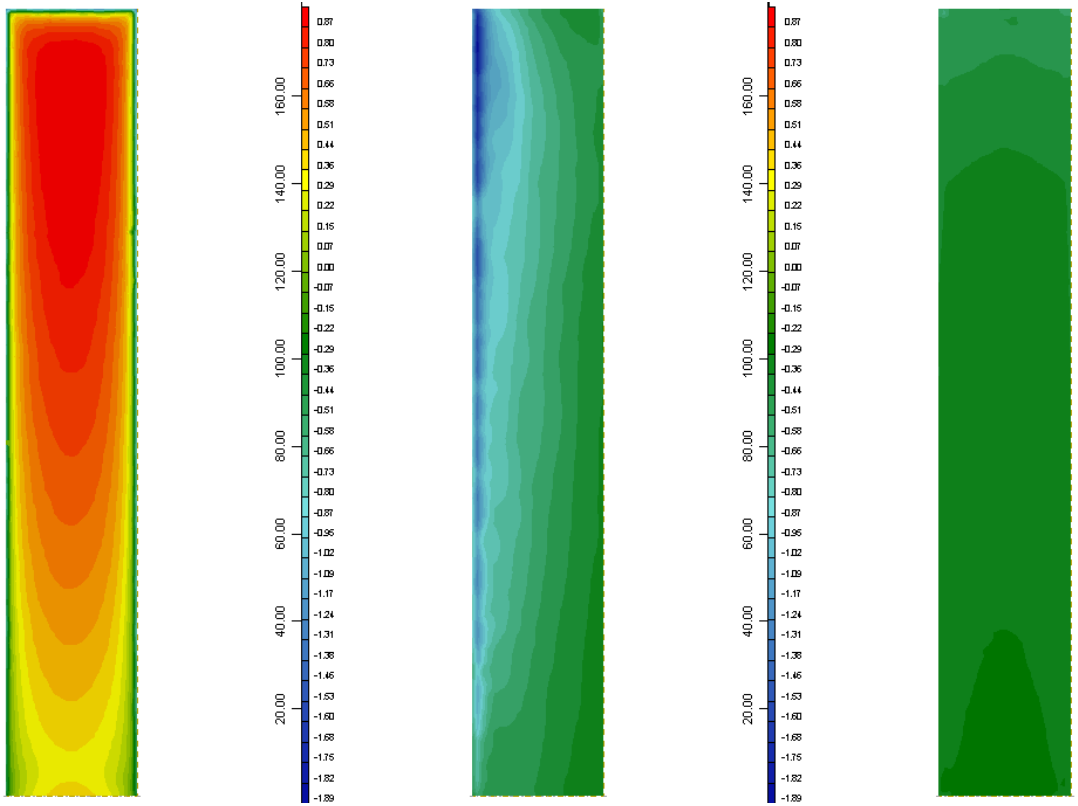
Assessment

	Grenzschicht Optimiertes Netz			Referenz [9]		
	k-ε	RNG	MMK	Messung	CFD	(DIN)
Staudruck	0,52	0,53	0,52	0,69	0,56	0,8
Sogspitze	1,63	1,56	1,59	1,50	2,00	1,5
Sog Mitte	0,90	0,83	0,85	0,69	0,76	0,3
Sog (0.7)	0,90	0,60	0.75	0,39	0,96	0,2
Sog (0.9)	0,43	0,50	0,49	0,34	0,39	0,5

- Maximum values are quite precise
- The flow detaches in the experiment at the middle of the roof, in the analysis only in the last end of the roof.
- Effect is well known for steep air foils, detachment occurs in the mid range, all RANS are within the last 10 %
  => LES / DES
- Questions of Reynold scaling effects are still open

Towers

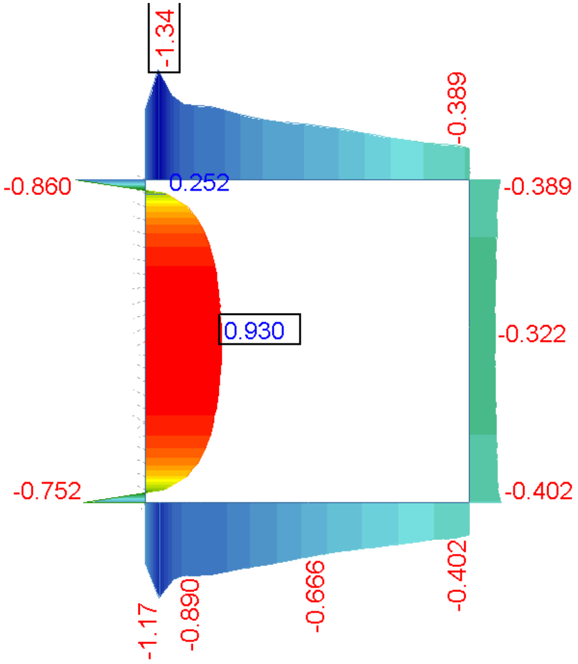


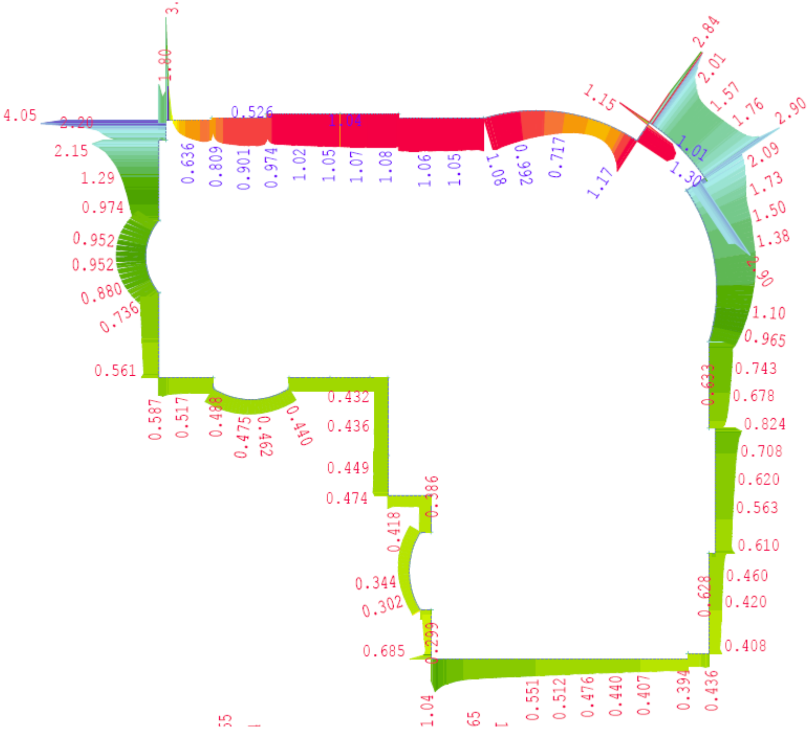


Pressures:

Front / Side / Rear

Pressures





- Much better pressure values achievable

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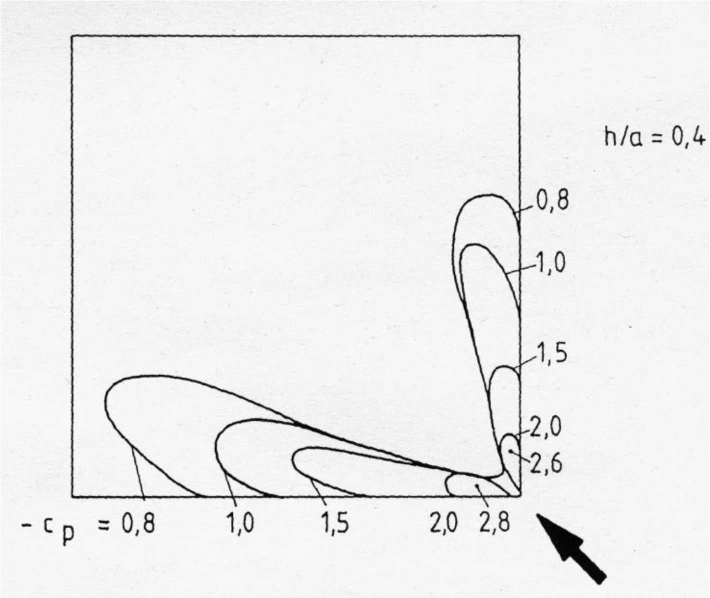
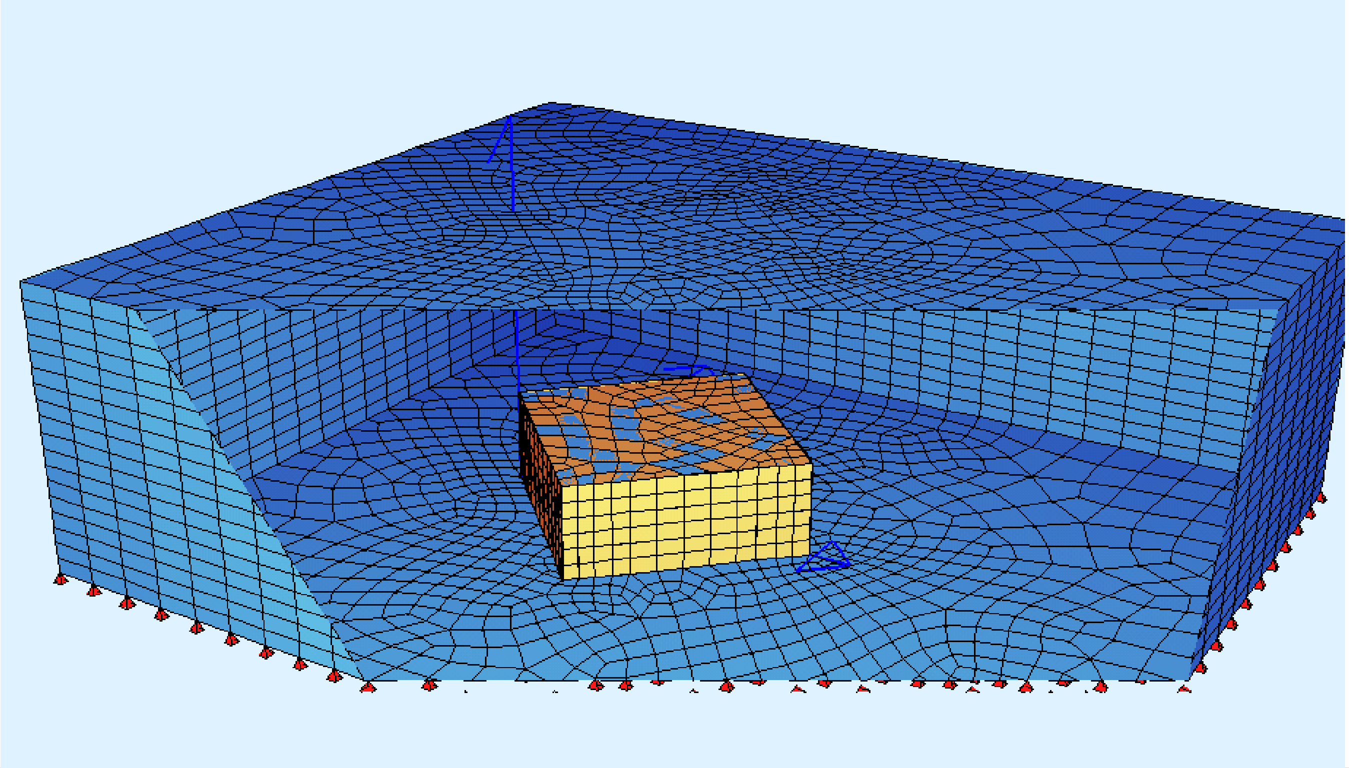
Wind on flat roof

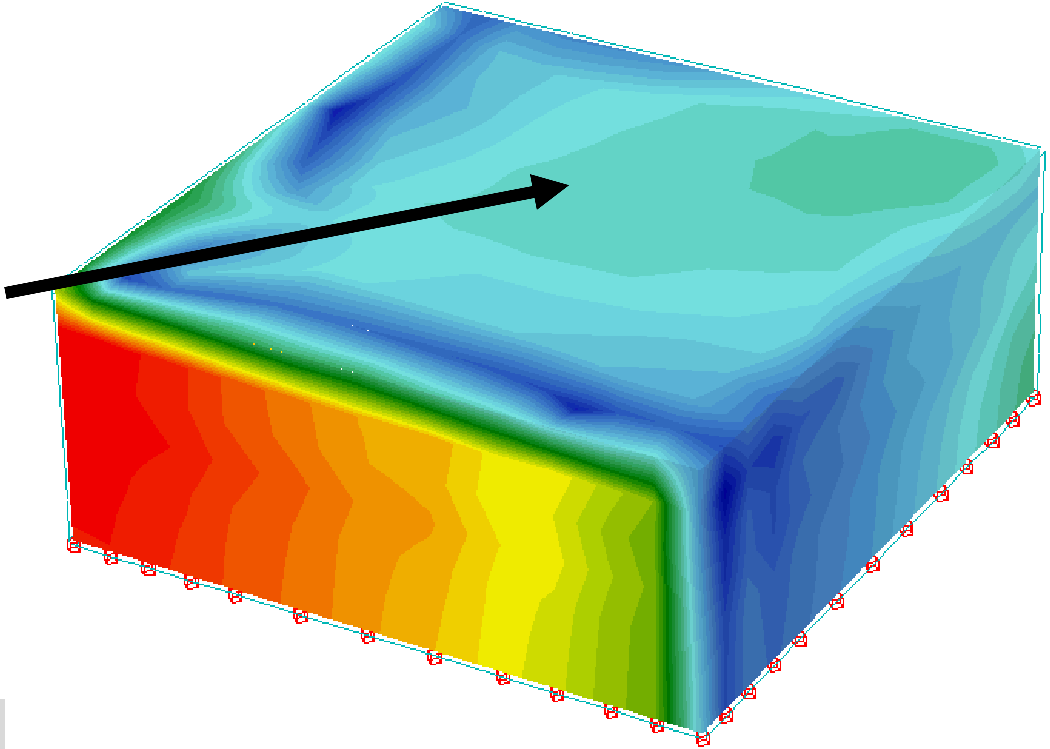


- Measurements from Prof. Gerhardt
- Suction peak values at the edge
- Height of roof 11.20 m
- v = 22.5 m/sec
- q = 316 N/m^2
- Mixed profile

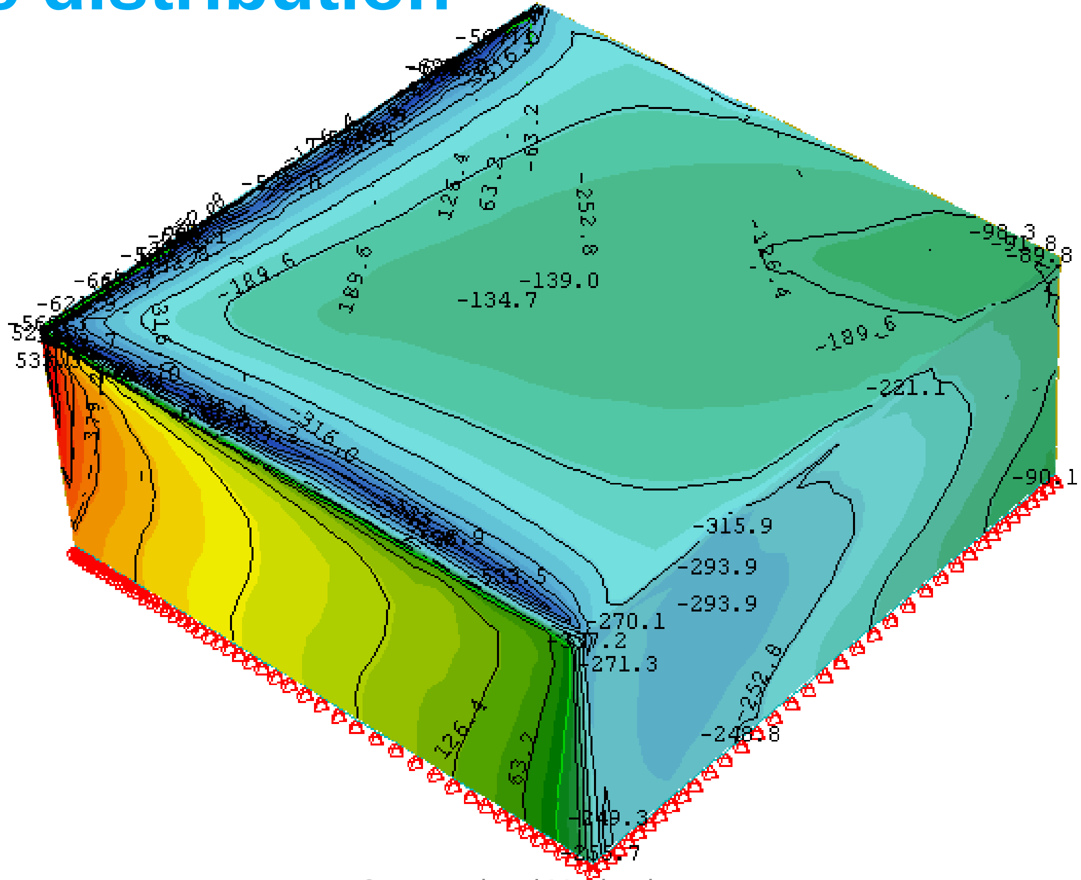
Wind on Flat roof



Coarse mesh pressure distribution



Pressure distribution



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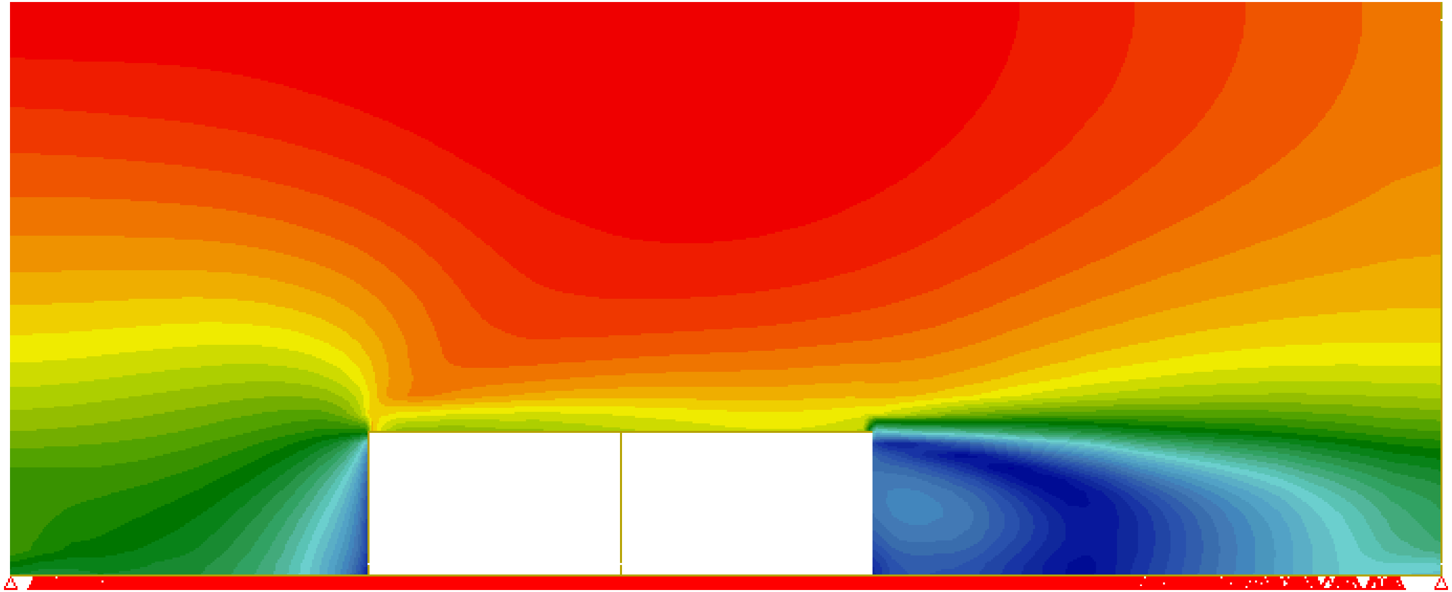
Velocity distribution



Comparison of Results

	cp-d peak value	cp-d mean value	cp-s peak value	cp-s middle/far end
Measurements	-	-	-2.8	-0.6 ?
Coarse mesh without turbulence	+0.81	+0.56	-1.06	-0.45
Coarse mesh with turbulence	+1.06	+0.66	-1.25	-0.35
Intermediate mesh with turbulence	+1.35	+0.60	-1.06	-0.27
Fine mesh with turbulence	+1.63	+0.71	-1.55	-0.50
Fine mesh II with turbulence	+1.73	+0.69	-2.20	-0.35
Values according DIN 1055	-	+0.70	-1.80	-0.70/+0.20

Measurements at the Silsoe Cube

z [m]	U [m/sec]	I_u	I_v	I_w	L_u^x [m]
1	6.97	0.243	0.196	0.077	11
3	8.65	0.208	0.166	0.072	33
6	9.52	0.193	0.150	0.078	53
10	10.13	0.186	0.151	0.083	62

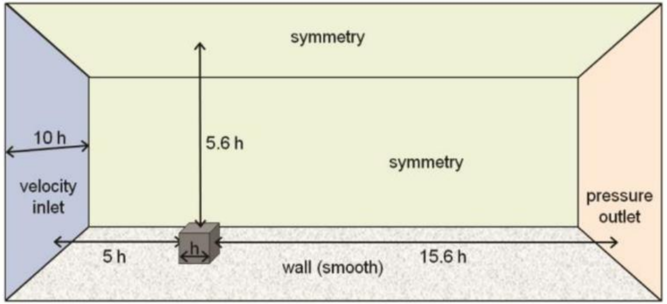
Turbulence Intensities at the Silsoe Cube

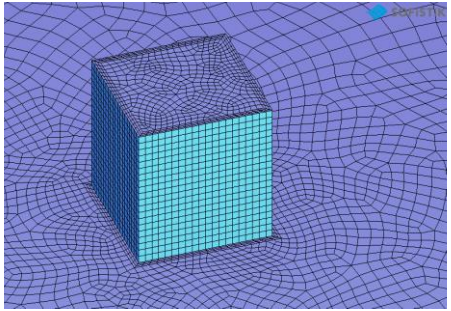
	z_0=0.008 u_*=0.575 m/sec		z_0=0.01 u_*=0.63 m/sec		z_0=0.05 u_*=0.94 m/sec	
z [m]	U [m/sec]	K [m²/sec²]	U [m/sec]	K [m²/sec²]	U [m/sec]	K [m²/sec²]
1	6,94	1,10	7,25	1,32	7,04	2,95
3	8,52	1,10	8,98	1,32	9,62	2,95
6	9,52	1,10	10,08	1,32	11,25	2,95
10	10,25	1,10	10,88	1,32	12,45	2,95

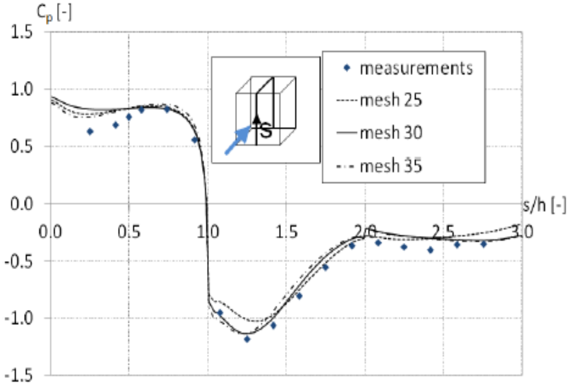
Integral Length Scales at the Silsoe Cube

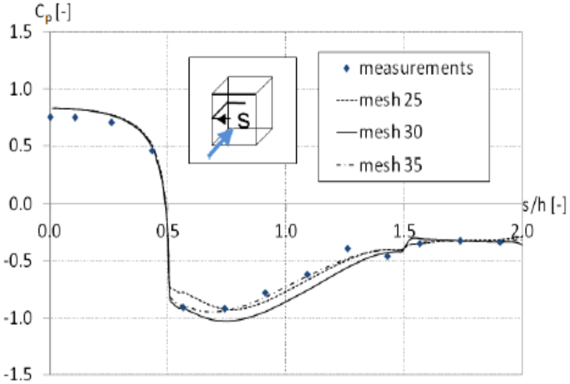
z [m]	L[m] measured	L[m] Eurocode	L[m] DIN/NAD	L[m] CFD	
1	11	31	170	0.41	
3	33	50	189	1.23	
6	53	67	203	2.46	
10	62	83	214	4.09	

Measurements and LES Analysis

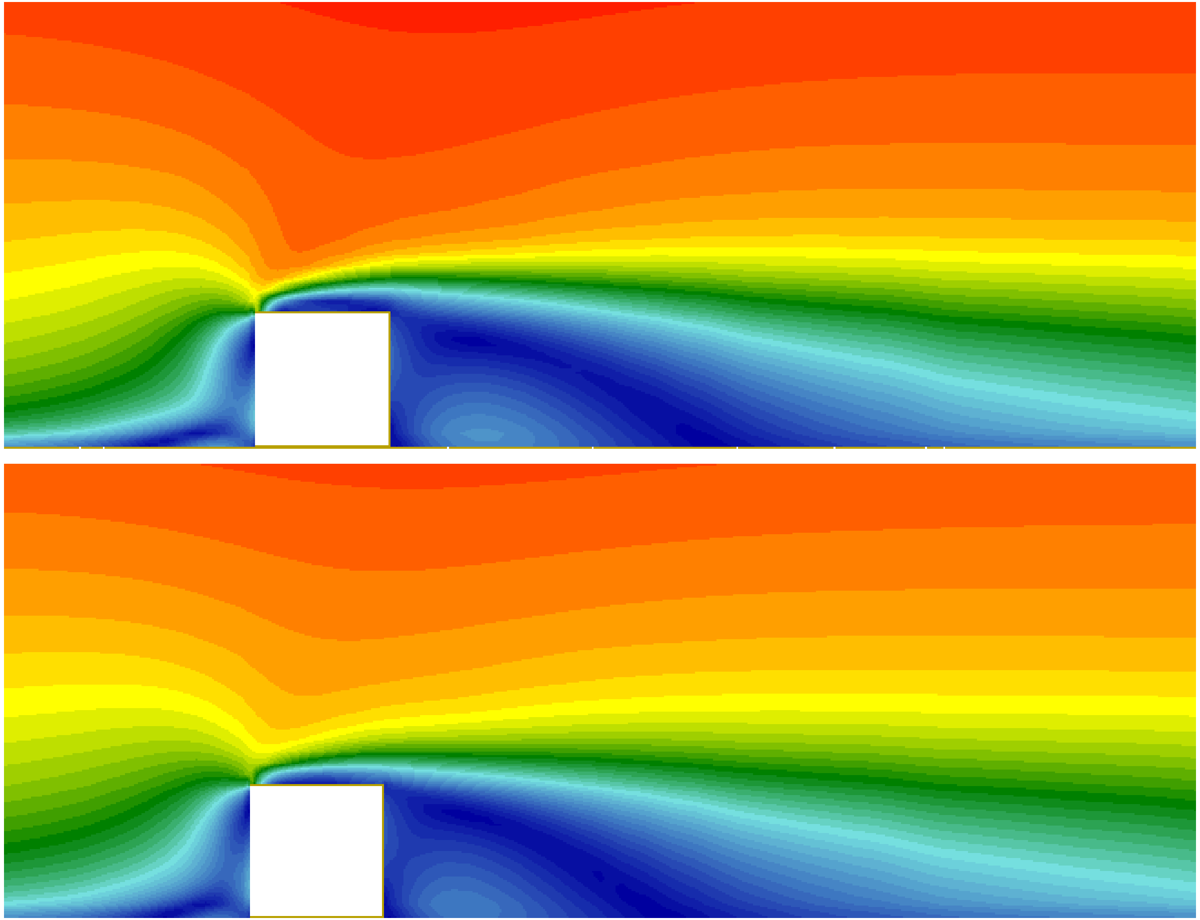






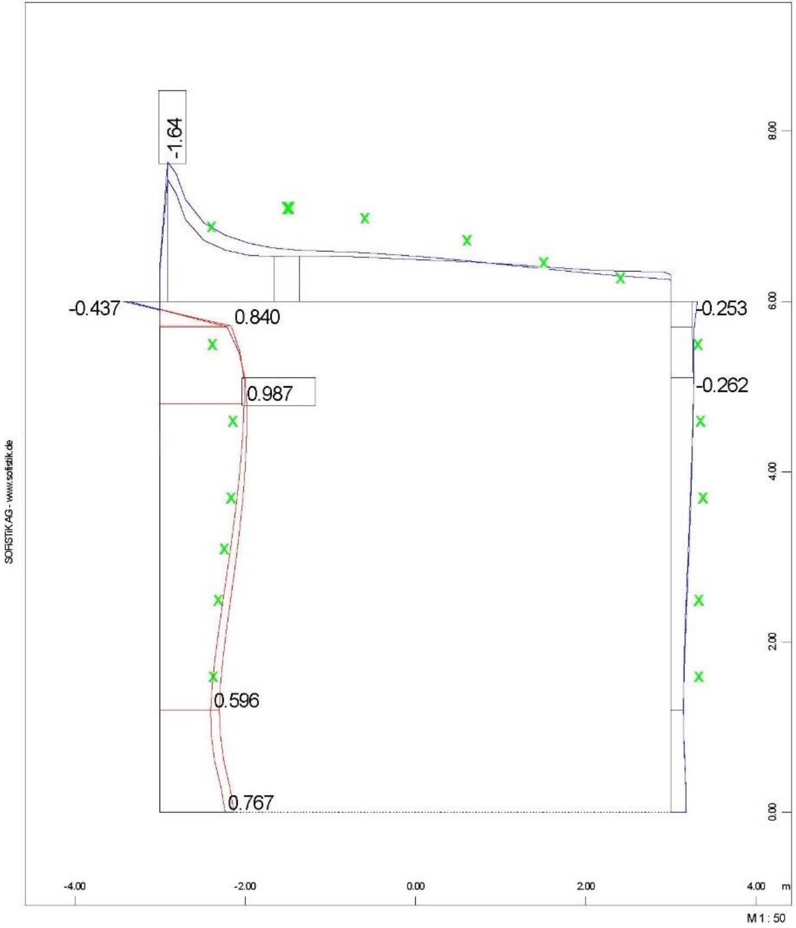


Fluid velocities with RANS

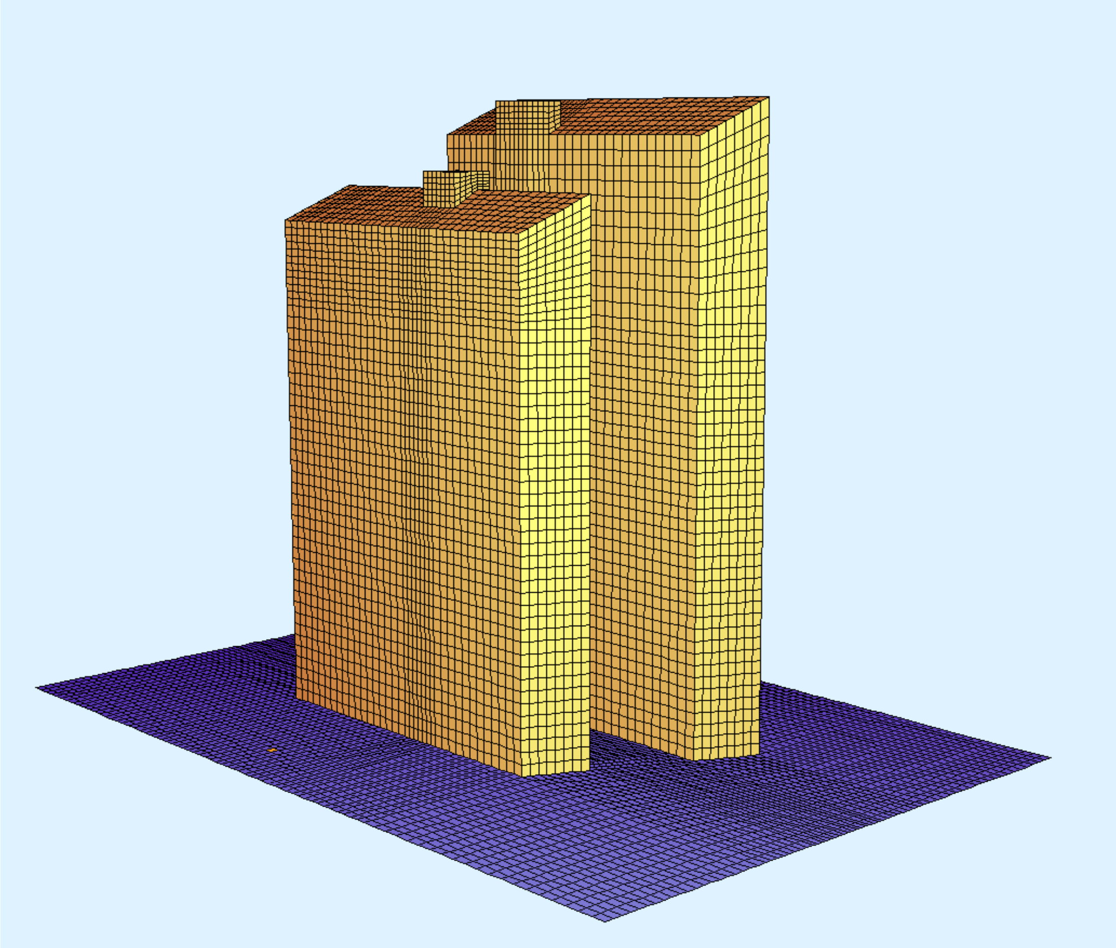


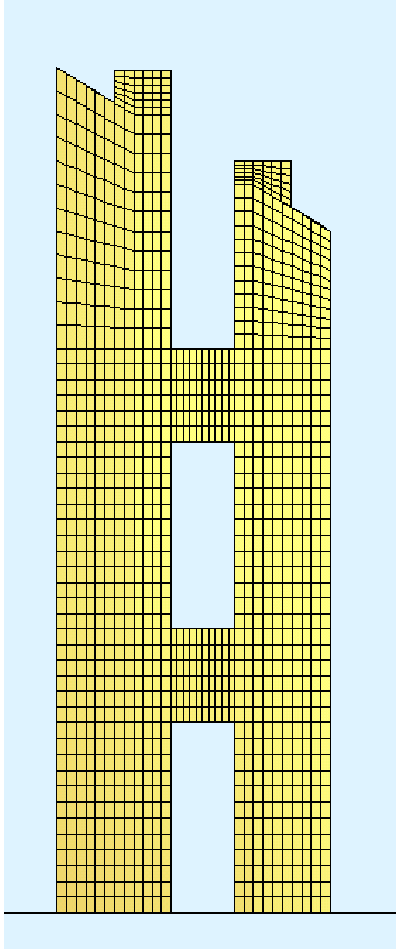
Pressures of RANS Analysis

- Significant influence of the boundary layer
- Low influence of the turbulence intensity
- Which pressure distribution on the roof is „correct“ ?



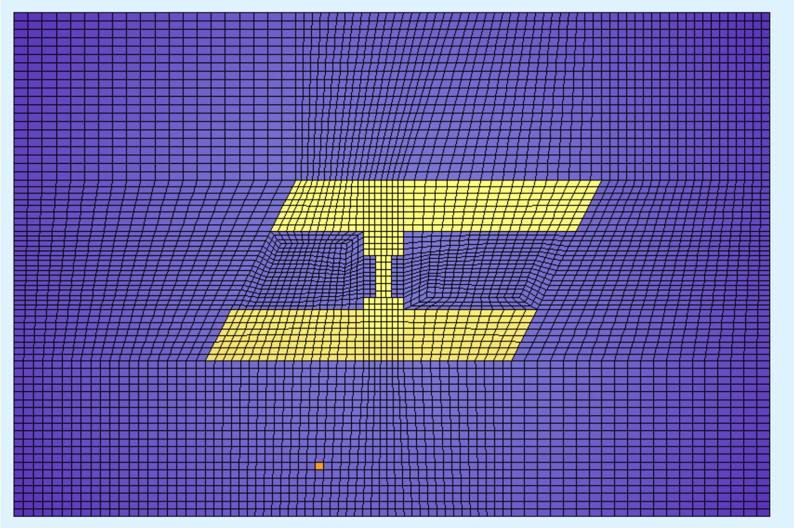
A larger example

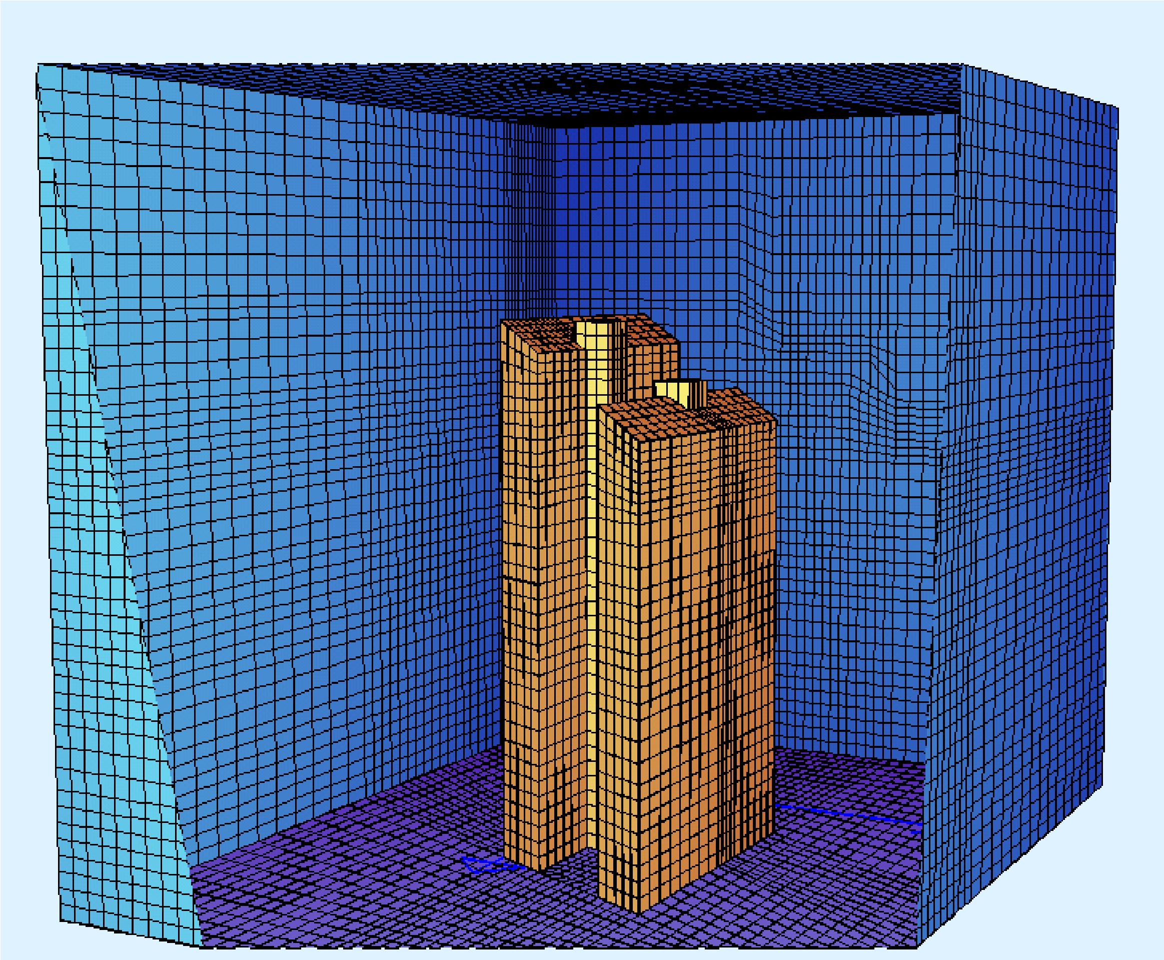




Highlight Towers Munich

- H = 129 m
- B =   48 m
- D =   78 m





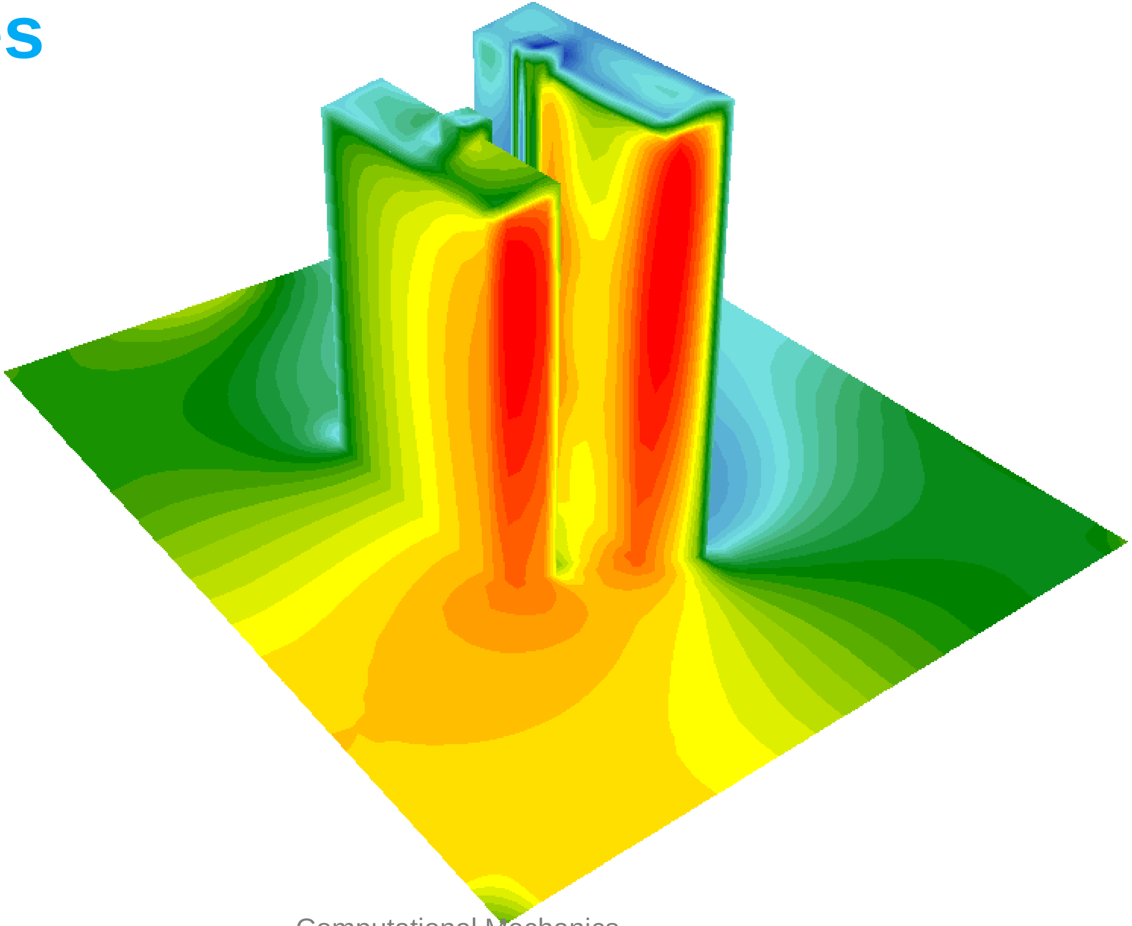
Structured Mesh

150 000 to 500 000 elements

Which Wind Profile ?

