Computational wind-structure interaction for analysis and design of flexible, light-weight and complex-shaped structures

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Chair of Structural Analysis, Technische Universität München

Flexible & light-weight structures in wind


Auditorio de Tenerife, Calatrava, 2003,
from www.wikipedia.org

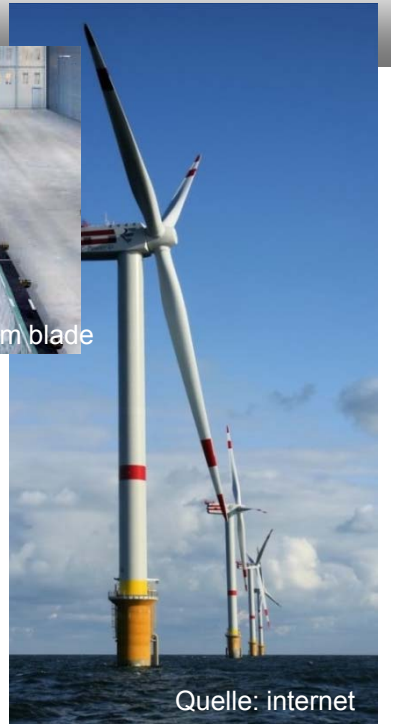

SL-Rasch GmbH


F. Otto, B. Rasch

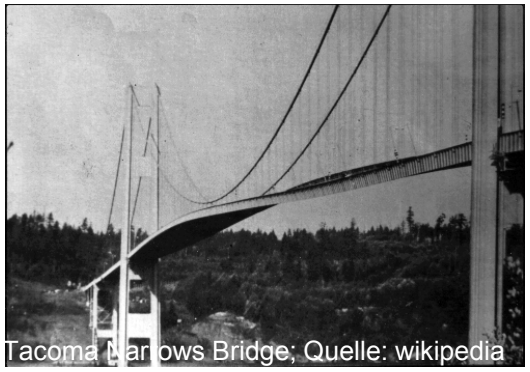

Tokyo Dome "Big Egg", 1988, Ishii, K.


Buidair, Barcelona


windkraft-journal.de; 75m blade

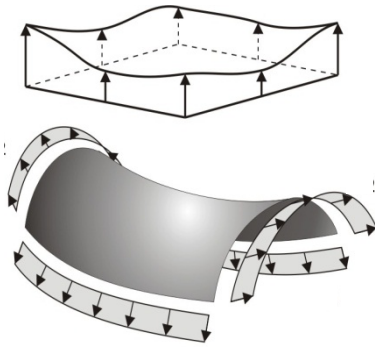

Quelle: internet


Behnisch, u.v.a. München 1972


Tacoma Narrows Bridge; Quelle: wikipedia

Agenda

- Preliminary considerations about load scenario
- Modular analysis and design framework
  → analysis: *what components & algorithms do we need?*
  → design: *predictive quality* of simulations needed!
- Environment for coupled simulations, special components:
  - FSI: coupling algorithms and non-matching grid treatment
  - Form finding - non parametric design
  - Wind generator
- Examples of real-world structures, esp. Ultra-lightweight inflatables
- Verification and validation is mandatory for design
  - presentation of a new FSI measurement campaign
  - validation procedure *(work in progress)*
- Summary & Outlook



