Co-simulation of wind-structure interactions

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11th. World Congress on Computational Mechanics (WCCM XI)

20.07.-25.07.2014, Barcelona

Chair of Structural Analysis, Technische Universität München

Flexible & light-weight structures in wind


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

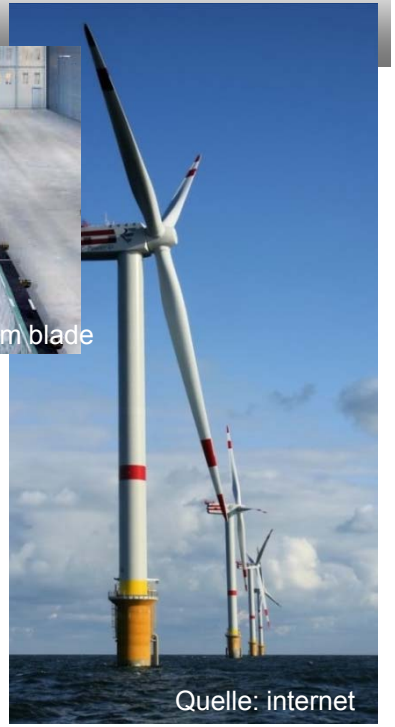

SL-Rasch GmbH


F. Otto, B. Rasch

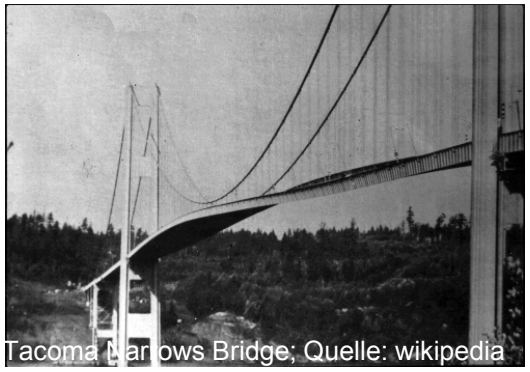

Tokyo Dome "Big Egg", 1988, Ishii, K.


Buidair, Barcelona


windkraft-journal.de; 75m blade

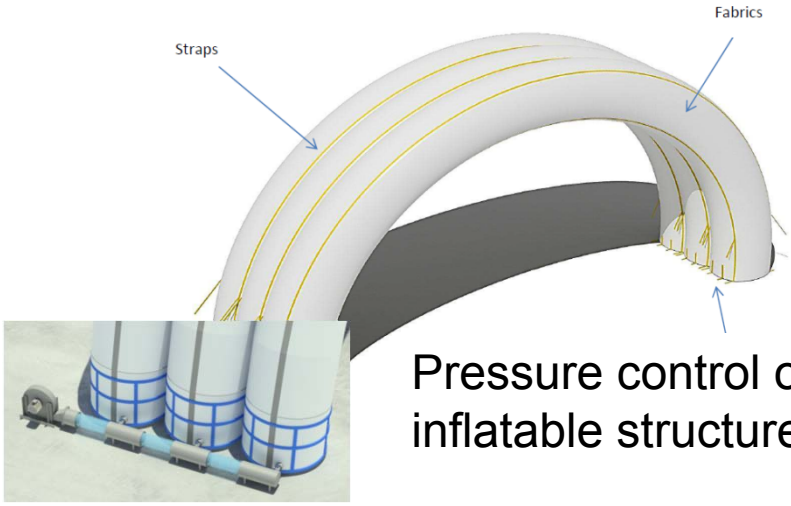

Quelle: internet


Behnisch, u.v.a. München 1972


Tacoma Narrows Bridge; Quelle: wikipedia

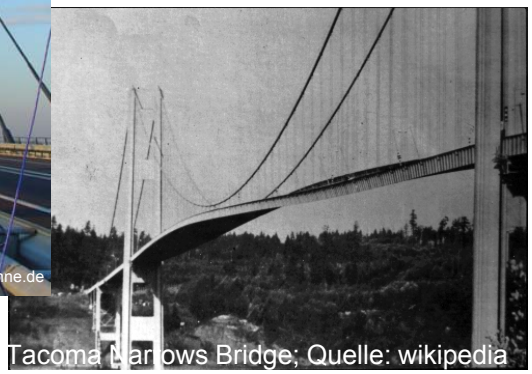
Adaptive structures in wind

TMDs



Pressure control of inflatable structures

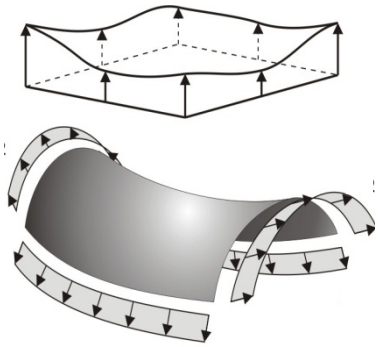
Cable Dampers



Blade pitch control

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 inlet generator
- Examples of real-world structures: high flexibility and lightness, additional challenges in computational structural analysis
- Summary & Outlook