Wind zone WZ 2 v_{ref} = 25 m/sec	DIN 1055			Expertise	
	Land Side	III	IV	III	IV
v_{top}	1.50 v_{ref}	1.35 v_{ref}	1.20 v_{ref}	1.33 v_{ref}	1.16 v_{ref}
$q_{ref,top}$ kN/m^2	0.880	0.708	0.562	0.691	0.572

Pressures



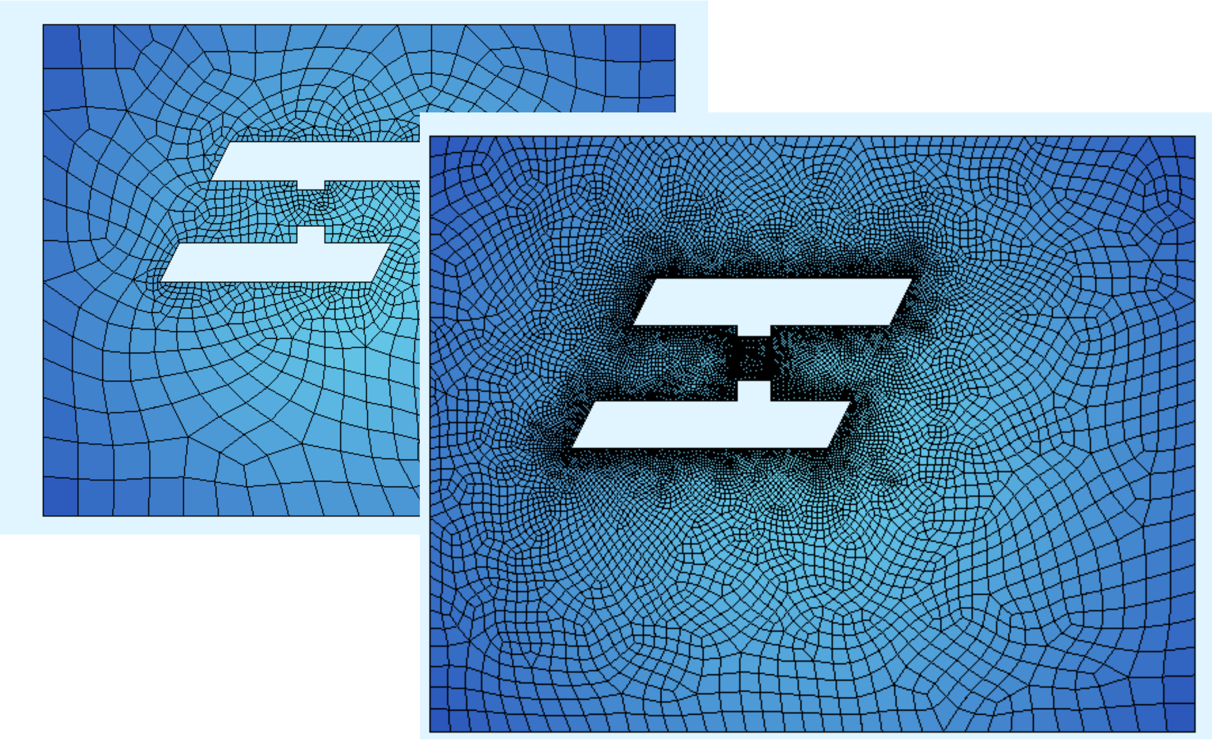
Pressures are to high !

- Cp >> 1.0 ?
- What may be the reason ?
  - Law of Bernoulli is not valid for viscous flow with shear stresses, but the viscosity should reduce the energy available to be converted in pressures.
  - The turbulent kinetic energy increases the pressures, but the effect is not as large as observed here. A turbulence intensity of 10 % will increase the total energy by only 1 %, but an increase of the velocity by 10 % will increase the pressure by a factor of 1.21.
  - If the flow is accelerated locally and hits a body behind, the pressure will be larger of coarse.

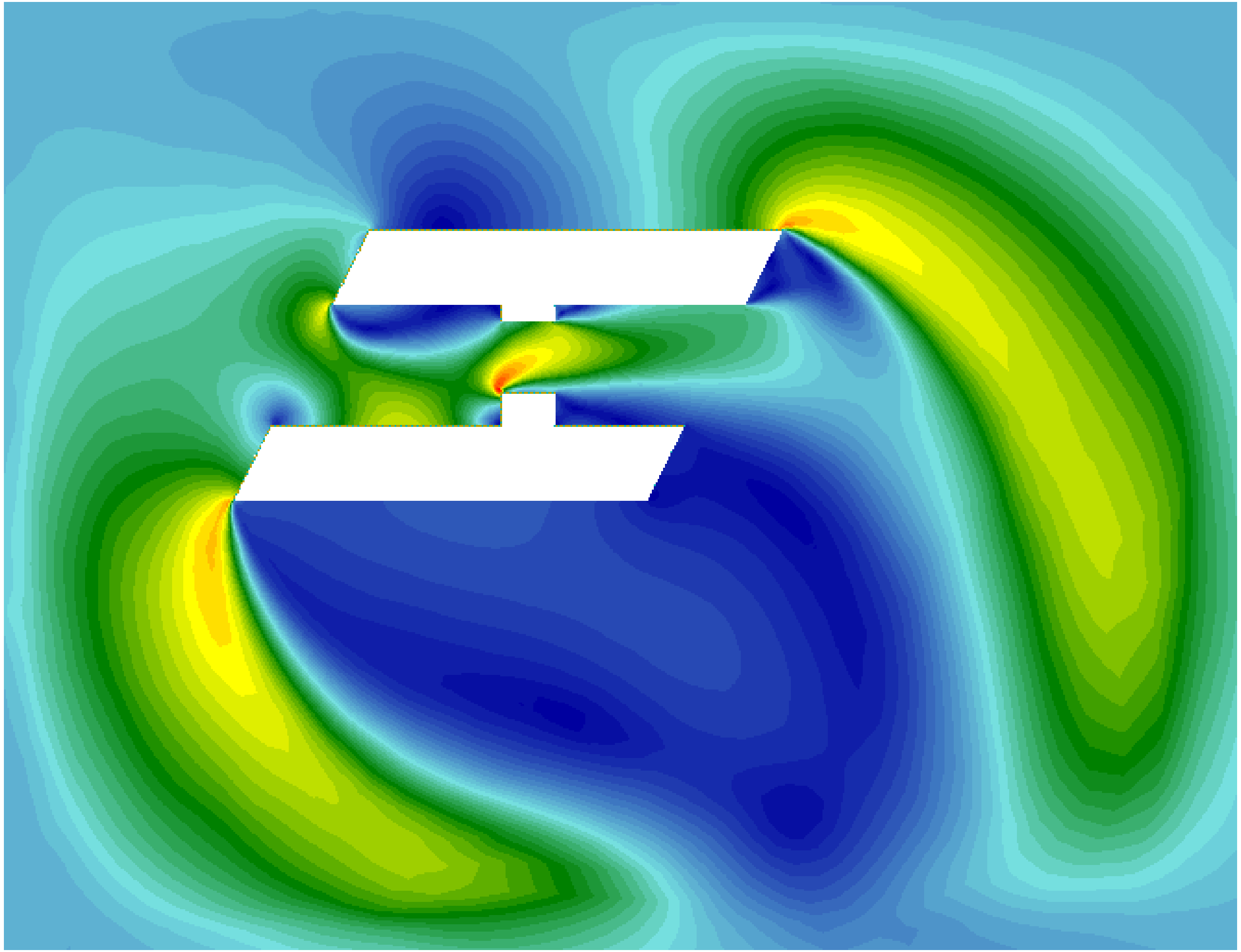
What to do ?

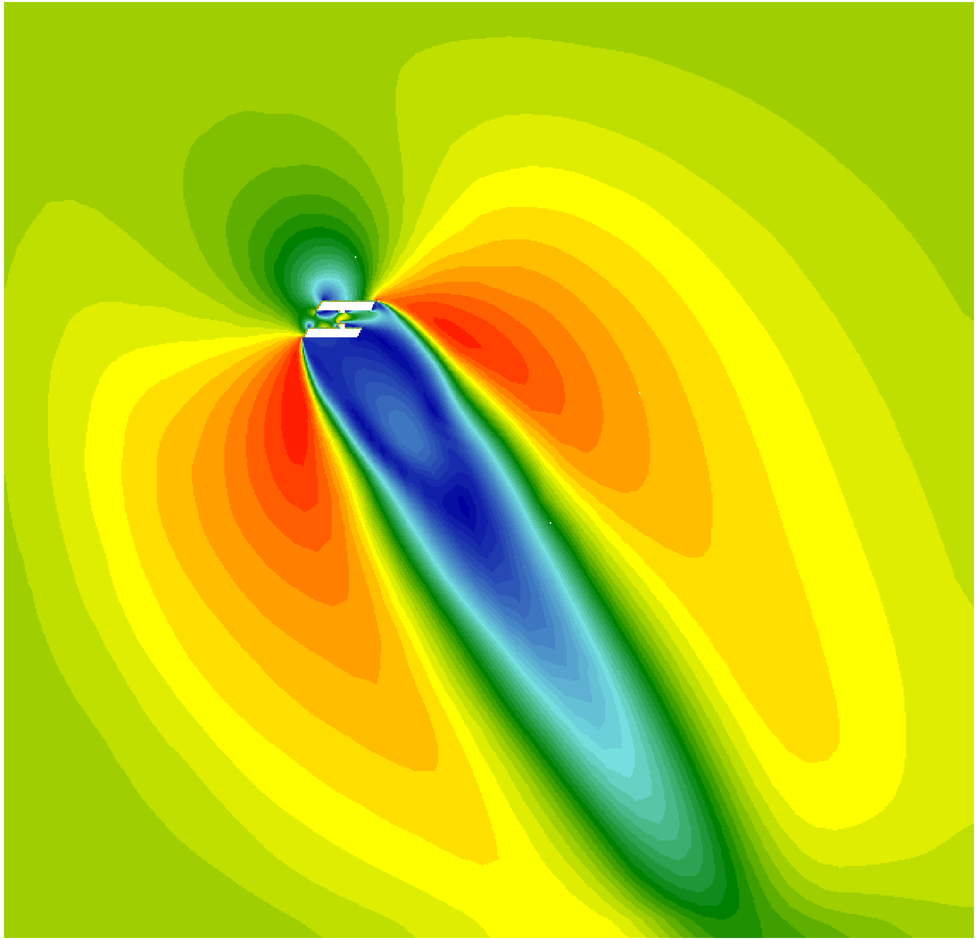
- Select a finer mesh ?
- Change some boundary conditions ?
- Larger Mesh ?
- Structured Mesh ?
- Change Integration parameters (app. 50 values)
  e.g. Relaxation, Solver-Type
- Transient Solution ?
- Quasi-steady state solution with a rather large time step of 10 to 100 times $\Delta h/v$

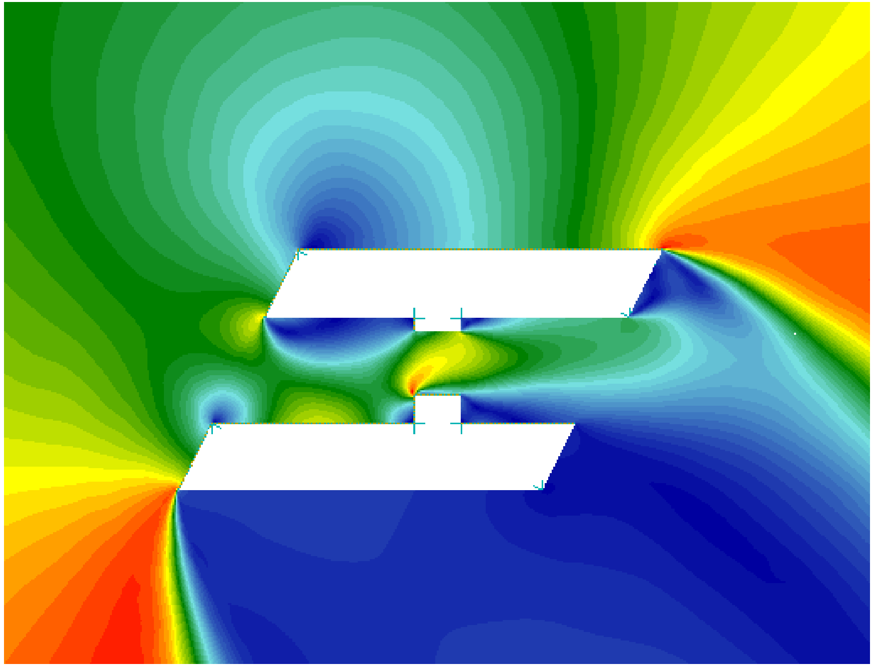
Try effects with a 2D Mesh !



„Squeezed“ Flow







„Free“ Flow

Effects of mesh size and total meshed region

Distance	No. Nodes	Pressure	Suction
40 m	1154	2078	7683
	13365	2020	7770
60 m	1749	1136	1903
	6620	1153	1910
160 m	2519	1030	1200
	8664	1162	1130
	20257	1212	1087
Maximum value	v_{ref} = 37.24	867	

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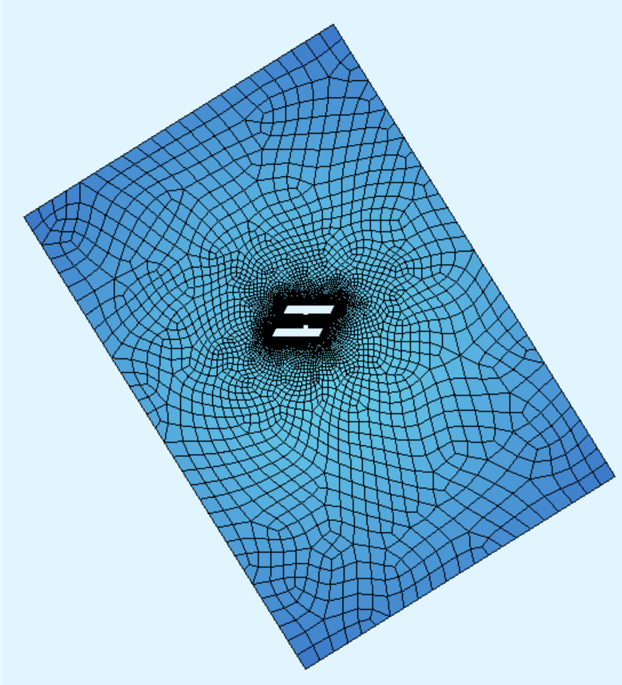
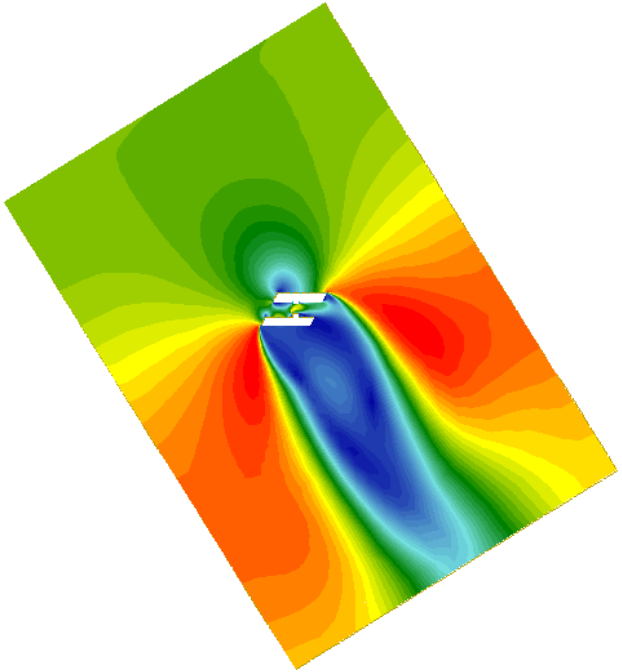
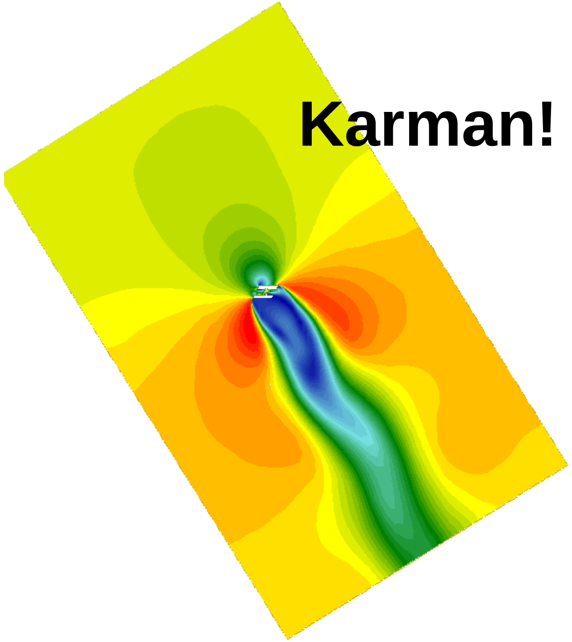
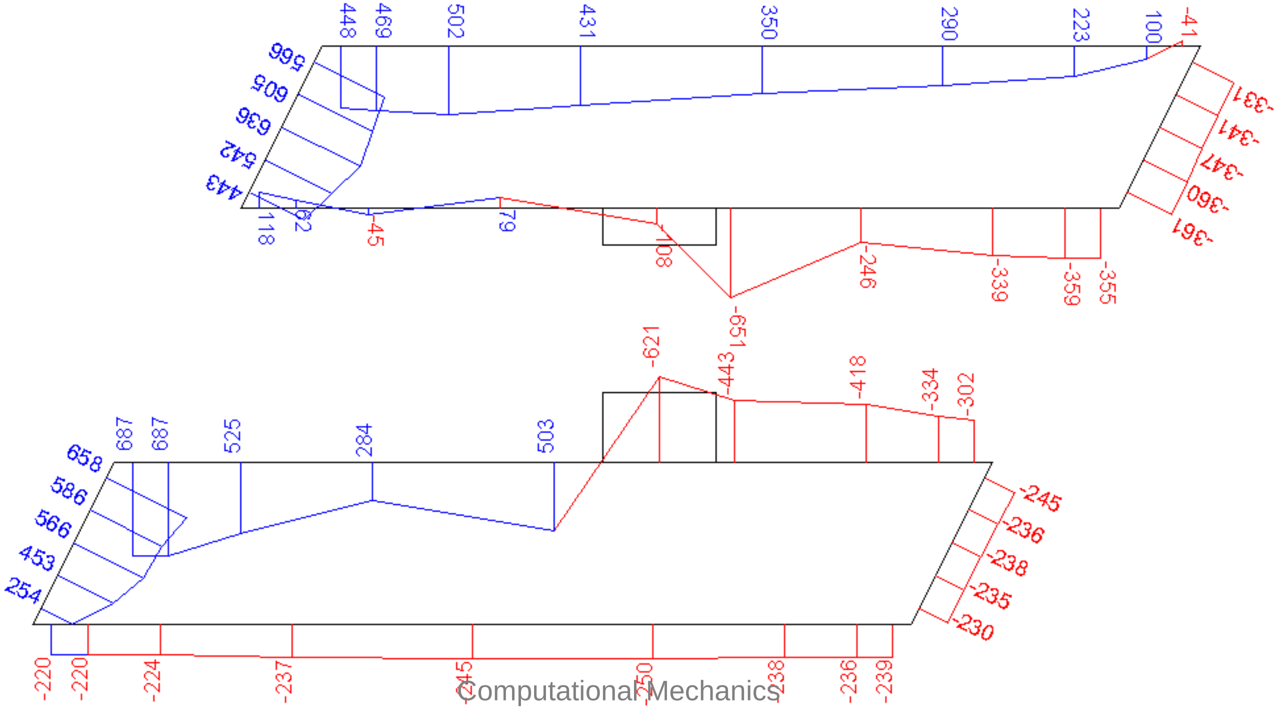
Skewed mesh







Pressures from Experiment



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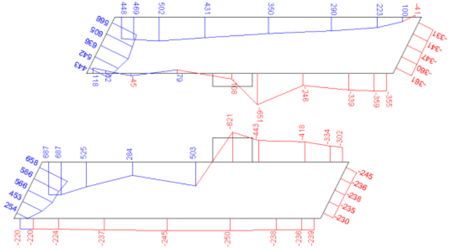
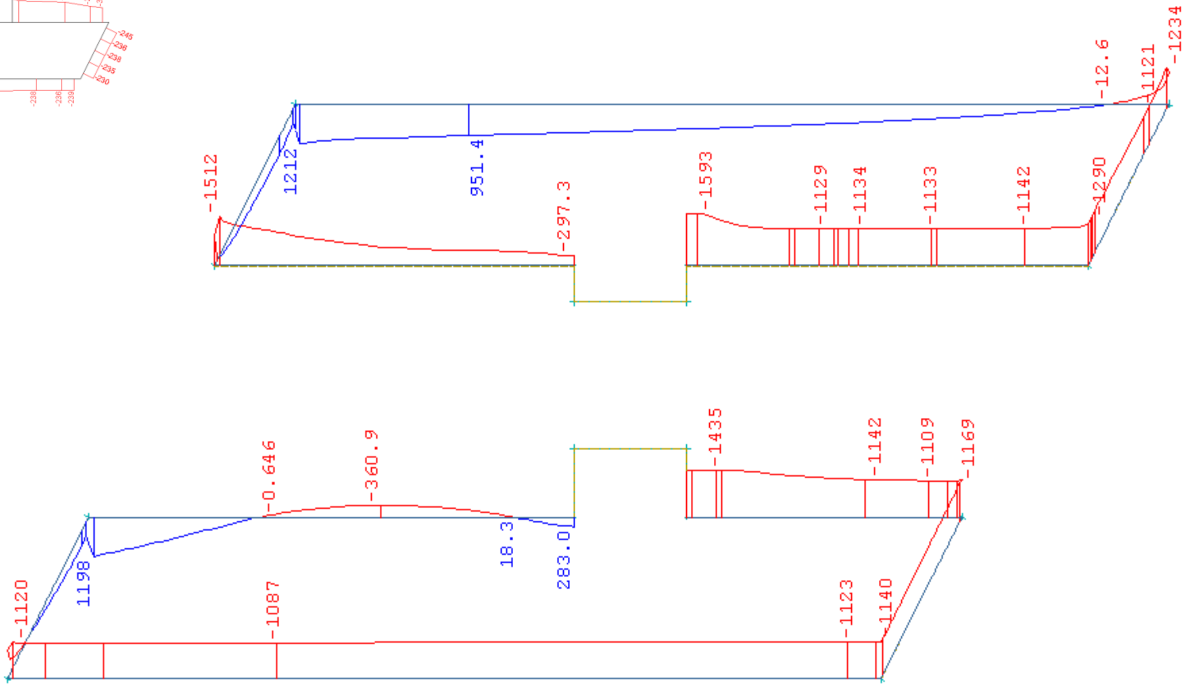
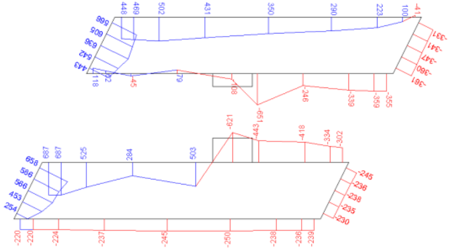
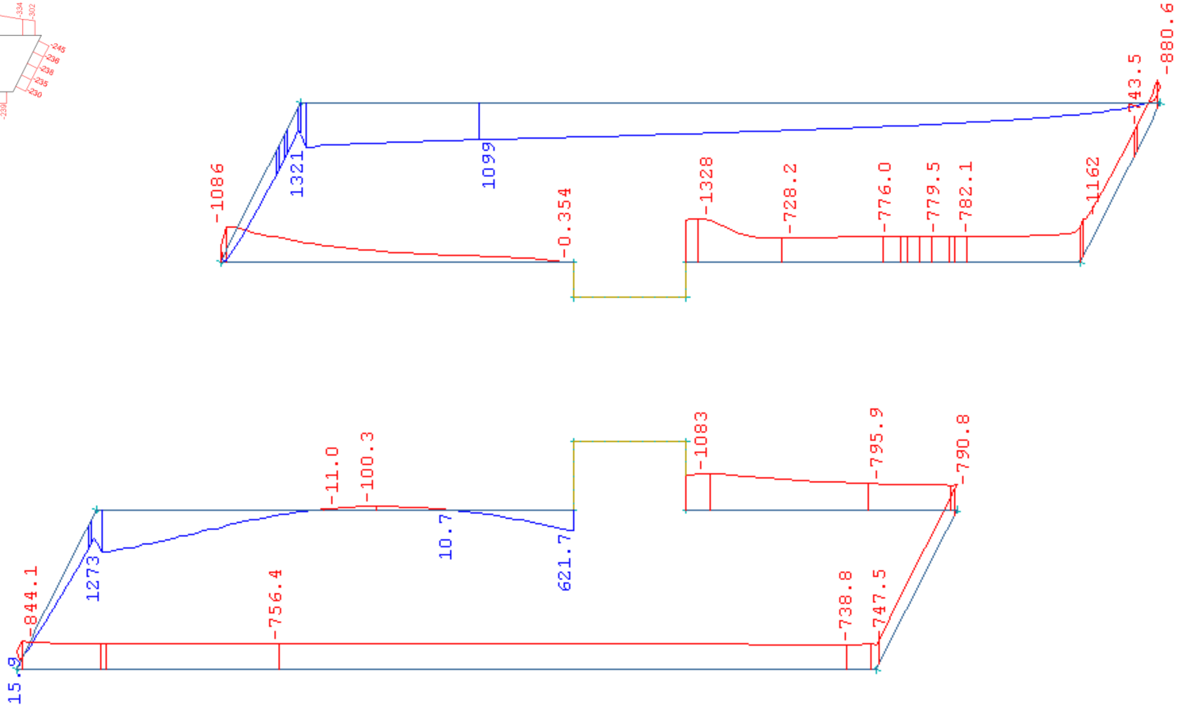
Pressures 2D Analysis
Boundary Conditions Type I



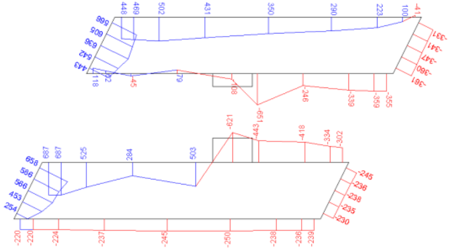


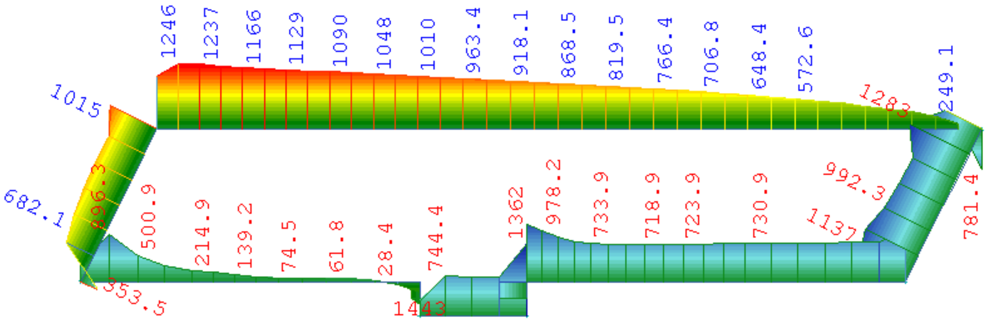
Pressures 2D Analysis
Boundary Conditions Type II

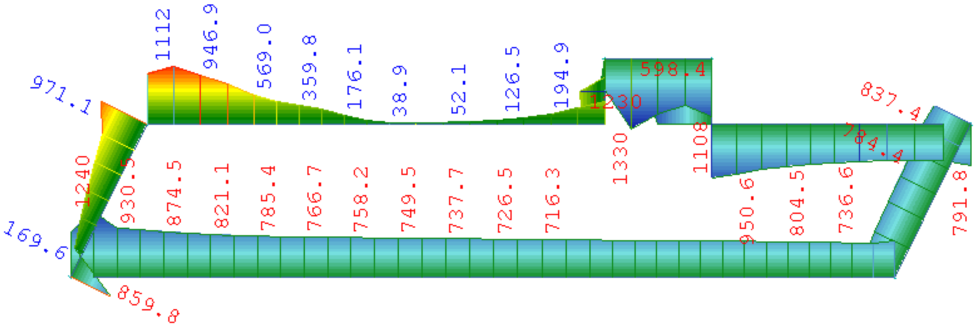




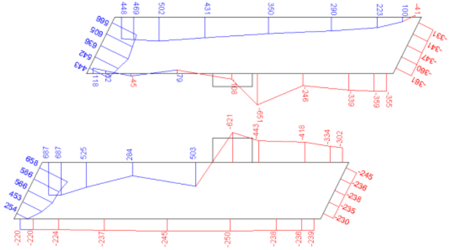
Pressures 2D Analysis Boundary Conditions Type IIw

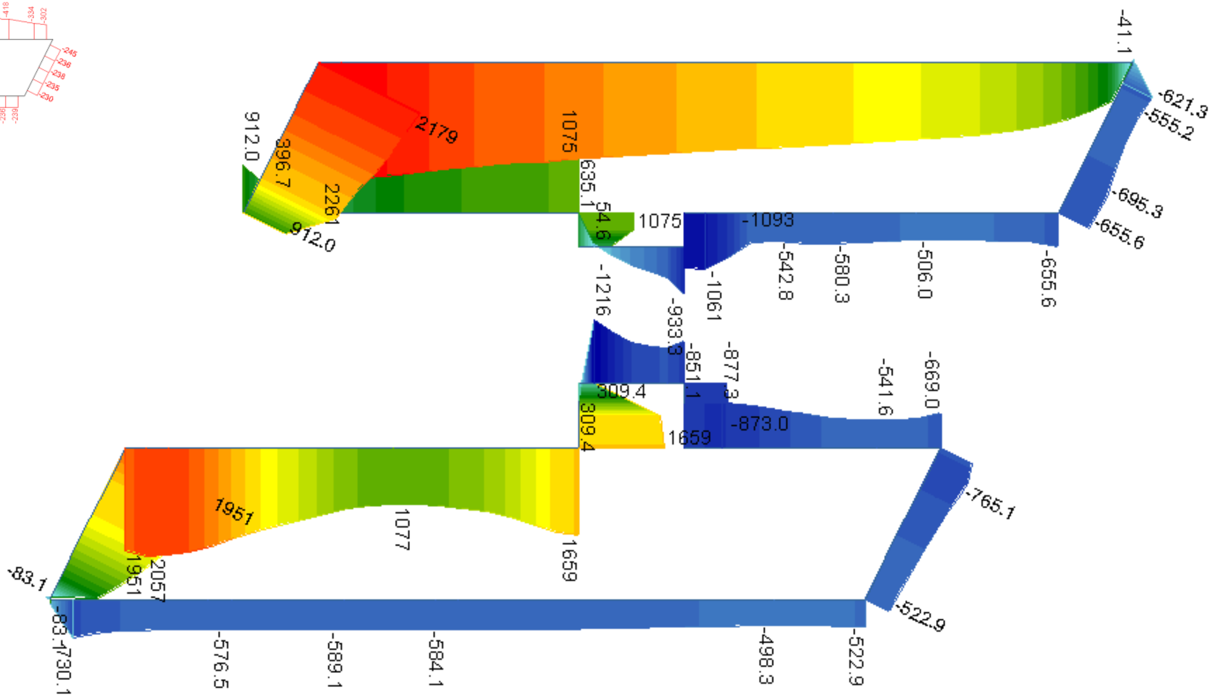




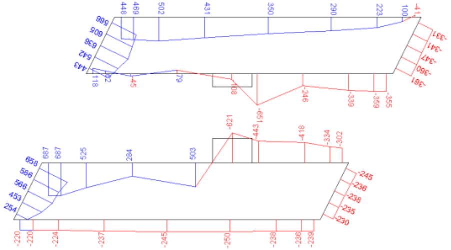


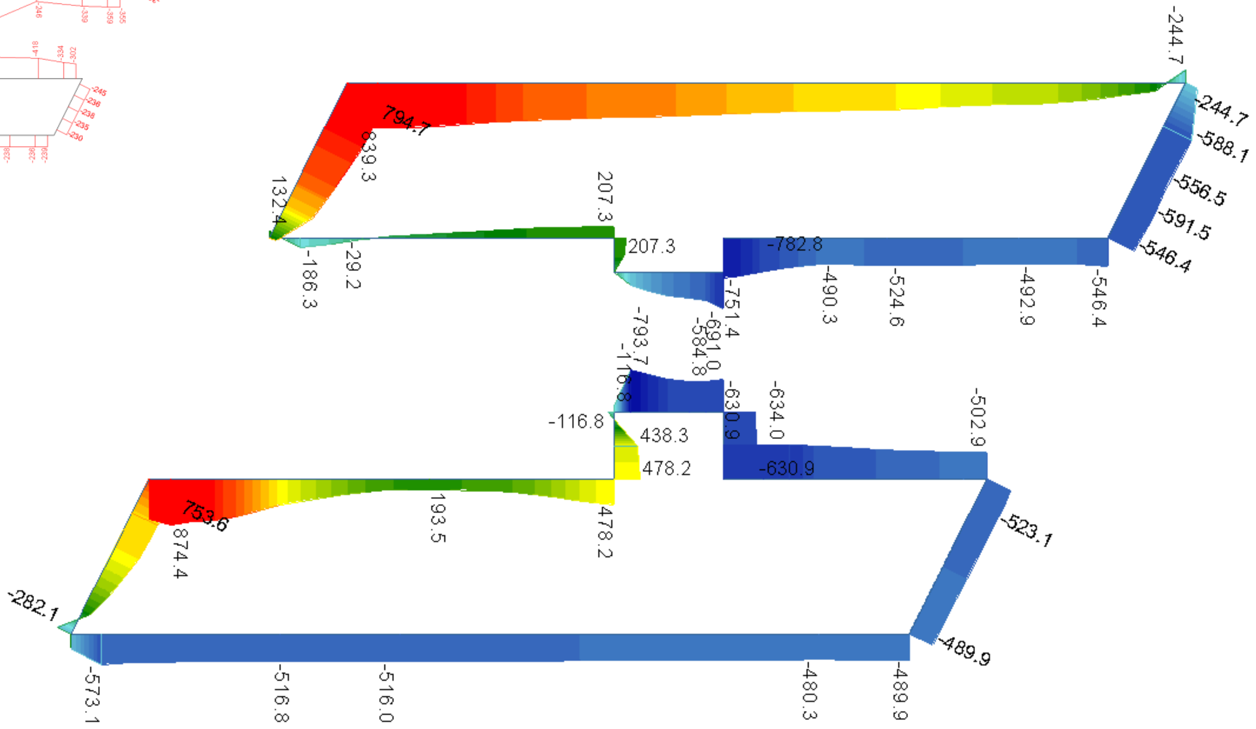
Pressures 3D ; a = 80 m



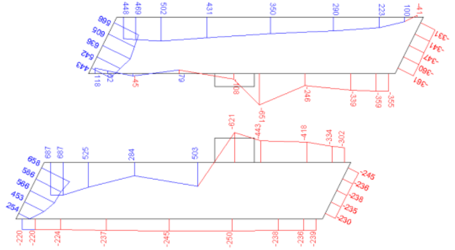


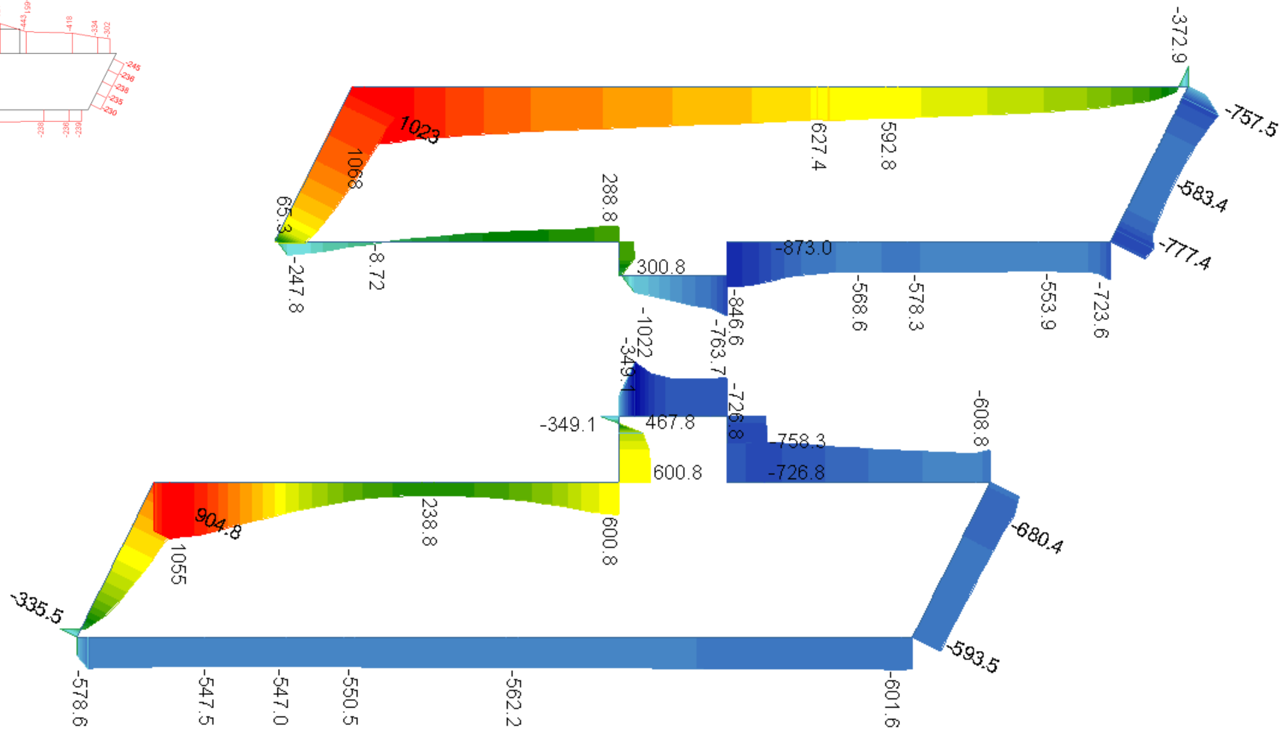
Pressures 3D ; a = 160 m



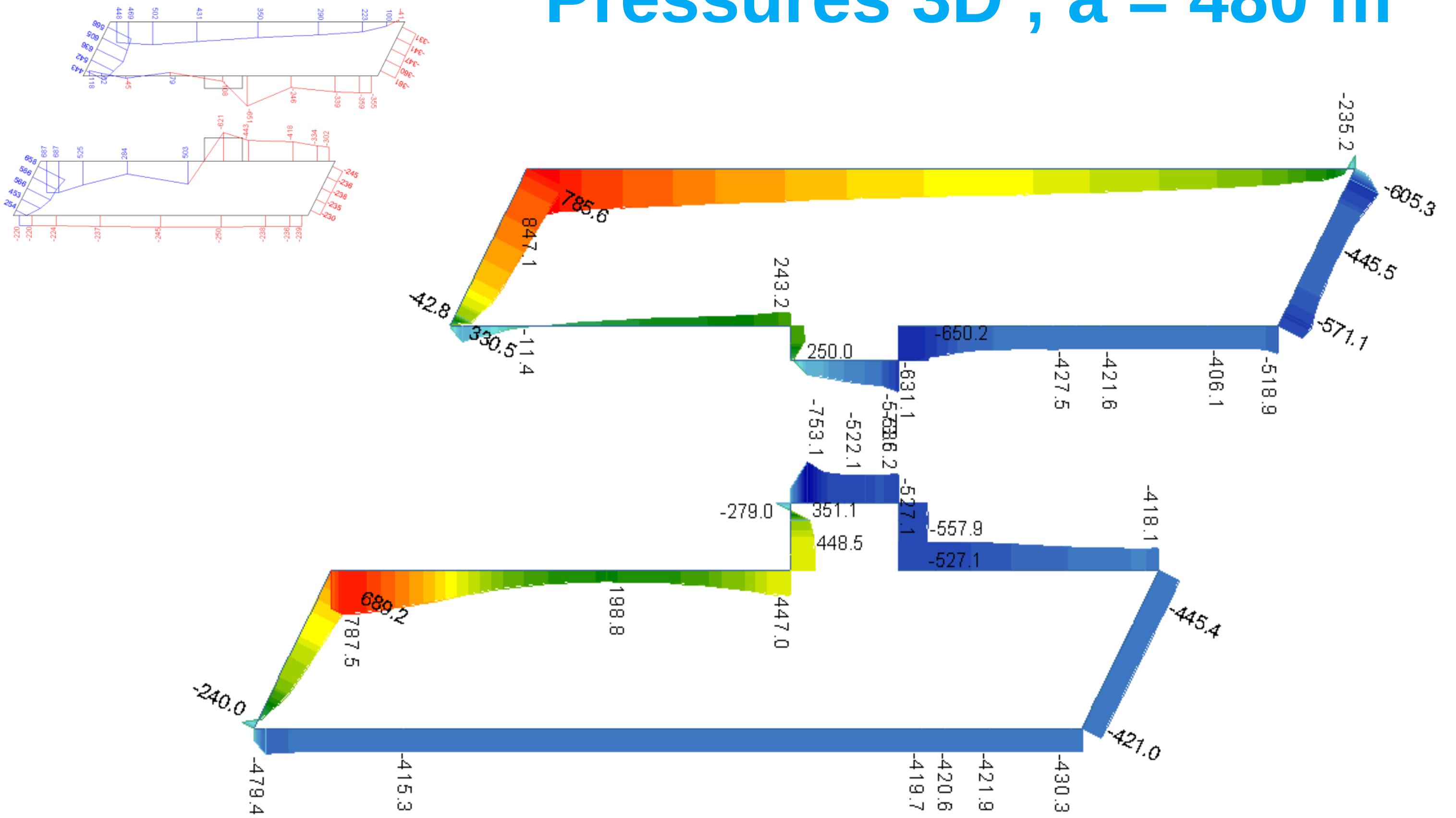


Pressures 3D ; a = 320 m





Pressures 3D ; a = 480 m



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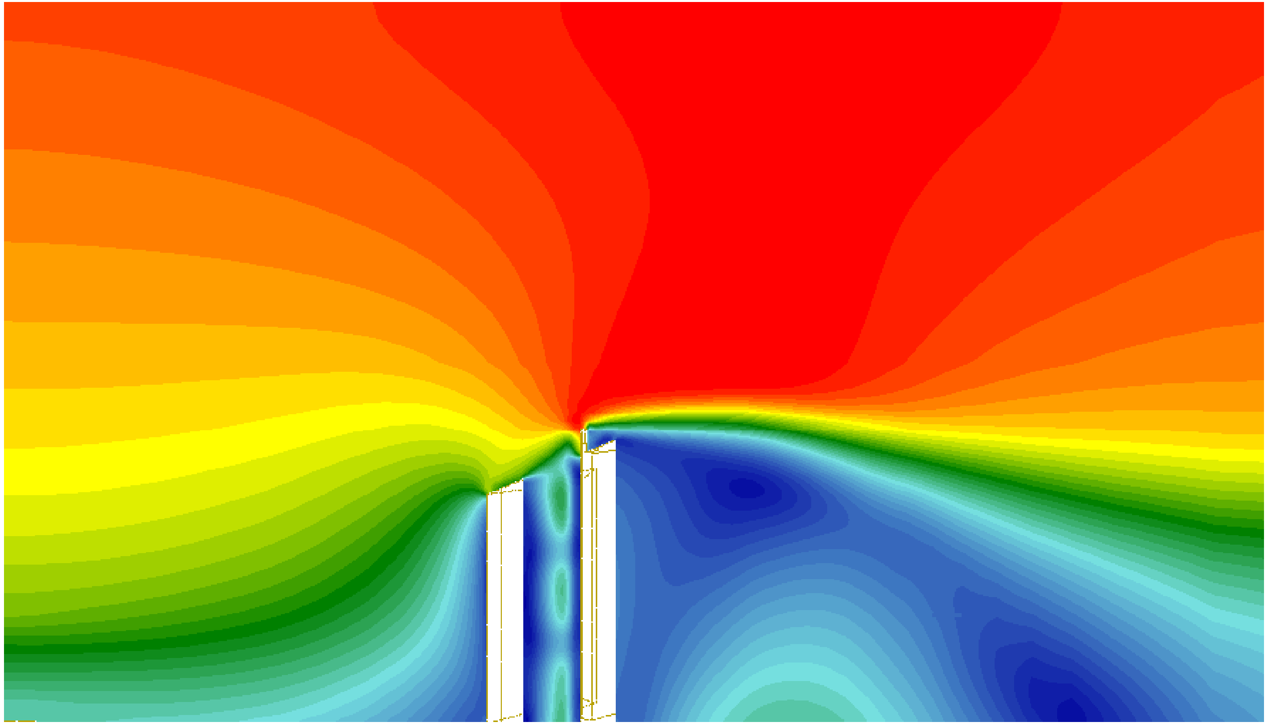
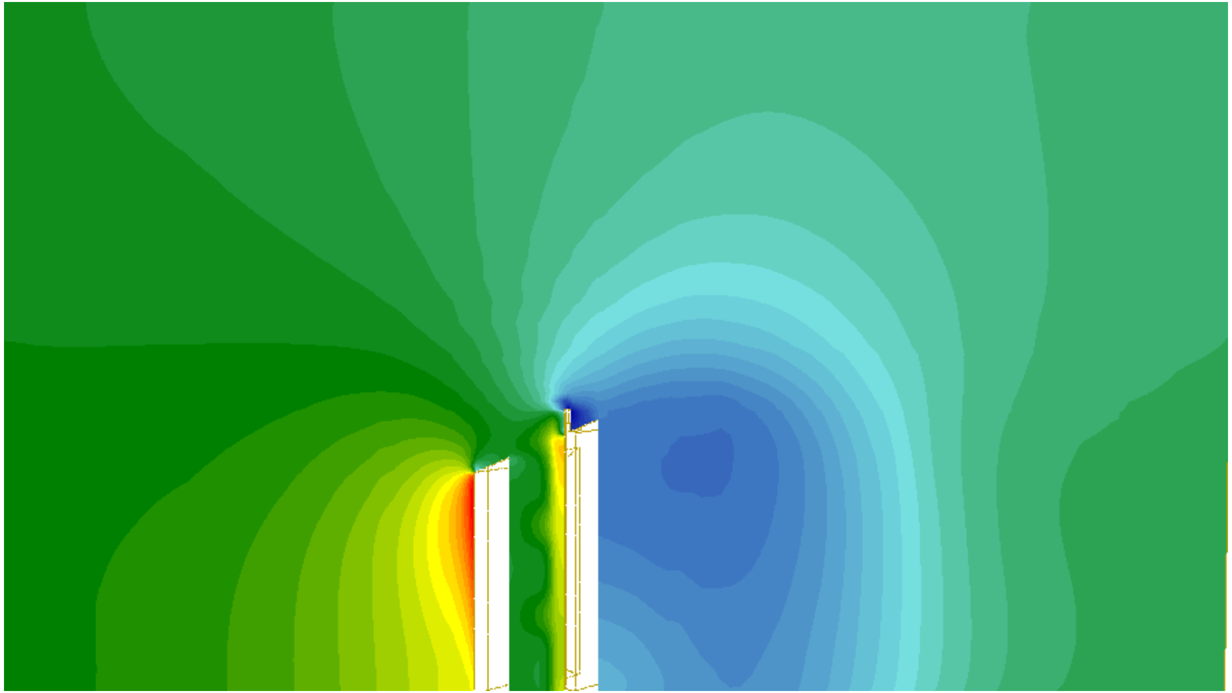
Comparison of Pressures