Partitioned FSI-Analysis

C. Gengnagel, 2006

CSD simulation

- *CARAT*

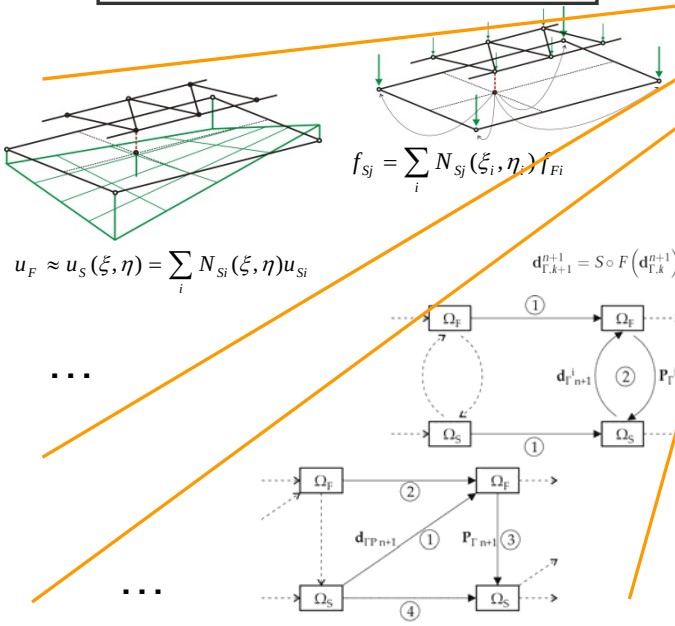
Coupling

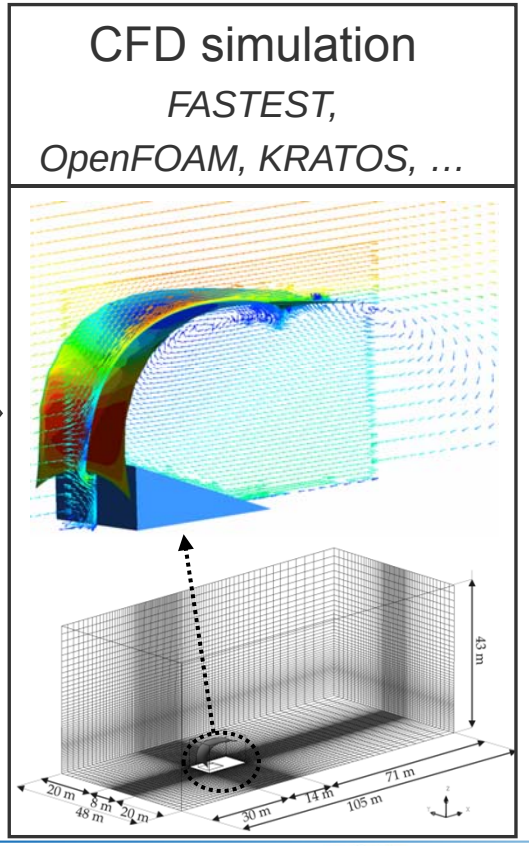
- *EMPIRE*

mapping & process control

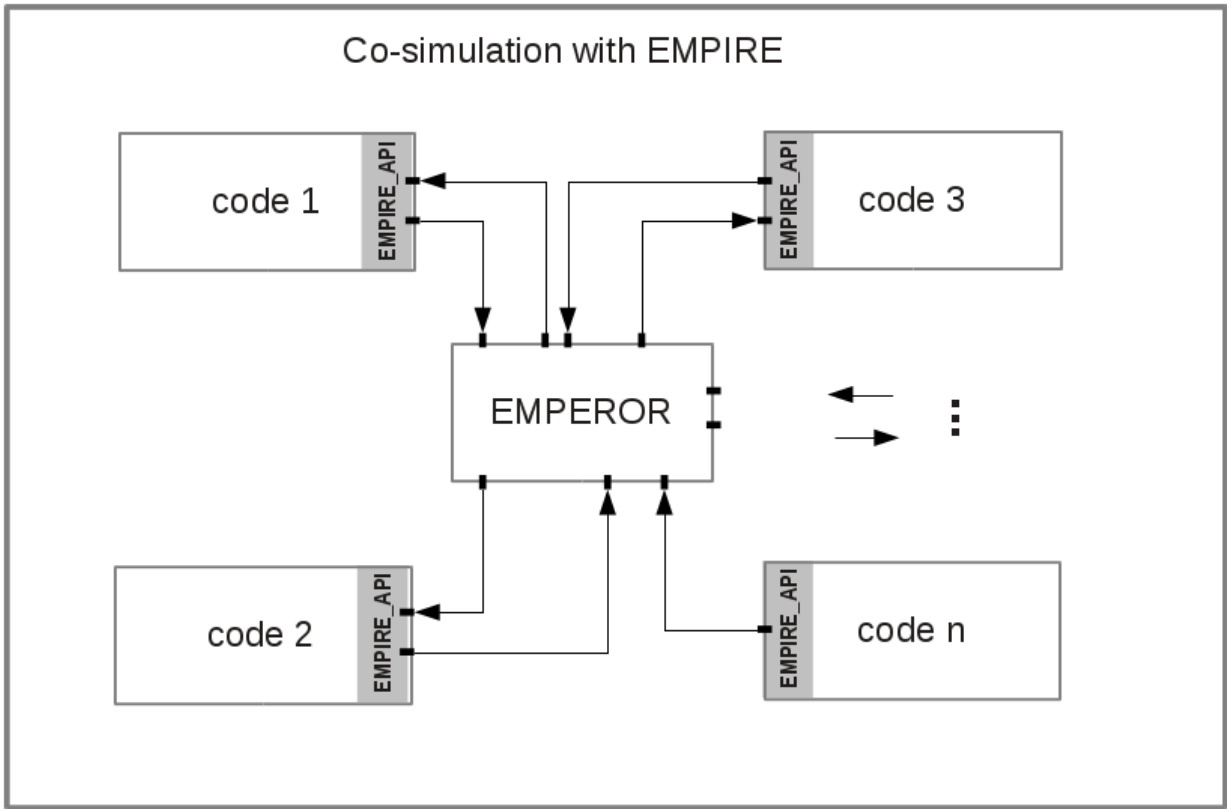
CFD simulation

FASTEST, OpenFOAM, KRATOS, …





Co-Simulation Framework



→ Constituents: components/modules, connections, filters

→ Co-simulation scenario defined by order of connections and loops

Modular numerical wind tunnel at Statik@TUM & CIMNE

Inlet generator

Wind profile

inlet generator

mesh

u'

turbulent component

$\bar{u}$

mean (logarithmic) velocity profile

$U = U(u,v,w) = U(\bar{u}+u',v',w')$

Turbulent velocity components

w'

u'

v'

Wind spectra

Turbulent component time series

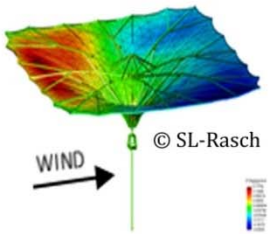
u

w

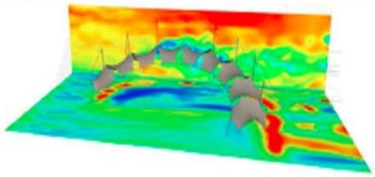
v

(here according to J. Mann)

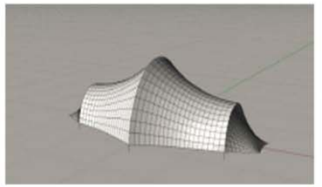
28m umbrella structure

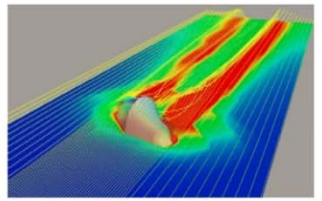


Wind load simulation of the Olympic stadium in Munich

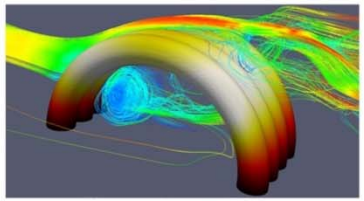


Simulation of expedition tents

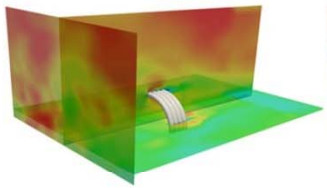


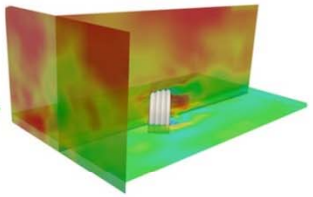


Hangar made out of membrane tubes



© Buildair





Numerical wind tunnel (WT)

WT inlet

$U = U_{given}$

wind

z

y

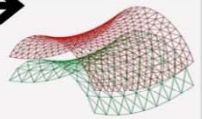
x

fluid domain and its own solver

mapping between wind generator mesh and WT domain inlet mesh

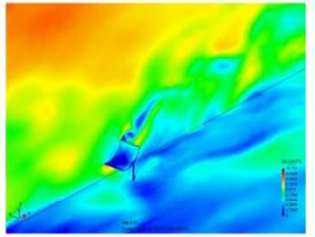
mapping between meshes

investigated structure with the respective structural solver

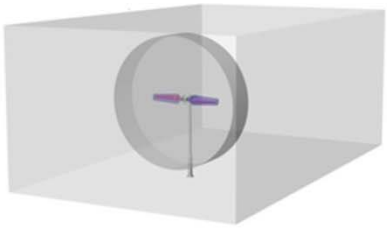


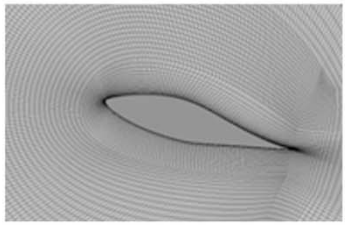
Solar throughs

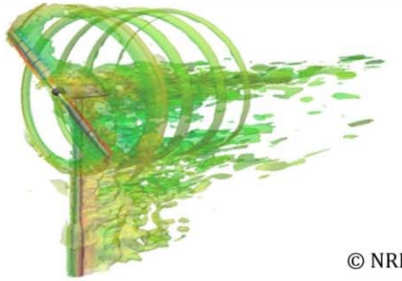
© Abengoa



Wind turbine FSI







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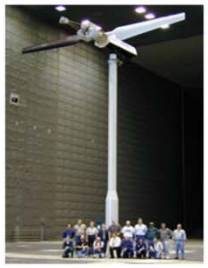


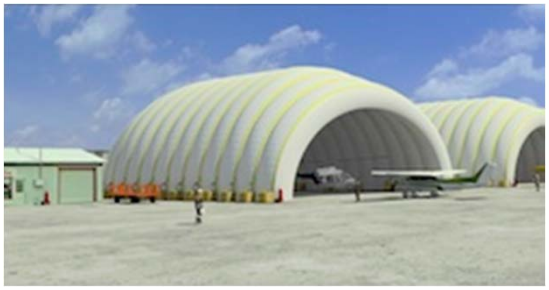
CARAT++ Structural solver

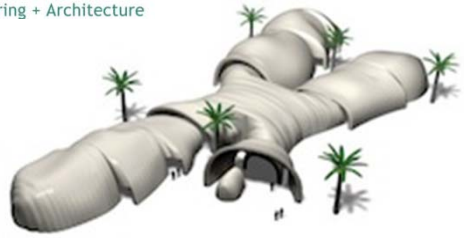
EMPIRE Coupling tool

Static TUM

Ultra-Lightweight: freeform-pneumatic structures

- EU-Project uLites: design, analysis & testing of ultra-lightweight pneumatic structures
  Partner: CIMNE, BuildAir, SL-Rasch, TUM, UniPd, CRIACIV
- PVC coated polyester fabrics, **thickness 0,5-1mm, span: 5-60m**
- Goal: - better evaluation of the wind-induced phenomena; wrinkling
  - required pressure increase to stabilize during storm