Partitioned FSI-Analysis

C. Gengnagel, 2006

CSD simulation

- *CARAT*

Coupling

- *EMPIRE*

mapping &

process control

CFD simulation

FASTEST,

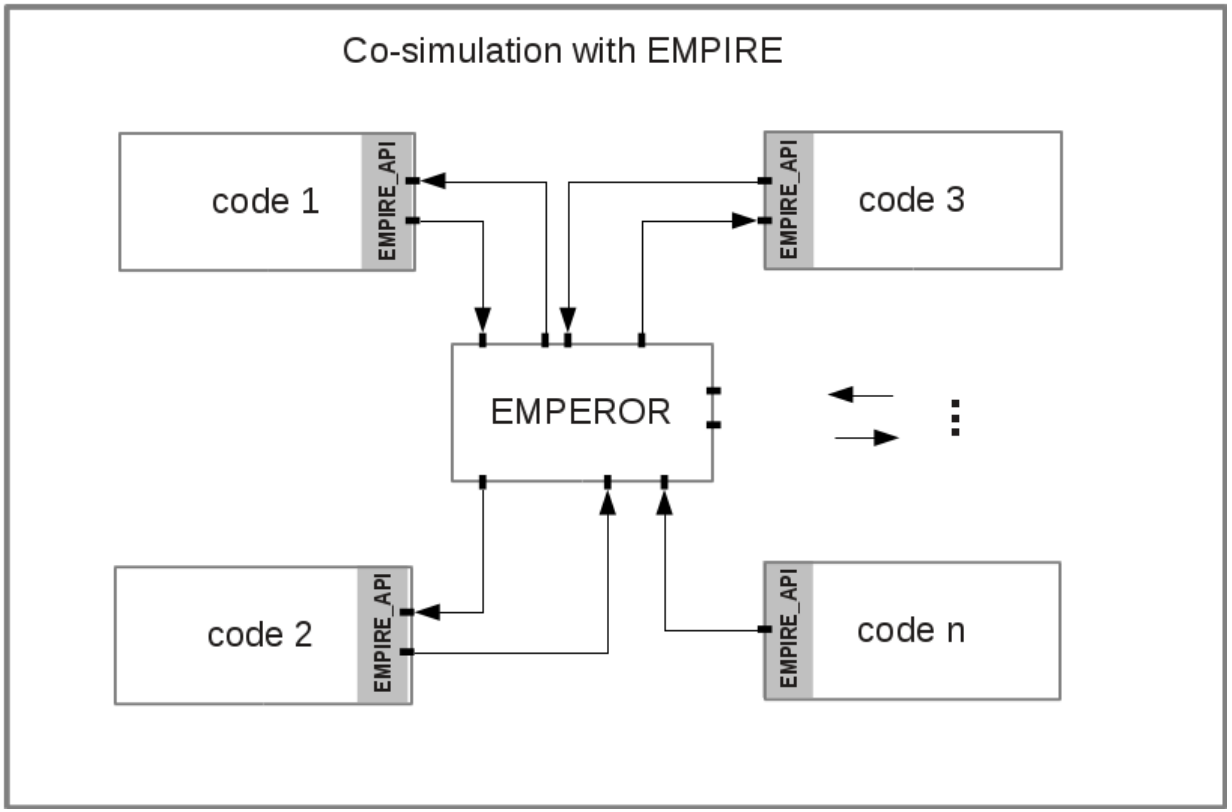
OpenFOAM, KRATOS, …

$$f_{Sj} = \sum_i N_{Sj}(\xi_i, \eta_i) f_{Fi}$$

$$u_F \approx u_S(\xi, \eta) = \sum_i N_{Si}(\xi, \eta) u_{Si}$$

$$\mathbf{d}_{\Gamma,k+1}^{n+1} = S \circ F\left(\mathbf{d}_{\Gamma,k}^{n+1}\right)$$