Distance / h	Nodes	Pressure B2	Pressure B1	Suction B1
80.0 / 2.5 m	80717	2261	2057 -1077	576
160.0 / 2.5	91875	839	874 - 194	517
160.0 / 1.0	783738	1068	1055 - 238	562
320.0 / 2.5	111325	1034	1006 - 272	550
320.0 / 1.0	1079473	852	793 - 215	409
480.0 / 1.0	1079189	847	787 - 199	420
Measurements		502	687 - 284	250
DIN-Values	GKL II	876	?	438

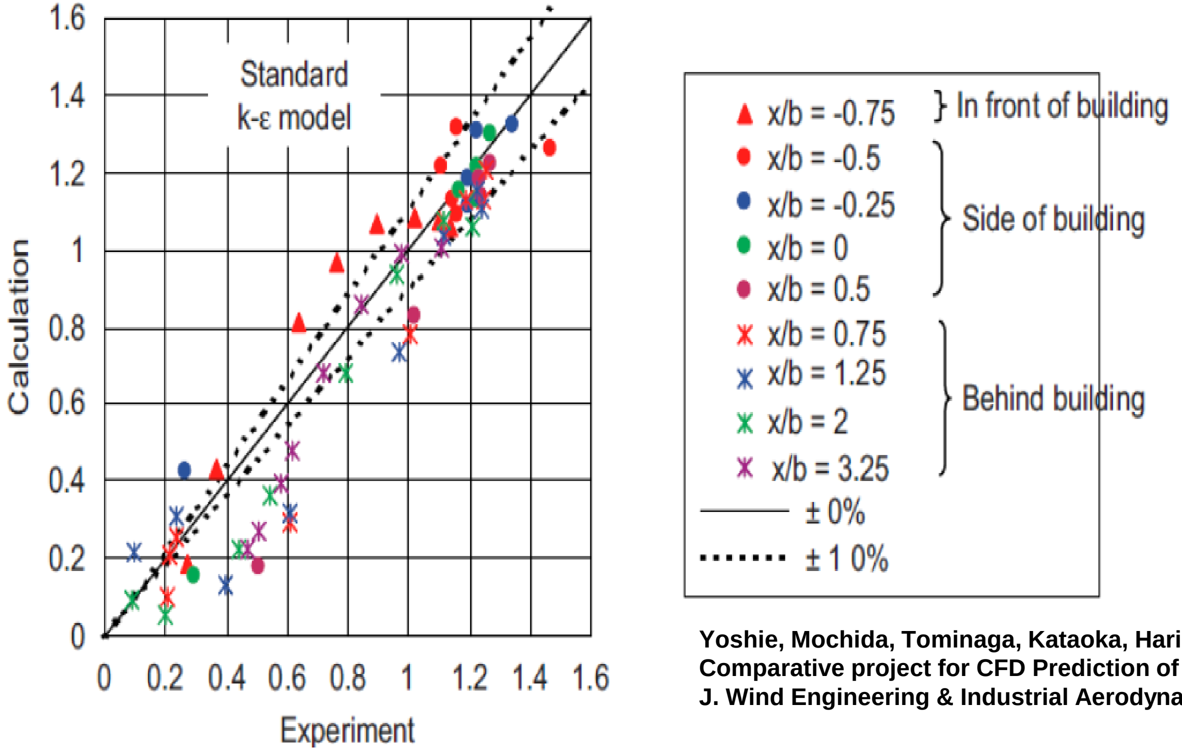
Velocities along the wind



Pressures along the wind



Benchmark for a 2:1:1 building

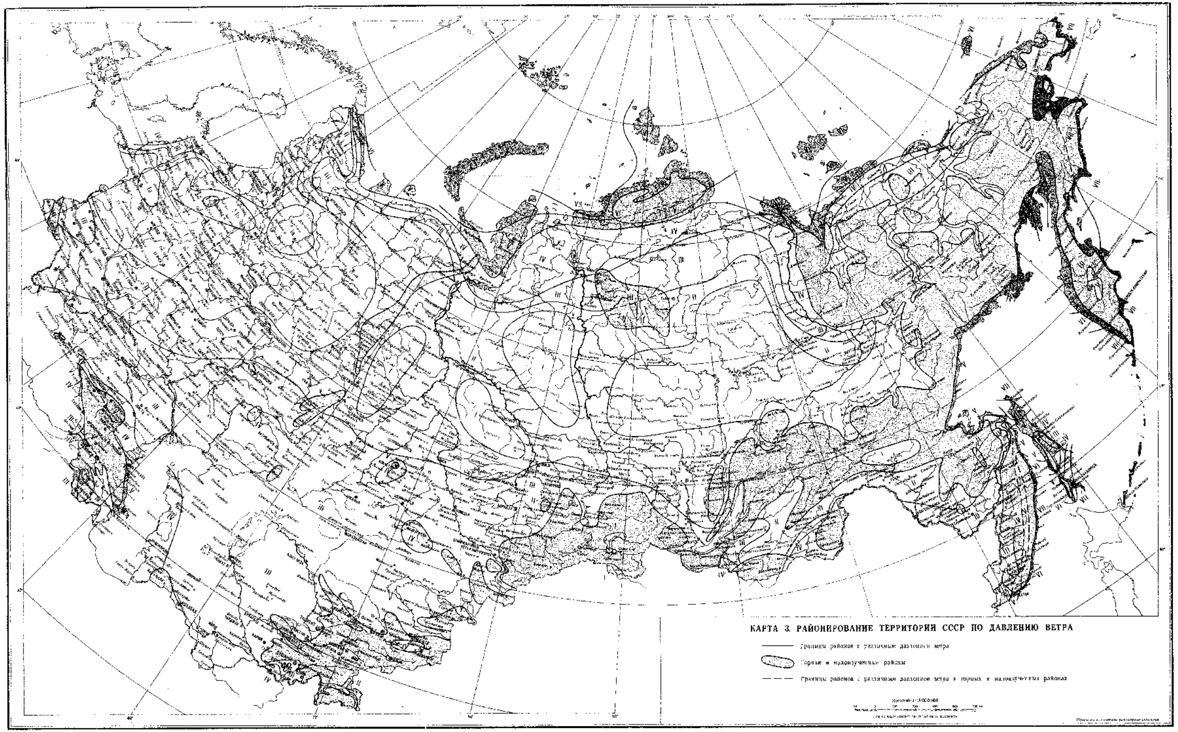


Yoshie, Mochida, Tominaga, Kataoka, Harimoto et. al.
Comparative project for CFD Prediction of wind env.
J. Wind Engineering & Industrial Aerodynamics, 2007

Practical Example

- Two connected high rise buildings with a height of 146 m at Krasnobogatirsky Place in Moscow
- Use of CFD for the analysis of wind loads instead of a wind tunnel test is not excepted very often, because there are known defects of the numerical procedures

Wind map of Russia in SNIP

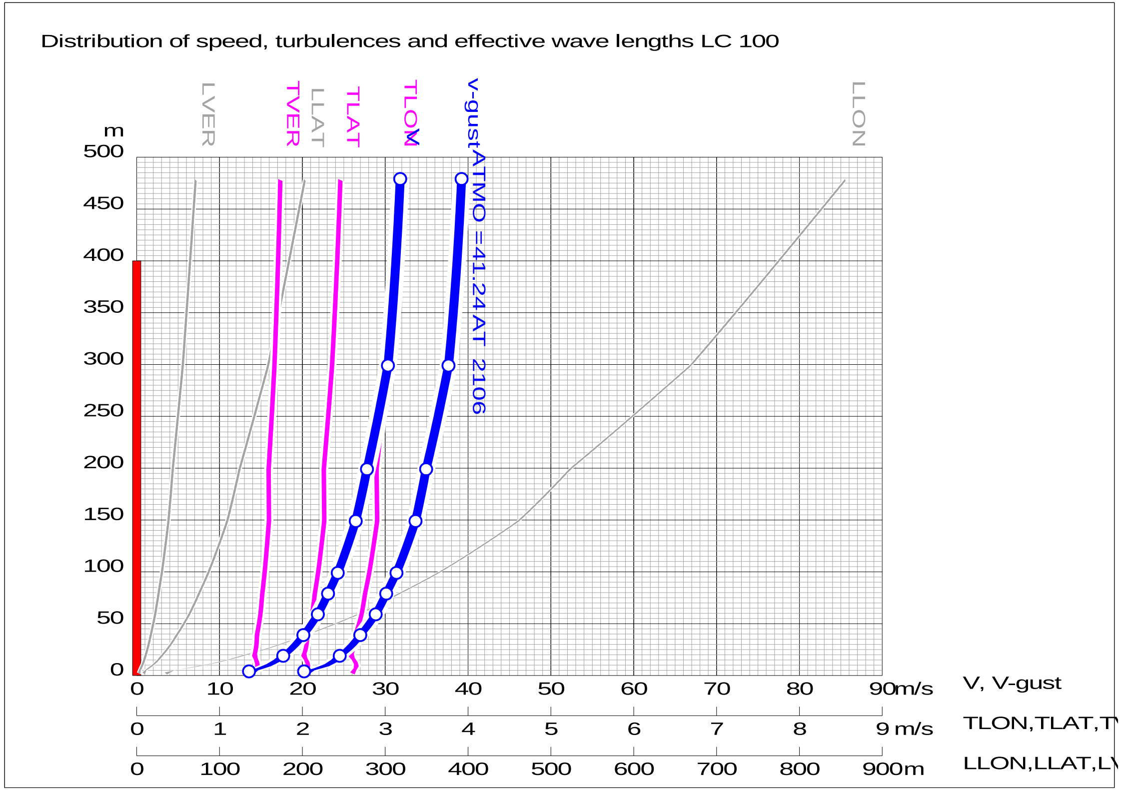


Environment

- located in the vicinity of buildings with up to 4 storeys and a forest, which can not be modelled with reasonable effort, thus we had to select a boundary layer wind profile based on the SNIP 2.01.07-85 wind design code.
- Moscow is in Wind zone I yielding a specified wind pressure of 230 Pa.
- The SNIP provides in Table 6 and 7 pressure factors k and pressure pulses η-gust along the height for a given roughness class B. From those two values we may get the mean wind velocity and the turbulence intensity:

$$v_{mean} = \sqrt{2p/\rho} \quad \rho = 1.25\frac{kg}{m^3} \qquad v_{gust} = v_{mean} \cdot \sqrt{1+\eta} \quad I = \frac{v_{gust} - v_{mean}}{2.65 \cdot v_{mean}}$$

Complete Wind profile



Turbulence Model

- Reynolds number of about 5 10^7
- Turbulence model is required
- standard k-ε model and the hybrid difference scheme, developed by Spalding is very robust.
- standard k-ε model over estimates the turbulence production in the stall point, and we might use other models like the MMK variant:
  - Reduction of pressure in stall point,
    theoretical maximum value is 1.0 (!)
  - Increase of suction values at the rear side
- other difference schemes may be used, but difficult to decide. We have not found significant improvements

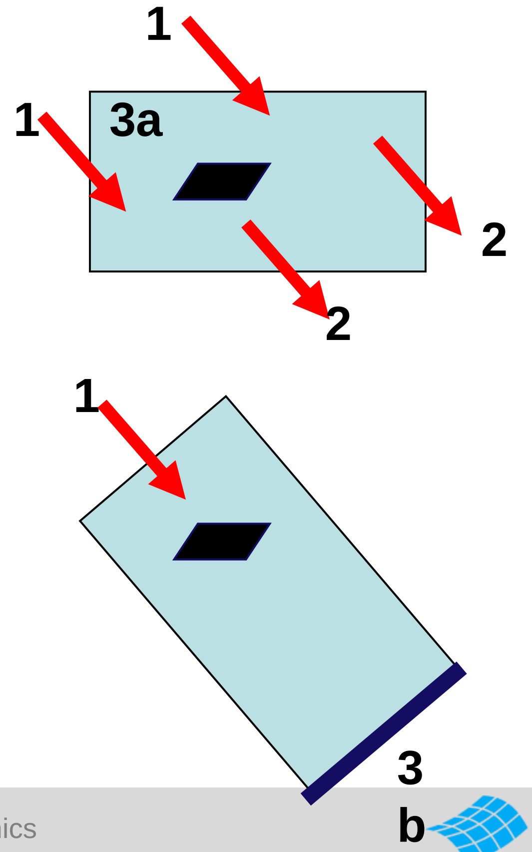
Inflow Boundary Conditions

- We have to specify the wind speed and the turbulence parameters.
- The turbulence energy can be taken from the SNIP specifications directly as stated above.
- We have also provisions for the turbulence length scale either by the integral wave length specified in the Eurocode between 120 and 220 m or the horizontal dimensions of the building with about 35 m. We then may use this length to calculate the dissipation constant ε by the formula:

$$\varepsilon = \frac{k^{3/2}}{L_t}$$

Boundary Conditions

1. Inflow Boundary
    - Velocities
    - Turbulence parameters
2. Outflow boundary
    - Velocities
3. Pressures
    - Arbitrary reference point
    - Outflow Area
4. Walls + Surface
    - Logarithmic wall law



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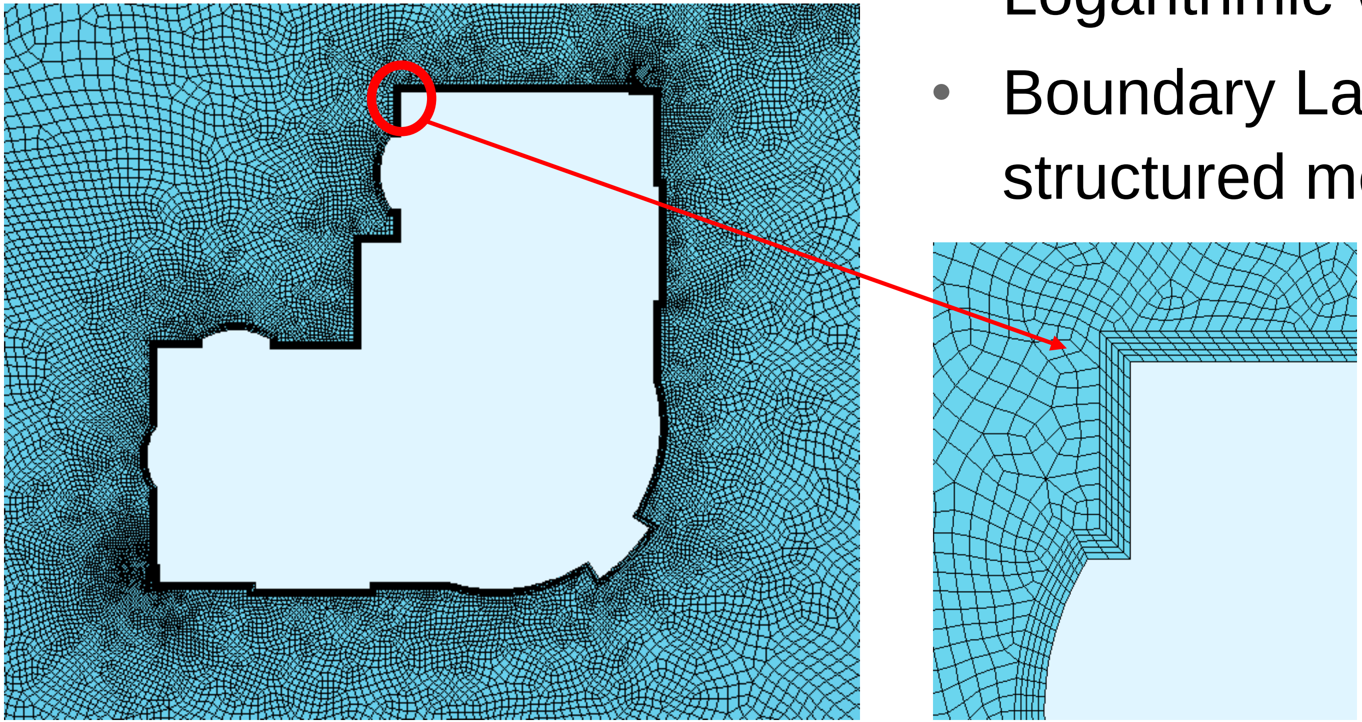
Wall Boundary Condition

- Logarithmic Wall Law
- Boundary Layer with structured mesh

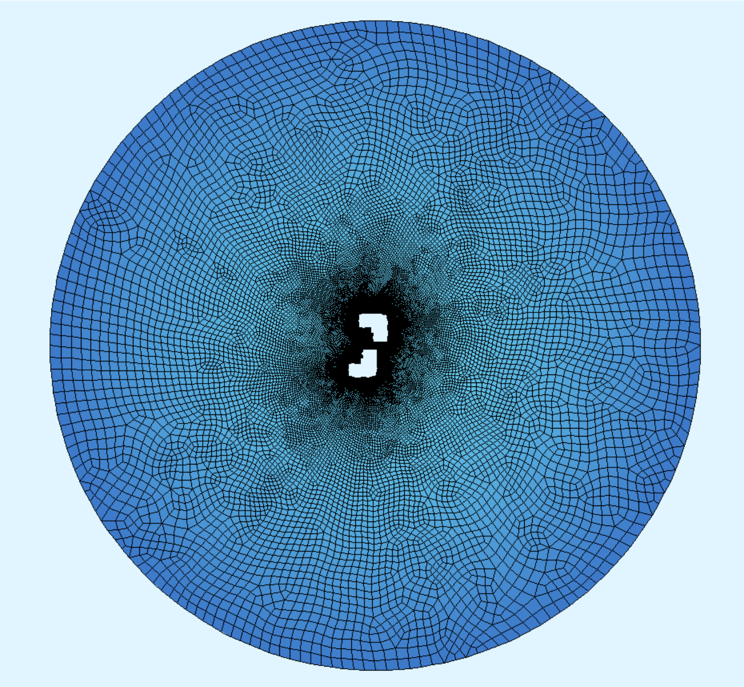


Mesh generation

- Model a sufficiently large air volume around the building
  - A blocking of the stream area with more than 3 % increases the obtained pressures considerably, it is recommended not to exceed 1 %
- Model a proper boundary layer for the wall boundary condition we have to take special care on the mesh generation.
  - An unstructured mesh behaves very poor when modelling the boundary conditions, convergence becomes difficult.
- Reynolds numbers are quite high use meshes with y+ < 50
  - An average mesh size of 0.90 m with a smallest size of 0.20 m at some corners of the surface of the building was selected

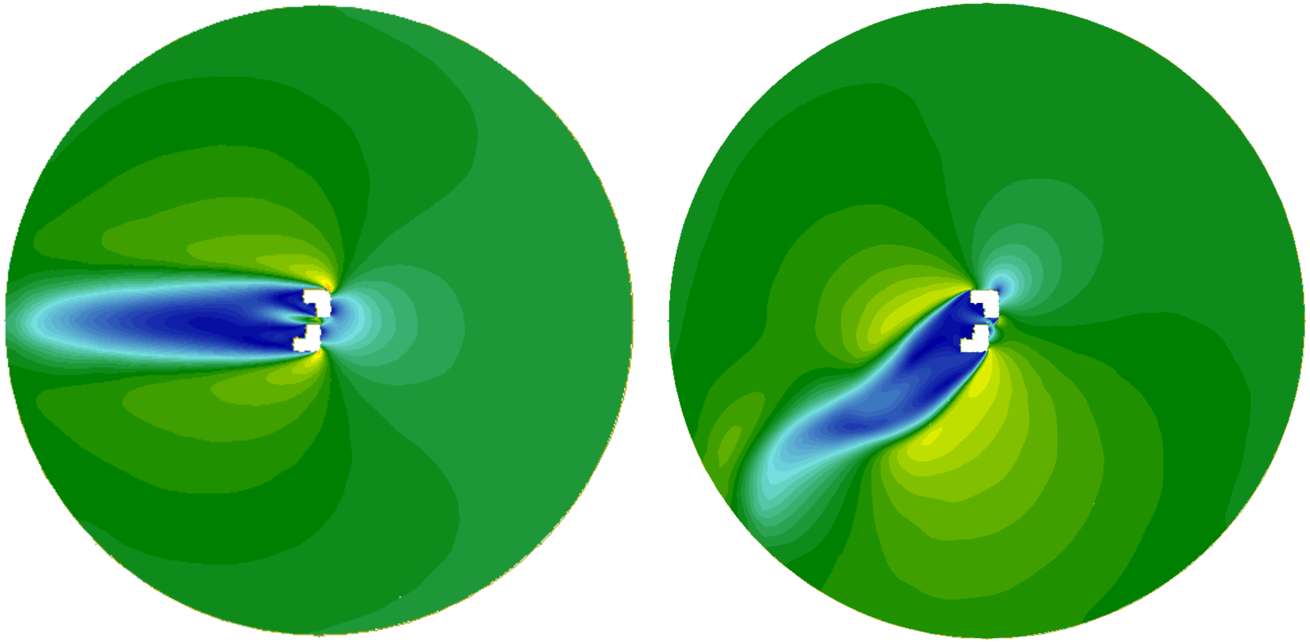
Isotropic Mesh

- Allowing Wind from any direction

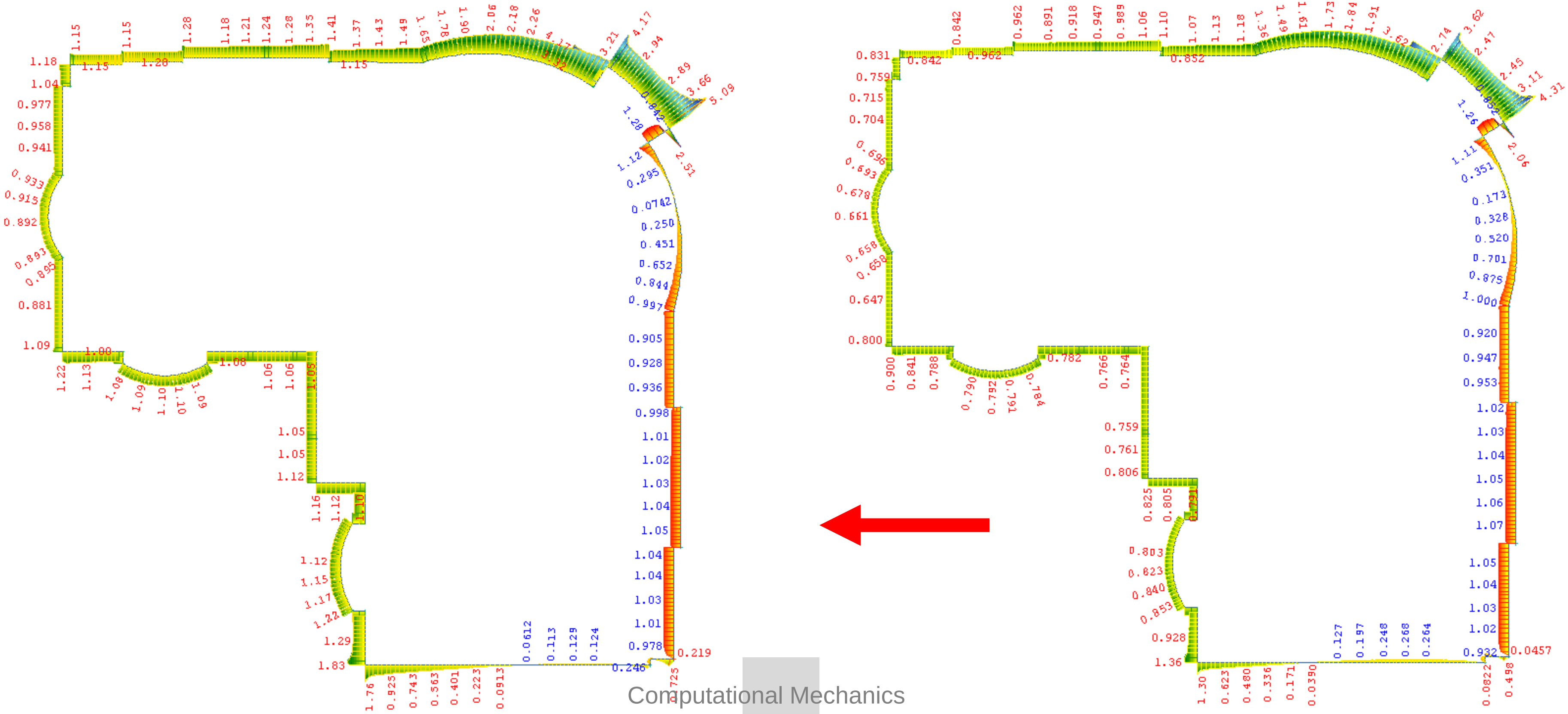


Steady state solution

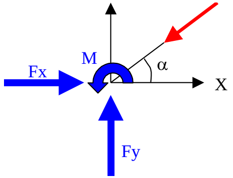
- „False Time Step“

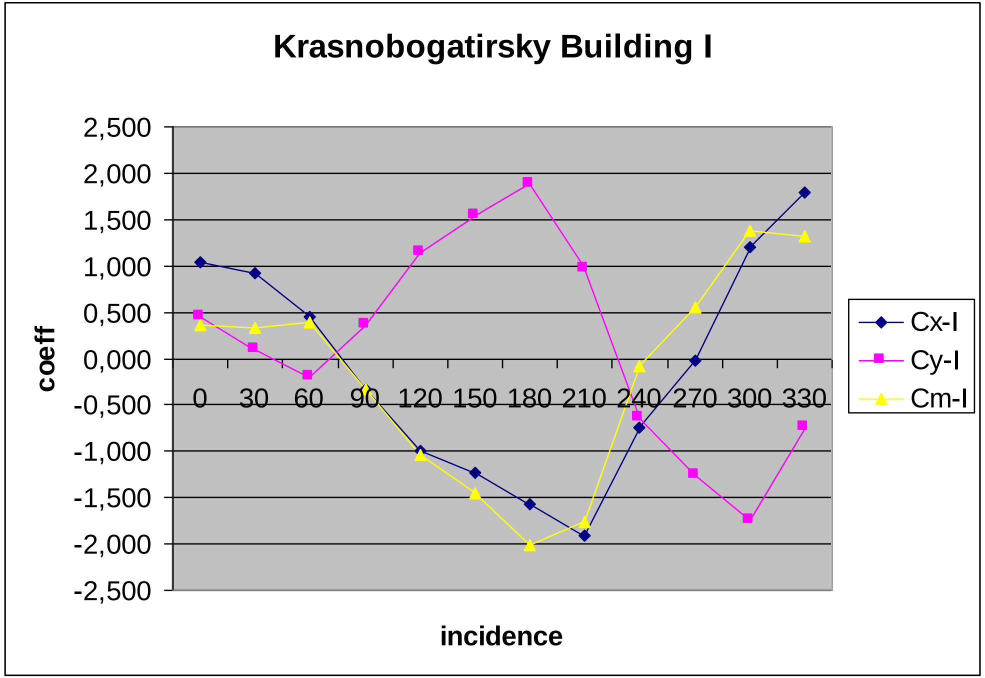


2D pressures small and large mesh extend

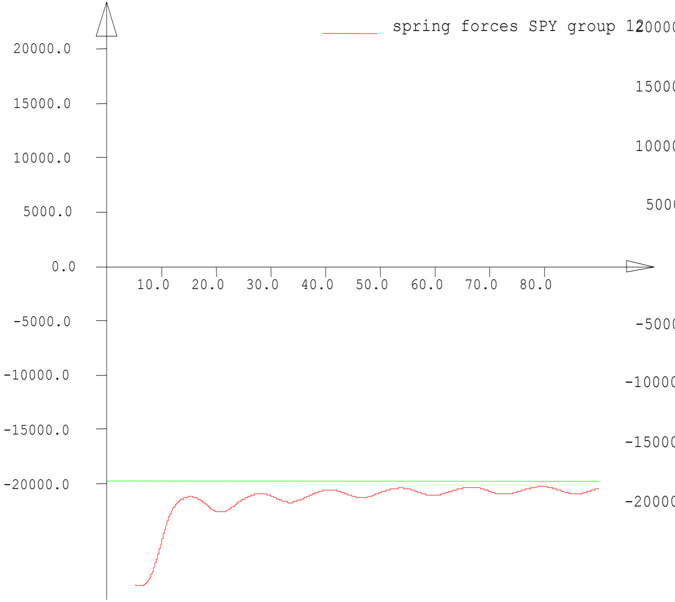


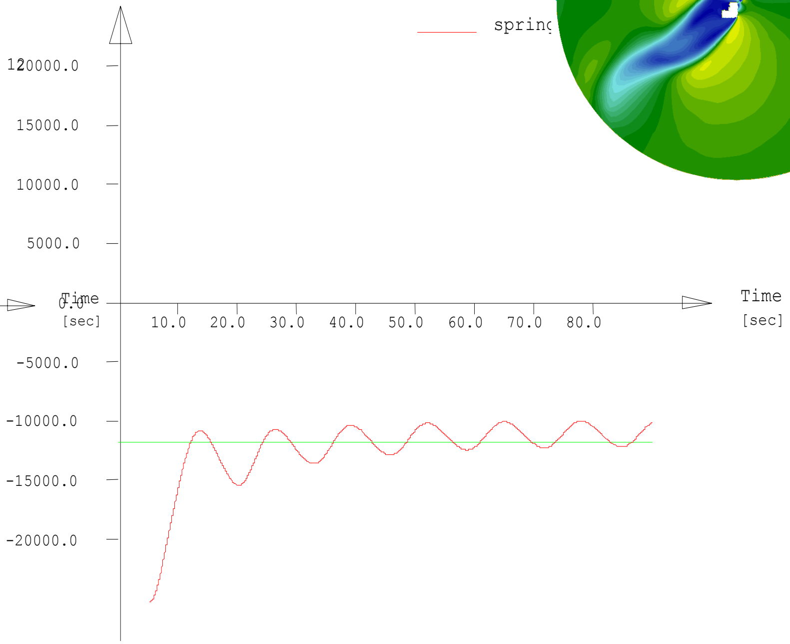
Resultant forces

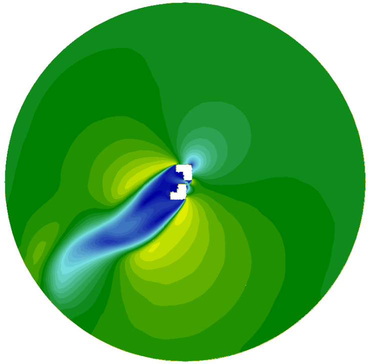




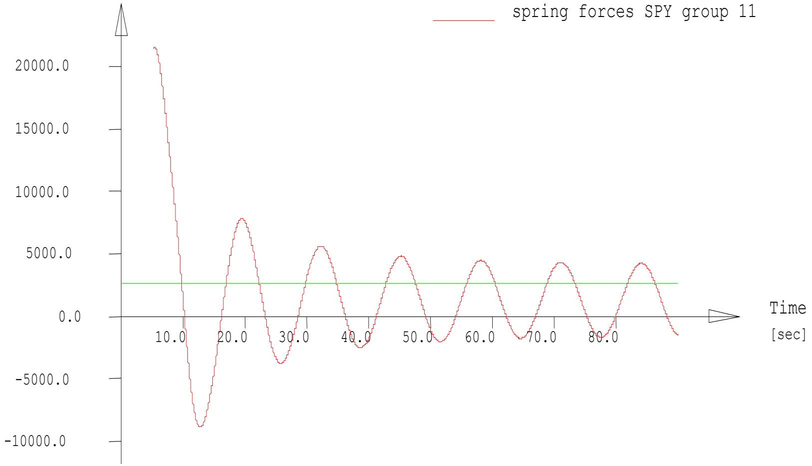
Transient Results of Interaction
1st Building, 60 degree attack

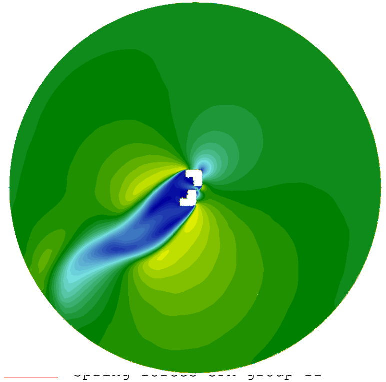


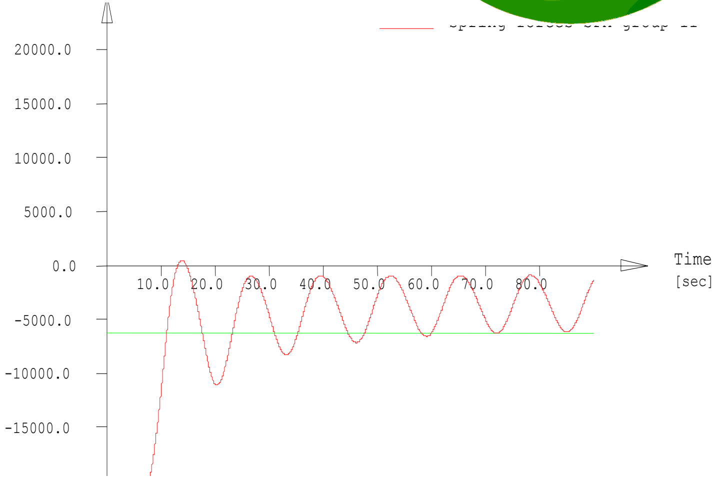




Transient Results of Interaction 2nd Building, 60 degree attack







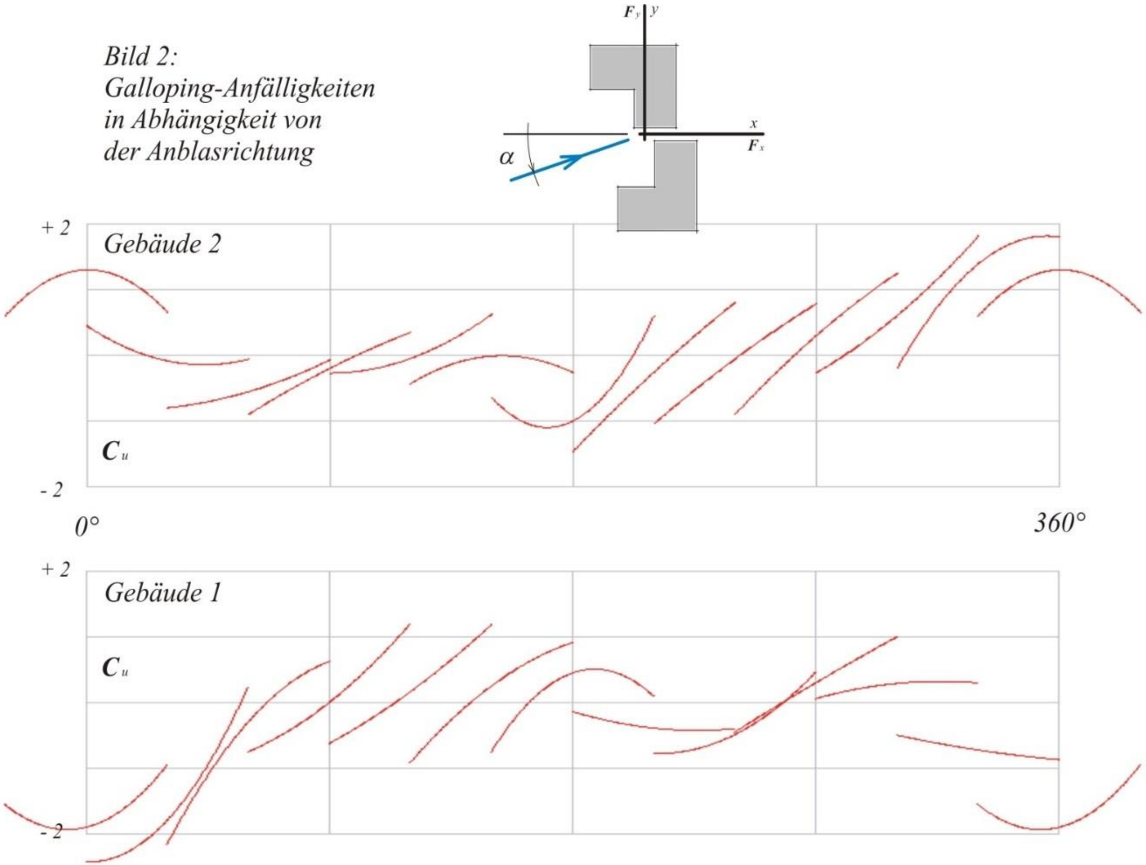
Dynamic Assessment

$$f = 0.4 \cdot \left[\frac{100}{H} \right]^{1,6} \quad 60\,m < H < 200\,m$$

- Estimate of Eigen frequency 0.20 Hertz
- Numerical Analysis 0.138 respective 0.171 Hertz
- Vortex shedding of 0.079 Hertz and thus a Strouhal number of 0.11.
- We may further estimate a coefficient c-lat of about 20% of the longitudinal value which would then be for the first building
  $c_{lat} = 0.18$
- For the second building we obtained a dynamic coefficient:
  $c_{lon} = c_{lat} = 0.45$

Galopping

- Take the drag coefficients from the grid of attack angles and create an estimate for the local derivatives



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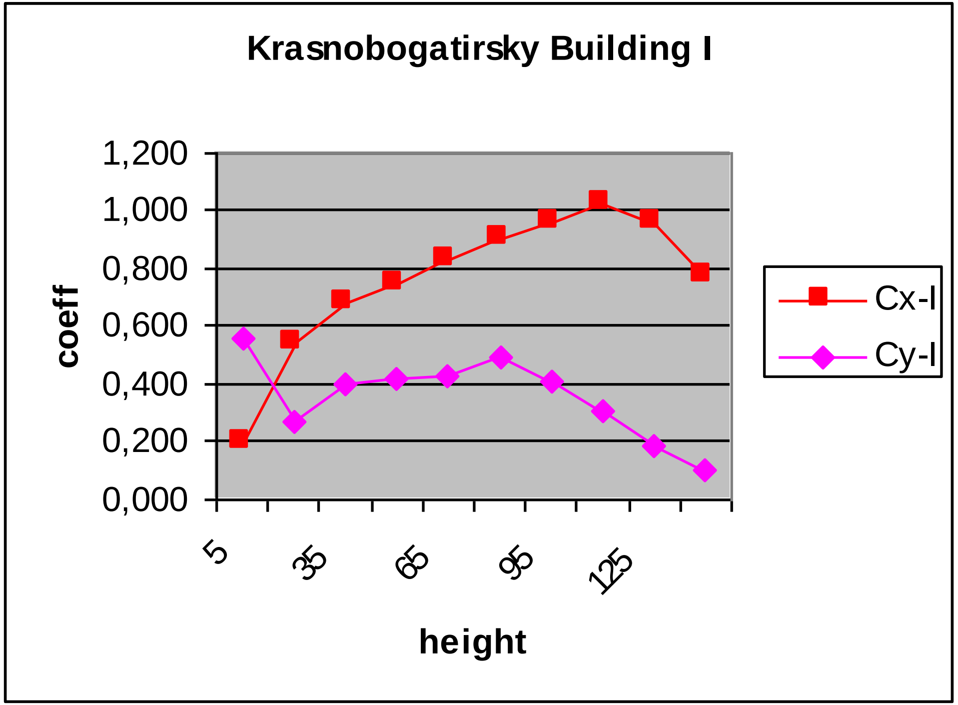
3D Meshing

- 2D mesh generator has created a quadrilateral surface mesh. From that mesh a triangular mesh is generated to become the advancing front of the unstructured tetrahedral mesher. But before starting the boundary layer is created by 6 noded wedge-type volume cells.
- numerical effort for a three dimensional analysis is much higher (1.3 Mio finite volumes)
- Steady state solution only

Resulting drag coefficients along the height



Observations

- The maximum pressure coefficients are close to 1.0, only at some edges we have local higher values. As it is known, that the k-ε model creates slightly higher pressures, the results are in an acceptable range.
- Maximum suctions are obtained at the edge of the roof up to –3.80 which is in good agreement with expected values.
- On the wind front we have a distribution of pressures according to the wind profile, but there is a nearly constant suction along the height at the sides and the rear.
- There is only a small disturbance of the flow pattern by the other buildings.

Comparison 2D and 3D @ 100m

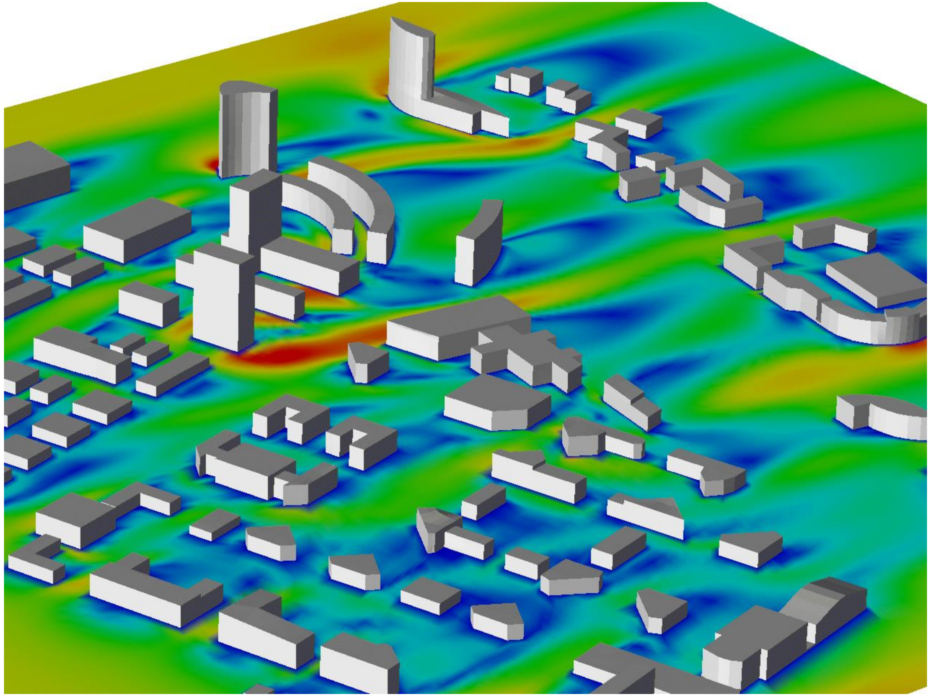
	Cx - I	Cy-I	Cx - II	Cy - II
2D	0.889	0.390	1.037	0.871
3D	0.981	0.357	1.073	0.654

- From that it may be justified to make the global analysis of the structure based on the 2D drag coefficients, and to use the 3D pressure coefficients only for local effects or a refined analysis.
- A transient 3D analysis has not been established therefore.
- Analysis Time between several hours and 2 days for the transient analysis of 12 directions on a standard Windows AMD Computer

Conclusions for bluff bodies

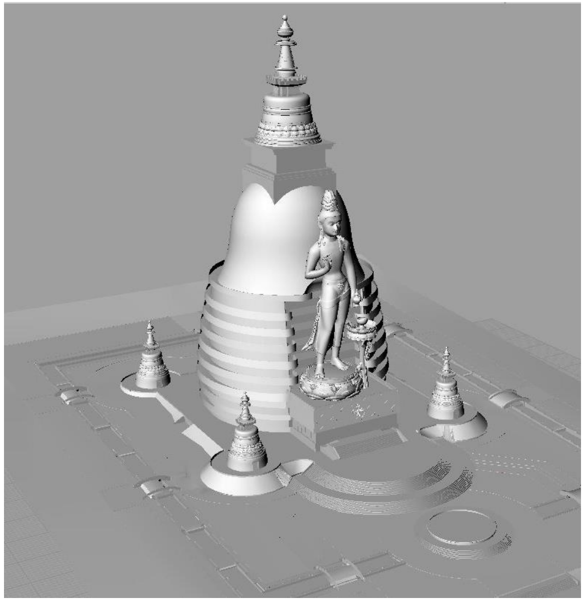
- CFD Analysis is better than expected!
- The may produce a better feeling for the qualitative effects of the flow.
- A wind tunnel test it still necessary in many cases!
- To what extend you want to know the wind loads ?
- There is no single solution, we have to cope with limit cases.
- A non linear transient analysis with Fluid-Structure-Interaction may be used for new design concepts, not available with a wind tunnel alone.