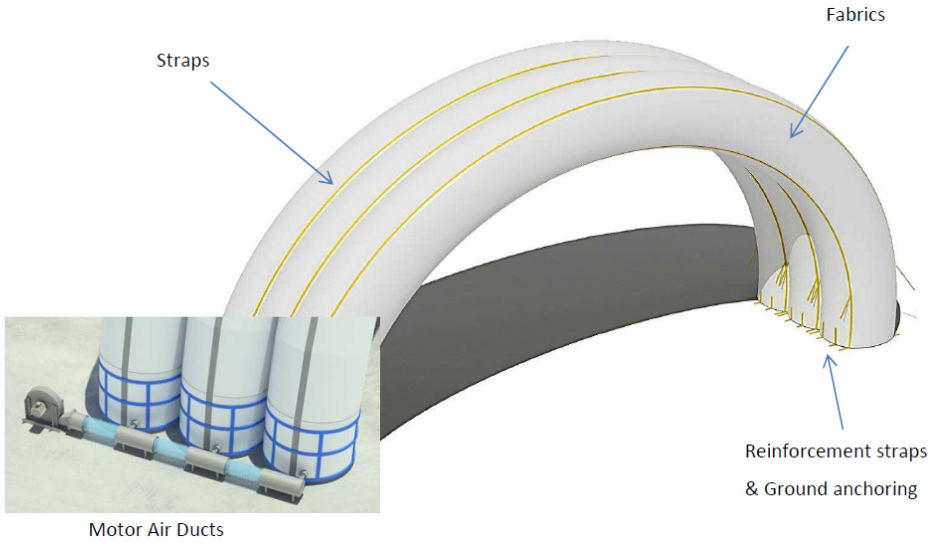


World‘s largest inflatable hangar (60m, Madrid)

Inflatable structures in wind: design tasks

- Keep **internal pressure** at a minimum for specific wind scenario:
  required electricity for fans & leakage increase vs. stiffening effect
- mobile shelter applications in different setups and regions:
  quick evaluation of anchoring forces under various conditions
- **Deformations** of pneumatic structure and strains in flexible solar panels must be known:
  design of attachement and reduce loss of electrical efficiency
- …

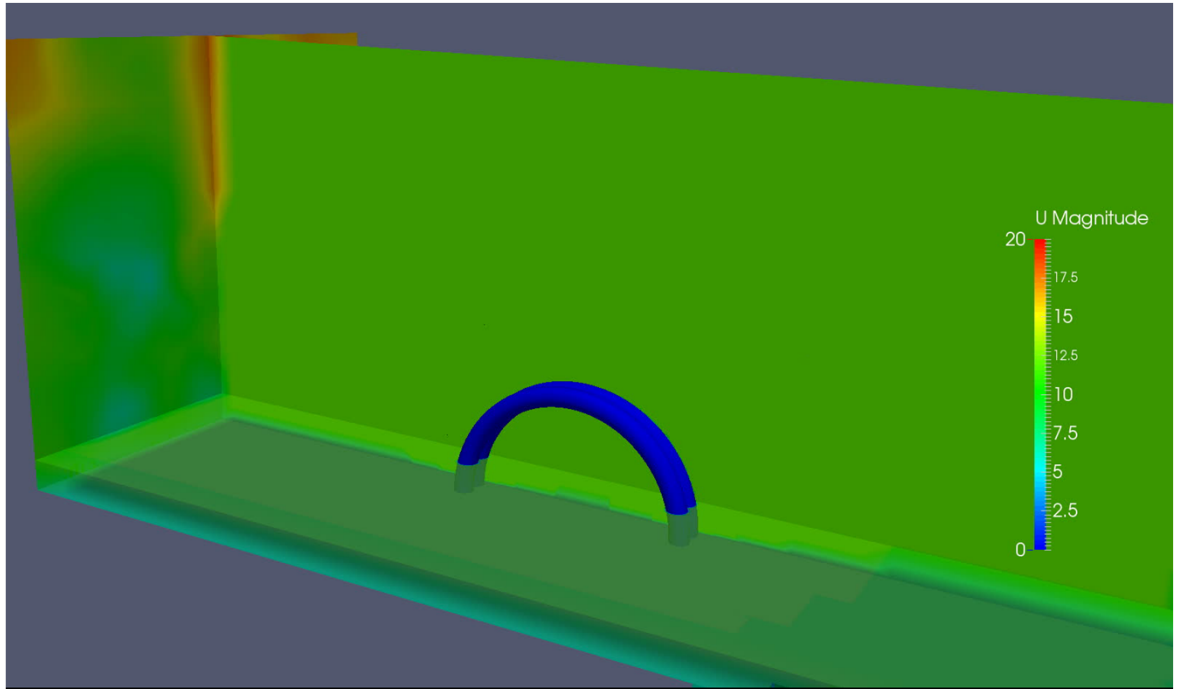
Flexible solar panels attached to the fabric



Components of a hangar prototype section

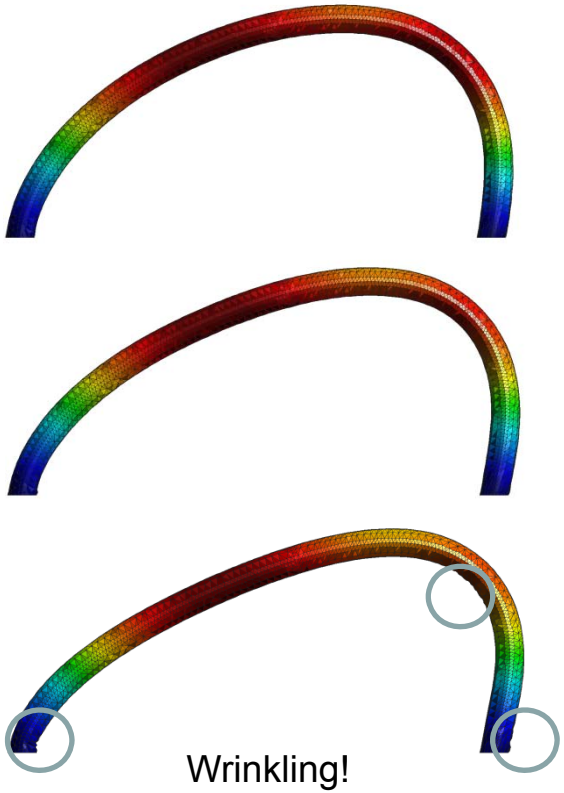
Ultra-lightweight structures with integrated photovoltaic solar cells: design, analysis, testing and application to an emergency shelter prototype

First single-field studies of „4-tube uLites-prototype“



Generated synthetic wind at inlet and CFD: wind field around prototype

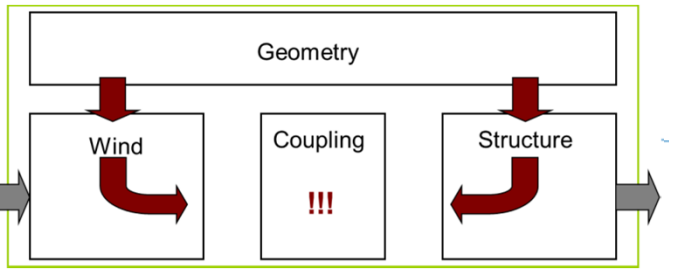
Geometrical nonlinear structural simulation of single tube:

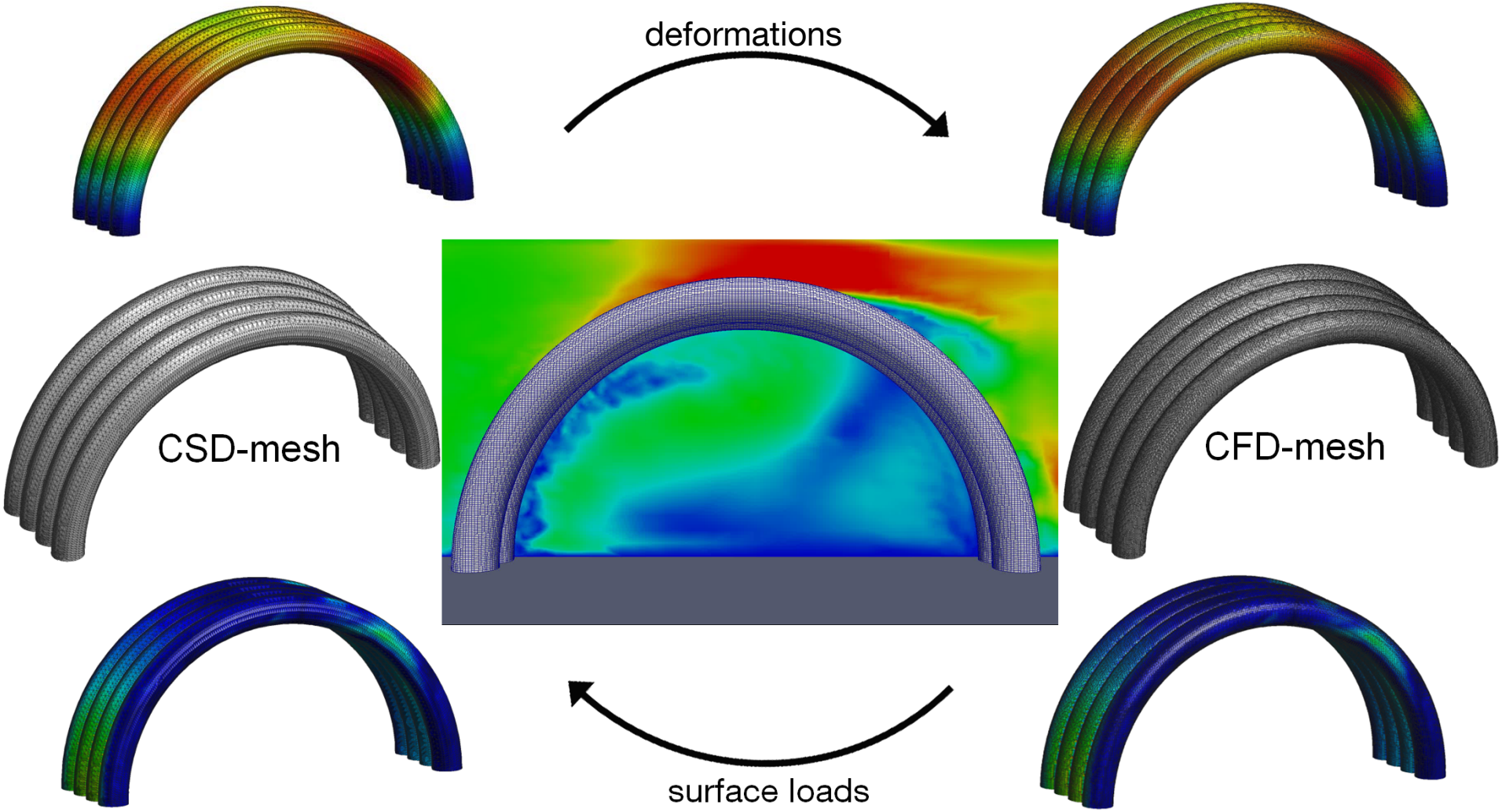


Wrinkling!

⇒ potential local wrinkling
⇒ nonlinear structural behavior
⇒ significant deformations are expected
⇒ simulation of fluid-structure interaction

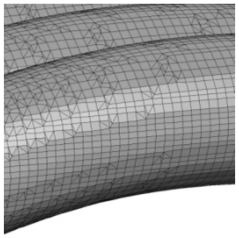
Wind-structure interaction

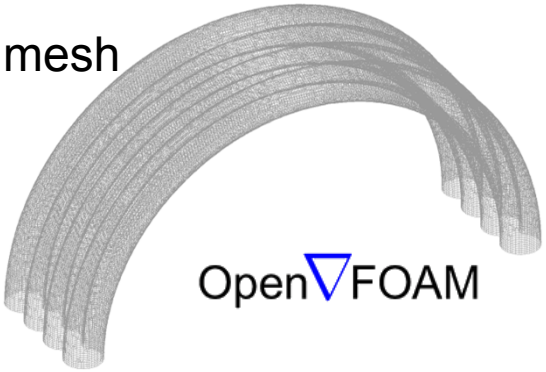




CFD-solvers: interface tracking vs. Interface capturing

→ OpenFOAM, FVM: ALE body-fitted mesh



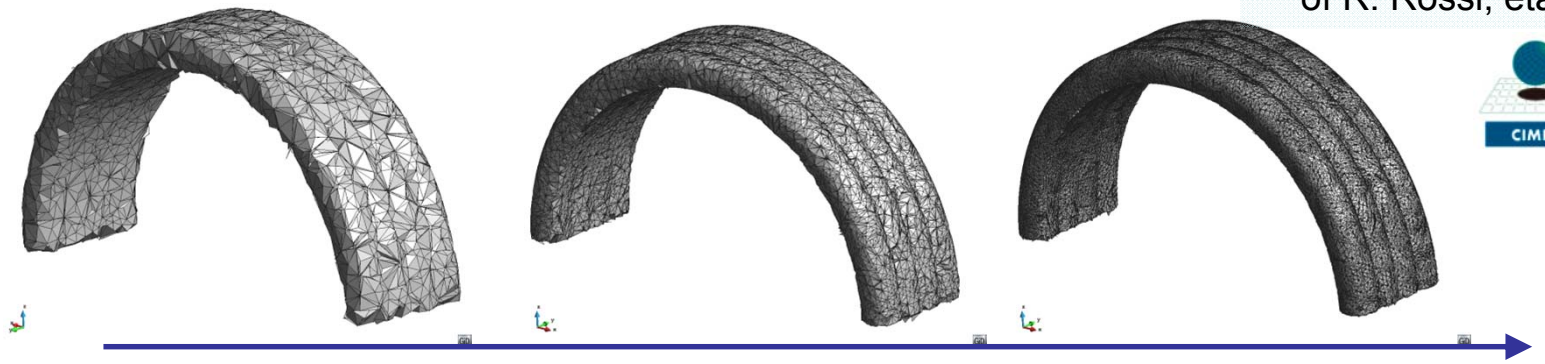


→ KRATOS, FEM: - ALE body-fitted mesh

KRATOS MULTI-PHYSICS

→see contribution of R. Rossi, etal.

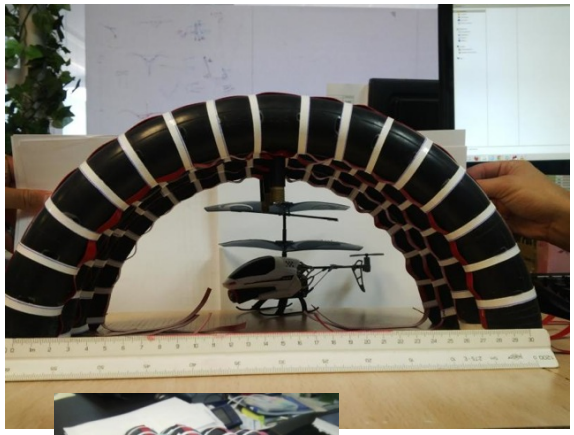
- fixed embedded mesh



CIMNE

Physical significance: validation for reliable design

⇒ Wind tunnel campaign and numerical prediction is in progress
⇒ Problem of scaling laws!, boundary conditions, damping, …
⇒ Final goal: reliable FSI-simulations in CWE for design support



???