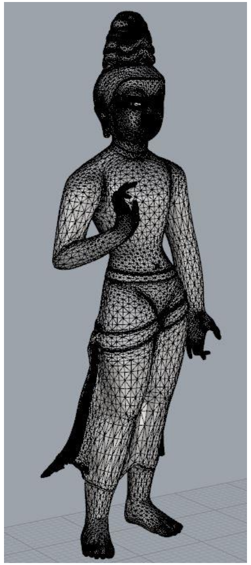
Mesh Generation Issues

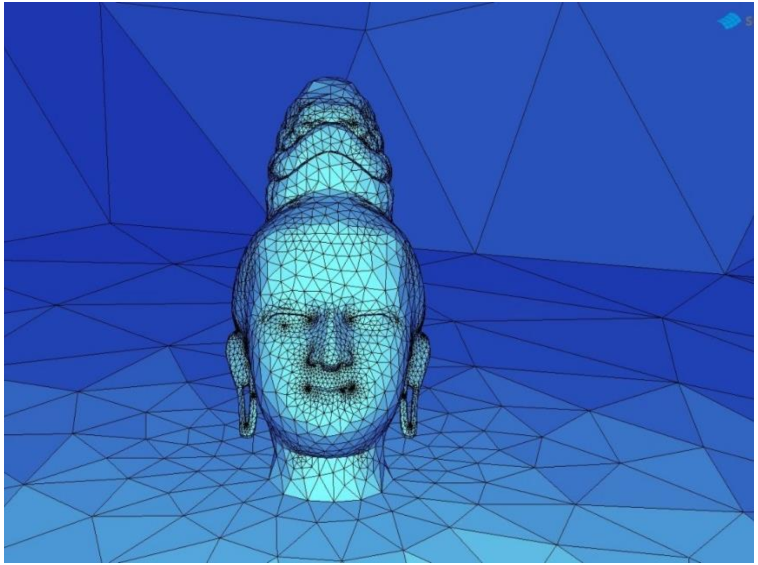


Mesh Generation Issues

(Rhino – STL Export – NETGEN Tetrahedral meshing in SOFiMSHC)



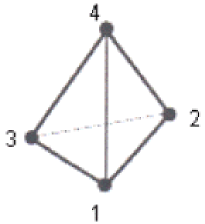


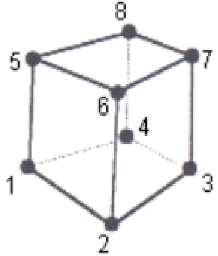


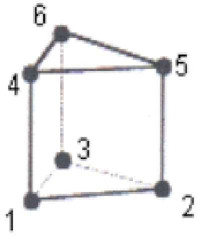
Grand Maitreya Project
Ulaanbaatar – Mongolia

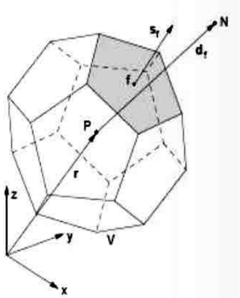
Finite Volume Types

- Tetrahedral:
  - easy meshing
  - Very poor numerics
- Hexahedral:
  - difficult meshing
  - good numerics
- Polyhedral:
  - Best of both ?



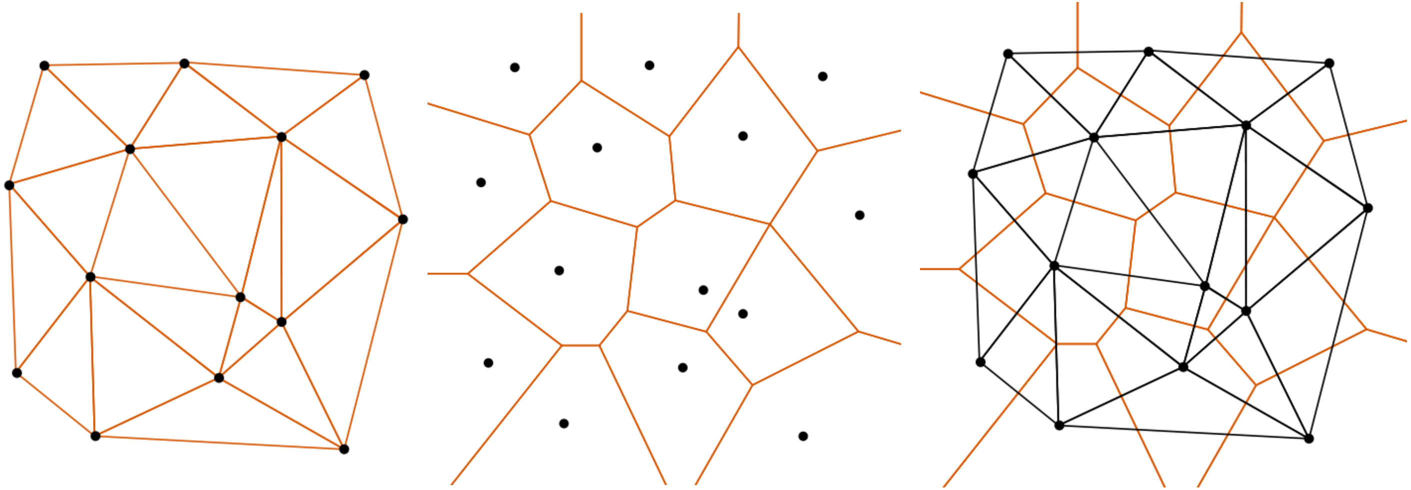






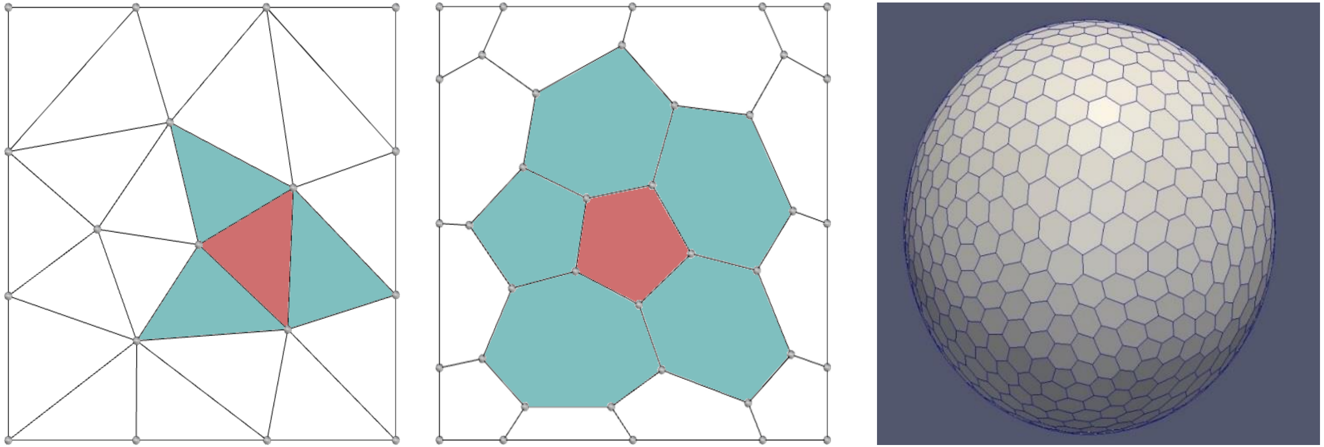
Polyhedral cells = A dual mesh approach

- Delauney - Triangularisation ⬄ Voronoi Mesh
- A more general solution is possible

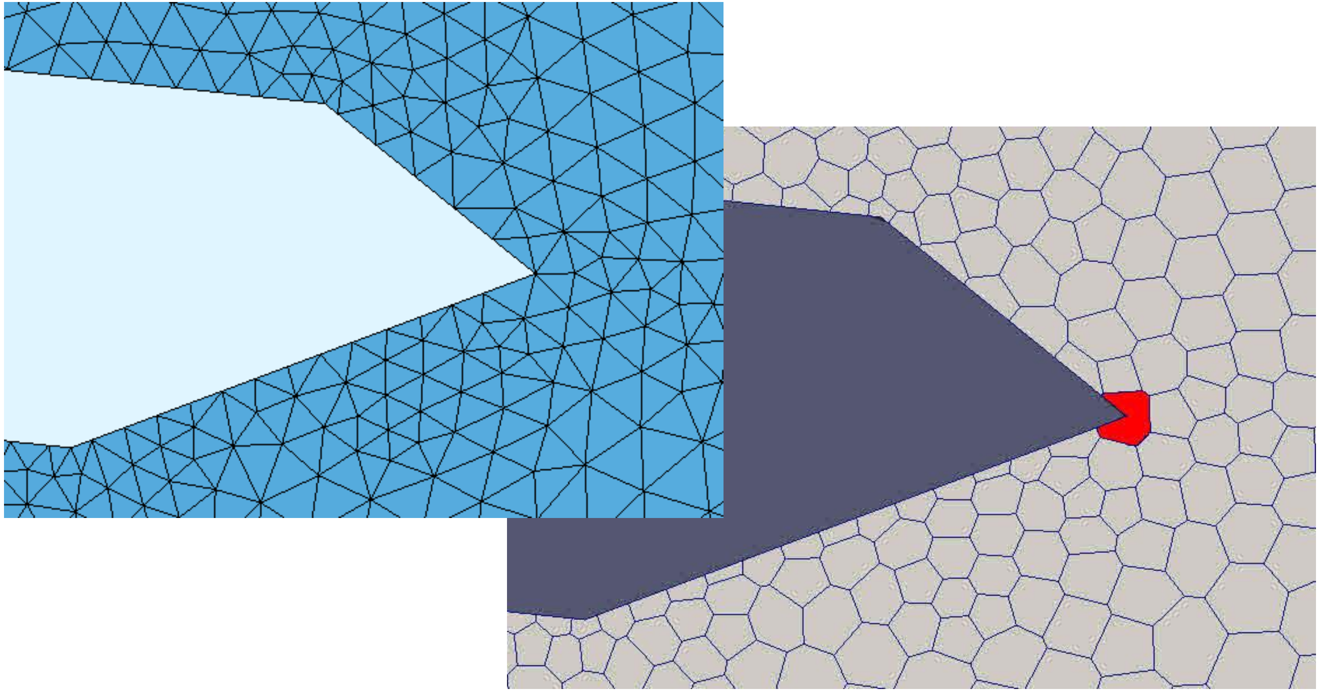


Why polyhedral cells?

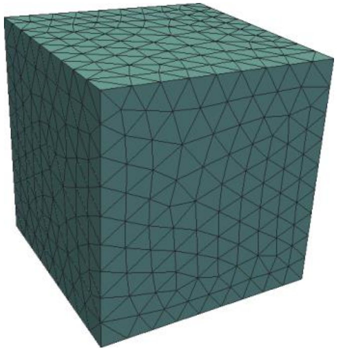
- Minimize the total number of faces / cells
- More neighbours (ca 14 instead of 4 or 6)



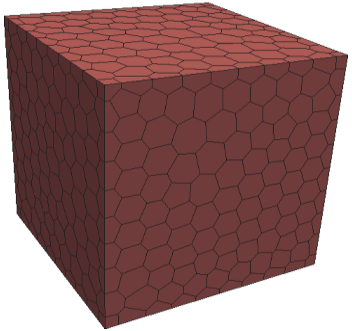
Some Problems with convex elements



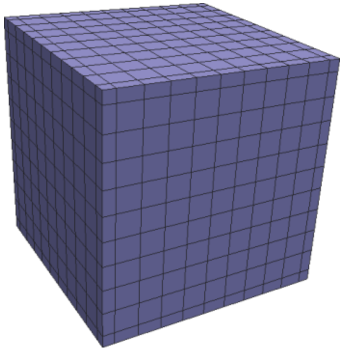
Performance Test



Tetrahedral Mesh: 6168 cells

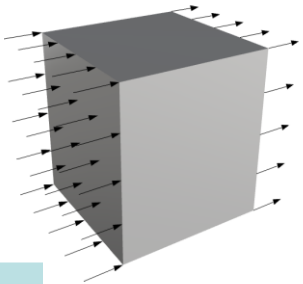


Polyhedral Mesh: 1336 cells



Hexahedral Mesh: 1331 cells

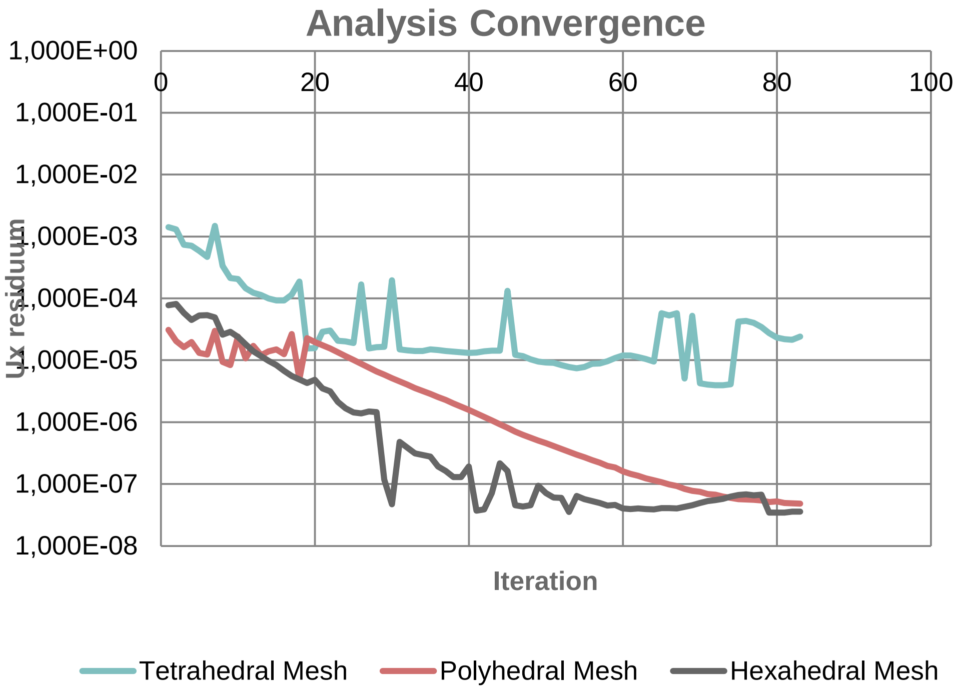
Performance Test



Residual is not the error of the solution!

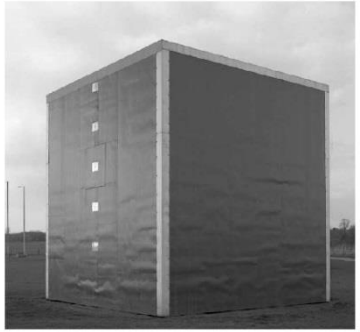
	Residual v-x	Residual v-y	Residual v-z	Residual mass	v-x [m/sec]	v-y [m/sec]	v-z [m/sec]
715 Tetrah. 800 Iterations	7.8E-6	7.1E-7	3.0E-6	5.6E-5	11.4	0.66	0.96
211 Polyhedra 800 Iterations	6.3E-8	7.6E-9	9.7E-9	2.9E-7	10.0	0.005	0.02
Reference					10.0	0.0	0.0

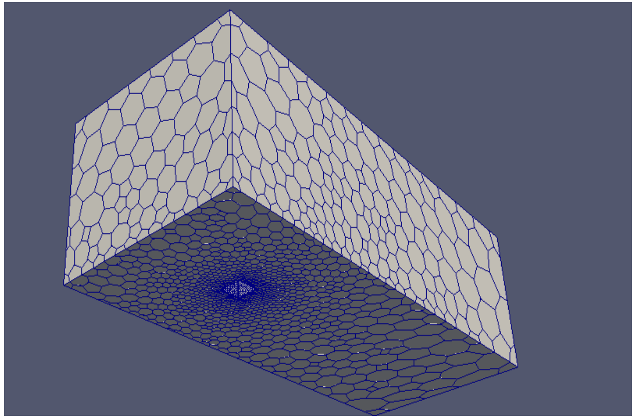
Convergence of larger meshes

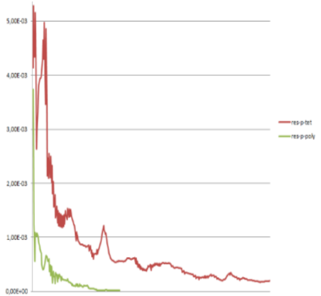


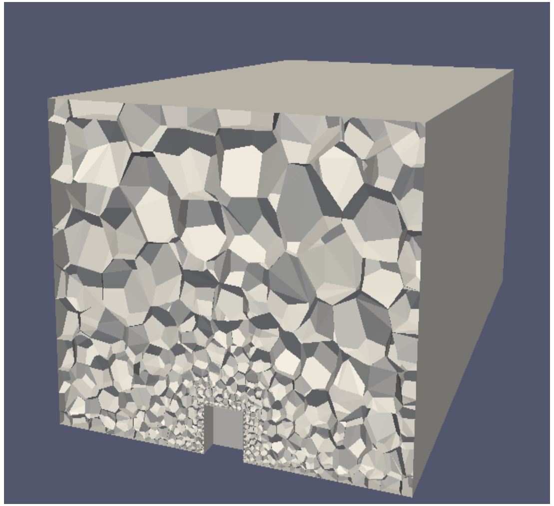
SOFiSTiK

Silsoe Cube

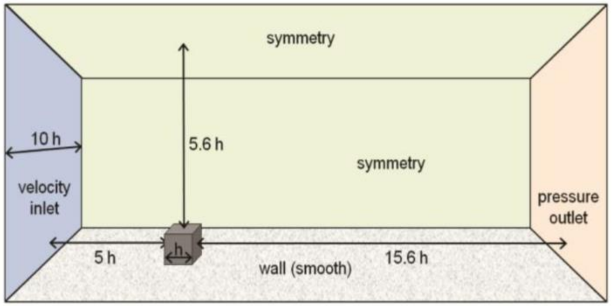


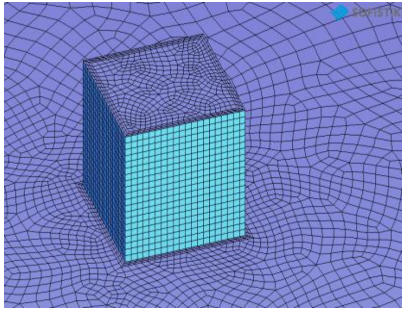


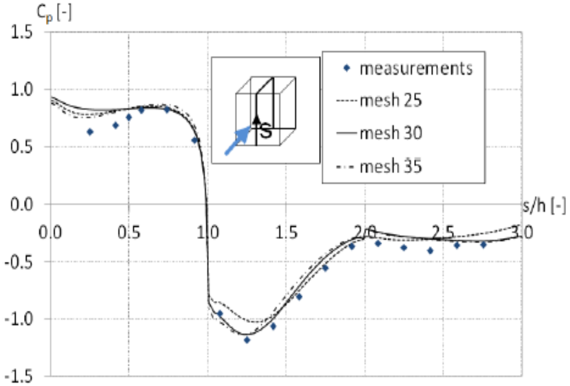

5,00E-03
4,00E-03
3,00E-03
2,00E-03
1,00E-03
0,00E+00
res-p-tet
res-p-poly

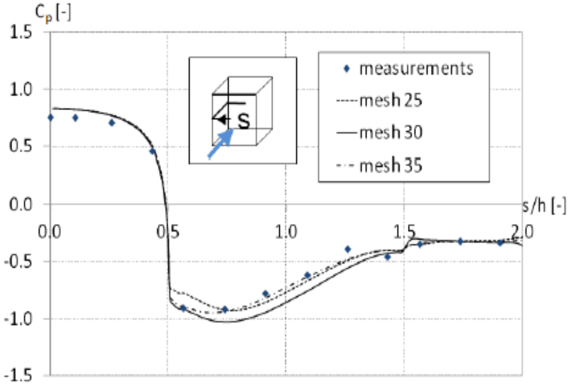


Reference: Measurements and LES-Analysis

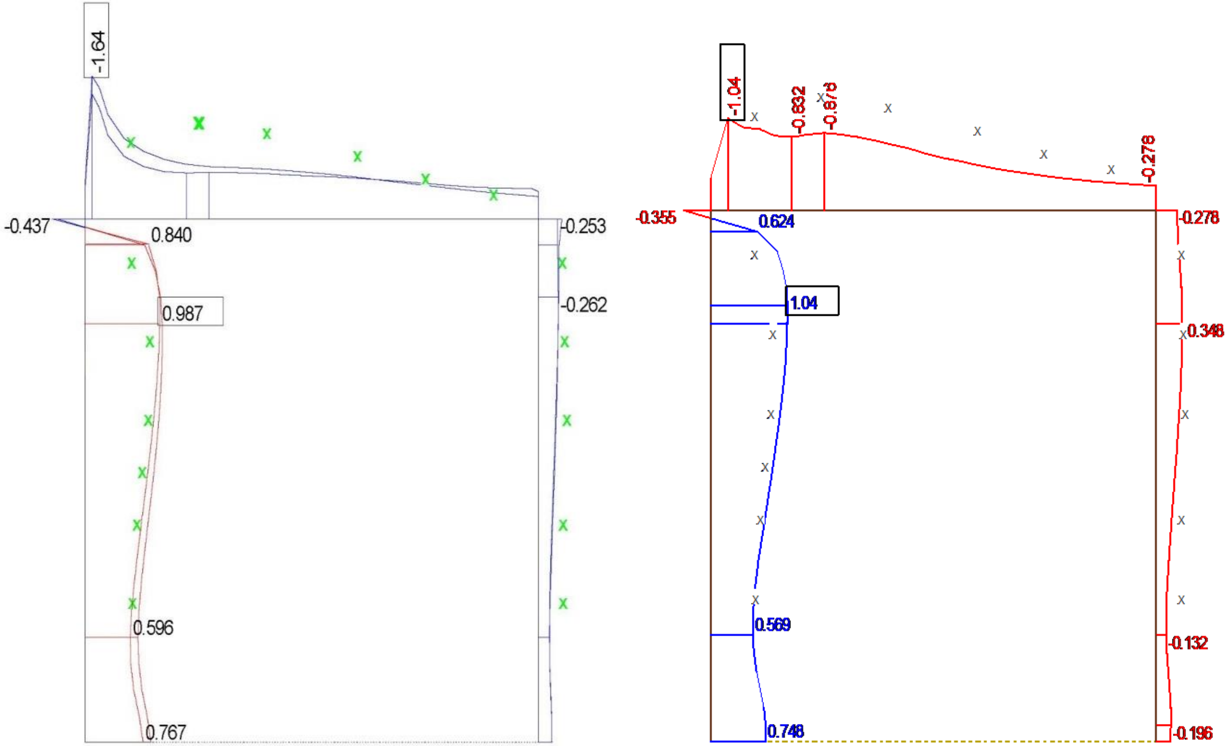




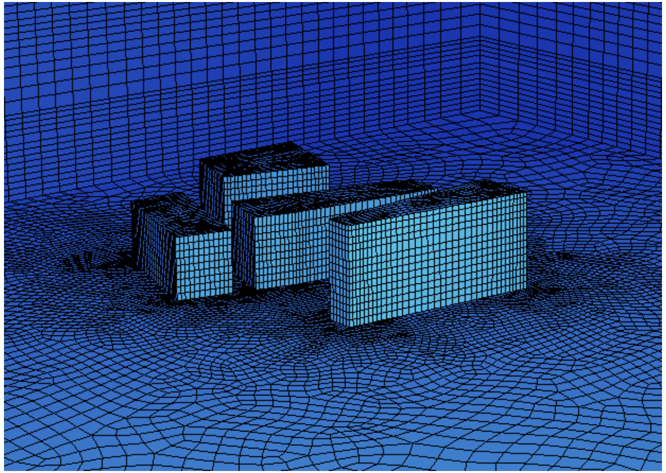


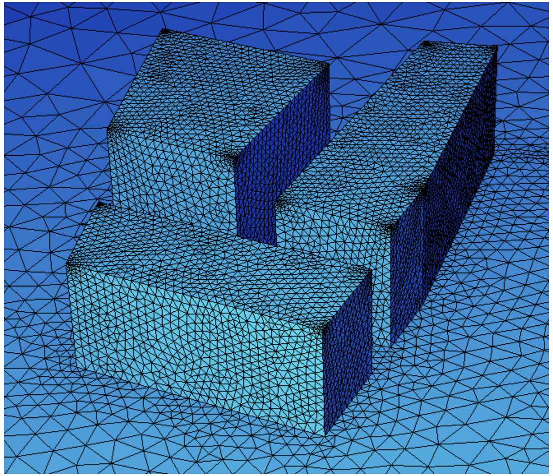


Tetrahedral - Polyhedral k-ε-RNG Pressures



Assembly of buildings (Hexaeder / Polyeder)



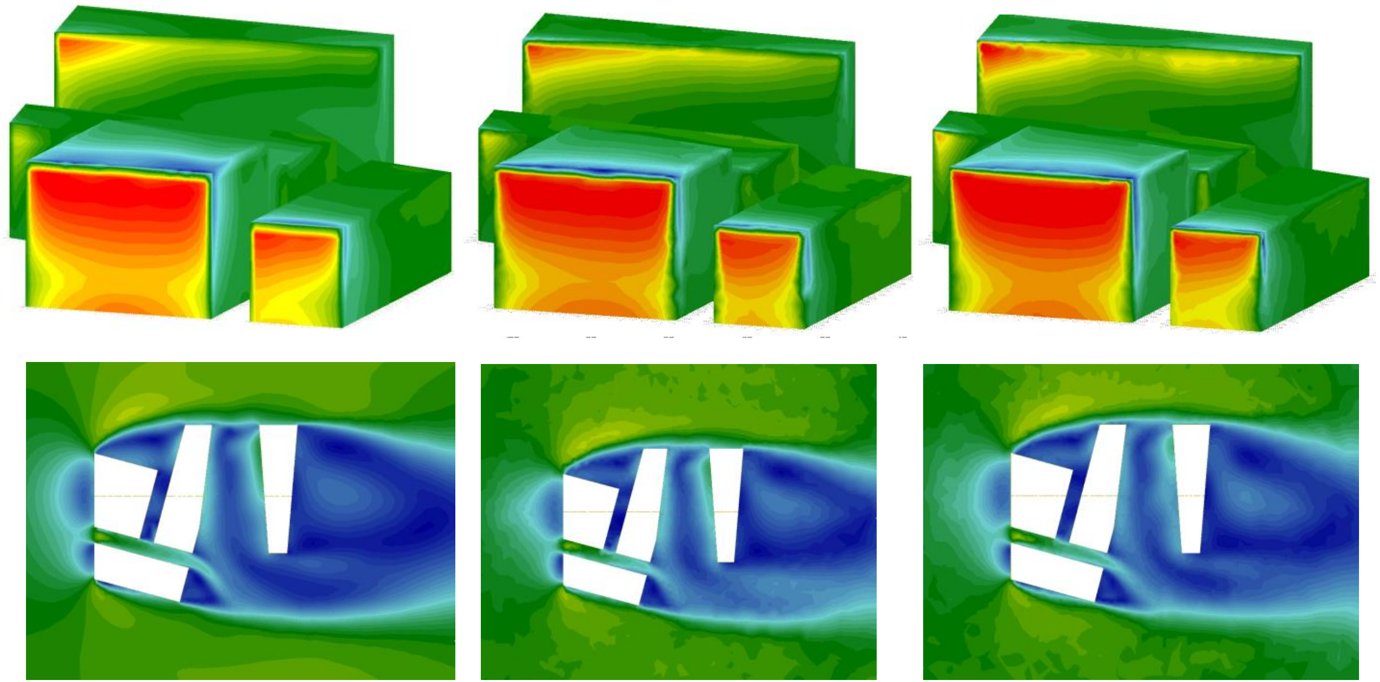


- v_{top} = 26 m/sec, z_0 = 0.30 m, Standard k-ε
- p_{ref} = 422 Pa

Numerical Parameters

	Hexahedra	Tetrahedra	Polyhedra
p-max [Pa]	505	625	557
p-min [Pa]	-793	-817	-683
Number of Cells	505534	287912	76377
Number of faces	595534	583964	515785
CPU [sec]	9000	5041	1295

Pressure Distribution and Isotaches (Hexahedra, Tetrahedra, Polyhedra)



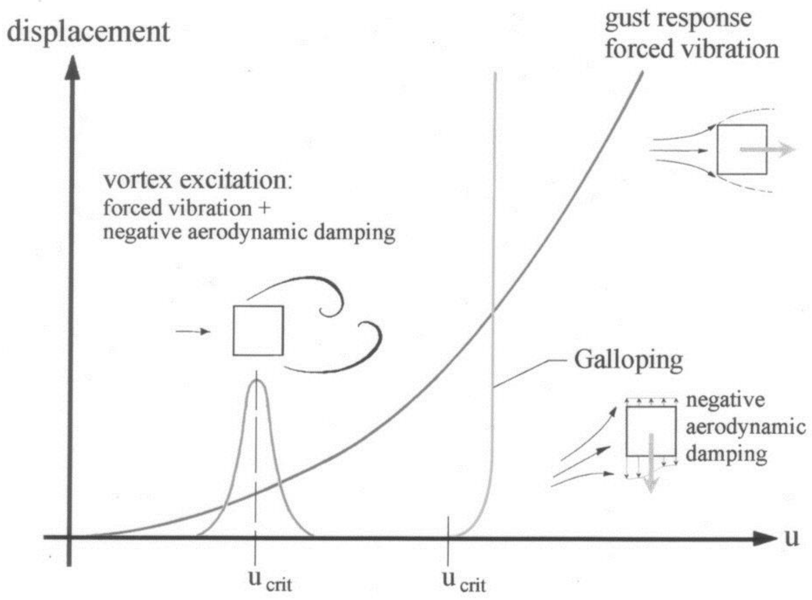
Wind on Bridges

- Famous Example of Tacoma Narrows Bridge
- Other Examples Great Belt Eastern Bridge

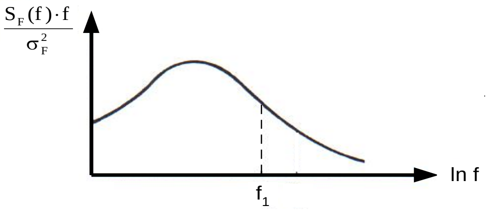
SOFiSTiK

Wind dynamics for bridges

- Gust-response (Buffeting)
- Vortex excitation (Karman)
- Aero elastic damping (positive or negative)
- Torsional divergence
- Galloping
- Flutter
- Interferences

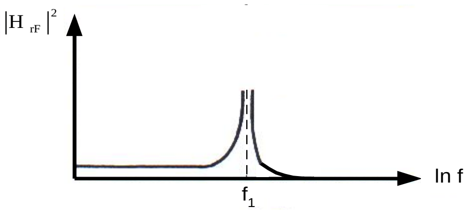


gust effects
the Eurocode 1991-1-4 procedure



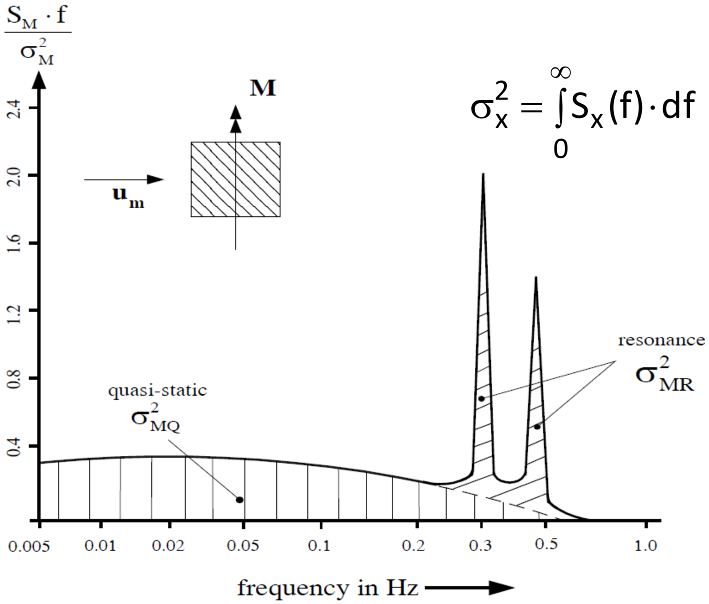
$$\underline{H}_x^T = \begin{bmatrix} H_{xF_1} \\ H_{xF_2} \\ .. \end{bmatrix}$$

$$\underline{H}_x^* = \begin{bmatrix} H_{xF_1}^* & H_{xF_2}^* & .. \end{bmatrix}$$



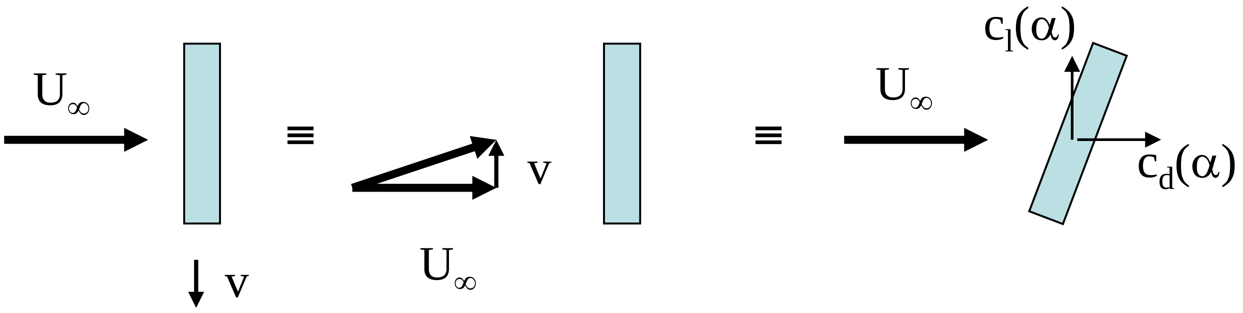
$$S_x = \underline{H}_x^* \cdot \underline{\underline{S}}_F \cdot \underline{H}_x^T$$

$$\sigma_x^2 = \int_0^\infty S_x(f) \cdot df$$



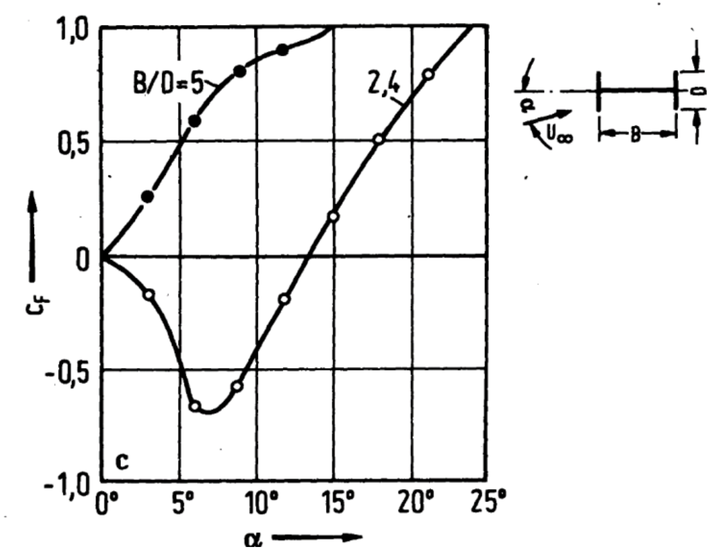
SOFiSTiK

Aero elastic damping



- A body in the wind moves in transverse direction
- Resulting in a virtual change of the angle of attack by
  $\alpha = \text{atan}(v/U_\infty)$
- The resultant vertical drag coefficient is
  $$c_v(\alpha) = c_l(\alpha)/\cos(\alpha) + c_d(\alpha)\tan(\alpha)/\cos(\alpha)$$
- For small angles one may use $\cos(\alpha)=1$ and $\tan(\alpha)=\alpha$
  $$c_v(\alpha) = c_l(\alpha) + c_d(\alpha)\,(v/U_\infty)$$

Aero elastic damping



- Dependant on the shape of the section the curve of the drag coefficient may be quite different, especially the derivatives may vary to a great extend.

Aero elastic damping

- For the change of the drag force within time we replace the function of the coefficient by its Taylor series and remove all constant parts:

$$\Delta F = \rho \frac{U_\infty^2}{2} \cdot H \cdot \frac{v}{U_\infty} \cdot \left[\frac{\partial c_l}{\partial \alpha} + c_d \right]_{\alpha=0}$$

- As this force is now proportional to the speed of the section it may be introduced in the equation of motion by an additional damping. (m = mass of oscillator)

$$D = D_{struct} + \frac{\rho \cdot U_\infty}{2 \cdot m} \cdot H \cdot \left[\frac{\partial c_l}{\partial \alpha} + c_d \right]_{\alpha=0}$$

Galloping

- Dependant on the sign of the derivative we have a positive or negative aero-elastic damping.
- For the latter case we have a certain critical wind speed where the total damping becomes negative. Then the oscillation becomes instable and the amplitudes grow steadily.
- If exchanging the modal damping by the logarithmic decrement δ, we get the stability criteria:

$$U_{crit} = \frac{2 \cdot \omega \cdot \delta \cdot m}{\pi \cdot \rho \cdot H \cdot \left[\frac{\partial c_f}{\partial \alpha} \right]_{\alpha=0}}$$

Torsional divergence

- There is a second type of instability given for the case that the change of the torsional moment per change of rotation becomes larger than the structural torsional stiffness.
- Again we have a critical wind speed for that type of failure:

$$U_{crit} = \sqrt{\frac{2 \cdot k_\alpha}{\rho \cdot B^2 \cdot \left[\frac{\partial c_m}{\partial \alpha}\right]_{\alpha=0}}}$$

Flutter

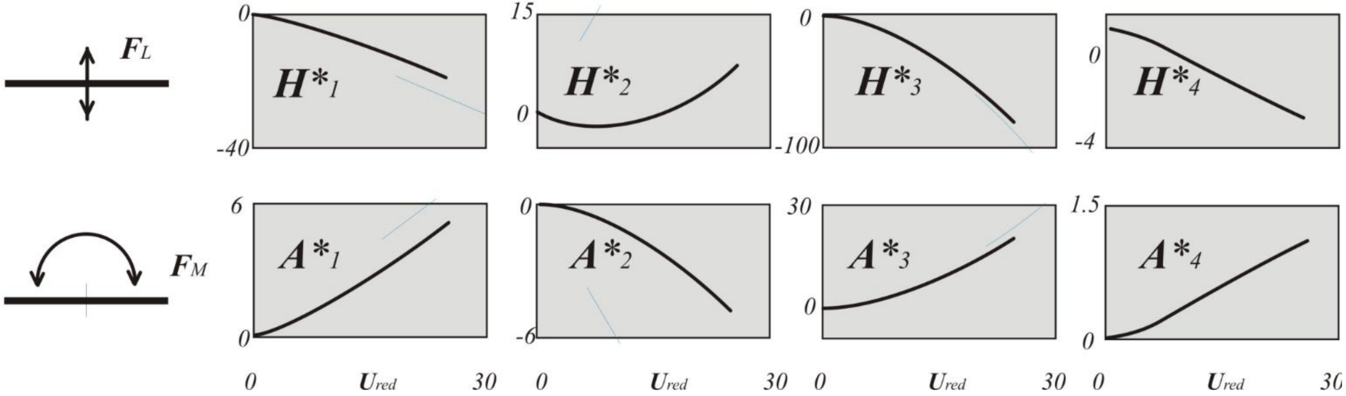
- If the coupling of the rotation with the transverse displacement is taken into account, we have forces and moments depending on displacements, rotations and their derivatives in time.
- Scanlan has suggested 8 coefficients to describe this highly non linear effects in a linearized form
- By that process the height H is replaced by the width B and from the Eigen frequency of the structure we get a reduced flutter frequency k:

$$U_{red} = \frac{U_\infty}{f \cdot B} \quad ; \quad k = \frac{2\pi \cdot f \cdot B}{U_\infty}$$

Scanlan's Derivativa (6 – 8 – 18)

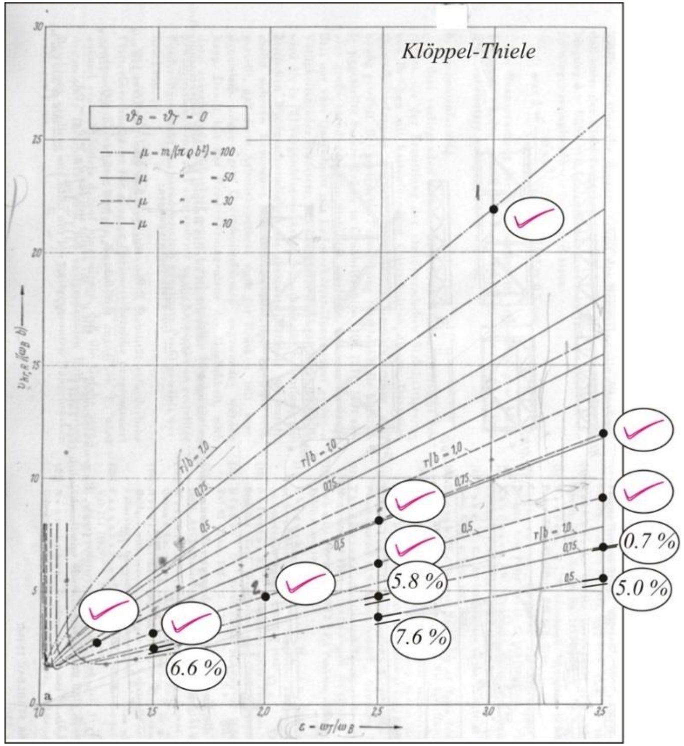
$$F_L = \frac{1}{2}\rho U^2 B * \left[KH_1^*(K)\frac{\dot{h}}{U} + KH_2^*(K)\frac{B\dot{\alpha}}{U} + K^2H_3^*(K)\alpha + K^2H_4^*(K)\frac{h}{B} \right]$$