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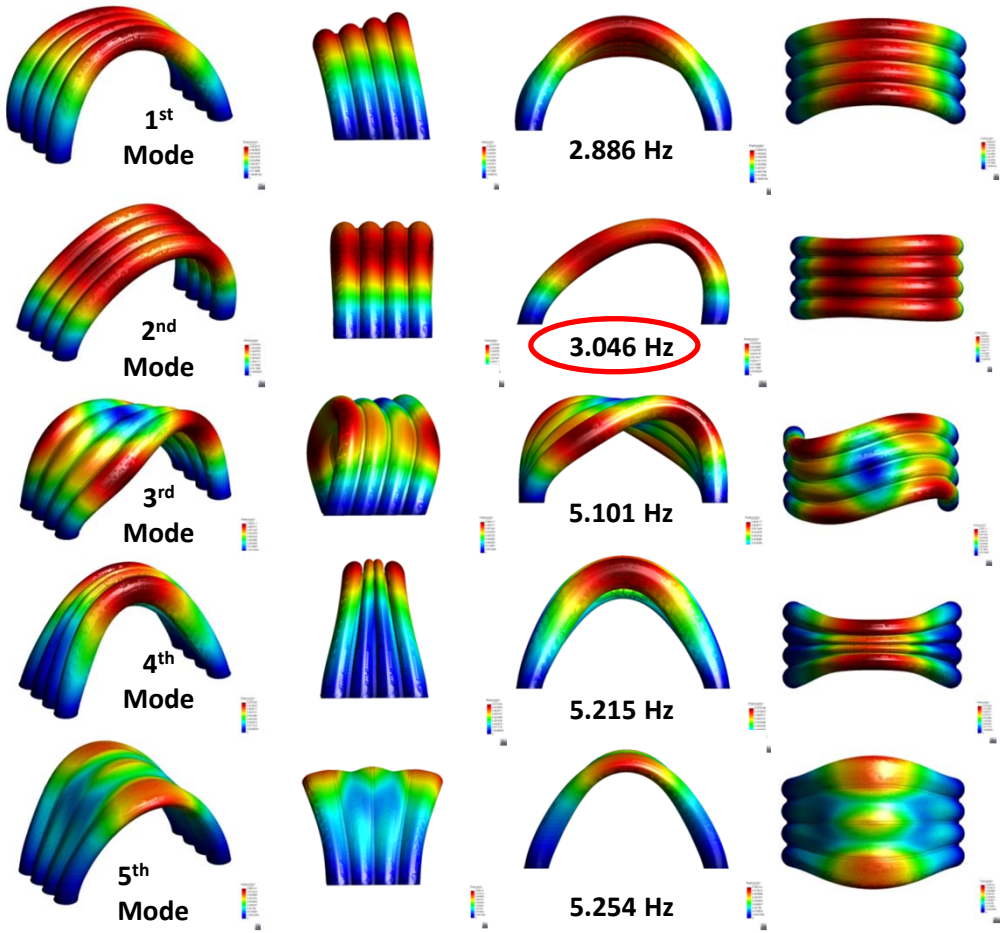
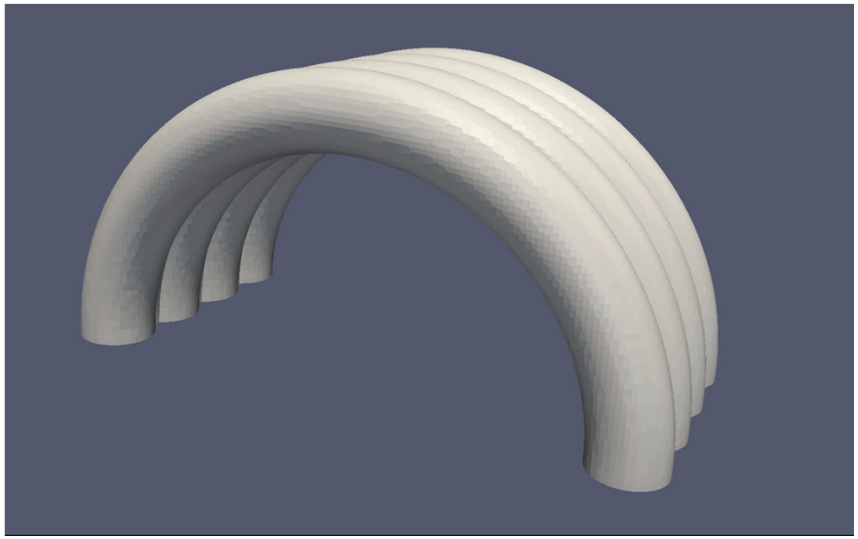
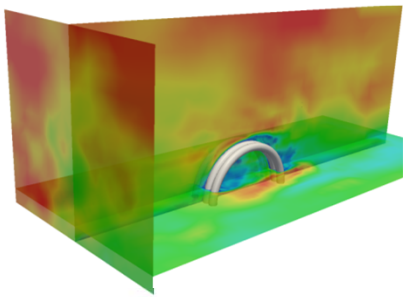
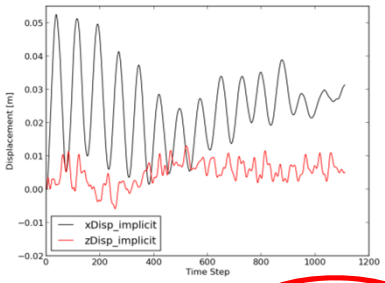
Predict Eigenfrequencies of 4-tubes prototype

First 5 eigen-modes: Eigenfrequ. analysis (Carat) VS. Coupled FSI simulation









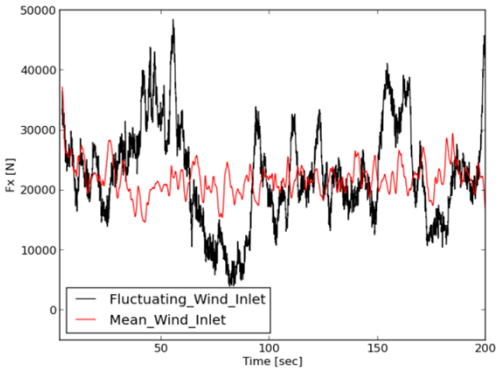
→ 2nd Eigen-frequency from FSI ≈ 1.25 Hz

→ significant coupling effects

Validation campaign for FSI-simulations in ABL-flow

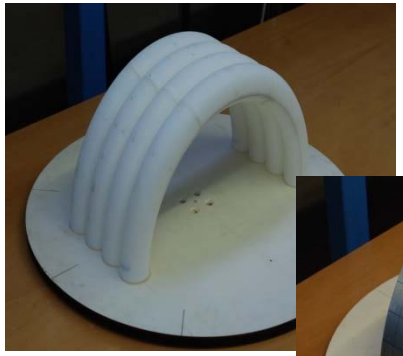
⇒ Problems for wind tunnel tests of inflatable structures:
scaling laws!, unclear boundary conditions, high damping, …

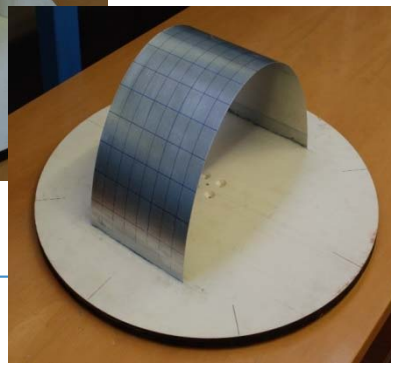
⇒ Necessity of proper wind modeling
for design of lightweight structures
(i.e. measurements in ABL needed):



⇒ Three different scenarios in wind tunnel with 4 velocities 5.5, 11,16.5, 22 [m/s]:
1. uniform flow
2. uniform flow with cube in upstream direction
3. ABL flow

⇒ Two different models:
1. Rigid with shape of 4-tubes prototype
2. Very flexible Aluminium shell with low damping





⇒ Measured:
Forces, Moments, Accelerations, Pressures

Measurement activities at CRIACIV–wind tunnel

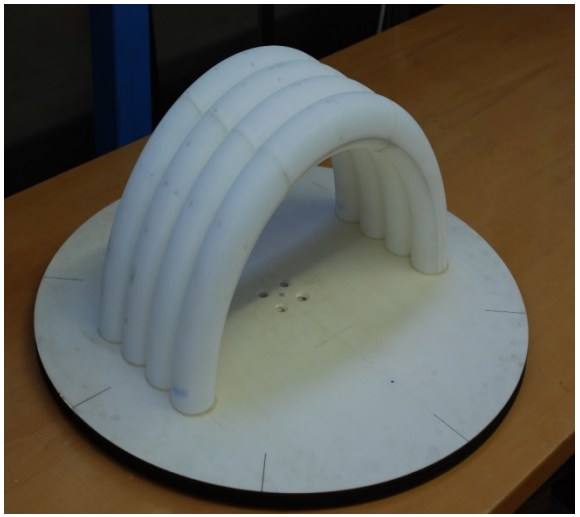
Model Construction and Tunnel Setup on Empty Test Section

Measurement Equipment Calibration

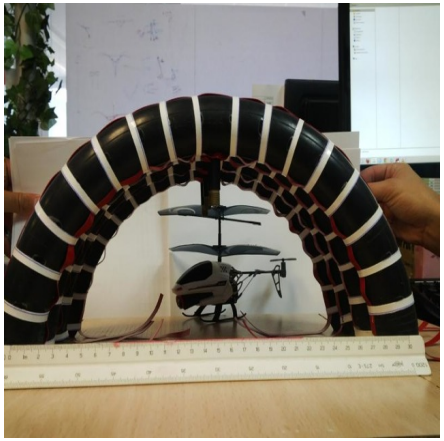
Rigid Model Testing for Uniform Flow and ABL Flow

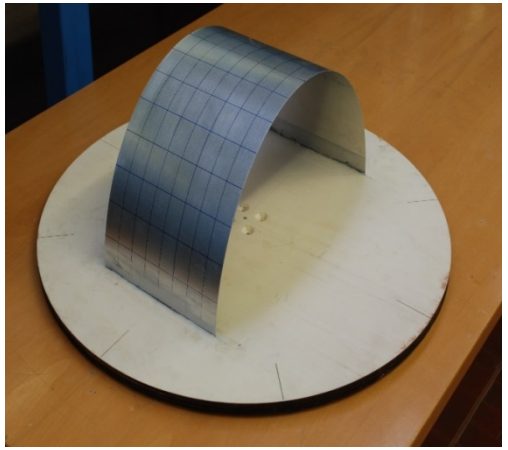
Aeroelastic Testing for Uniform Flow with Cube and without Cube

Aeroelastic Testing for ABL Flow



Rigid Model

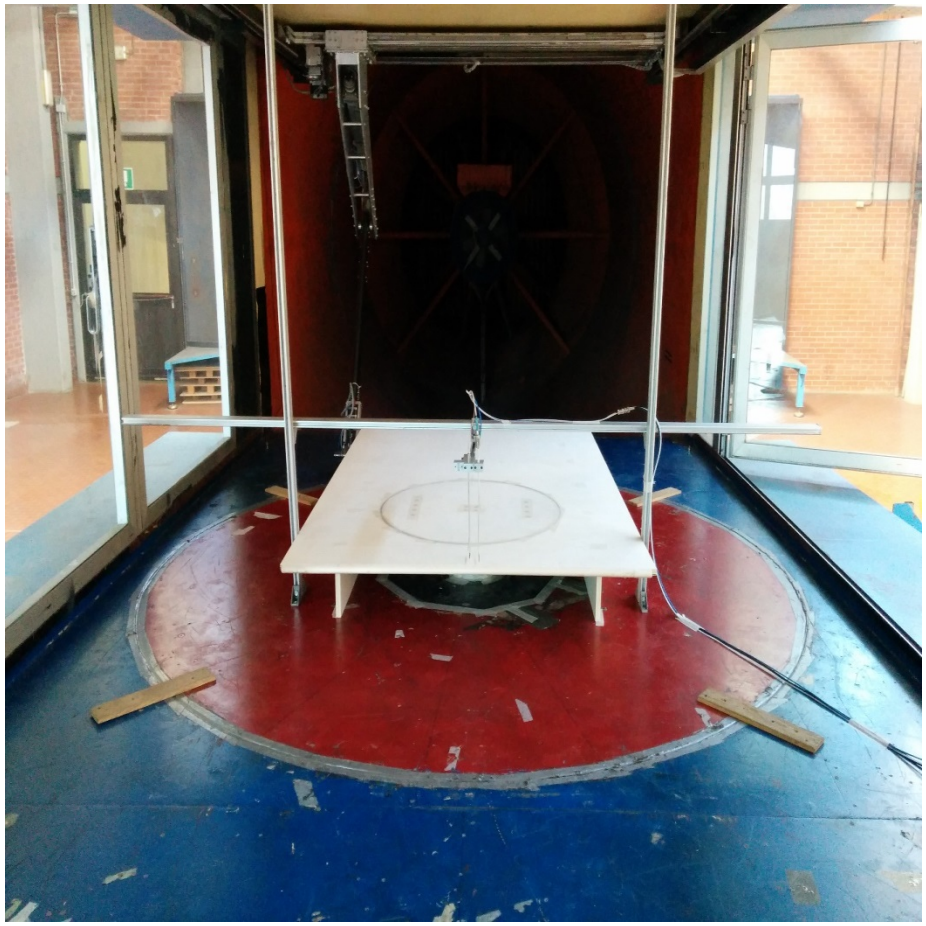




Elastic Model

Tunnel Setup

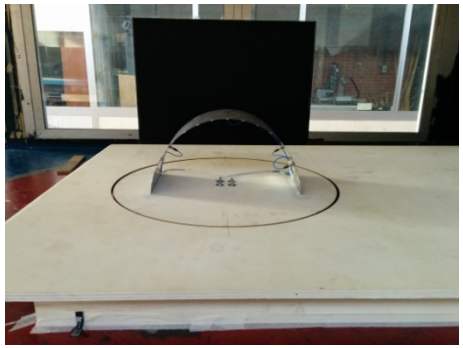
- Uniform Flow

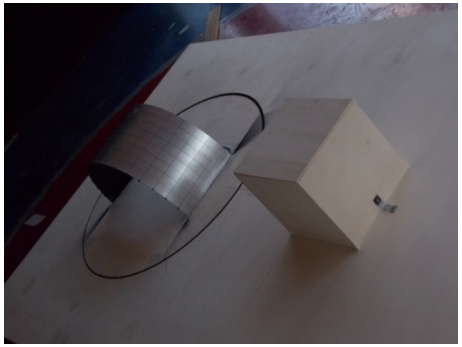


- Atmospheric Boundary Layer (ABL)