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



SOFiSTiK

Flutter diagram according Klöppel-Thiele



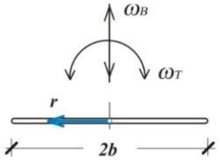
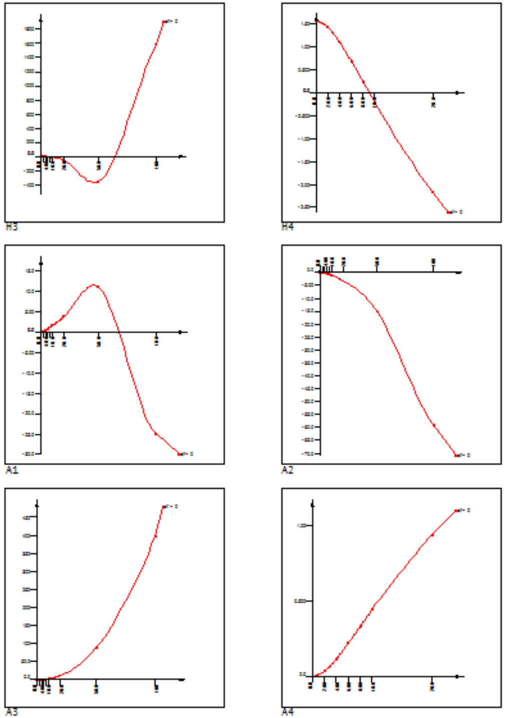
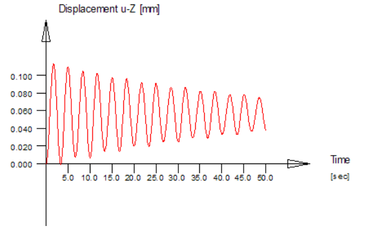
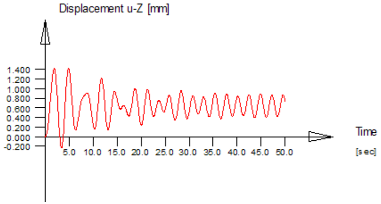


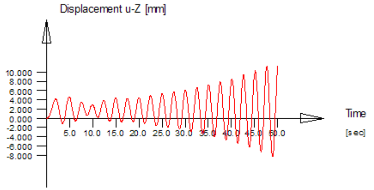
Bild 5: Gegenrechnung des Klöppel-Thiele Stabilitätsdiagramms

Flutter of a plate

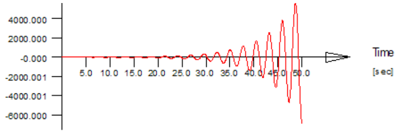








2.5*WIND



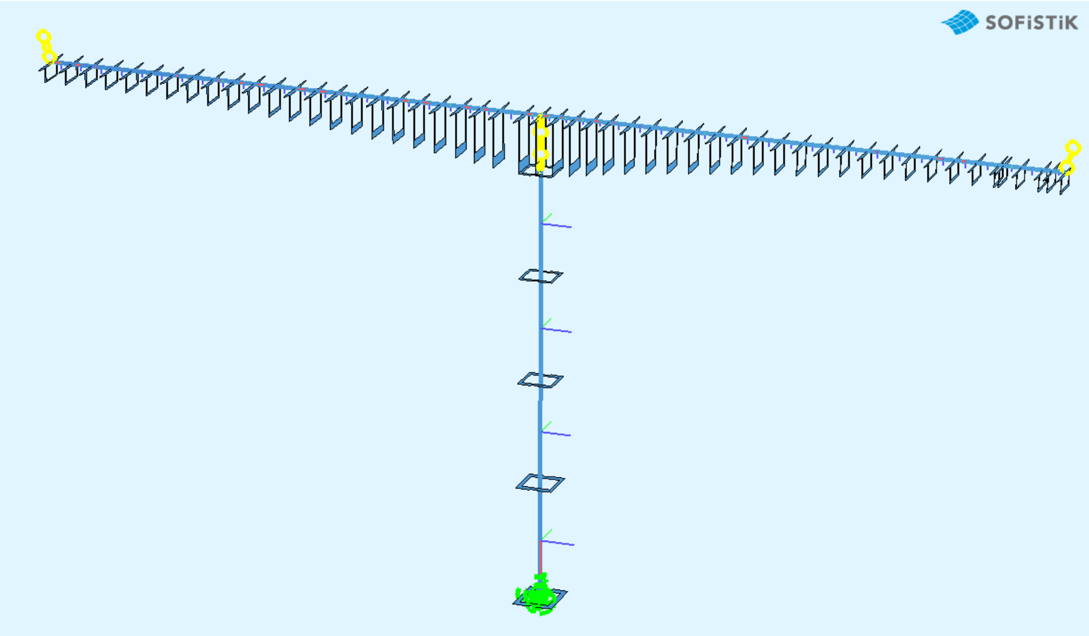
3.0*WIND

Other possibilities

- Scanlan's Derivativa are semi empiric / Taylor only
- How to judge the curves to be correct ?
- We need a frequency, here sensed from history
- Alternative „Indicial Functions“ ?

$$M(t) = \frac{1}{2}\rho\bar{u}^2\left(2B^2\right)\frac{\partial C_M}{\partial\alpha}\left[X_\alpha\frac{\partial\alpha}{\partial t} + \int_0^t X_{M\alpha}(t-\tau)\frac{\partial\alpha}{\partial\tau}d\tau\right]$$

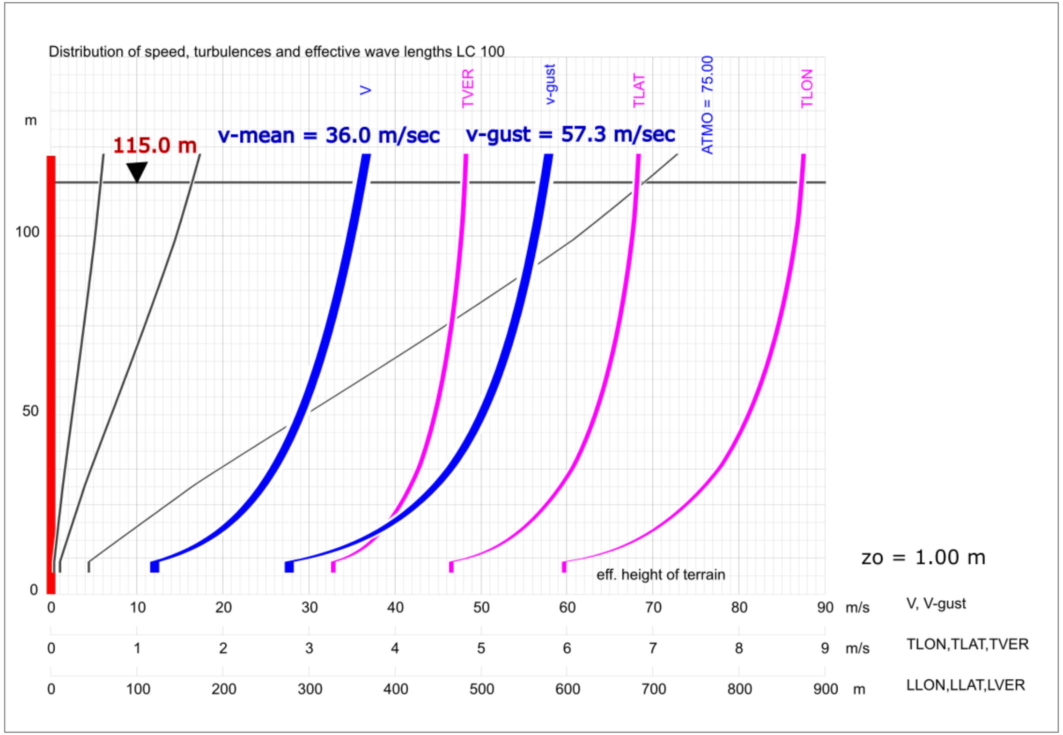
Dynamic Wind Loading on a Bridge



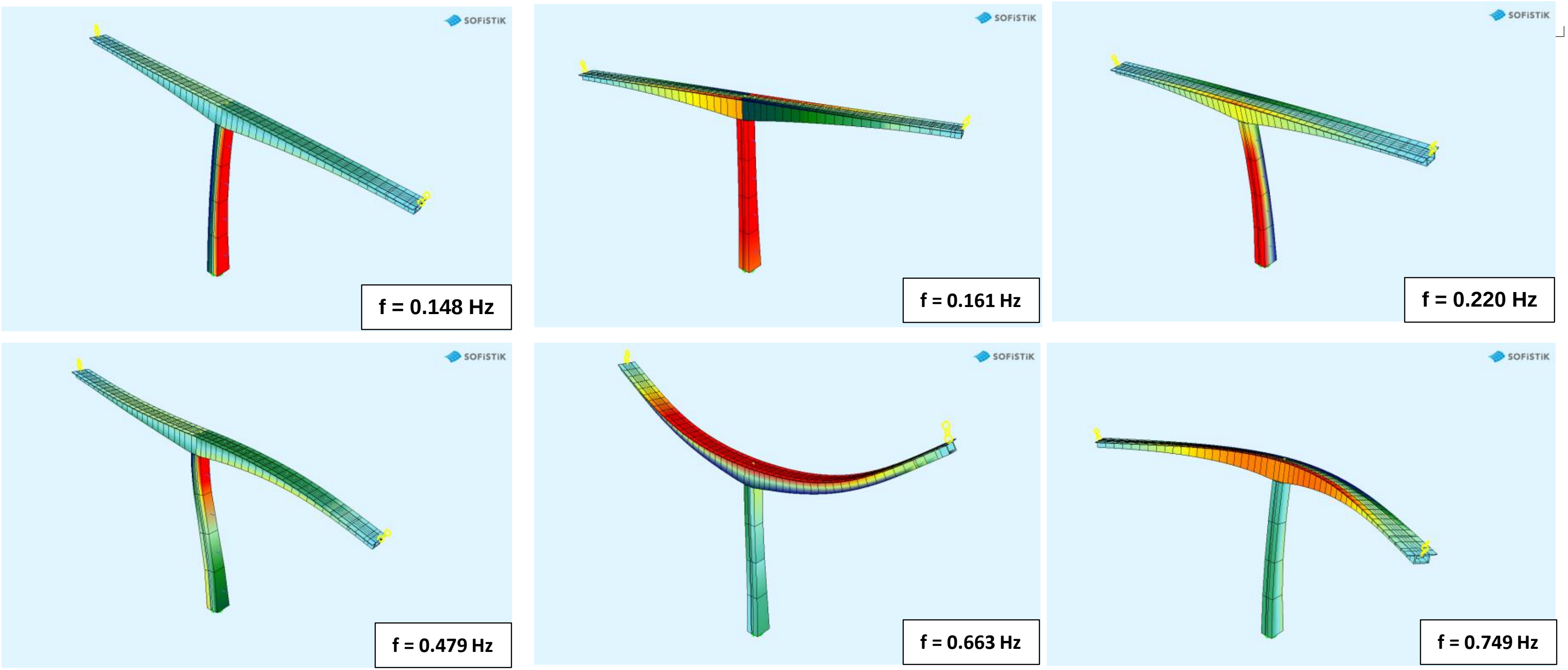
The Bridge selected for the Study

- Metsovitikos Bridge owned by Egnatia Odos A.E.
- Design by DOMI S.A. and Leonhardt Andrä und Partner
- Checking Engineer: Mott MacDonald
- Main span: 235 m, total length 540 m, piers height 103 m
- Critical construction stage for cantilever length of 120 m to both sides
- Solutions in the frequency and the time domain

Location and Wind Parameters



Eigenforms and Frequencies



Eigenvalues and modal damping

Eigenvalues

No.	LC	λ [rad2/sec2]	error [-]	ω [rad/sec]	f [Hz]	T [sec]	ξ [o/o]	Meff X[o/o]	Meff Y[o/o]	Meff Z[o/o]
1	1	8.6226E-01	0.00E+00	0.929	0.148	6.766	0.774	41.6	0.0	0.0
2	2	1.0219E+00	0.00E+00	1.011	0.161	6.216	0.716	0.0	0.1	0.0
3	3	1.9093E+00	0.00E+00	1.382	0.220	4.547	0.621	0.0	75.1	0.0
4	4	9.0399E+00	0.00E+00	3.007	0.479	2.090	0.540	40.0	0.0	0.4
5	5	1.7350E+01	0.00E+00	4.165	0.663	1.508	0.483	0.4	0.0	28.4
6	6	2.2121E+01	0.00E+00	4.703	0.749	1.336	0.534	0.0	1.1	0.0
7	7	1.0684E+02	0.00E+00	10.336	1.645	0.608	0.980	0.9	0.0	1.7
8	8	1.3609E+02	0.00E+00	11.666	1.857	0.539	1.058	0.0	0.0	0.0
9	9	1.6463E+02	0.00E+00	12.831	2.042	0.490	0.827	0.0	0.0	47.2
10	10	1.9545E+02	0.00E+00	13.980	2.225	0.449	1.484	0.0	14.4	0.0
11	11	4.2102E+02	2.44E-08	20.519	3.266	0.306	1.227	0.5	0.0	19.1
12	12	4.2179E+02	3.89E-07	20.538	3.269	0.306	1.785	0.0	0.0	0.0
13		4.7088E+02	3.23E-08	21.700	3.454	0.290	Σ(Meff)[1]	83.4	90.7	96.8
14		8.1033E+02	1.70E-03	28.466	4.531	0.221				

[1] Total effective mass in X-, Y- and Z-direction.

No. eigenmode number
LC load case
λ eigenvalue
error relative eigenvalue error
ω circular eigenfrequency
f eigenfrequency
T eigenperiod
ξ modal damping ratio
Meff effective modal mass in X-, Y- and Z-direction

logarithmic damping

5 % pier

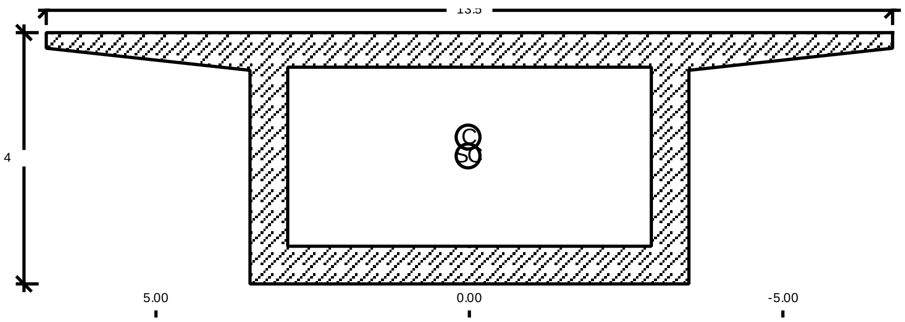
3 % bridge

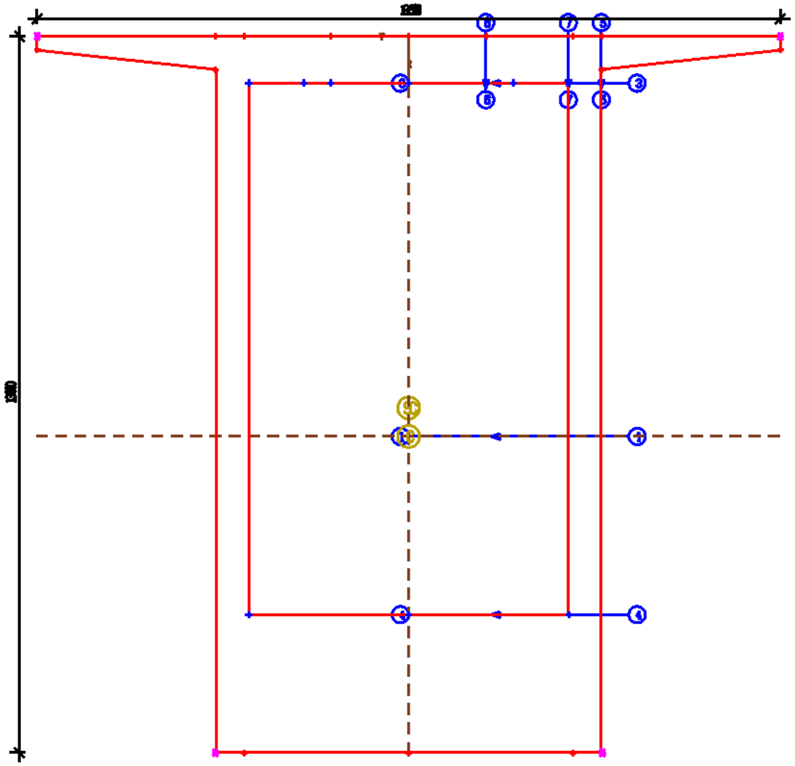
⇒ modal

0.079 pier

0.048 bridge

Sections





- Hollow Box
- B = 13.5 m
- H = 4.0 m up to 13.0 m

Wind drag coefficients from literature

the legend says that all values are referenced to the full width, but the text makes a reference to the height which seems to be more reasonable.

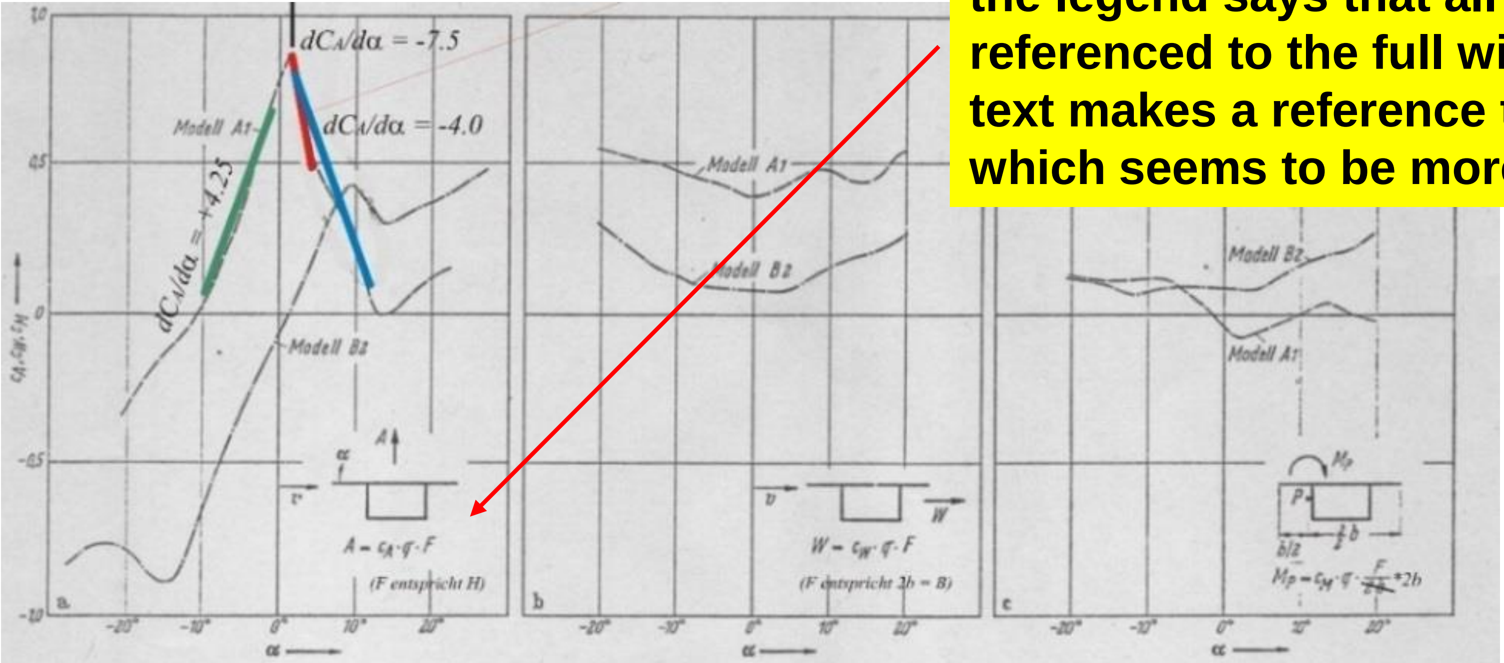
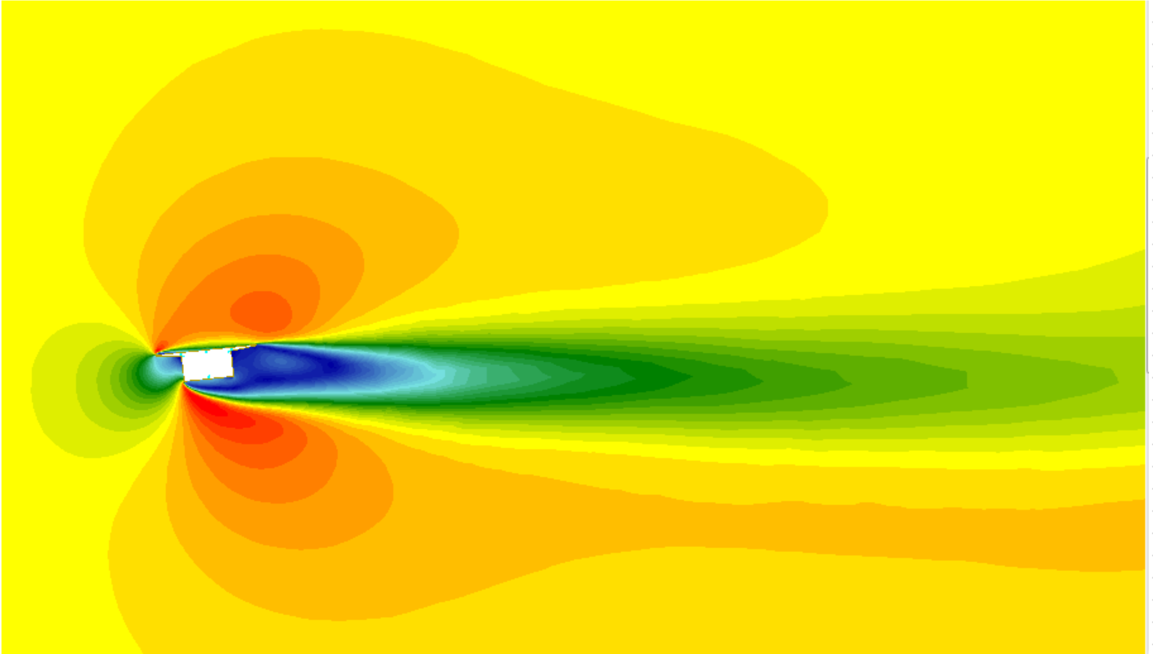
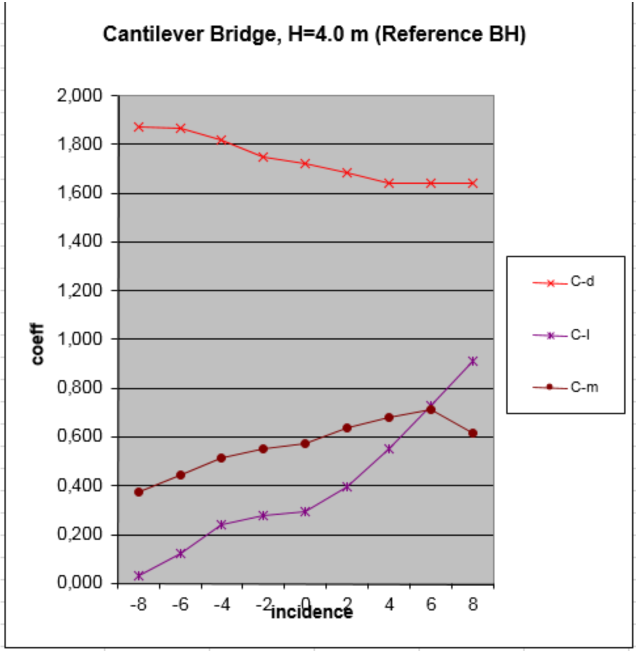


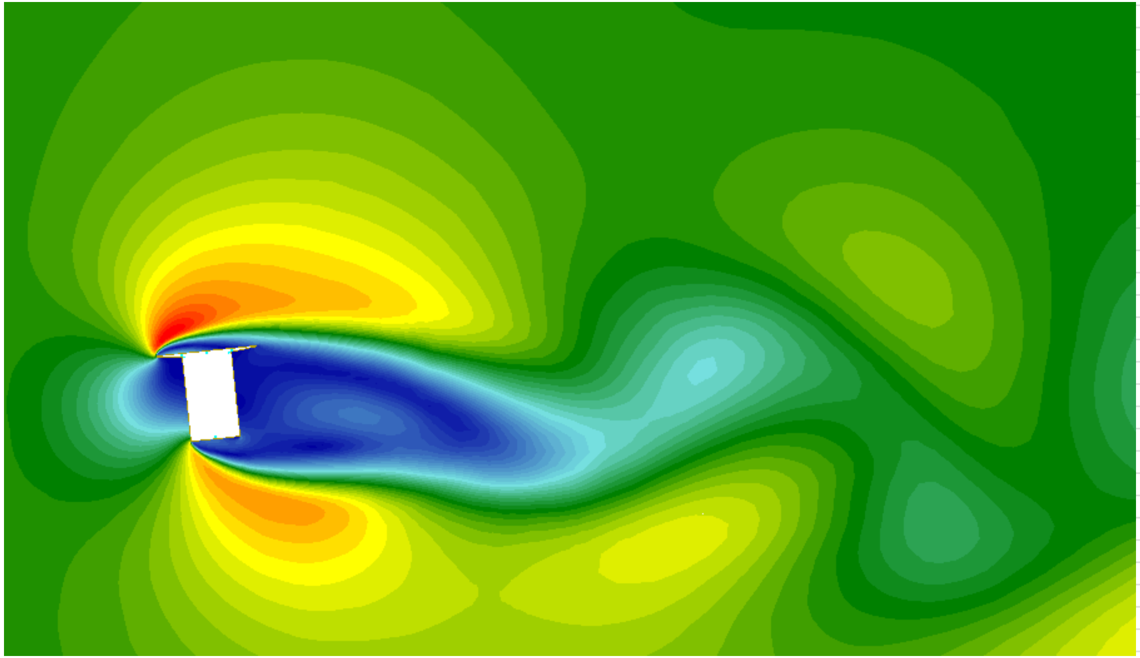
Bild 13. Gemessene Luftkraftbeiwerte für die Modelle A 1 und B 2; Re ≈ 800 000 (bezogen auf Modellbreite 2 b)
a) Beiwert c_A (α) b) Beiwert c_W (α) c) Beiwert c_M (α)

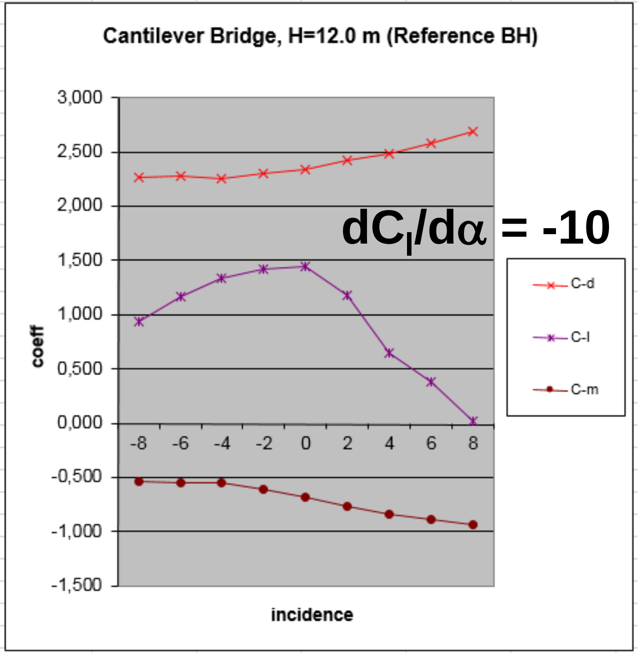
Wind drag coefficients for low section from CFD Analysis: positive derivatives!





Wind drag coefficients for high section from CFD Analysis: negative derivatives





$dC_l/d\alpha = -10$

SOFiSTiK

Drag and Lift coefficients

- Variation due to longitudinal turbulence (buffeting):

$$dF_L = C_d \cdot A_{ref} \cdot q_o \cdot 2k_p \cdot I_{lon}$$

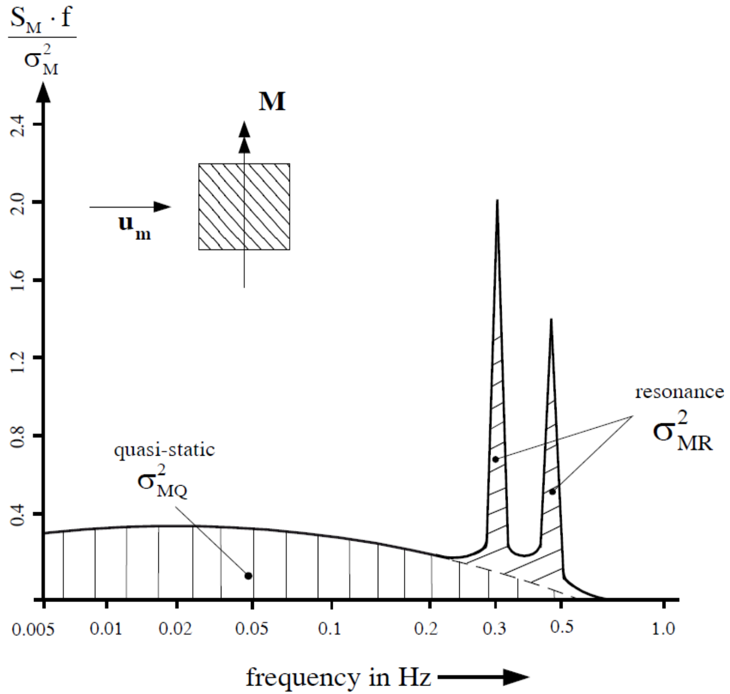
$$dF_V = C_l \cdot A_{ref} \cdot q_o \cdot 2k_p \cdot I_{lon}$$

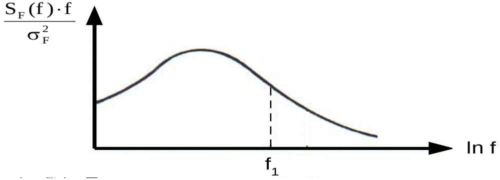
- Greater variation of vertical force from angle of attack:

$$dF = \frac{1}{2}\left[C_l\left(+\propto_{dyn}\right) - C_l\left(-\propto_{dyn}\right)\right] \cdot A_{ref} \cdot q_o$$

$$dF = \frac{dC_l}{d\propto} \cdot A_{ref} \cdot q_o \cdot 2k_p \cdot I_{ver}$$

Solution I – EN 1991-1-4 appendix B





$$S_y(f) = |\alpha_a|^2 \times |\alpha_m|^2 \times S_z(f)$$

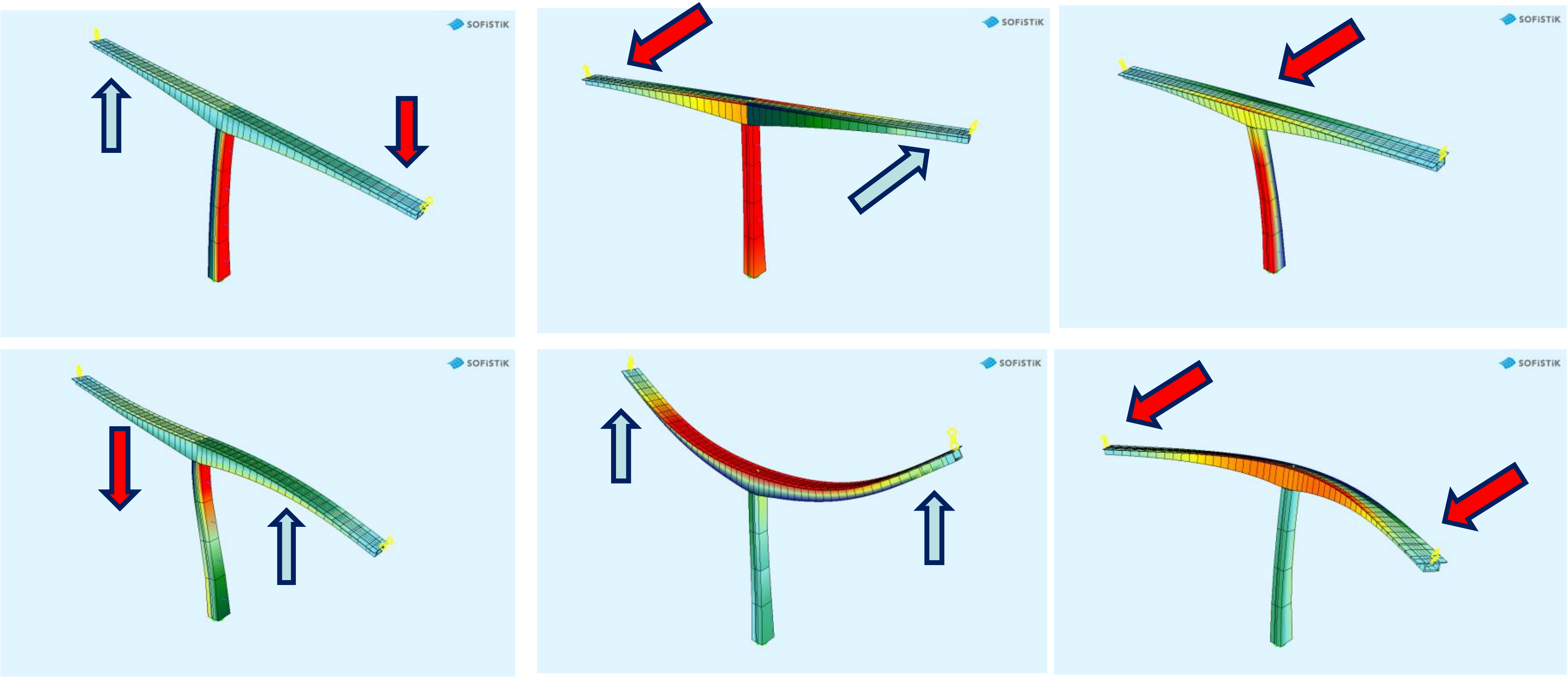
$$\alpha_a = aerodynamic\ transfer\ function$$

$$\alpha_m = mechanical\ transfer\ function$$

$$q_{dyn} = q_{mean} \cdot \left(2 \cdot k_p \cdot I_v(z) \cdot \sqrt{B^2 + R^2}\right)$$

$$R^2 = \frac{\pi^2}{2 \cdot \delta} \cdot S(z, f) \cdot R_h(\eta_h) \cdot R_b(\eta_b)$$

Solution II – Use multiple frequencies



Contribution of the individual modes

A wind expert software

Modes	Fréquence (Hz)	masses Généralisée (kg)	σ_{dyn} (cm)	σ_{qs} (cm)	σ_{total} (cm)
1	0.338	656 354	9.00	1.79	9.18
2	0.486	2 042 566	1.67	0.43	1.73
3	0.544	120 957	2.53	0.65	2.62
4	1.207	97 839	2.37	0.70	2.47
5	1.233	285 767	0.66	0.20	0.69

$$S_i = \sqrt{\sum S_{im}^2} = \sum f_{im} \cdot S_{im} \text{ where } f_{im} = \frac{S_{im}}{\sqrt{\sum S_{ij}^2}}$$

- Establish coherent loadings for every frequency
- Calculate resonant Response from spectra, frequency, wind speed (2)
- Select Background response or assume it to 1.0 (1)
- Calculate modal response

$$q_{dyn} = q_{mean} \cdot \left(2 \cdot k_p \cdot I_v(z) \cdot \sqrt{B^2 + R^2}\right)$$

$$R^2 = \frac{\pi^2}{2 \cdot \delta} \cdot S(z, f) \cdot R_h(\eta_h) \cdot R_b(\eta_b)$$

Coherences of the longitudinal Turbulence Component

$$Coh_{xy}(\omega) = \frac{\left|S_{xy}(\omega)\right|^2}{S_{xx}(\omega)\cdot S_{yy}(\omega)}\ ;\ \psi_{xy}(\omega) = \frac{S_{xy}(\omega)}{\sqrt{S_{xx}(\omega)\cdot S_{yy}(\omega)}}$$

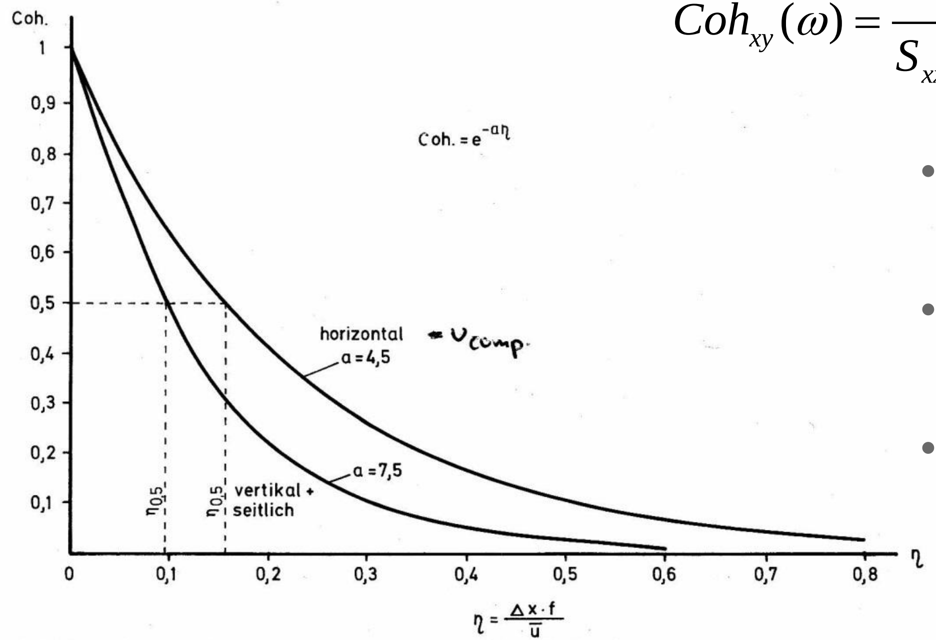


Bild 2.9: Kohärenzfunktion der atmosphärischen Turbulenz [16]

- Coherence along is larger than transverse/vertical
- A pure positive function is in conflict with a zero mean value.
- Unity for small frequencies is not true for separations large that the gust size.

(Dyrbye, Hansen, 1996)

Rushewey: Frost, Long, Turner – NASA Technical Paper 1359, 1978

Coherences

- Davenport 1962/1977:

$$\Psi_u(r_y, r_z, n) = \exp\left(-\frac{n}{U}\sqrt{\left(C_y r_y\right)^2 + \left(C_z r_z\right)^2} \right)$$

- Krenk 1995/
  ESDU 86010 :

$$\Psi_u(\kappa_1 r) = \frac{2}{\Gamma(\gamma)}\left[\left(\frac{\kappa_1 r}{2}\right)^{\gamma} K_\gamma(\kappa_1 r) - \left(\frac{\kappa_1 r}{2}\right)^{\gamma+1} K_{1-\gamma}(\kappa_1 r)\right]$$

- SOFiSTiK - SOFiLOAD
  (ESDU 86010):

$$HWD_k^i = k_{ki} \cdot \frac{U}{f}$$

Coherences ESDU 86010

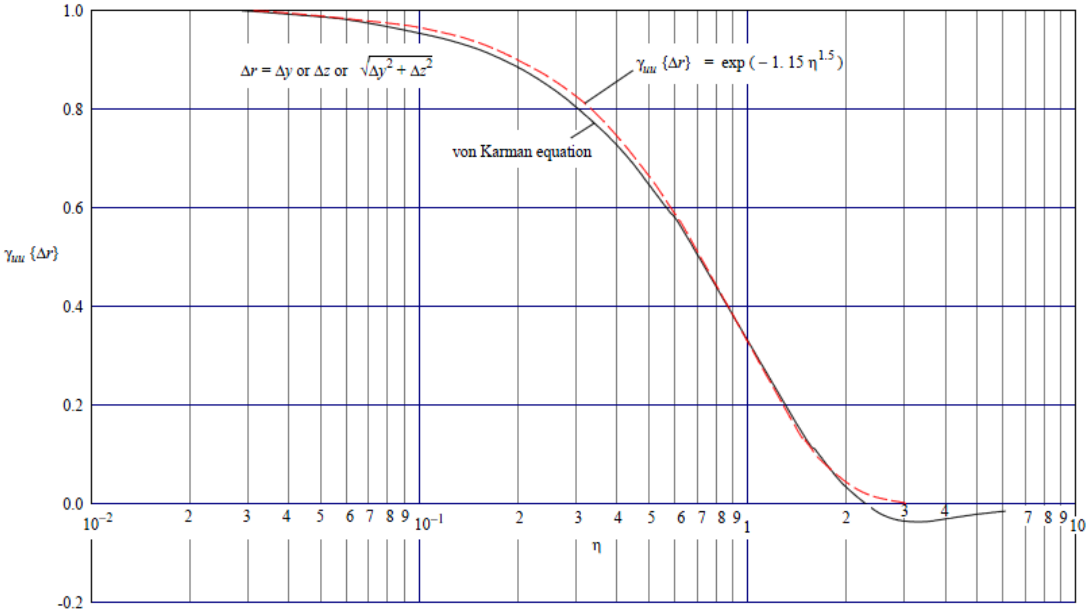
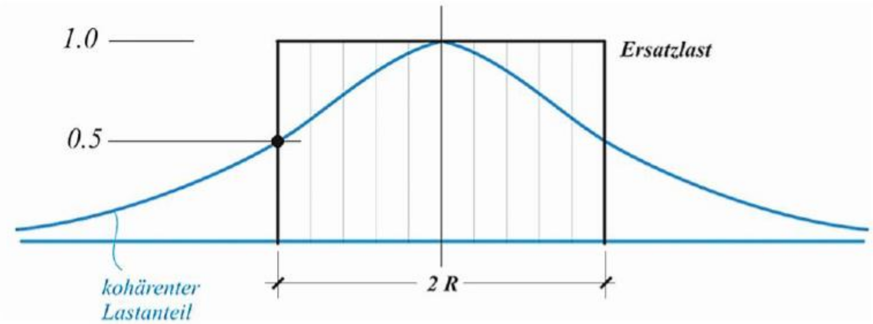
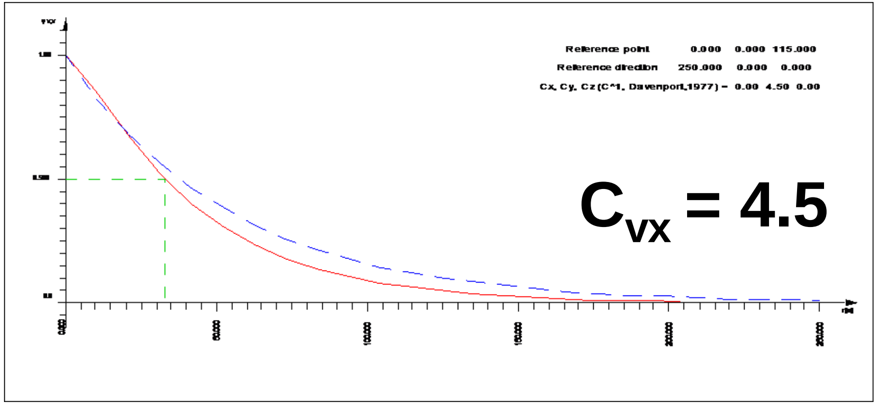


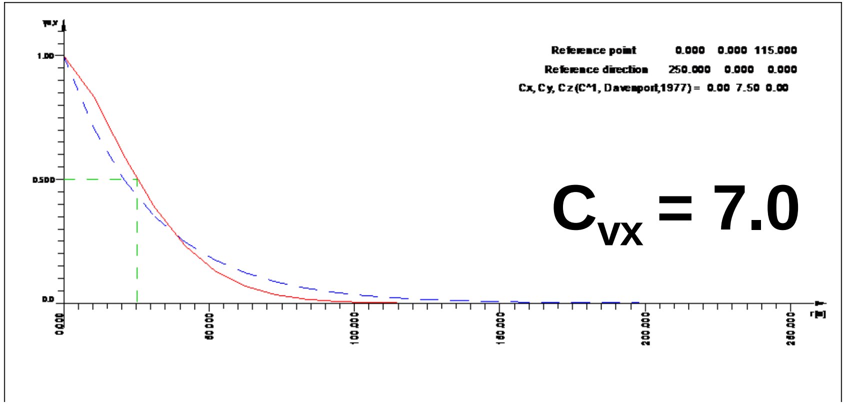
FIGURE A2 $\sqrt{\text{COHERENCE}}$ FUNCTION FOR u-COMPONENTS WITH TRANSVERSE SEPARATIONS

Coherent loadings ?




```
v,v: f = 0.148 Hz, hvd= 33.050 m
u,v: f = 0.161 Hz, hvd= 25.309 m
u,v: f = 0.220 Hz, hvd= 18.612 m
v,v: f = 0.479 Hz, hvd= 12.090 m
v,v: f = 0.663 Hz, hvd=  9.096 m
u,v: f = 0.749 Hz, hvd=  5.468 m
```





Modal load participation factors per load function

LC	Mode	Φ·p	Φ2·p	Mode	Φ·p	Φ2·p
180	191@ 1	-7.372E+00	2.355E-03	194@ 4	-3.713E+00	1.398E-02
	192@ 2	-7.051E+00	6.327E-03	195@ 5	4.853E+00	9.258E-02
	193@ 3	1.286E+01	9.883E-02	196@ 6	1.735E+00	3.217E-02
	Σ				3.098E+02[1]	2.462E-01[2]

[1] Σ(ϕ·p)² - sum of squares of the modal values (ϕ·p)
[2] Σ(ϕ2·p) - sum of modal values (ϕ2·p)

Modal Responses

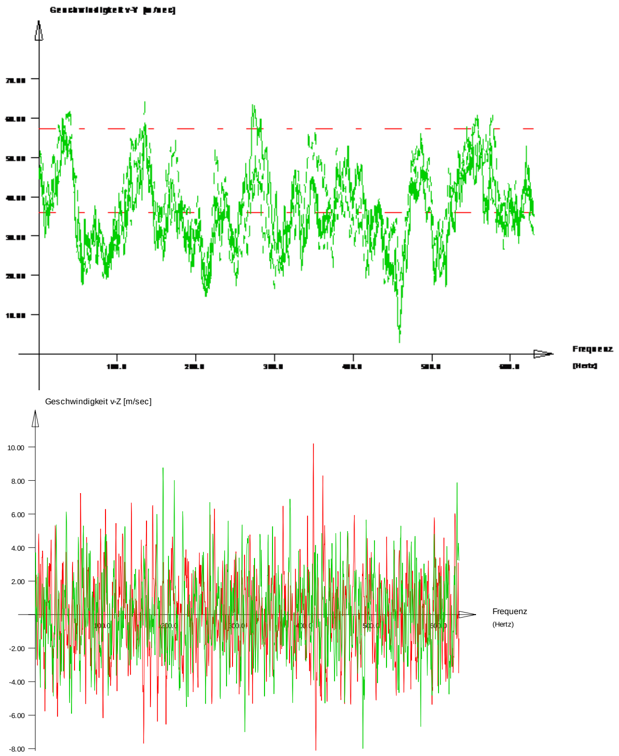
LC	Mode	q,max	f[Hz]	ξ[o/o]	T[sec]	S(ξ,T)
180	1	-1.550E+01	0.148	1.162	6.766	1.813
	2	-1.406E+01	0.161	1.035	6.216	2.038
	3	2.073E+01	0.220	1.067	4.547	3.078
	4	-1.287E+00	0.479	1.003	2.090	3.133
	5	7.971E-01	0.663	1.003	1.508	2.850
	6	1.289E-01	0.749	0.908	1.336	1.643

Response of periodic loading is exact including the phases.
Contributions of all functions will be added as sum of squares.