Flow scenarios for the flexible model tests

Uniform flow



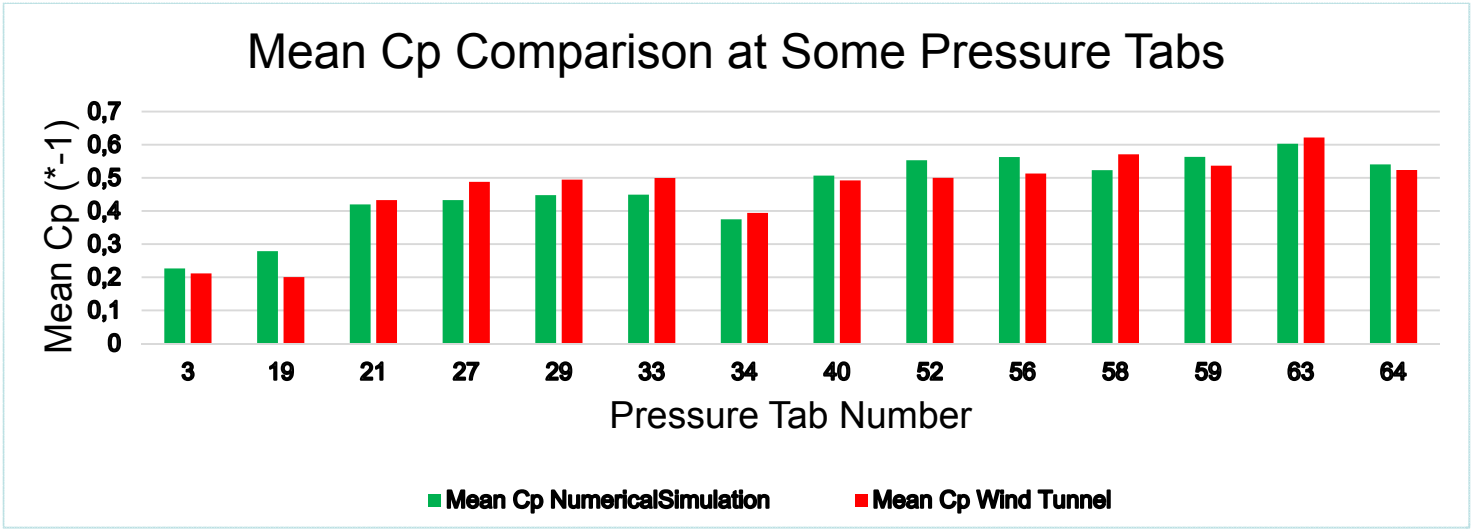


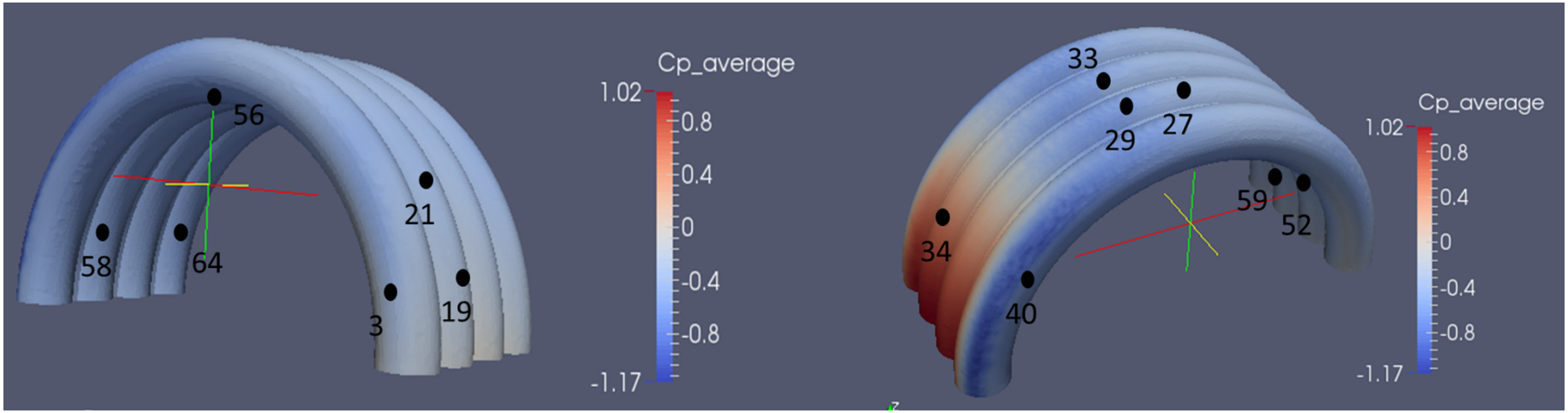
Uniform flow with cube

ABL flow

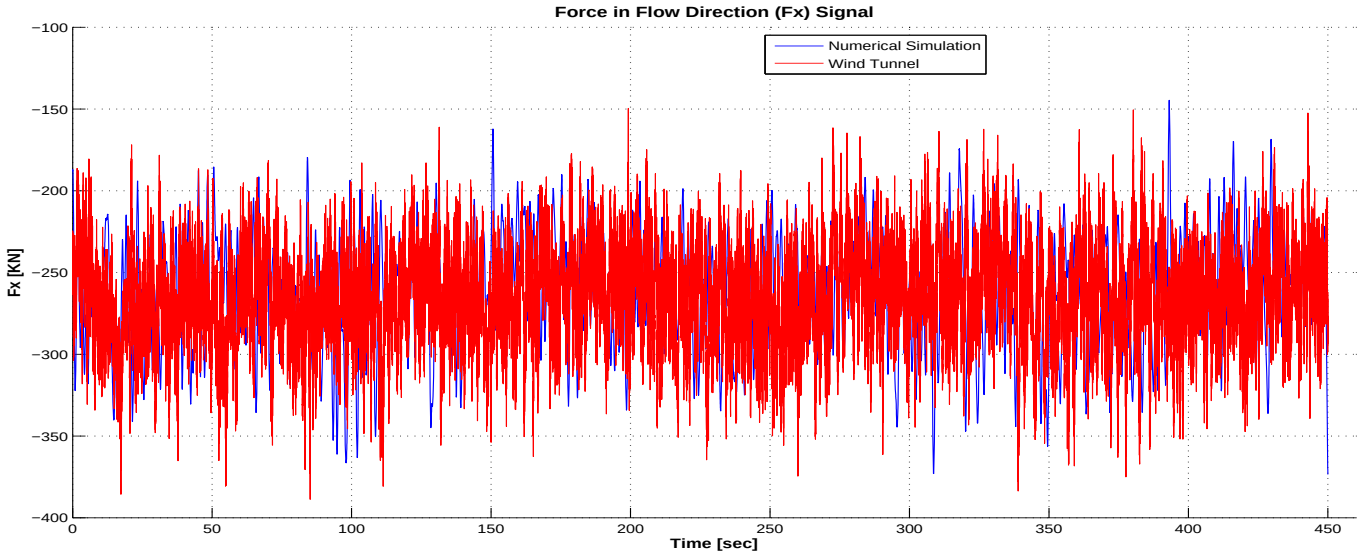
FIRST SIMULATIONS!

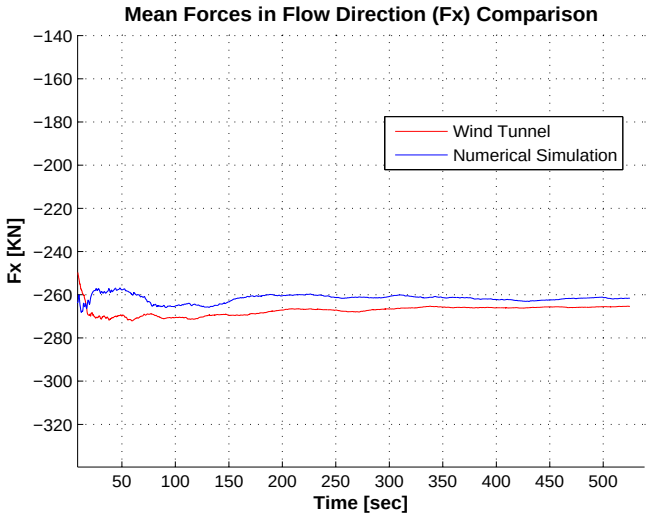
Uniform flow case: CFD and measurement

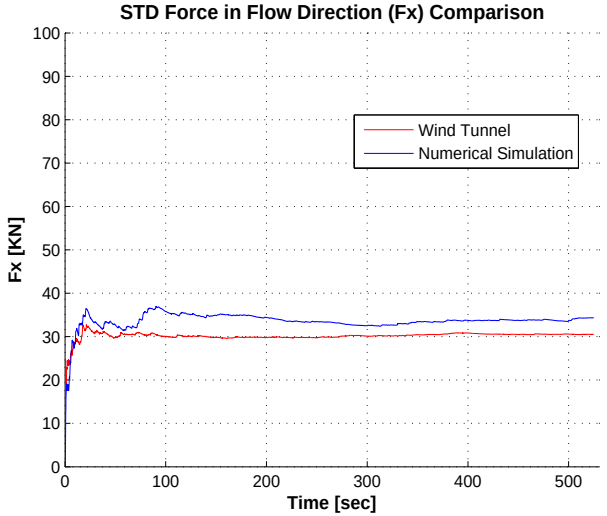




FIRST SIMULATIONS!