LC load case
Mode eigenmode number
q,max maximal modal coordinate response per loading function
f[Hz] eigenfrequency
ξ[o/o] modal damping ratio
T[sec] eigenperiod
S(ξ,T) pseudo-acceleration spectral response normalized w.r.t. ground acceleration

Solution III – Transient Analysis

- Generate an artificial turbulent wind
- Calculate for every time step the relative wind speed
- Calculate the loadings based on the current angle of attack

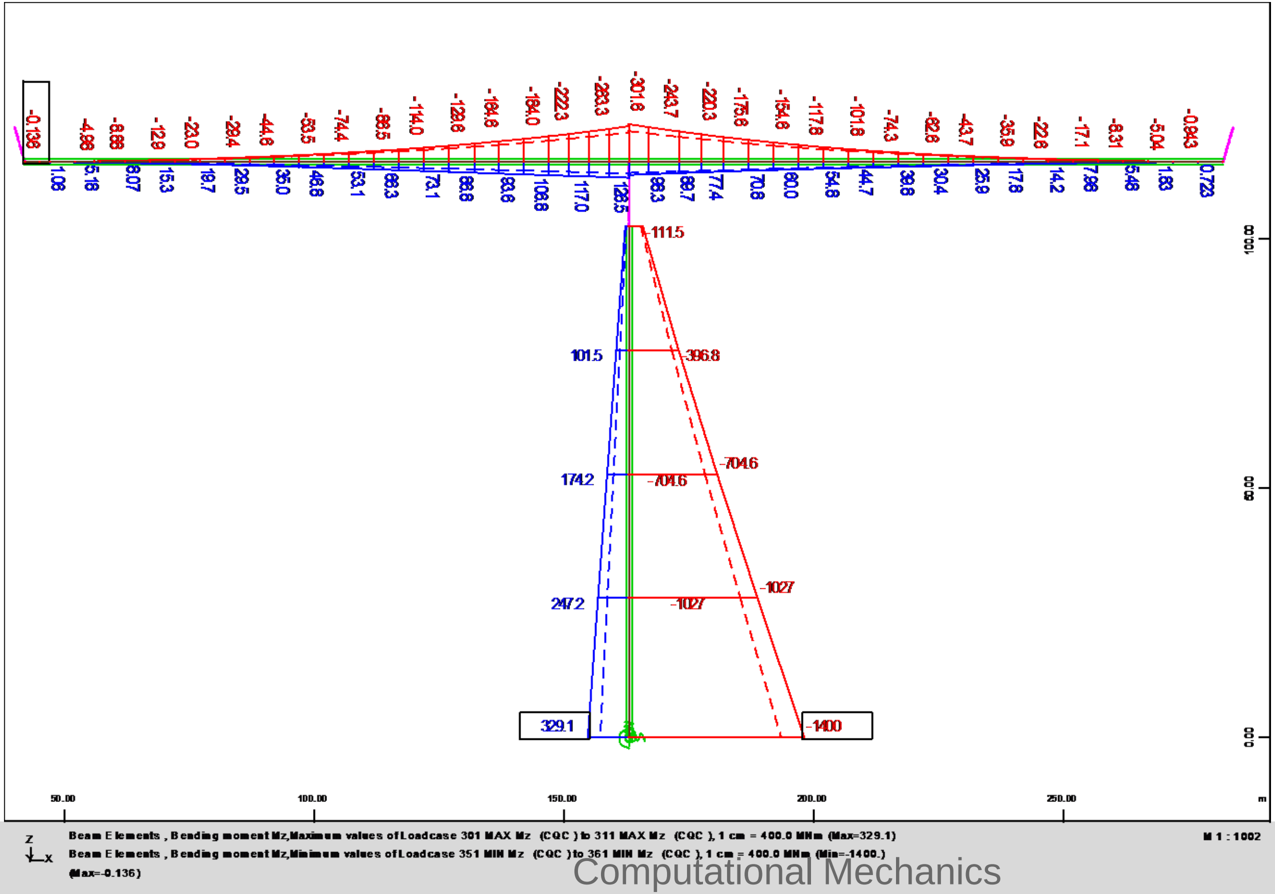


Solution III – Stochastics

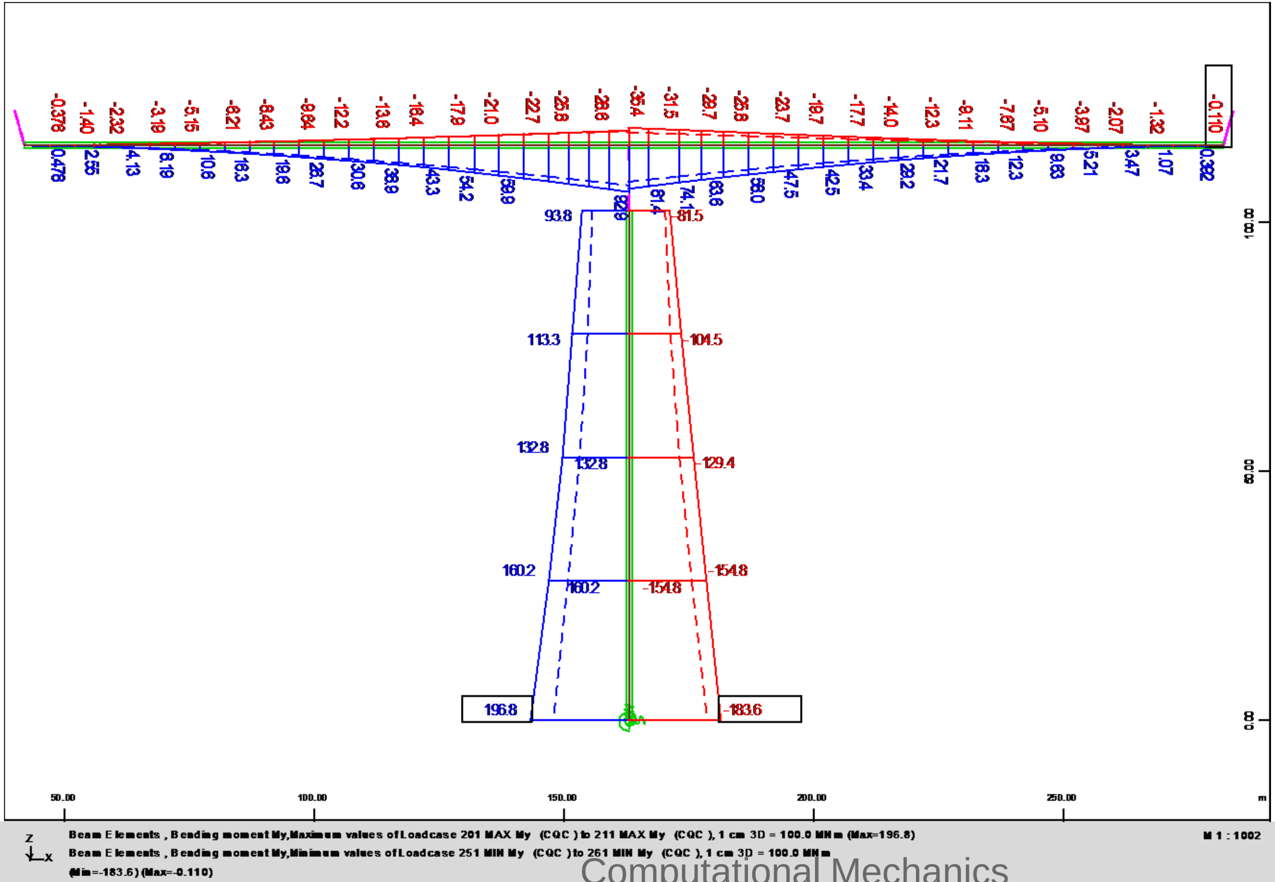
- Multiple Runs required, our suggestion: take 11.
- EN 1998 (earthquake)
  - Select extreme values from 3
  - Select mean values from >5
- How to treat collapses ?

Number of Collapses	Likelihood for Various P[C|MCER] Values				
	0.05	0.10	0.15	0.20	0.30
0 of 11	93%	74%	51%	30%	7%
1 of 11	7%	23%	36%	38%	21%
2 of 11	0%	3%	11%	22%	29%
3 of 11	0%	0%	2%	8%	24%
4 of 11	0%	0%	0%	2%	13%
5 of 11	0%	0%	0%	0%	5%

Results M_z along wind deformation



Results M_y transverse deformation



Analysis Method	M_y – Bridge [MNm]	M_z - Bridge [MNm]	M_y-Pier [MNm]	M_z-Pier [MNm]
Static gust wind	43.2	-149.1	1.2	-879.5
Buffeting acc. Eurocode (f3)	61.9	-213.6	-	-1105.0
Static equivalent wind (f1-f3)	95.4	-154.1	153.5	-762.9
Spectral analysis (f1-f3)	38.1	125.8	198.9	555.6
Spectral analysis (f1-f6;B3=2.5)	66.0	130.0	207.8	555.6
Spectral(f1-f6) + Mean wind	83.1	-189.0	208.3	-911.7
MIN (History 1-3)	-29.2	-310.6	-164.9	-1400.0
MAX (History 1-3)	92.9	126.5	161.7	306.0
MIN (History 1-11)	-35.4	-310.6	-183.6	-1400.0
MAX (History 1-11)	92.9	126.5	196.8	329.1
Mean of MIN (History 1-11)	-26.4	-246.6	-143.6	-1216.0
Mean of MAX (History 1-11)	79.9	92.9	151.2	229.0

Conclusion

- Spectral Analysis has some drawbacks
  - It is little bit magic to select the correct values
  - It does not include aeroelastic damping automatically
  - It does not allow for structural nonlinearities
  - Modal solutions may ignore relevant deformation modes
- I always believed that the transient solution is better
- Now I am pretty sure!
  The extra computer time is not a relevant issue.

A Bridge with a great height (Millau)

- Wind tunnel tests have been performed with a very low turbulence and an intensity of 9-10 %.
- For a terrain roughness z_0 of 0.30 m a turbulence intensity of 9.4 % is obtained in 200 m height.
- CFD Analysis with constant inflow conditions

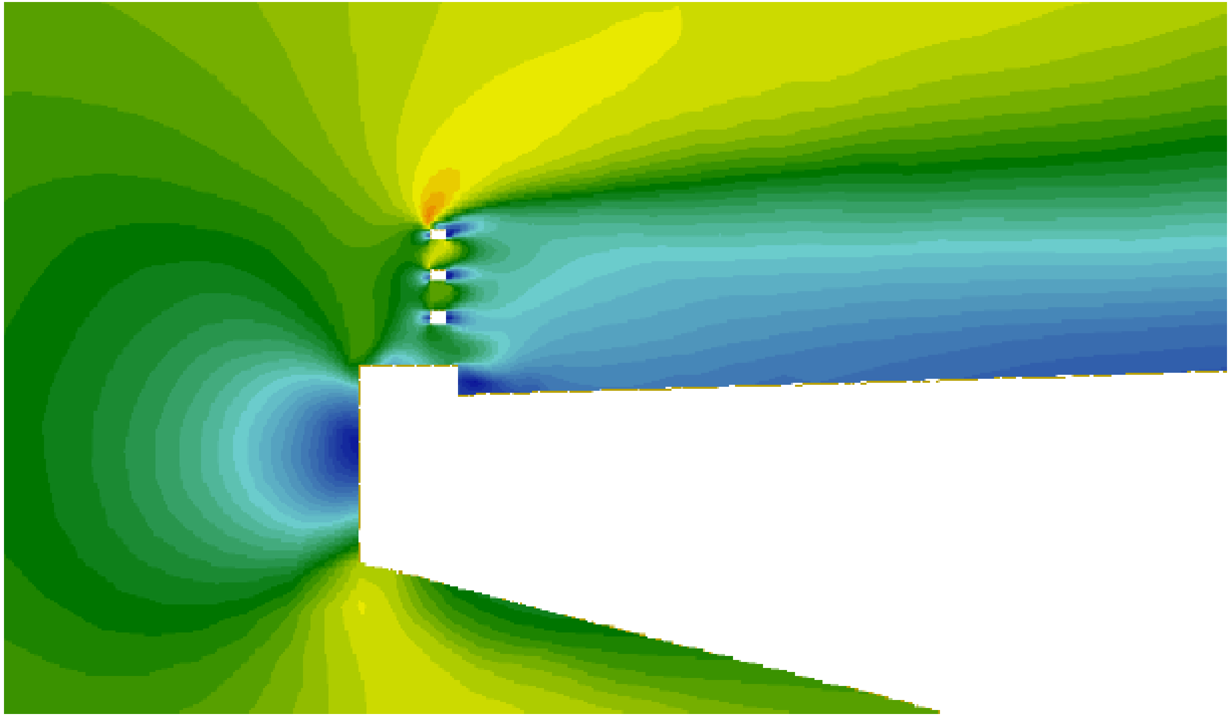
Integral Length Scale

- Length scale for CFD would be 81.0 [m] in 200 m height.
- For these height Eurocode defines a longitudinal measure of 300 [m], DIN of 260 [m], Counihan ca. 250 [m] as well. With 20 % for the vertical length scale this yields a value between 50 and 60 m.
- Vortices of this size will be disturbed by a section with a height of h = 4.50 [m]!

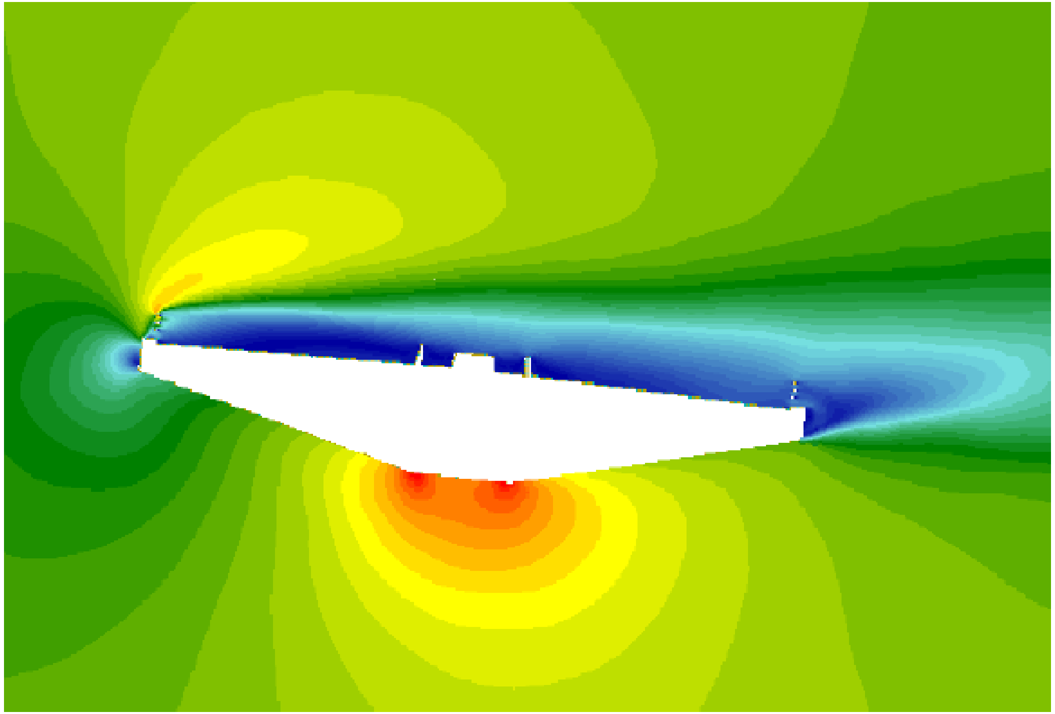
Section of Millau Bridge

- Sections in steel and in concrete
- With or without wind shields
- Wind tunnel tests for a section with intradosed fixing of cables, but not the cables itself
- Wind shields as perforated plates with 50 % permeability

Flow field at wind side

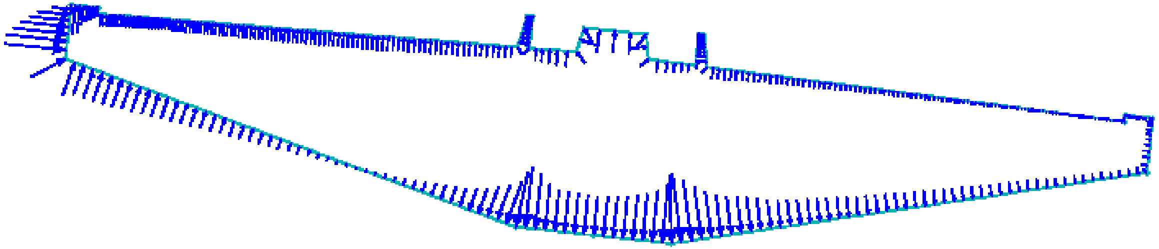


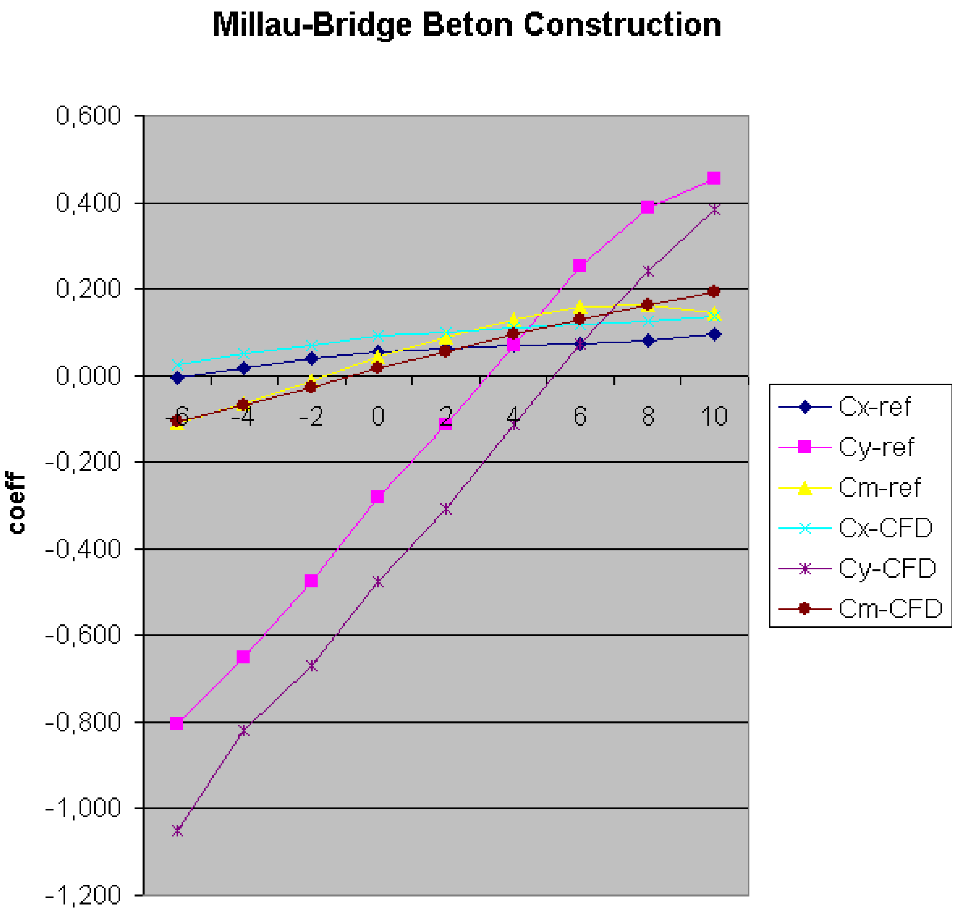
Angle of attack = rotating the section

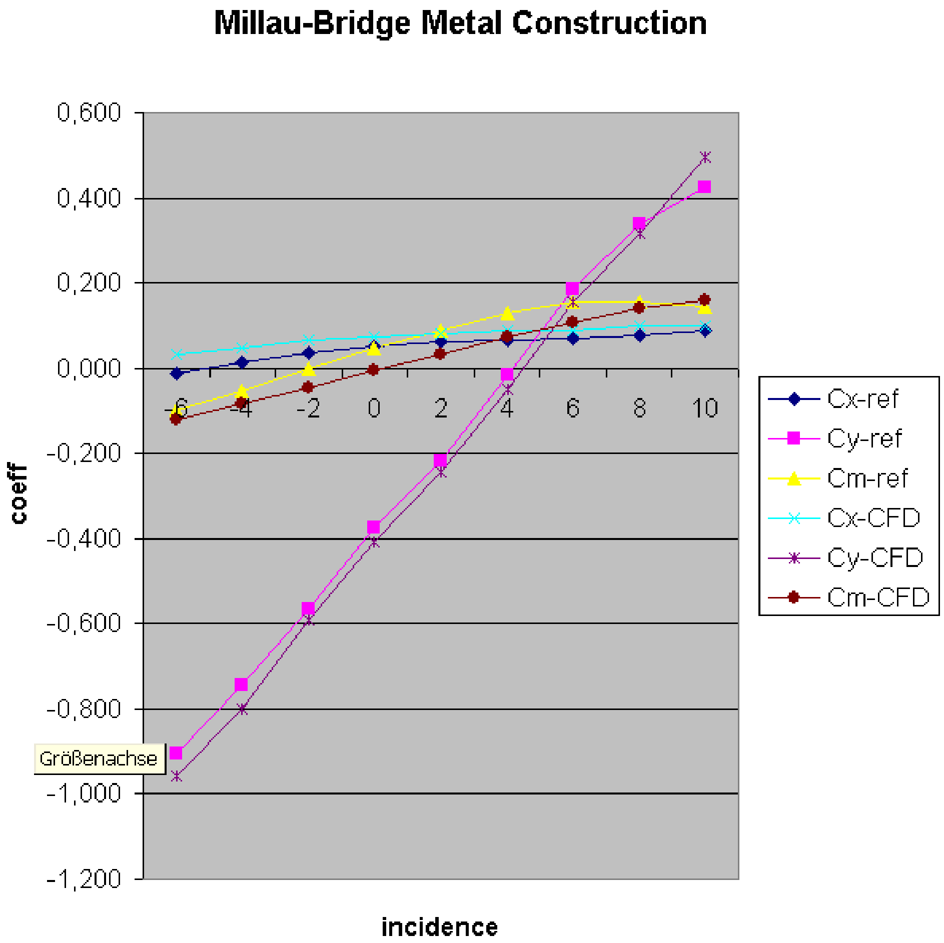


SOFiSTiK

Forces on bridge



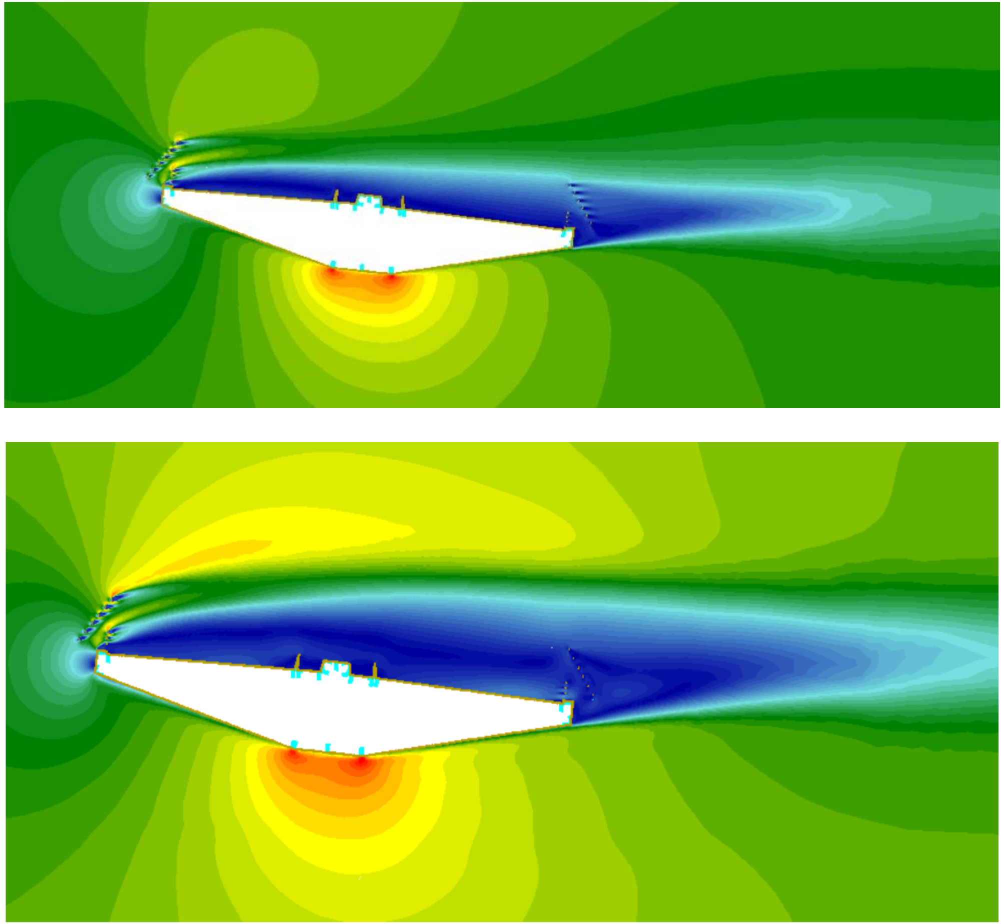

Millau-Bridge Beton Construction
0,600
0,400
0,200
0,000
-0,200
-0,400
-0,600
-0,800
-1,000
-1,200
coeff
-6
-4
-2
0
2
4
6
8
10
Cx-ref
Cy-ref
Cm-ref
Cx-CFD
Cy-CFD
Cm-CFD


Millau-Bridge Metal Construction
0,600
0,400
0,200
0,000
-0,200
-0,400
-0,600
-0,800
-1,000
-1,200
coeff
-6
-4
-2
0
2
4
6
8
10
incidence
Größenachse
Cx-ref
Cy-ref
Cm-ref
Cx-CFD
Cy-CFD
Cm-CFD

Remarks

- Results, especially the slope of the curves is obtained with good quality
- The quantity fits within the range of the wind tunnel experiments, however the drag and lift coefficients are less than those of the tests
- There are deviations between Test and Model
  - Reynolds number, geometric scale: 1:75, wind speed 1:2
  - Surface modelling and modelling of wind shields

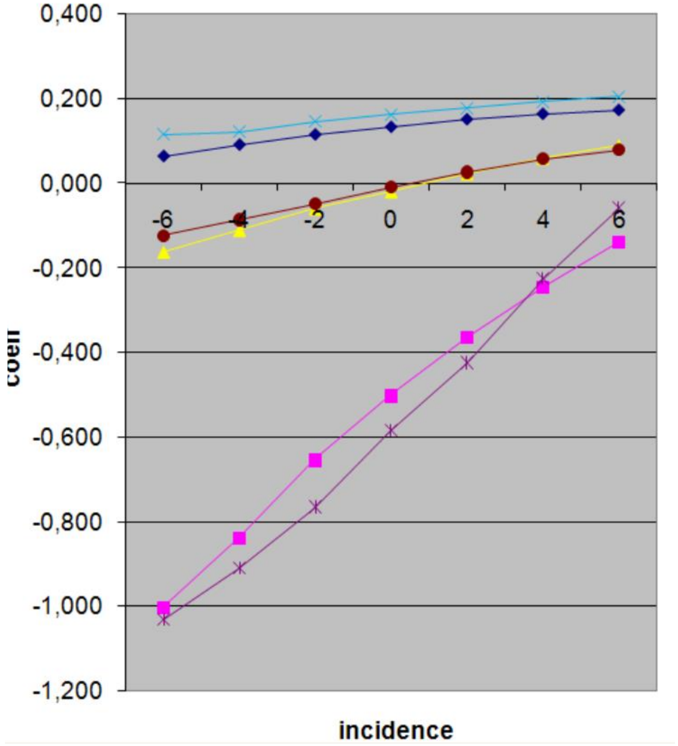
Influence of turbulence (high / low)



Drag coefficients

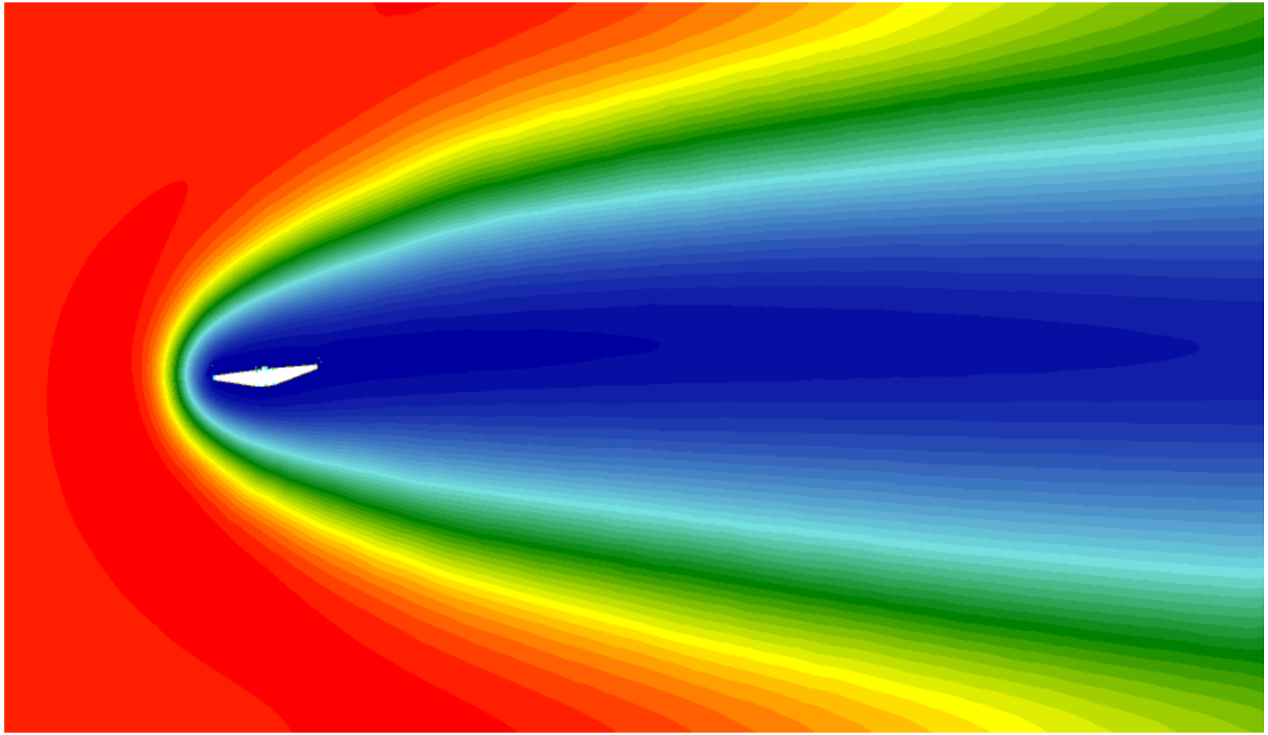
α = −6.0°	c_d	c_l	c_m
CFD I = 9.4 %, L = 81 m	0.197	−1.097	−0.096
CFD I = 9.4 %, L = 4.60 m	0.129	−1.017	−0.112
CFD I = 0.5 %, L = 0.25 m	0.052	−0.983	−0.142
Wind tunnel I = 9.0 %, L=?	0.064	−1.002	−0.162
Wind tunnel I = 0.5 %, L=?	0.058	−1.083	−0.175

α = +6.0°	c_d	c_l	c_m
CFD I = 9.4 %, L = 81 m	0.302	0.089	0.145
CFD I = 9.4 %, L = 4.60 m	0.213	0.136	0.113
CFD I = 0.5 %, L = 0.25 m	0.153	0,045	0,075
Wind tunnel I = 9.0 %, L=?	0.173	−0.139	0.089
Wind tunnel I = 0.5 %, L=?	0.166	−0.116	0.096

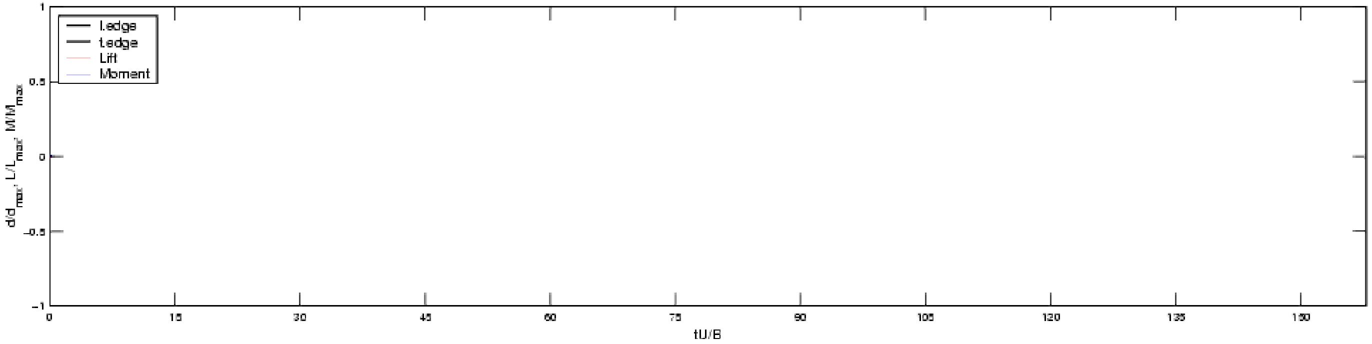


SOFiSTiK

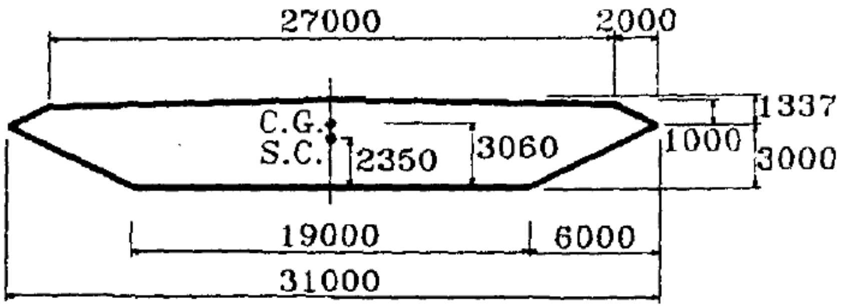
The flow for a reasonable large length scale



Vortex particle method



Great Belt East Bridge

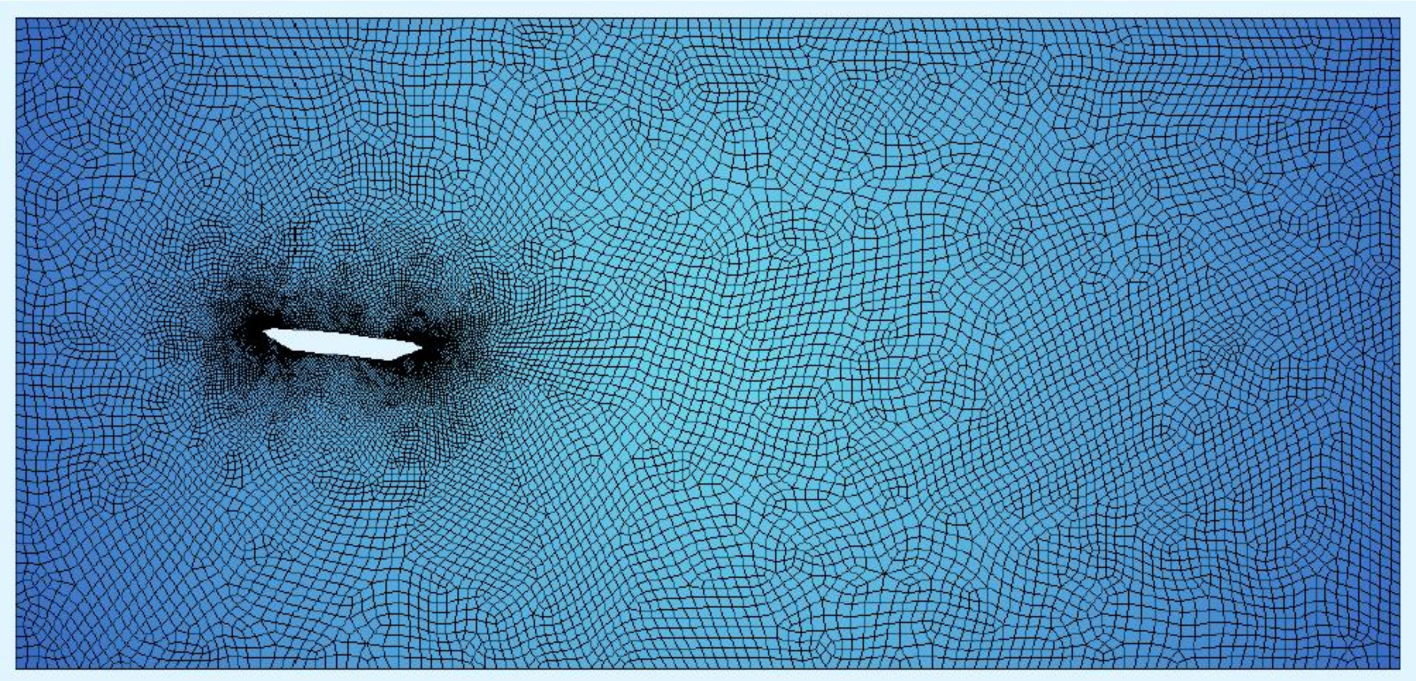


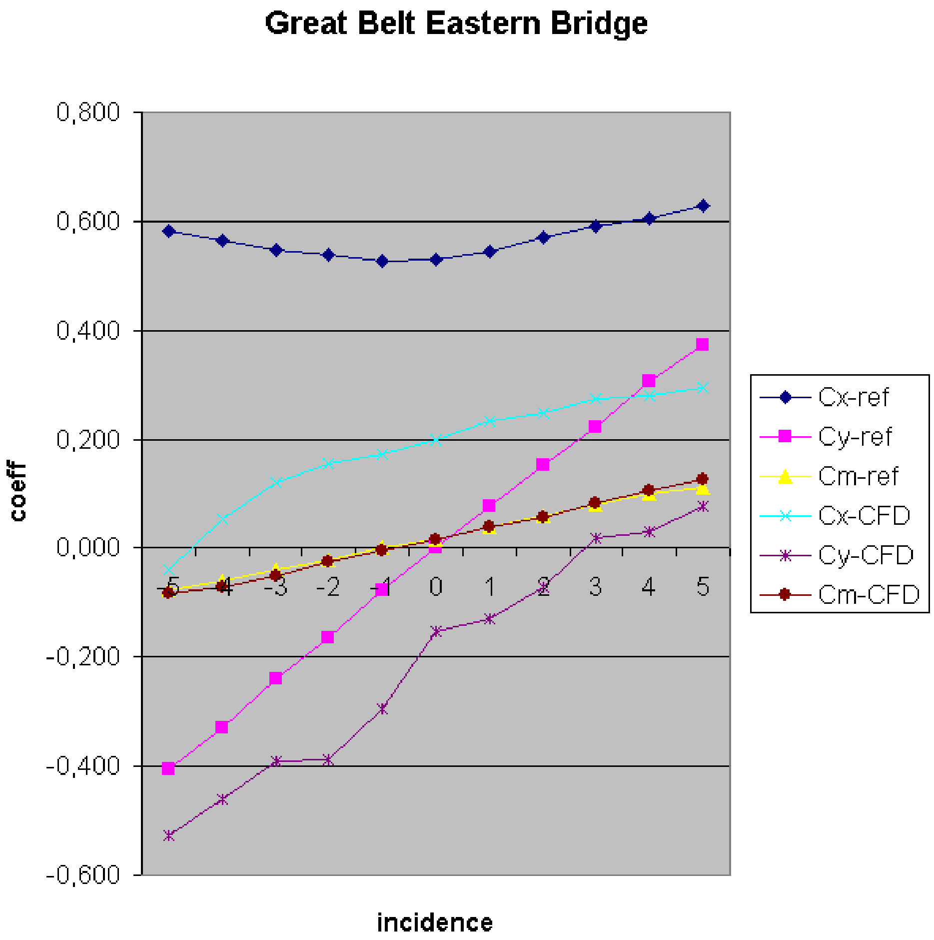
- Very simple geometry
- Wind tunnel tests available
- CFD-Analysis available in literature
- V = 40 m/sec, Re >1 E7

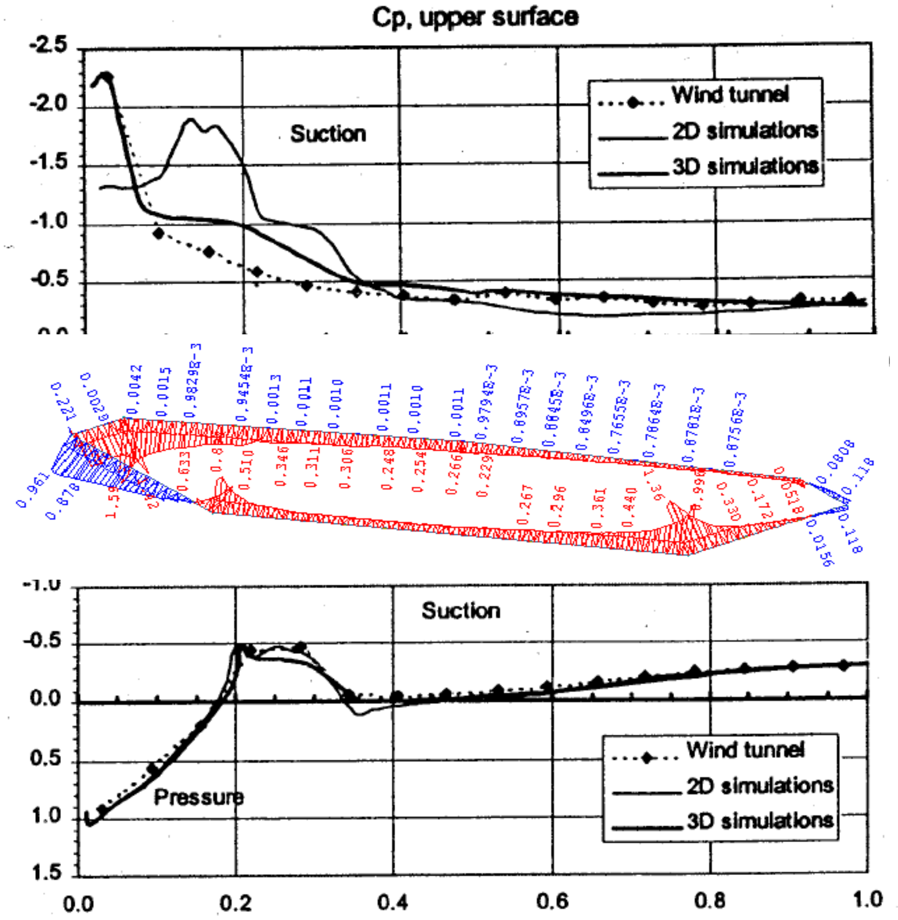
Select the mesh size !

- Shear velocity u_τ approx. 1.0 m/sec
  (boundary layer theory for plate) => y = 0.016 mm
  but from adaptive run y =0.5 to 0.8 mm
- So
  - either use a mesh size below y+ without the wall function
  - Or use the wall function and select the minimum size of the mesh to become between 40 and 300 y+
- selected a mesh for the 2nd case with wall function

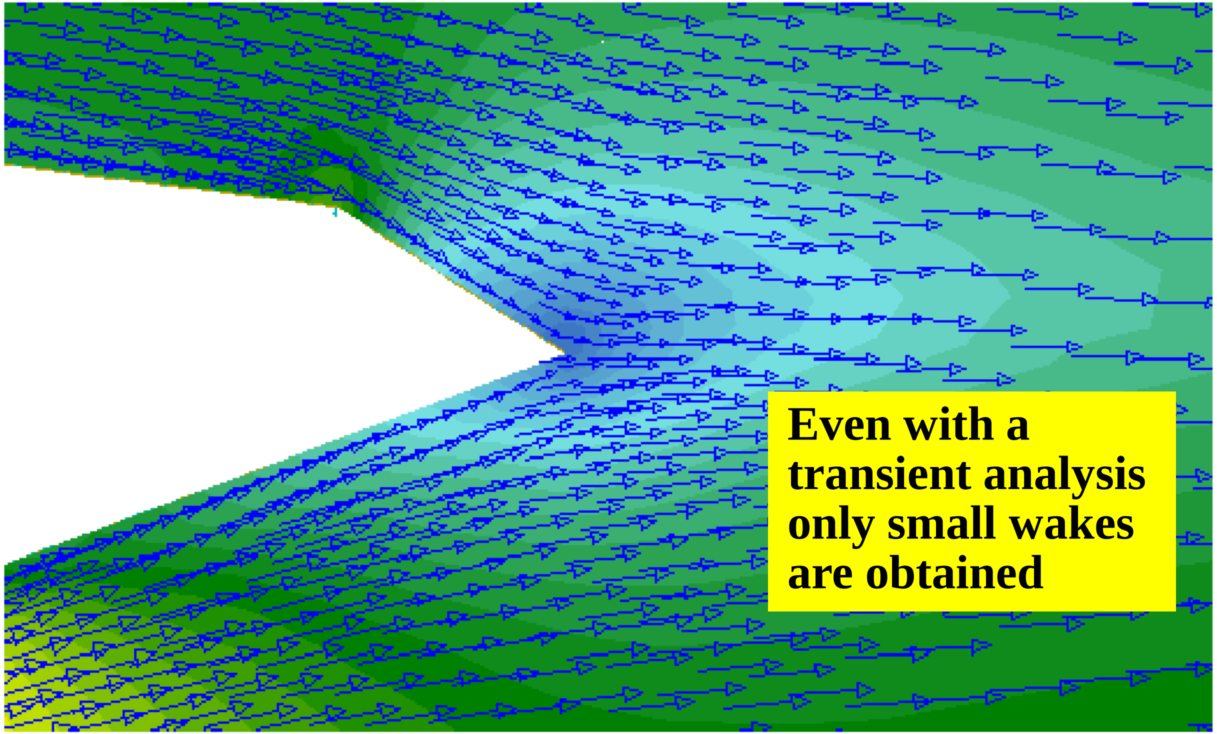
FE / FV - Mesh




Great Belt Eastern Bridge
0,800
0,600
0,400
0,200
0,000
-0,200
-0,400
-0,600
coeff
-5
-4
-3
-2
-1
0
1
2
3
4
5
incidence
Cx-ref
Cy-ref
Cm-ref
Cx-CFD
Cy-CFD
Cm-CFD


Cp, upper surface
-2.5
-2.0
-1.5
-1.0
-0.5
Suction
Wind tunnel
2D simulations
3D simulations
Suction
Pressure
-0.5
0.0
0.5
1.0
1.5
0.0
0.2
0.4
0.6
0.8
1.0
Wind tunnel
2D simulations
3D simulations

There are no wakes !



Even with a transient analysis only small wakes are obtained

Parameters to play with

- Mesh size
- Turbulence model
  - None ?
  - k-ε standard, k-ε RNG, k-ε MMK
  - k-ω
- Inflow
  - Turbulence intensity, dissipation rate
- Boundary Condition
  - Wall, simple „no slip“

Results

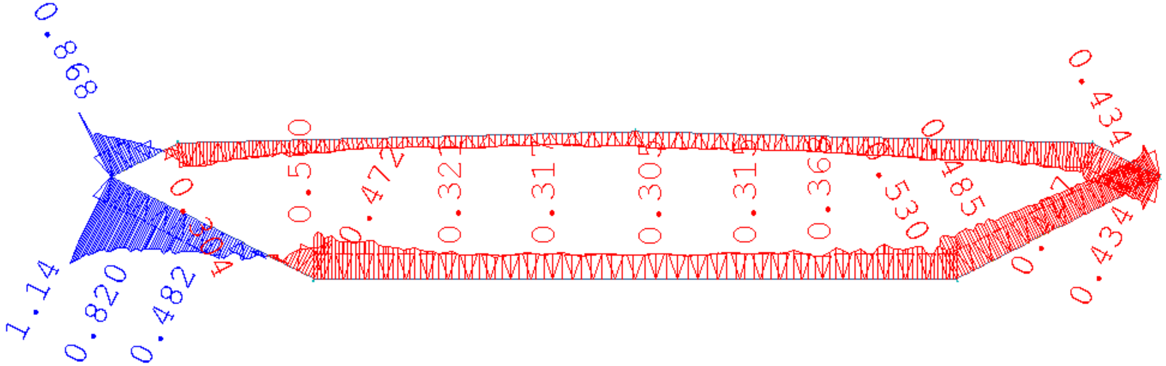
	lower cp-max	lower cp-min	cp-end	upper cp-min	cd	cl
Standard compress.	1.10	-0.78	0.141	-1.64	0.287	0.184
RNG compress.	0.96	-0.98	0.118	-1.59	0.250	0.145
MMK compress.	0.94	-0.59	0.114	-1.61	0.240	0.153
Reference	1.00	-0.50	-0.300	-2.30	0.65	0.43

- Compressible flow increases the quality of pressures
- The RNG and the MMK behave better with respect to the pressure values than the Standard model
- Draft and lift are still far away

There is something fishy

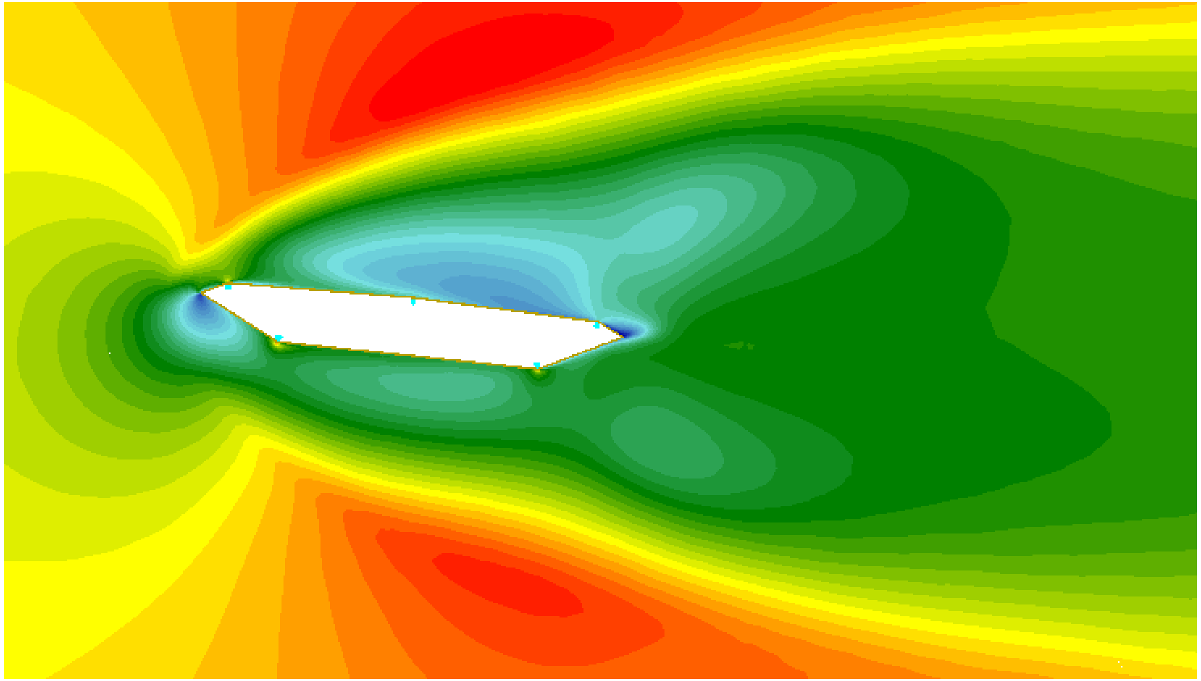
- Comparison with an other CFD code yield same effect
- There is a strong influence of the Reynolds number for this section (see high pressure results by Schewe)
- Published results in literature are rather doubtful
  the parameters used are seldom described
- But there are hints that the wall function is a problem
- So we try to run the model with turbulence but without wall function (which is extremely wrong for a CFD expert)

Pressure distribution

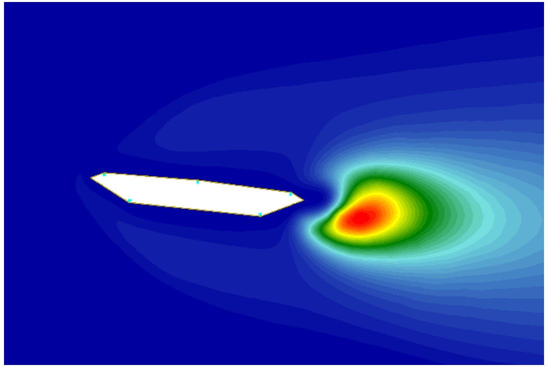


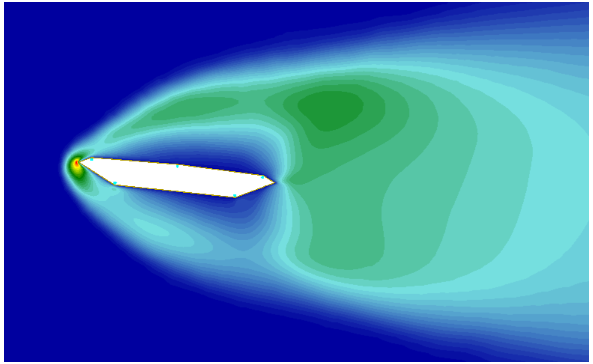
- Distribution is acceptable
- The drag coefficient is now to high, but if we discard the high shear stress we obtain cd = 0.64 !

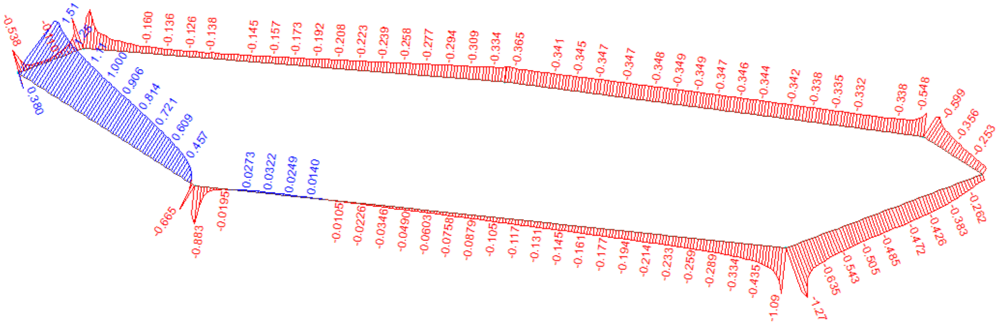
Another Result with lower turbulences



Results (k, μ_t, p)







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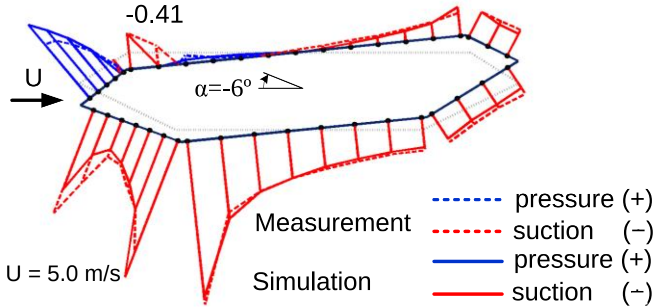
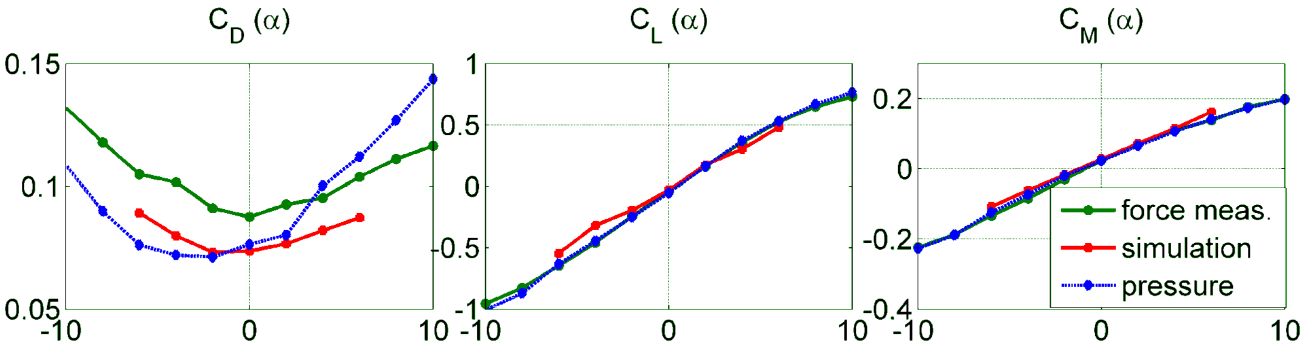
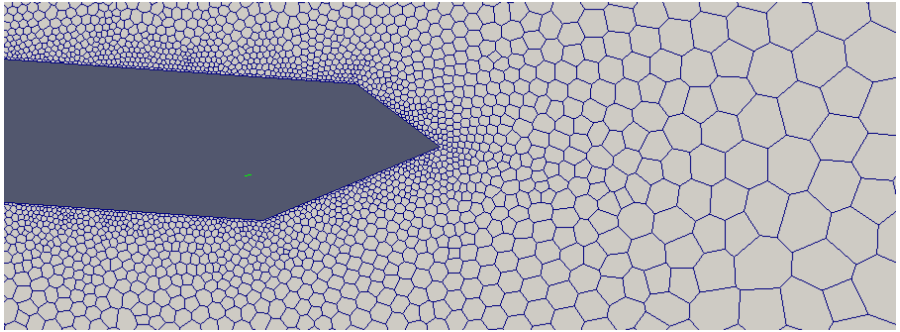
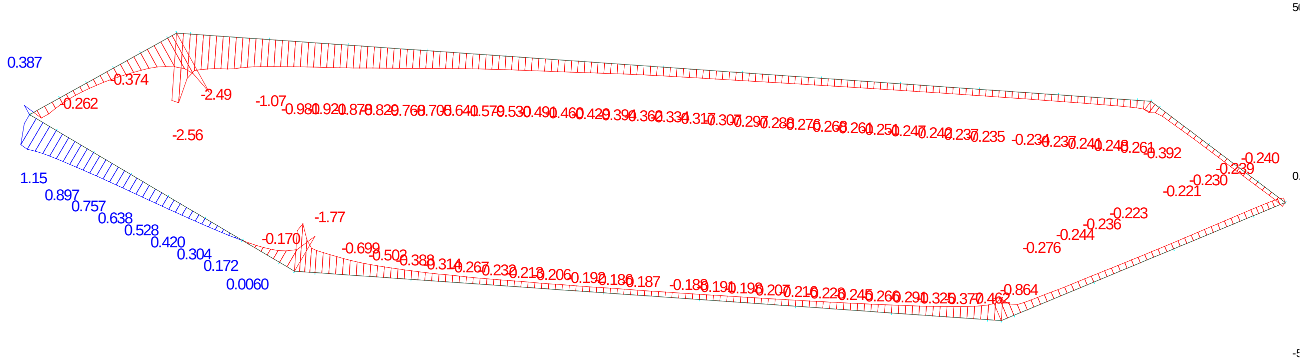
CFD + Wind Tunnel Tests (A. Sarkic)





Solution with polyhedral cells



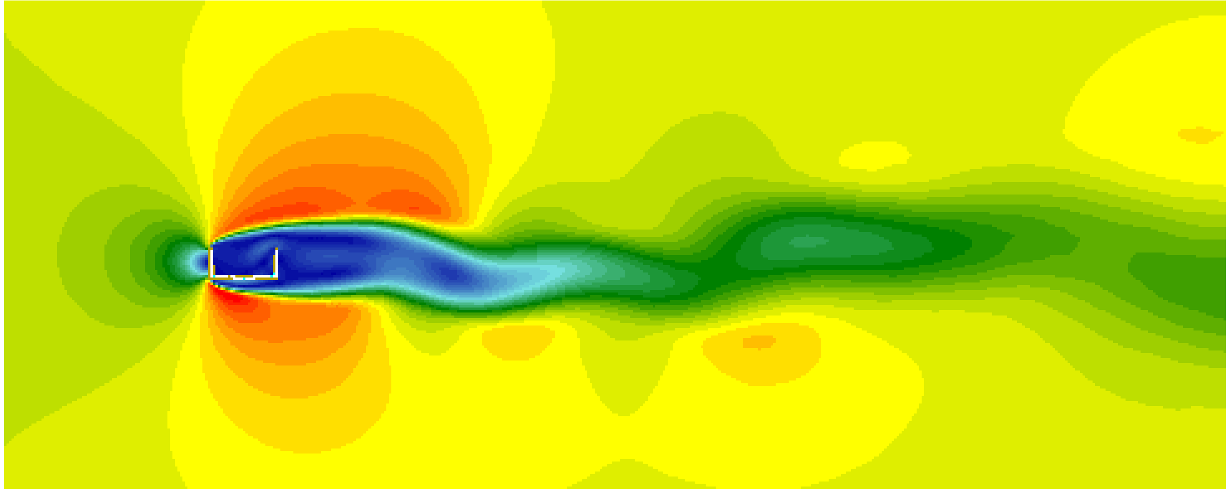


Comparison of Results

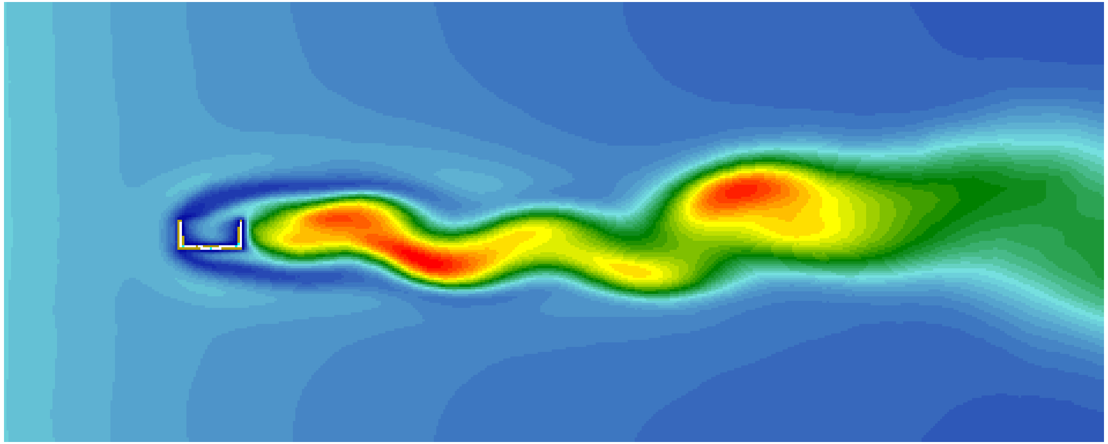
	y+	cd	cl	cm
Experiment		0.095	0.380	0.109
Referenz		0.062	0.370	0.100
Hybrid (h=4.0 mm)	25.3 – 51.8	0.039	0.316	0.111
Hybrid (h=0.6 mm)	2.3 – 11.2	0.056	0.319	0.121
Polyhedra (h=6.0 mm)	5.7 – 44.5	0.040	0.278	0.107
Polyhedra (h=2.0 mm)	0.4 – 20.5	0.048	0.351	0.120

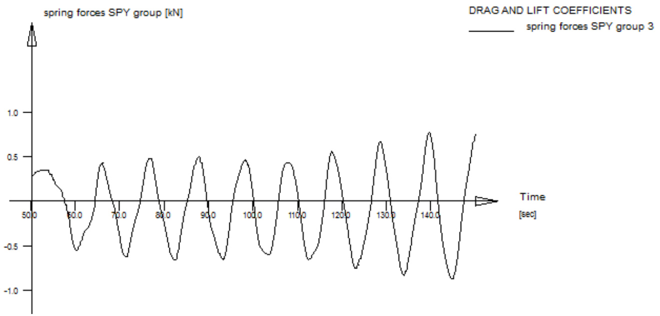
A Note on the Mesh Size

- A coarse mesh analysis:

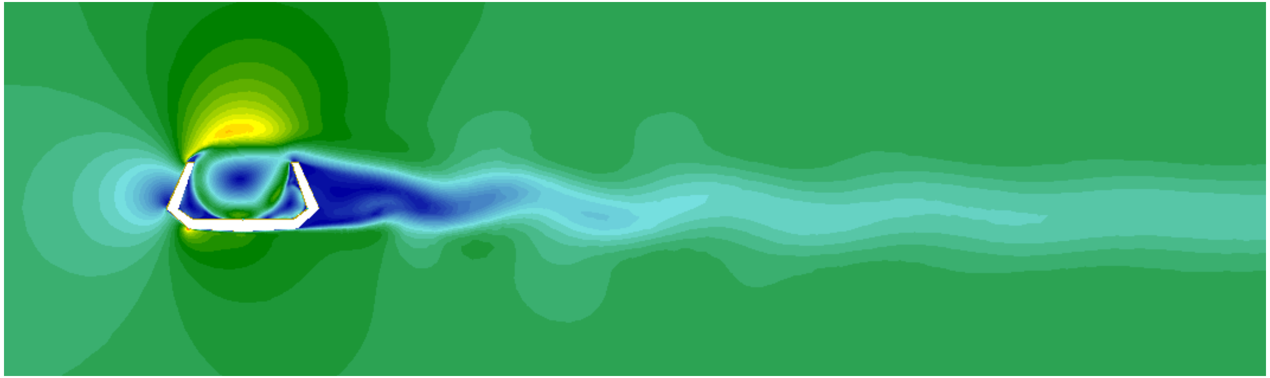


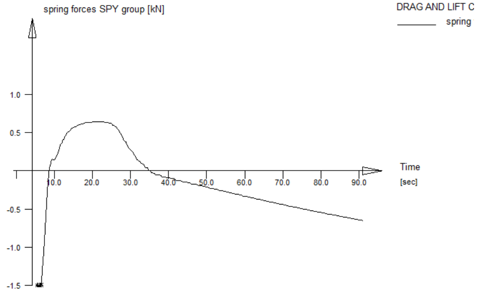
Turbulent Viscosity and Lift Coefficient





Mesh size reduced by a factor of 5

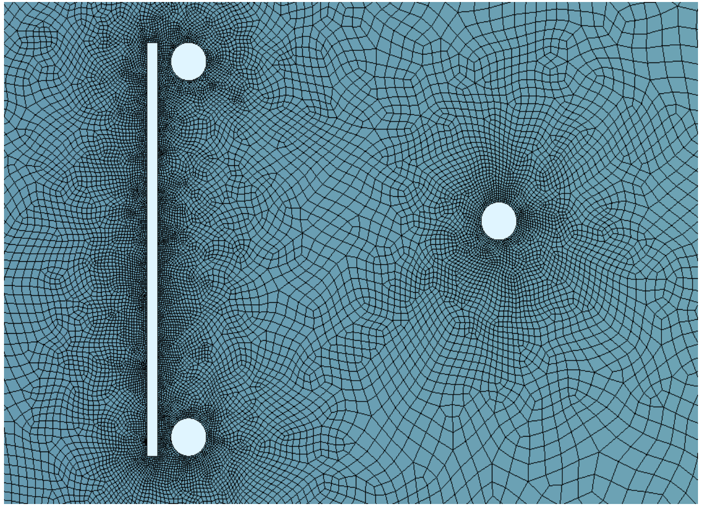


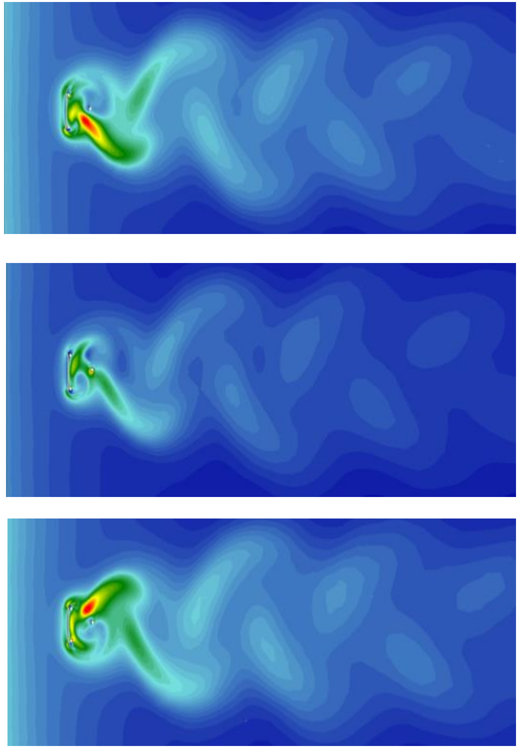


Conclusion

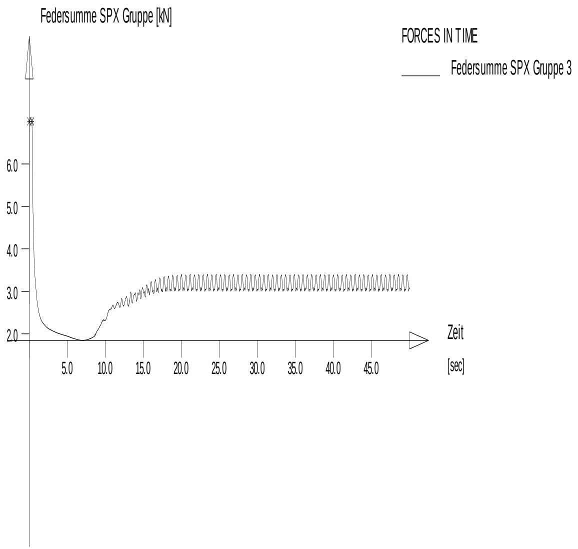
- It is possible to have results even with rather coarse mesh
- If we look deeper, we find quite a lot of problems
- However using CFD in the design phase gives valuable insight for many details
- It can not been used for replacing the wind tunnel
- If we know better about the discrepancies we might reach the state of the racing car industry:
  - We know that the results are wrong by 40 percent, so we add such a factor to our numerical results.

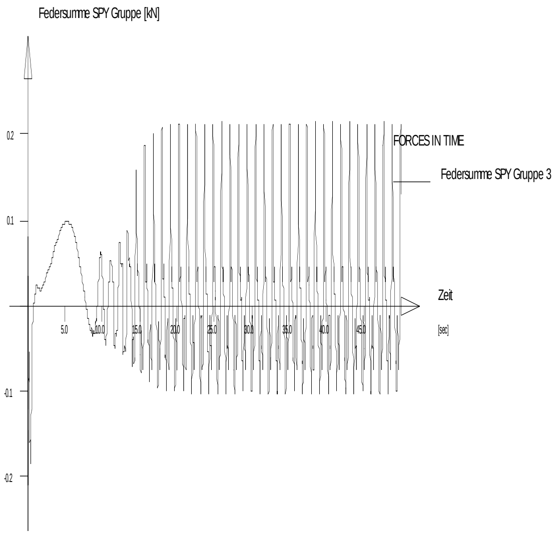
A Recent Project: Vortex & Galloping



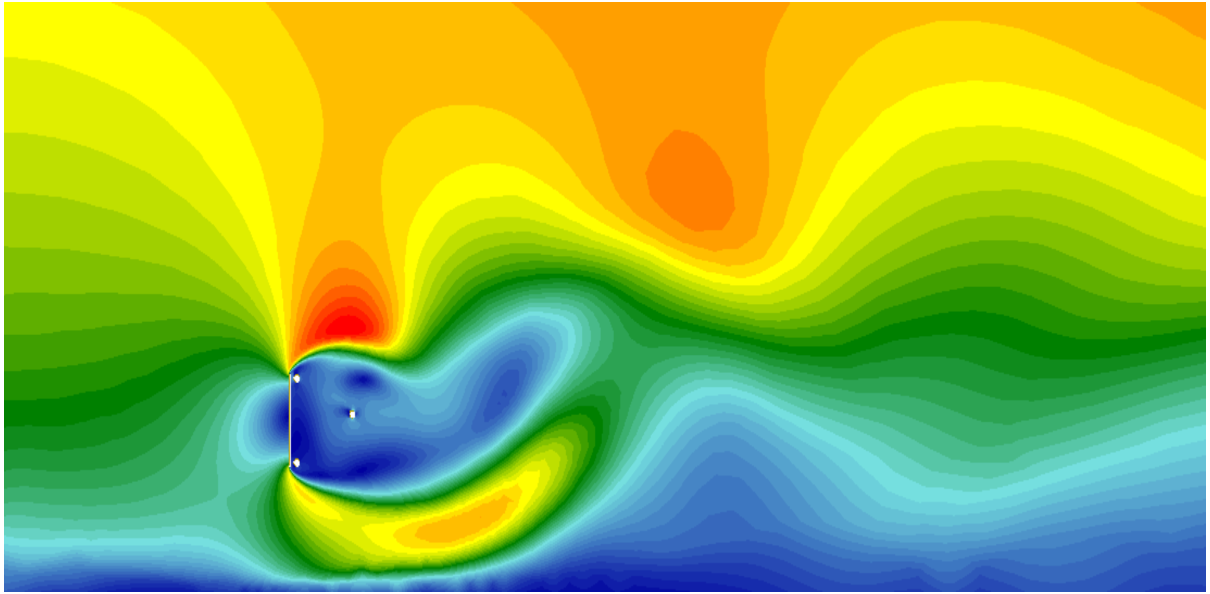


Transient Drag and Lift in Free Field





The influence of the ground

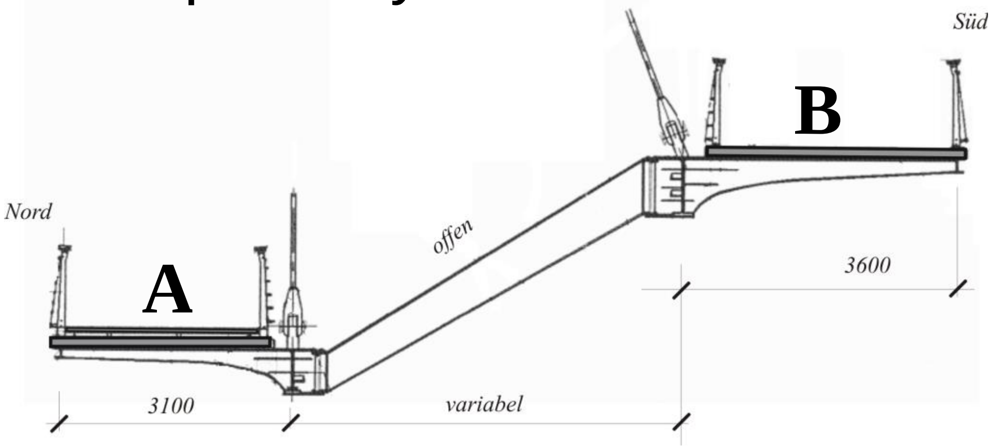


Design: Marc Mimram, Paris
Wind Engineer: PSP-Technologie GmbH, Aachen

Checks by: Leonhardt Andrä & Partner, Stuttgart

Characteristics

- Spans of main bridge:
  43.72 + 183.37 + 43.72
- Thickness of pathways t = 15 cm



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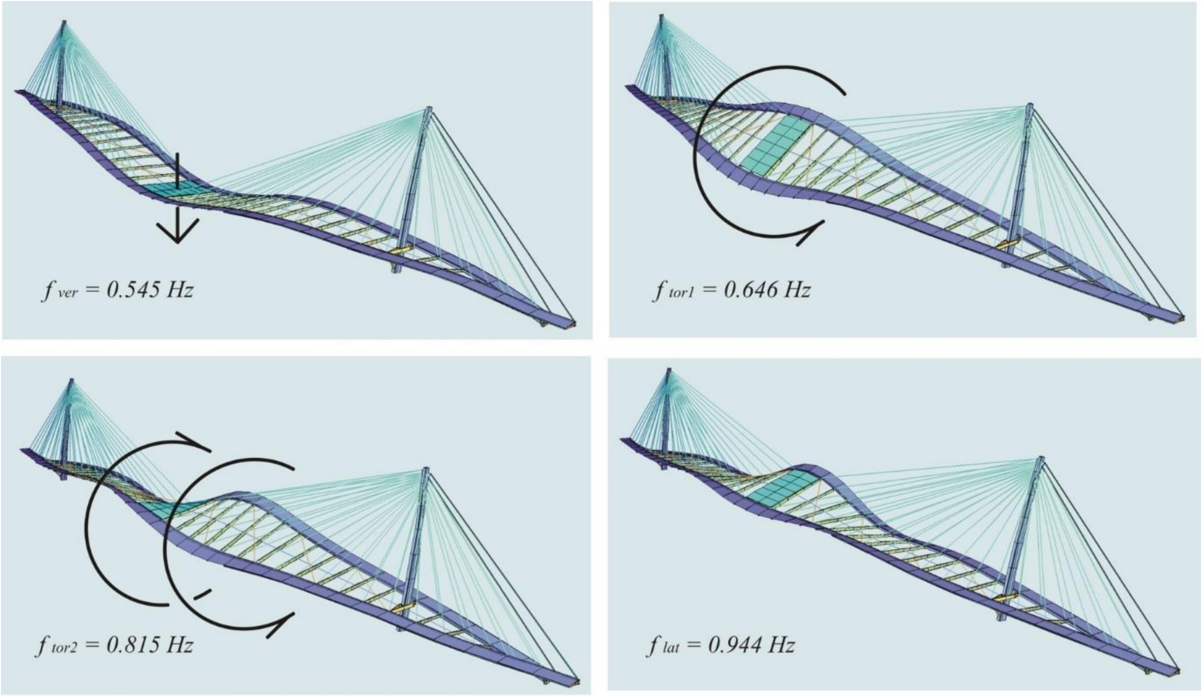
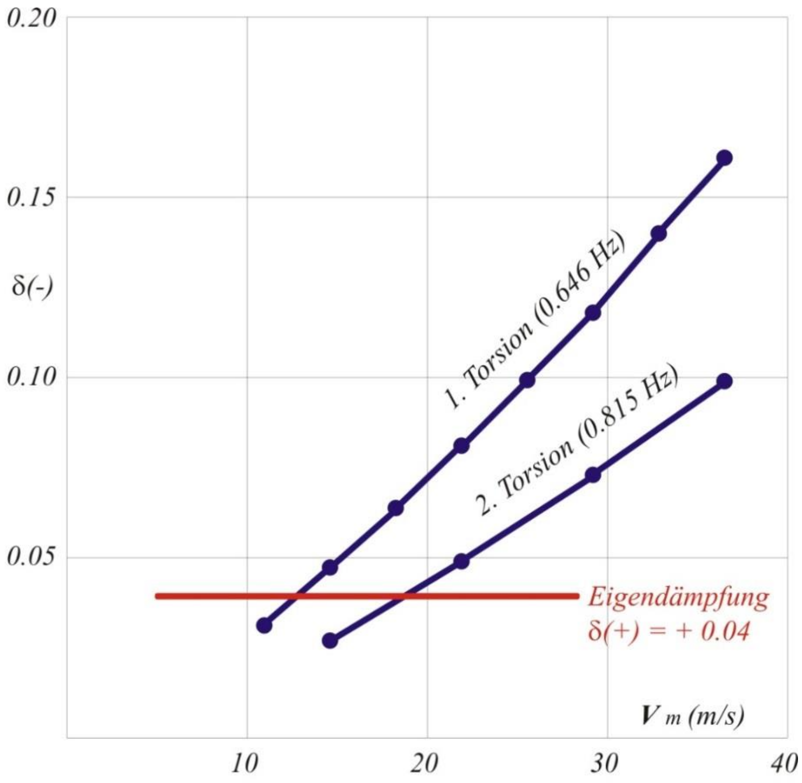
Eigenfrequencies (undamped)



SOFiSTiK

Dynamic Sensitivity

- Sharp edges of section
- Interference
- Small torsional stiffness
- Negative aero elastic Damping
- Torsional Galloping
- Pedestrians
  (1 Hertz horizontal!)
- **Tuned Mass Dampers are mandatory !**



Numerical Simulation

- Wind climate (the global wind)
- Topology (local wind)
  - 10 - min wind (Mean value + Gust + Spectra)
- Aerodynamics (Drag coefficients)
  - Wind tunnel tests / CFD
- Dynamics (Response of the structure)
  - Non linear transient time history analysis
  - Aero-Elasticity (Damping, Galloping, Flutter)
- Design of the structure
  - 100 year life time

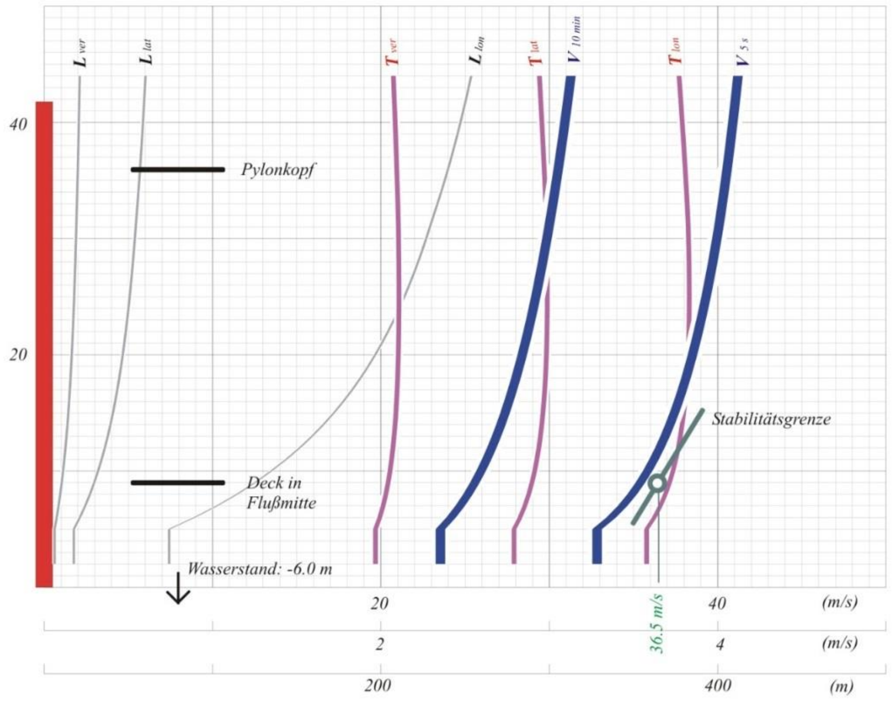
Wind climate (global + local)
(10 Minutes of 100 Year-Wind)

- 25 years of measurements of meteorological station Lahr

  v = 27.2 m/sec

- Atmospheric wind from long term measurements and a global wind map an a surface roughness of z = 0.01 m

  v = 25.3 m/sec



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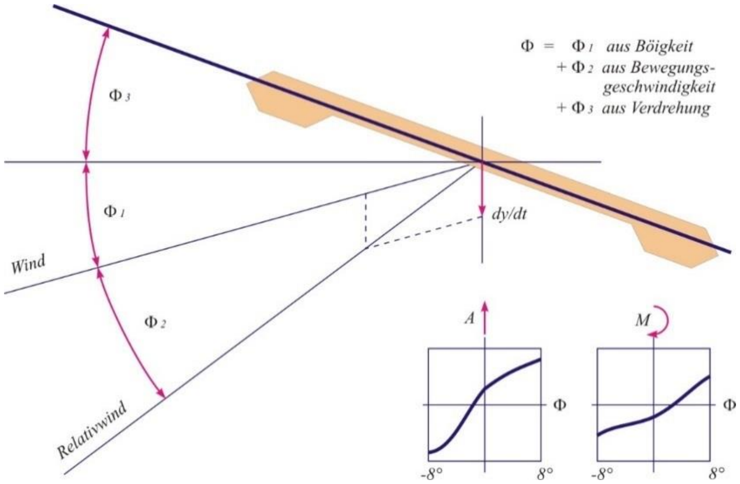
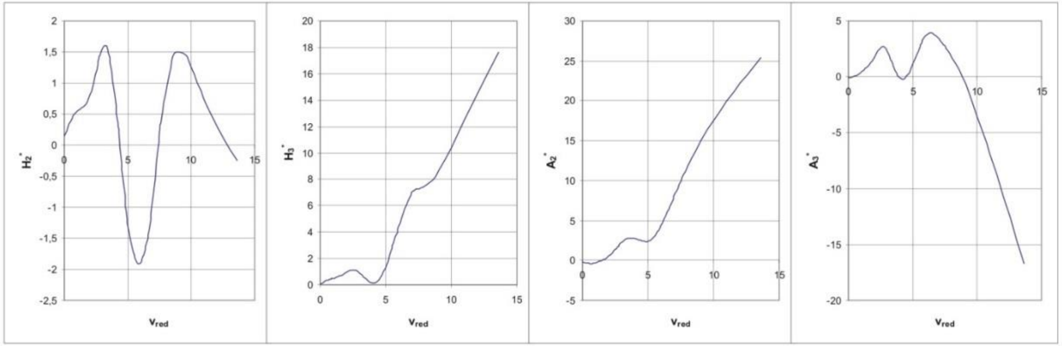
Analysis procedure for wind part I

- For each wind direction one base wind case
- Global atmospheric wind + topology
- Subtask I
  - Create wind profile
- Subtask II
  - Create wind spectra in all points of the structure accounting for coherences
- Subtask III
  - Create wind histories

Aero dynamics

- Wind tunnel
- CFD
  (Vortex Particle
  Method)