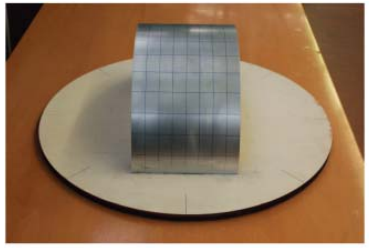


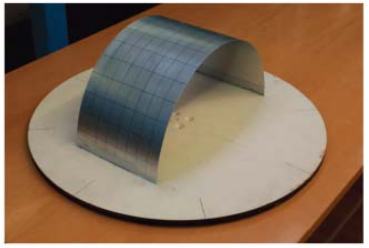




Dynamic properties of flexible, thin-walled structure

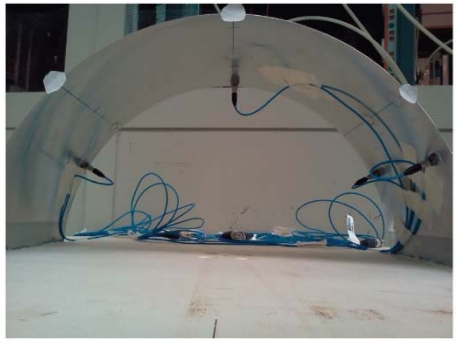
Experimental identification of EFs





Flexible, aeroelastic model

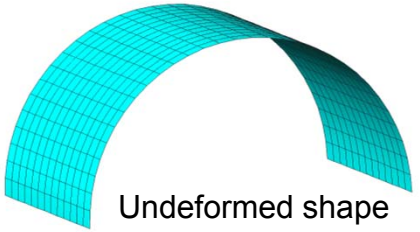
Setup for dyn. identification



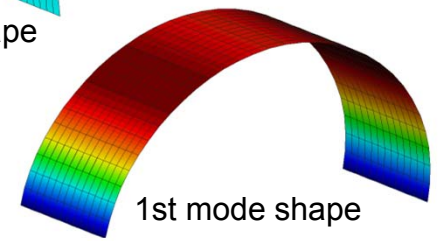
Arrangement of accelerometers

Mode nr.	Frequ. [Hz]
1	11,7
2	26
3	30

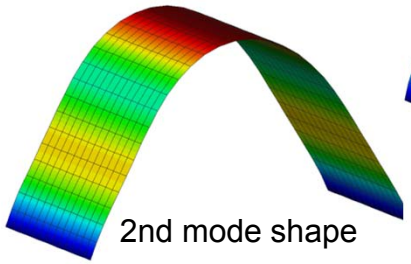
Computation of EFs



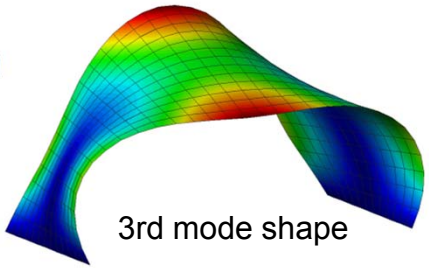
Undeformed shape



1st mode shape



2nd mode shape

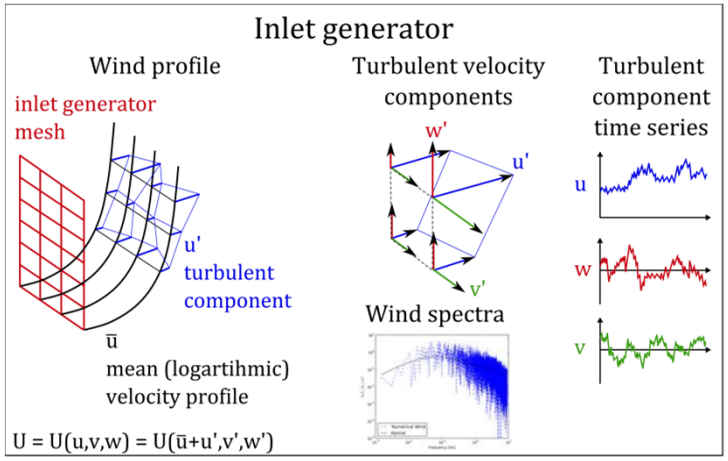


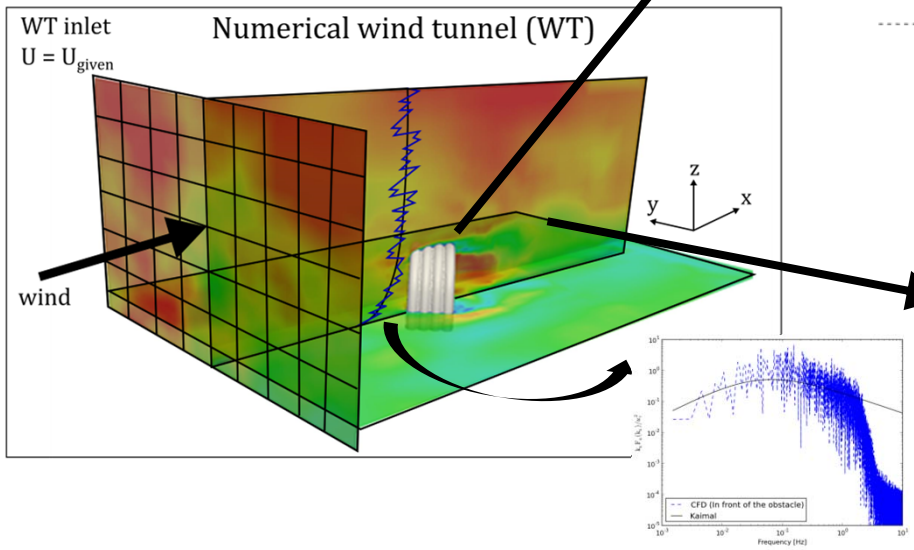
3rd mode shape

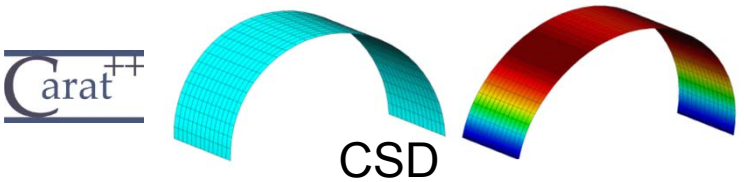
Mode nr.	Frequ. [Hz]
1	13,6
2	29,9
3	30,5

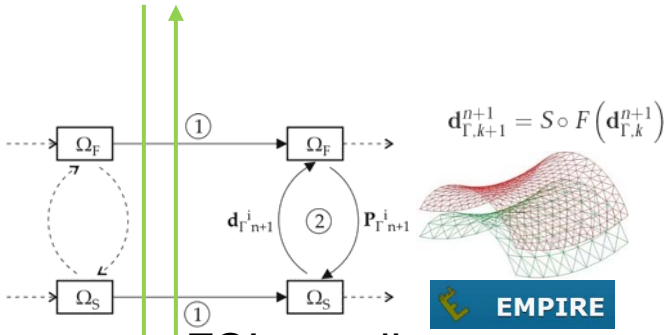
Many more validation steps to be done …

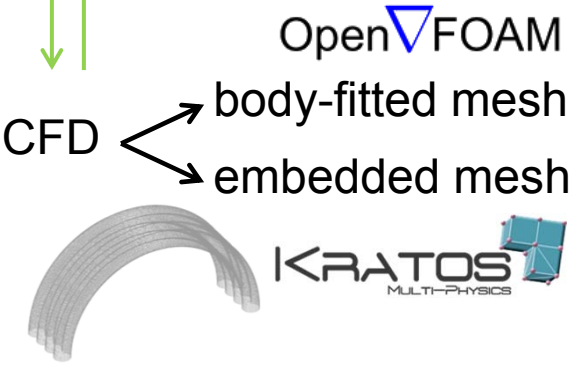
Systematic, stepwise validation concept:



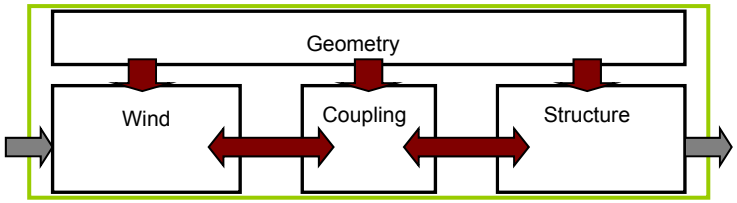








confidential results



Summary

- Thin-walled structures: light, flexible, complex geometry
  → large deformations & potentially flow-induced vibrations
  → potential local effects in case of membranes: wrinkling

- Transient wind loads
  → atmospheric boundary layer flow
  → effects of buildings in upstream direction

- Coupling: modular software framework (non-matching grids, coupl. algorithms)

- Validation is indispensable for predictive CWE:
  → impossible down-scaling of ultra-lightweight structures
  → definition of wind tunnel campaign considering fluid-structure interaction
  → 3 different generic flow scenarios
  → rigid and flexible models
  → FSI simulations with ALE-based and embedded solvers