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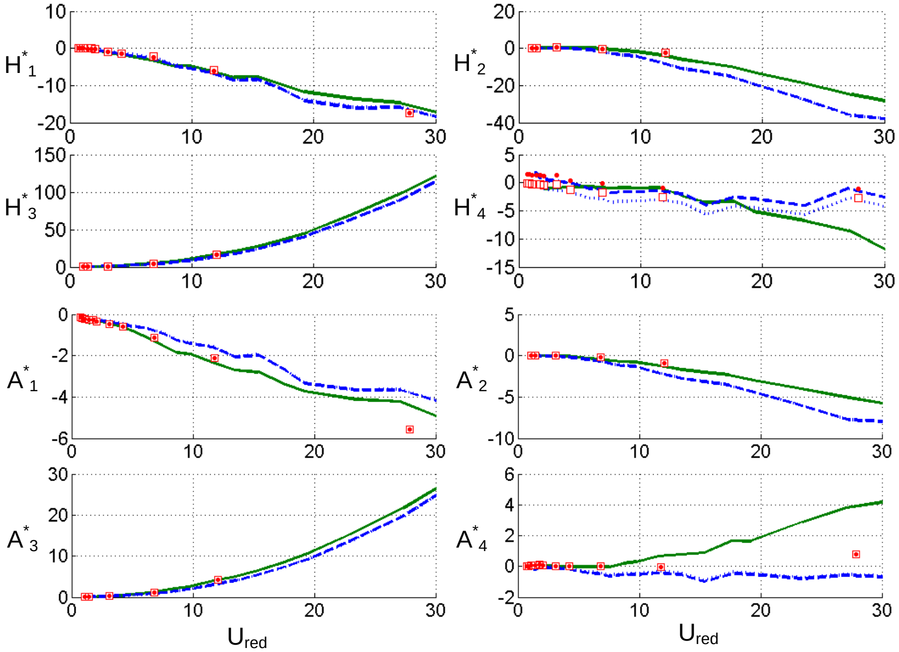
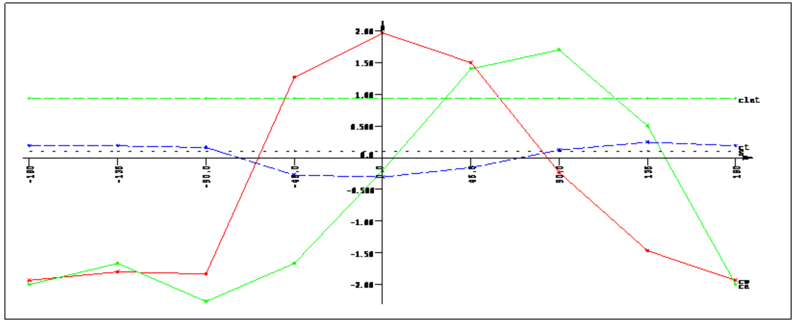
CFD + Measurements (Sarkic)



Force meas.; Pressure wr; Pressure wo; □ Simulation wr; • Simulation wo
(wr-with, wo-without subtracting the reference measurement)

Drag Coefficient Variants

- Values found in Literature for
  - Circular sections, Simple Bluff bodies
  - Roofs and walls
  - Rolled steel shapes
- User defined factors for element groups
- User defined local variants of factors similar to load patterns (e.g. suction at edges)



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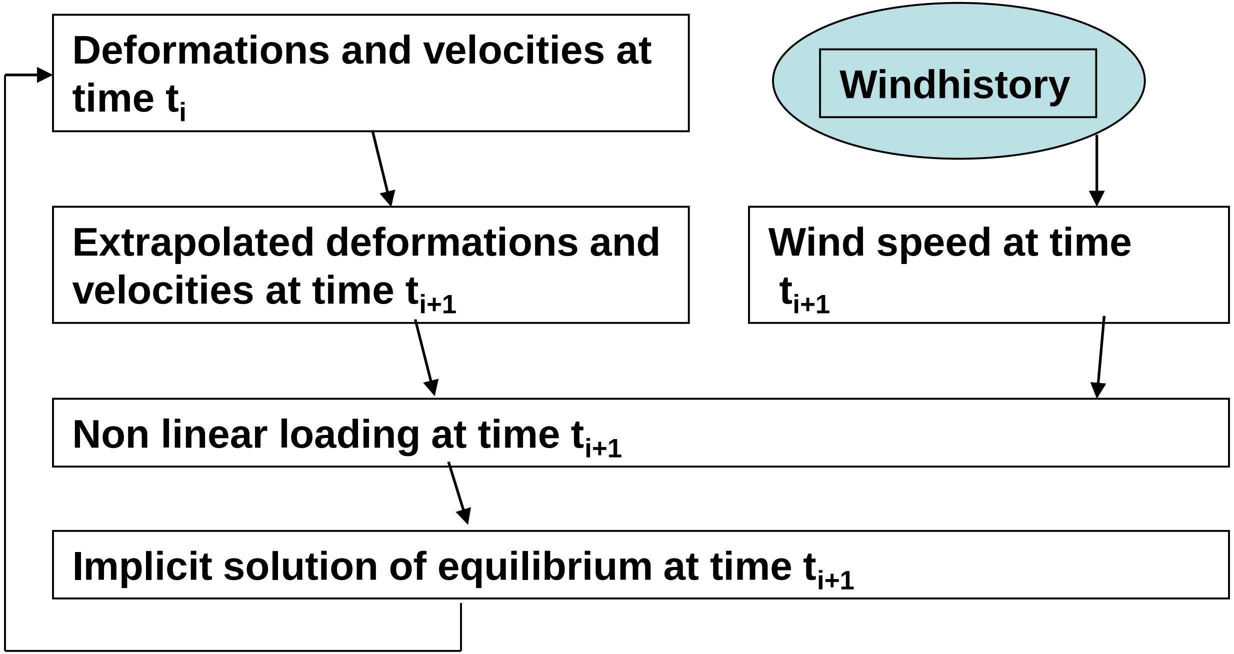
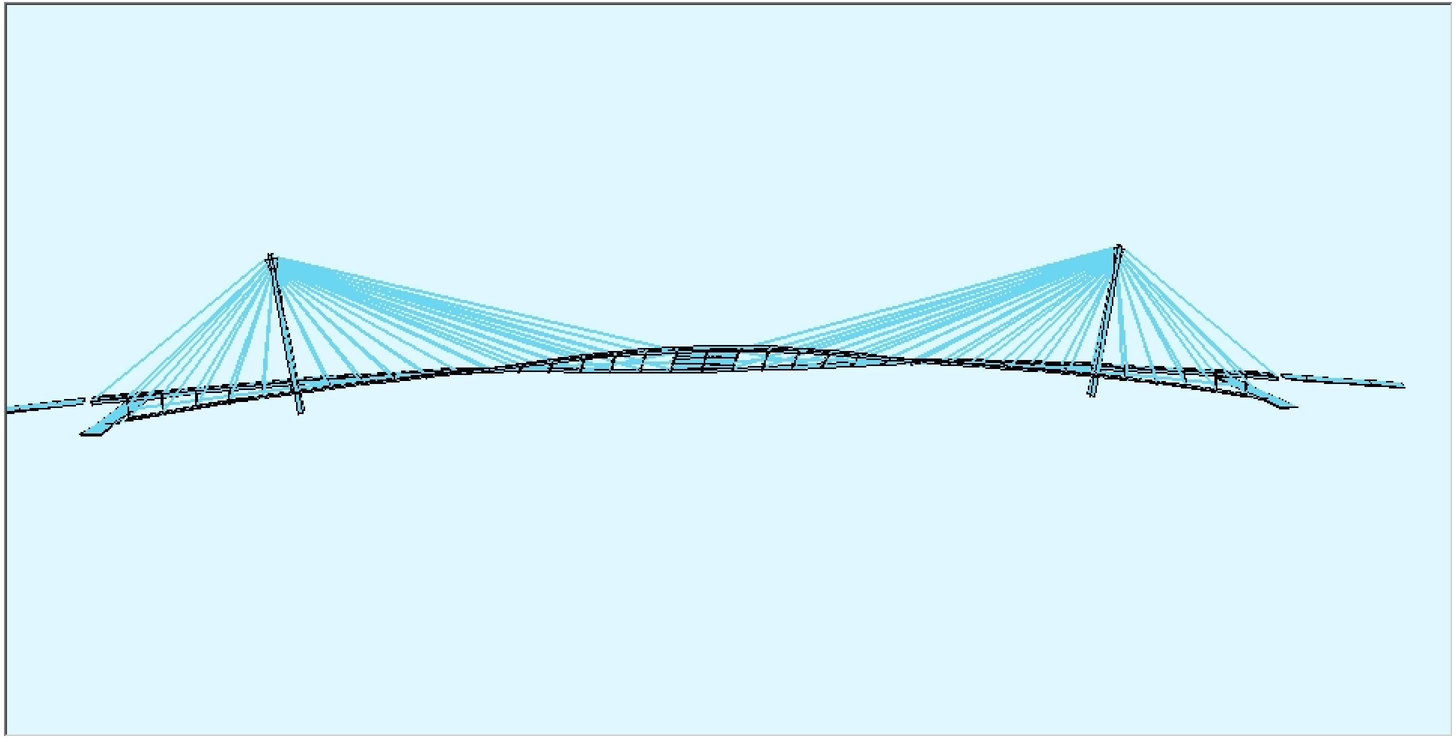
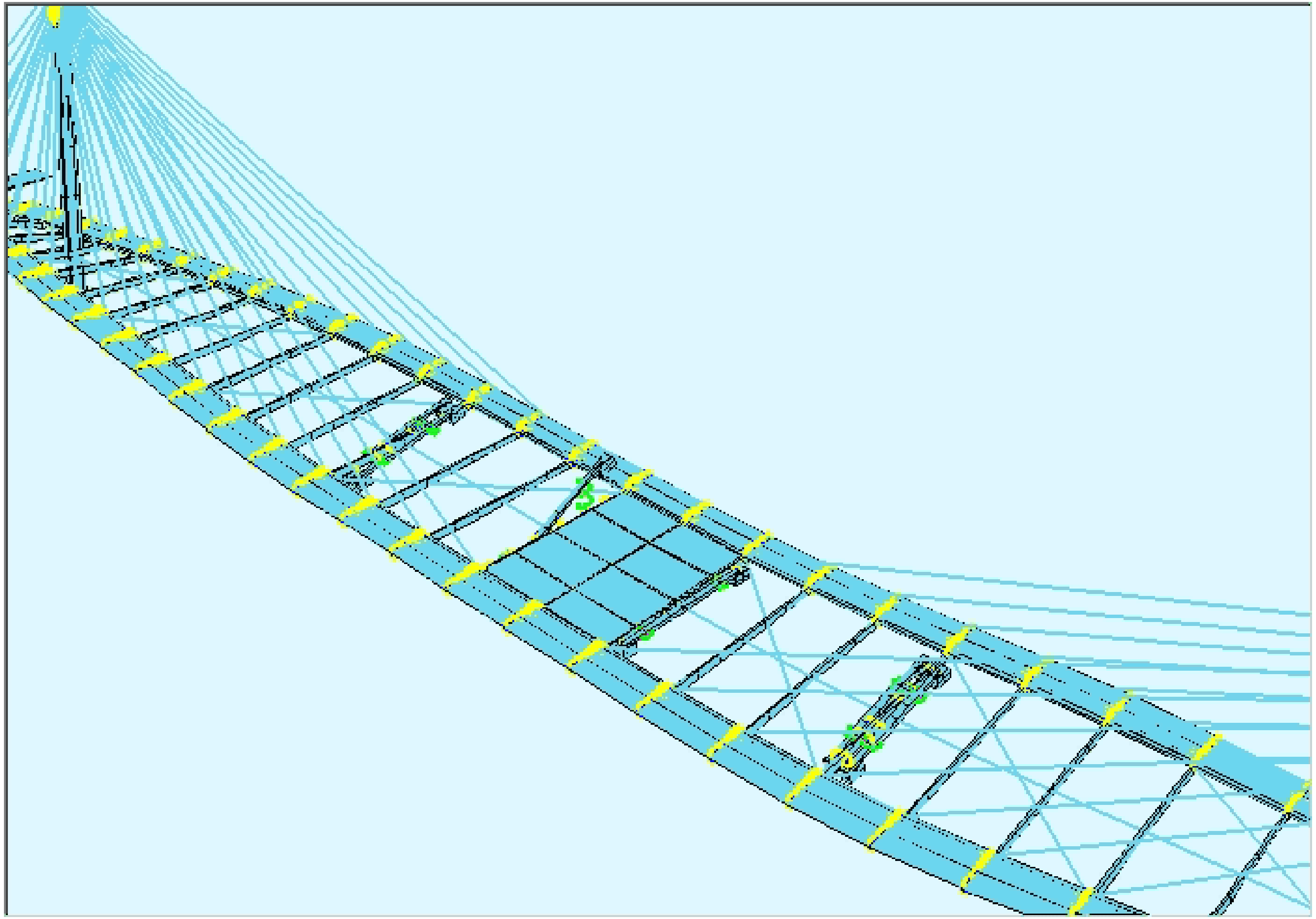
Analysis procedure for wind part II



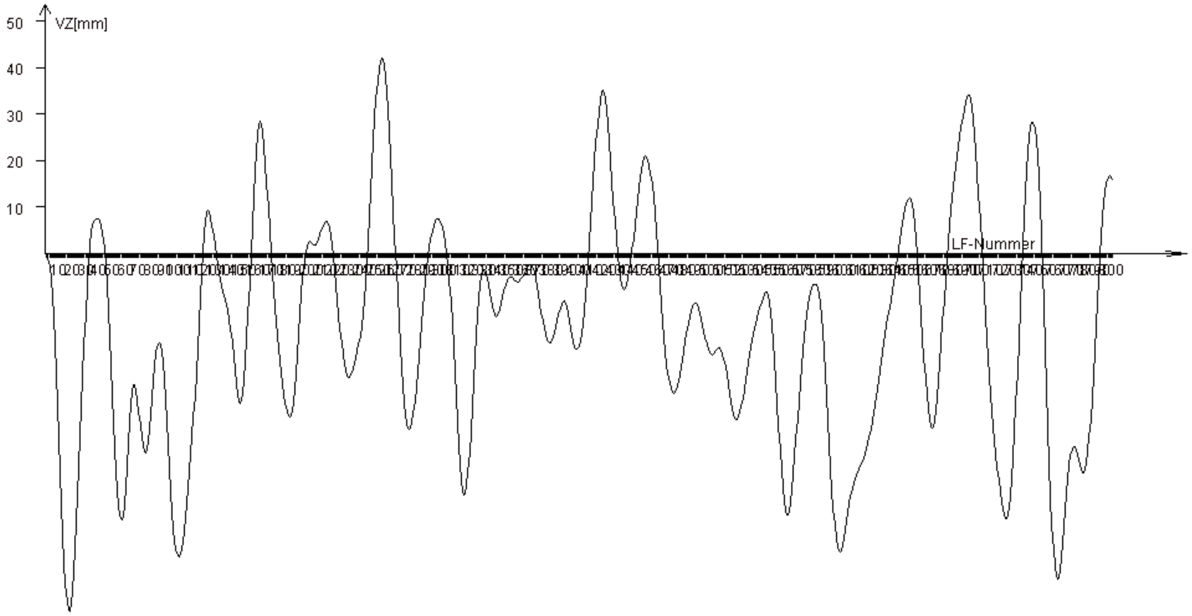
Instability (constant wind)



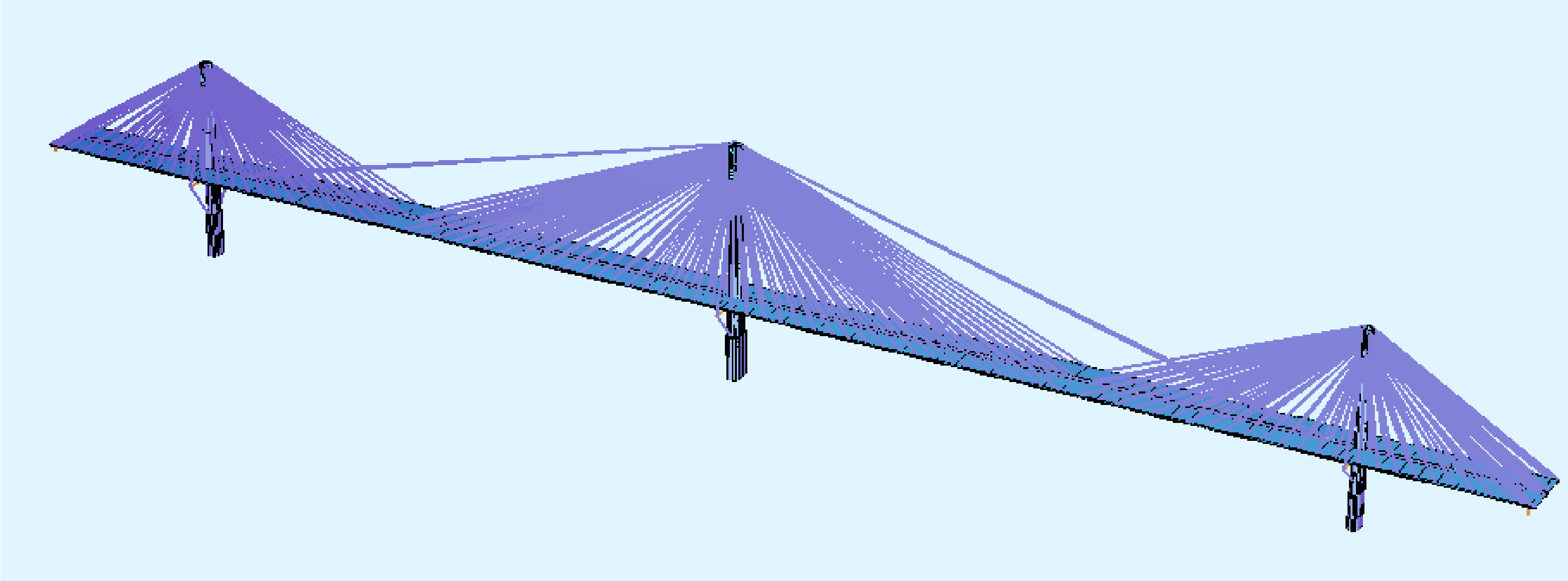
Effectiveness of TMD



Response of deformations

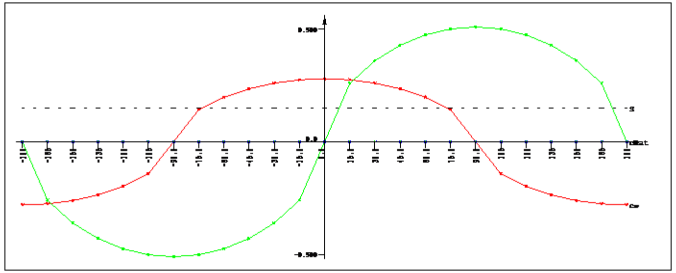


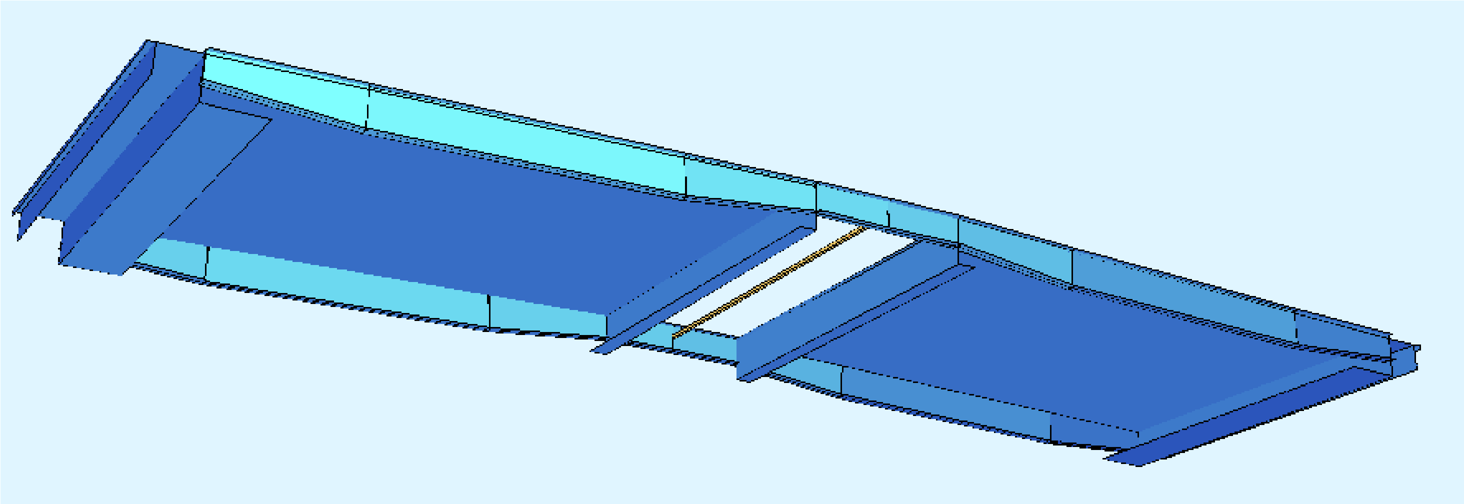
Tingkau – Bridge, Hongkong



Checking Analysis by Schlaich, Bergermann and Partner

Cross Section





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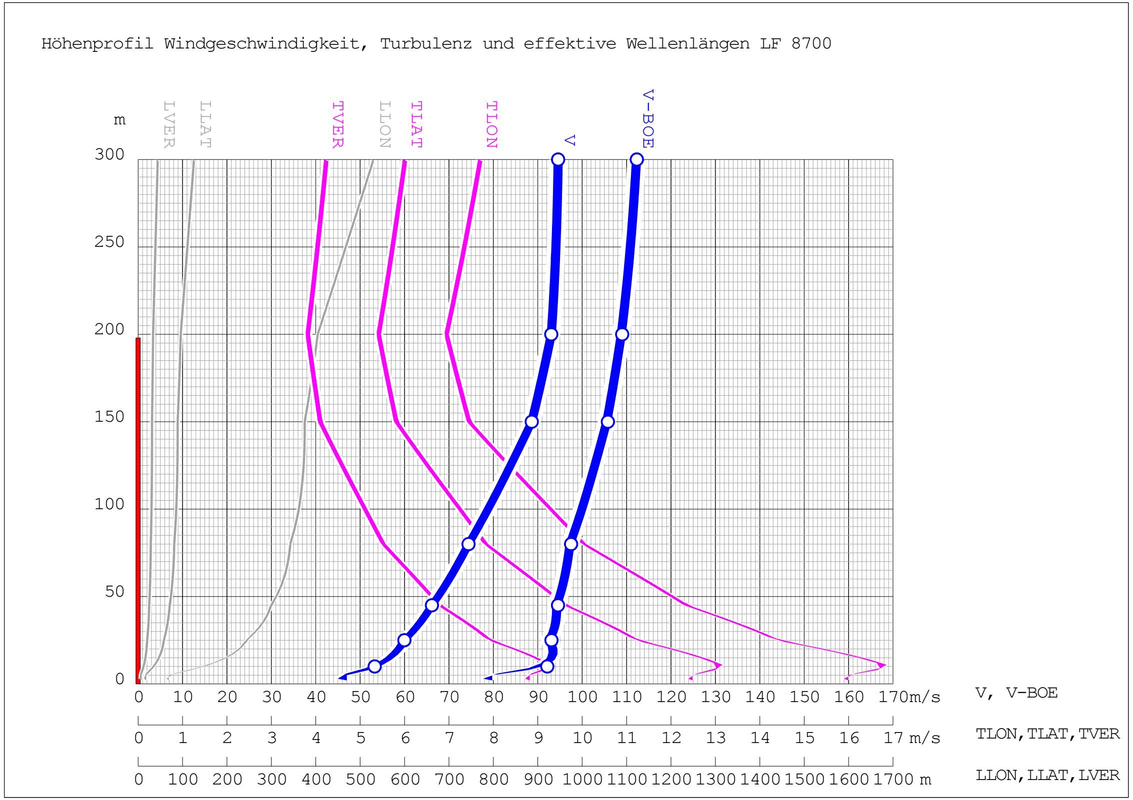
Wind profile

- Wind profile given as 1 h mean values + gust speeds => Conversion.



Safety concept

- Safety factors provided by client:

  $\gamma_f = 1.9$ for mean values
  $\gamma_f = 1.4$ for wide band wind
  $\gamma_f = 1.2$ for narrow band wind

- It is better to increase the wind speed by $\sqrt{\gamma}$ than to multiply the loads (aerodynamic damping)
- Turbulence ($v_{gust} – v_{mean}$) receives its own factor from

$$q_{ult} = 1.9 * q_{mean} + 1.4 * (q_{gust} - q_{mean})$$

- Narrow band wind is accounted for by enlarging the damping.

Advantages of numerical solution

- Non linear transient analysis copes for
  - Changes of the wind flow
  - Aerodynamic effects (Damping)
  - Aerodynamic effects (Flutter)
  - Aerodynamic effects (Torsional galloping)
  - Nonlinear material (Hysteresis = Damping)
  - Tuned mass dampers
- Variants of tuned mass dampers
  - Where to install
  - Effectiveness, Malfunction
- 10 to 20 % Savings in forces within structures

Errors with the simplified approach

- Every section moves individually in the wind
- Transient movements of the air are not included.
- Especially the time needed to establish a different flow field is not accounted for. Phase differences between movements of the bridge and the wind forces are not included.
- A complete FSI might solve all these problems but the numerical effort is much to high.

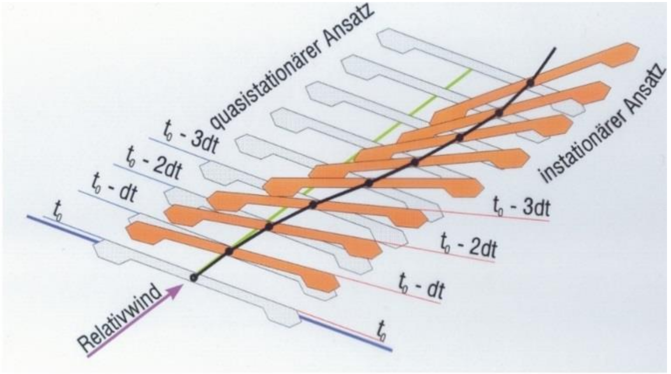


Bild 2: Unterschiedliche Bewegungsmodelle und Rechenansätze der Windkraftberechnung

Work Flow I – Wind tunnel

- Identify sensitive parts
- Measurements of drag forces of a prismatic bar which is moved periodically in the wind tunnel
- This gives transient wind forces and the scanlan-derivativa derived from those.
- Wind forces are dependant on the angle of attack, different series of measurements are required.
- Reactions depend on the amplitudes!

Workflow II - Analysis

- The history of the displacements h(t) and α(t) will be approximated by a harmonic function.
- This identifies a current matching frequency, amplitude and angle of attack.
- The wind forces are evaluated based on the Scanlan $H^*_1 \div H^*_4$ resp $A^*_1 \div A^*_4$.
- There are also solutions with 18 instead of 8 derivativa to account for the movement in the wind direction.

Example Brandangersund-Bridge

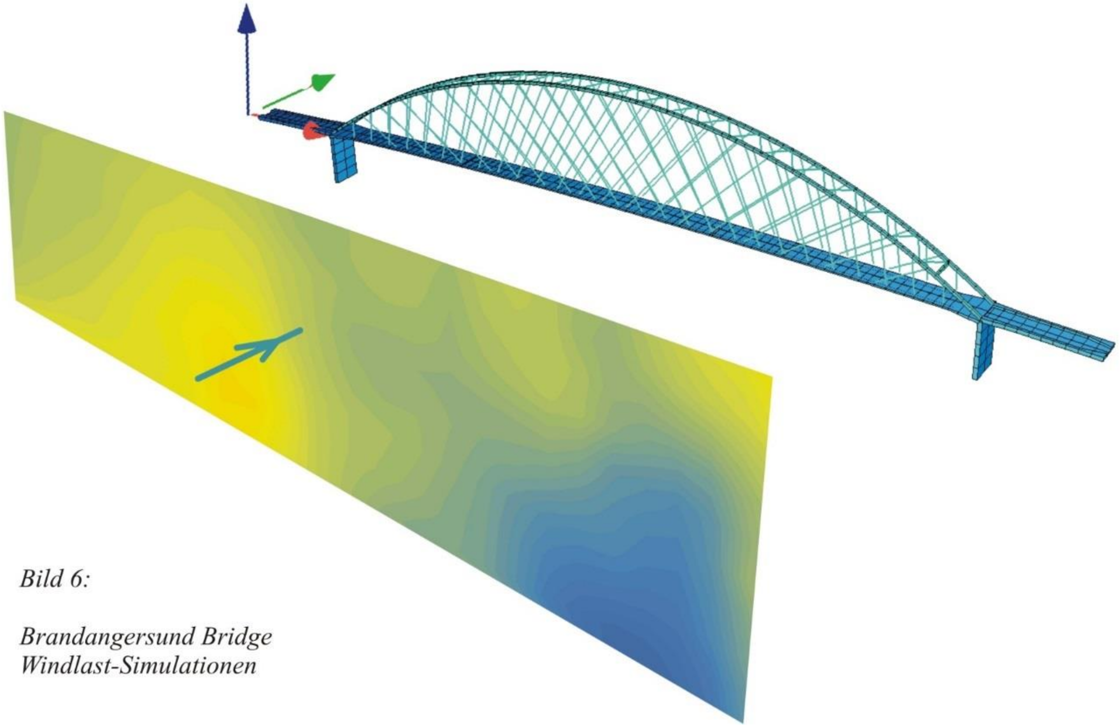
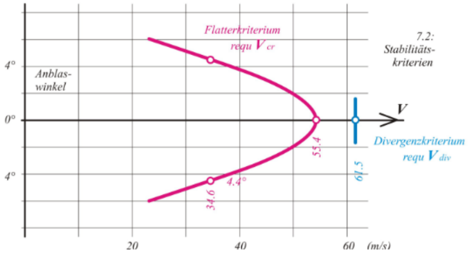


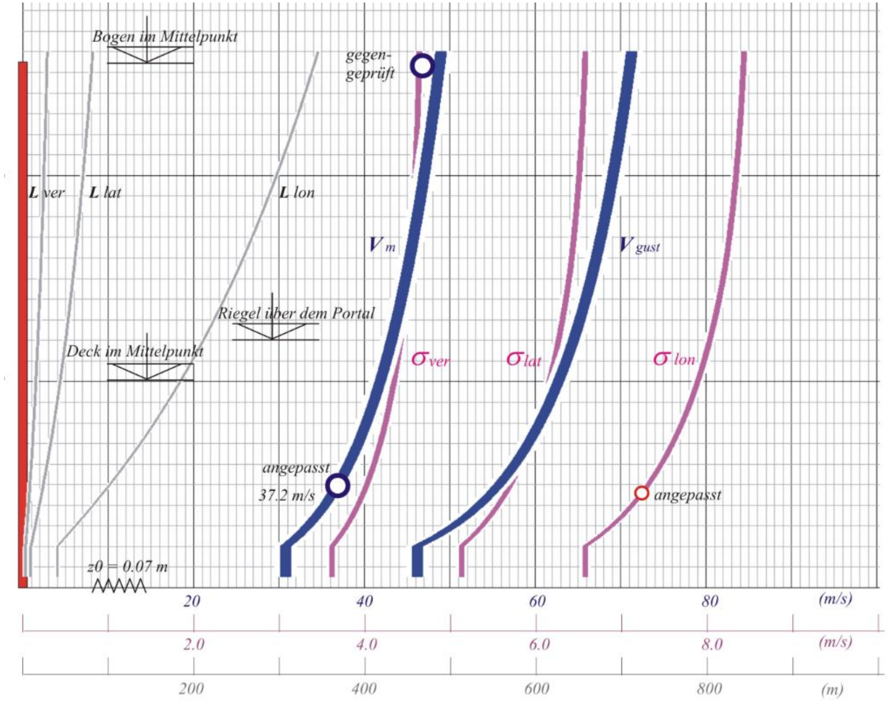
Bild 6:

Brandangersund Bridge
Windlast-Simulationen

Parameters of Brandangersund-Bridge

- Arch
  Span width 240 m
  Height 30 m
- Section
  width only 7.6 m
- Wind parameter:
  an art of its own
- Stability limits





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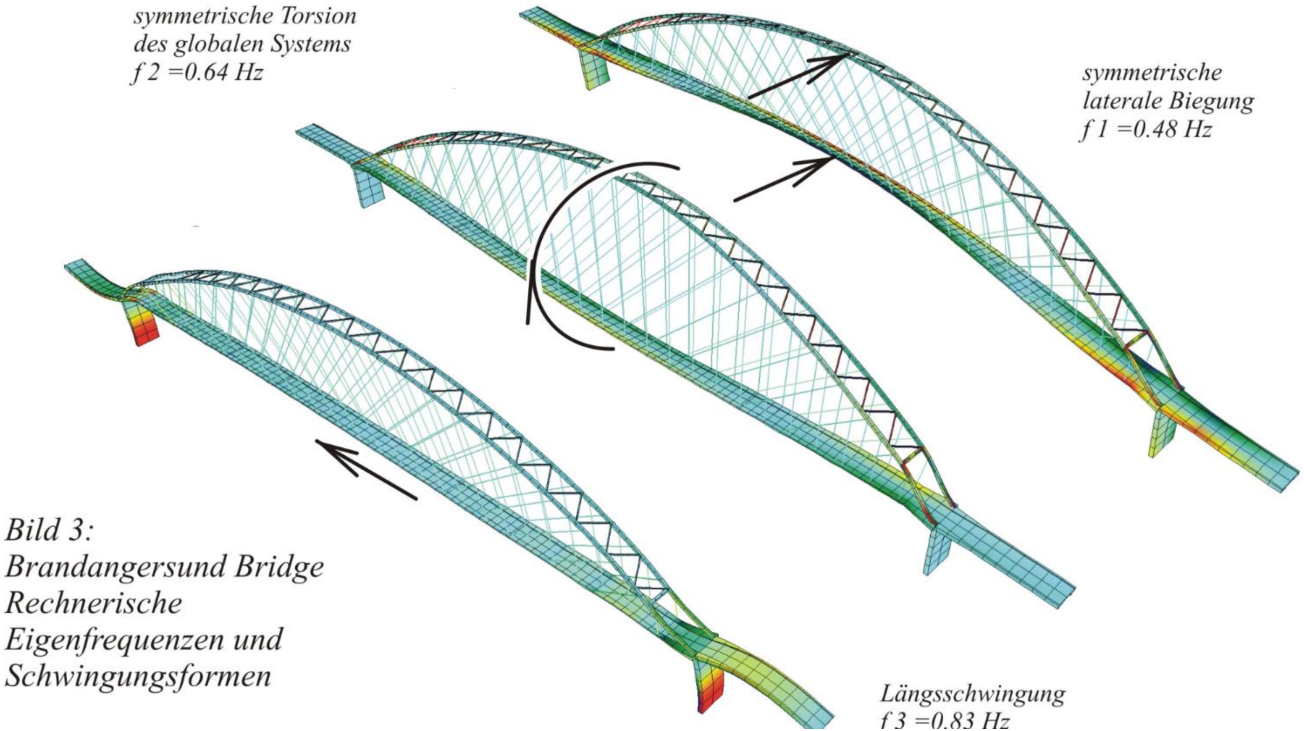
Eigenfrequencies



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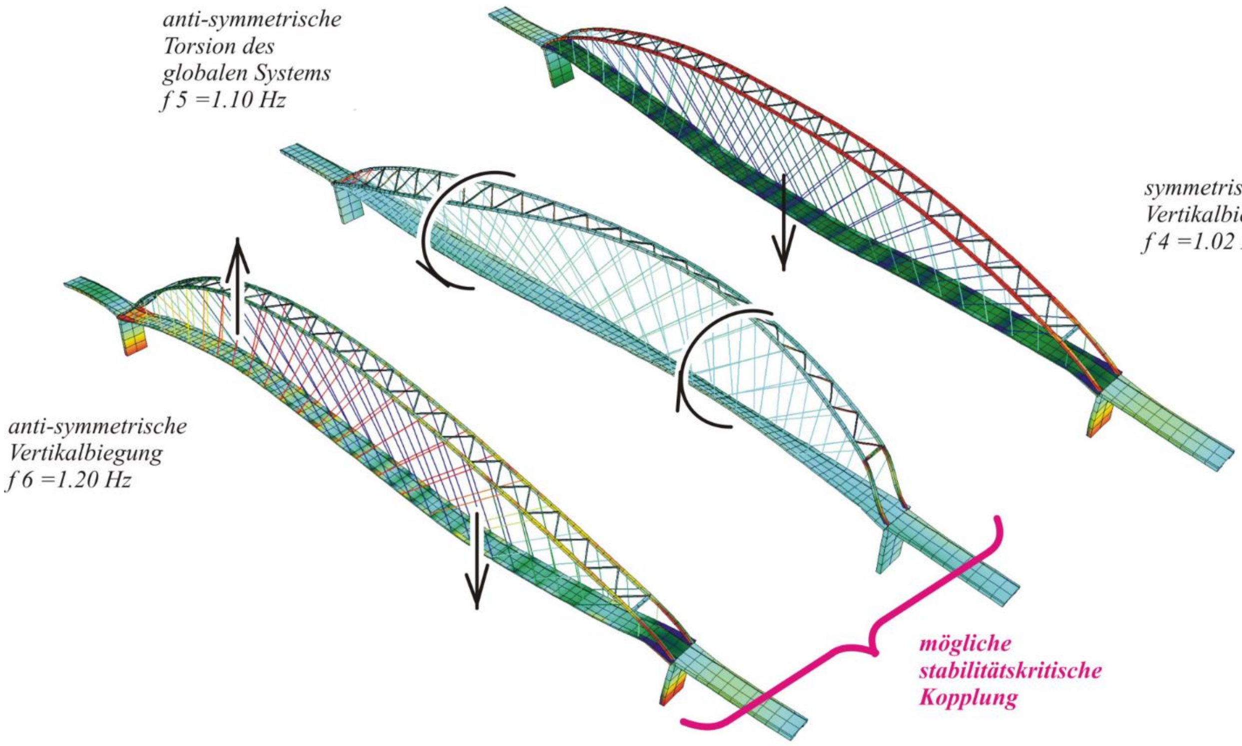
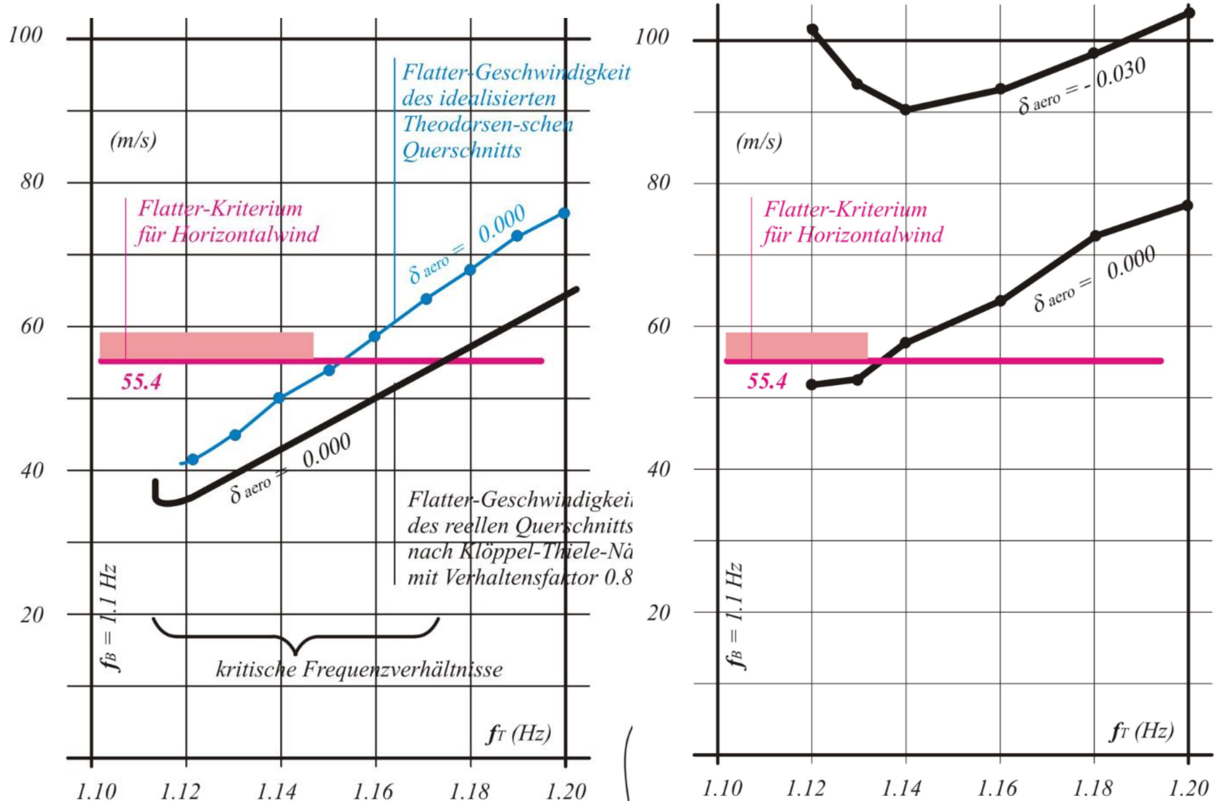
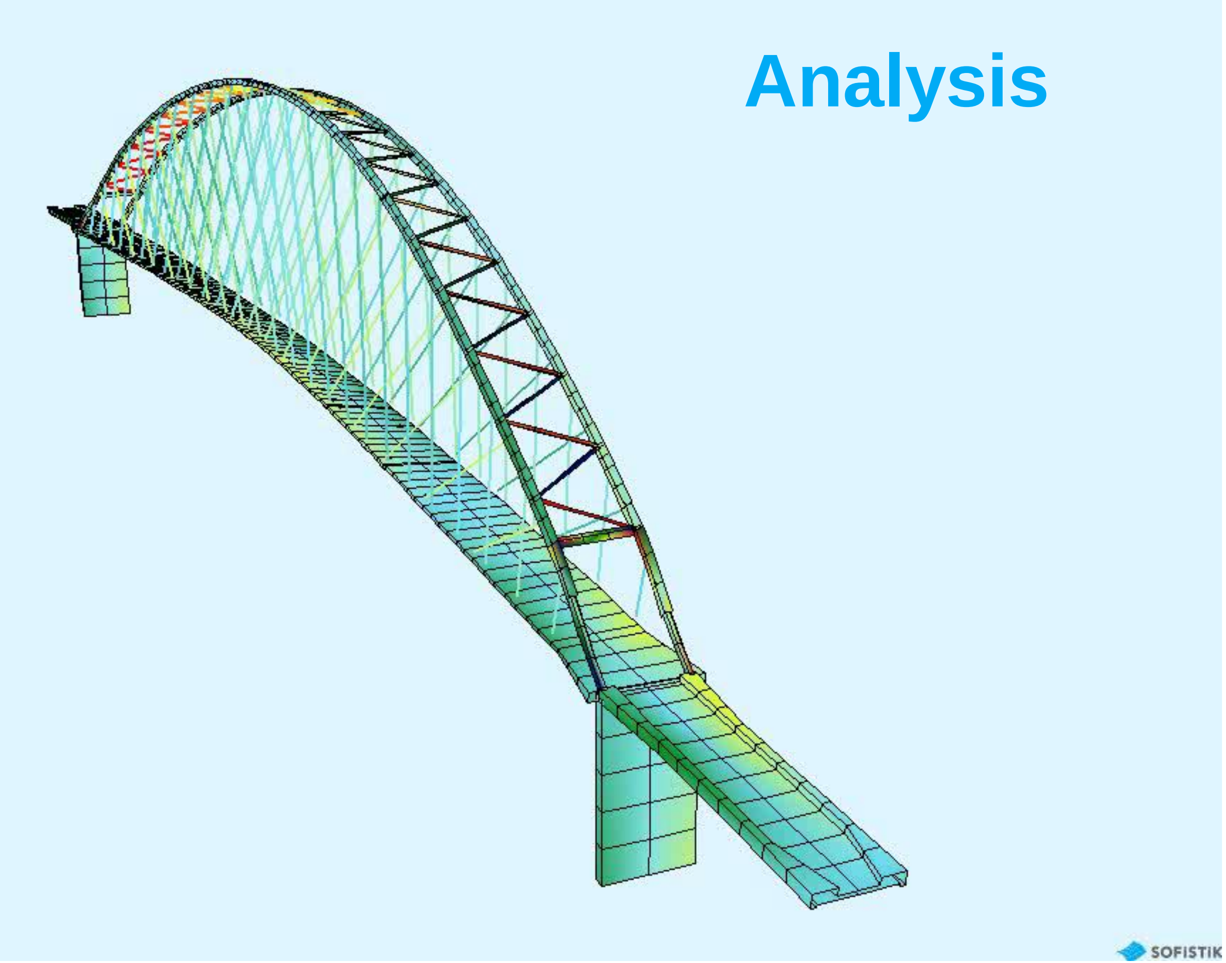
Eigenfrequencies



Stability check




Analysis
SOFISTIK

Assessment

- This bridge established extreme requests (3rd check)
- We are very close to the stability limits
- Forces caused by wind load where higher than for the stable condition, a secondary effect from the vicinity to the stability limits
- Development of torsional deformations more than proportional
- Classical analysis methods could not be applied, a nonlinear analysis including secondary effects was necessary
- Horizontal bending moments from gusts exceeded the value of the mean wind by a factor of 4. The most important part was the secondary effect of the torsional divergence (ca 20 %) while the effect of the derivativa was only 6 to 8 % in that case.