Co-Simulation Framework



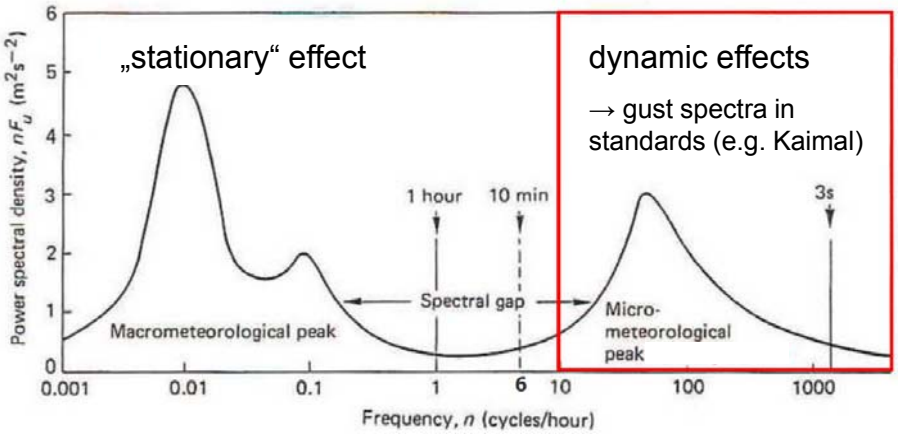
→ Constituents: components/modules, connections, filters

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

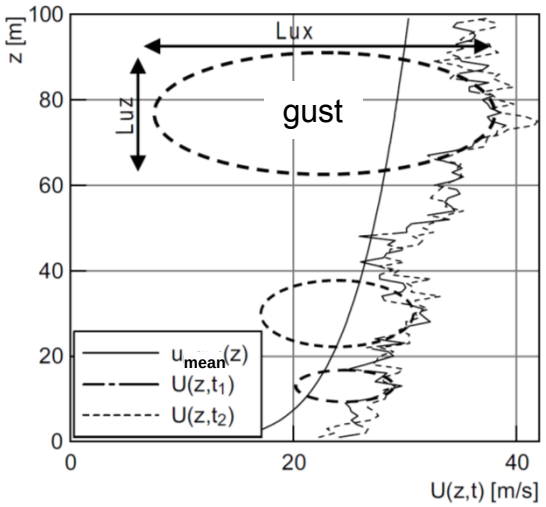
confidential results

Characteristics of atmospheric boundary layer

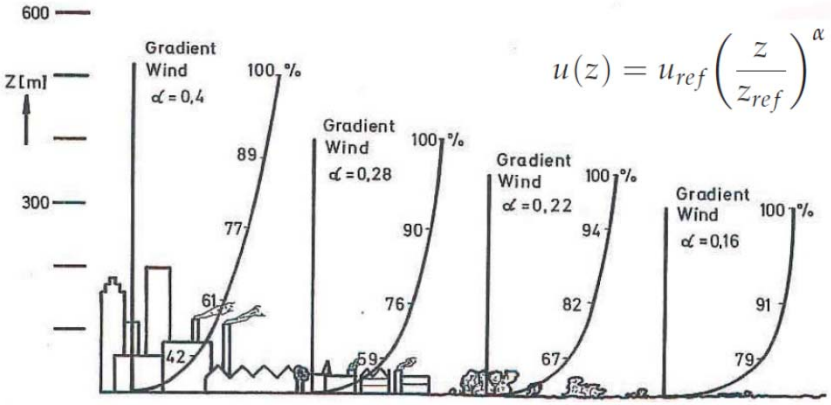
Statistics of longitudinal wind velocity (van der Hoven)



Wind profiles at time t_1 and t_2



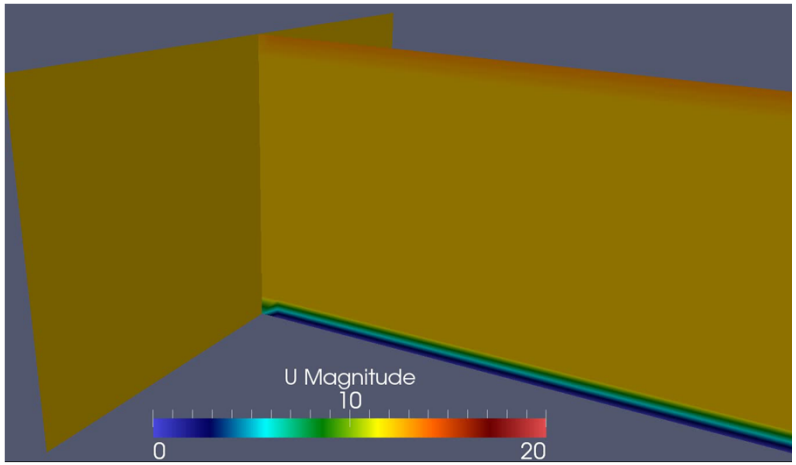
Mean wind velocity profiles (Davenport)



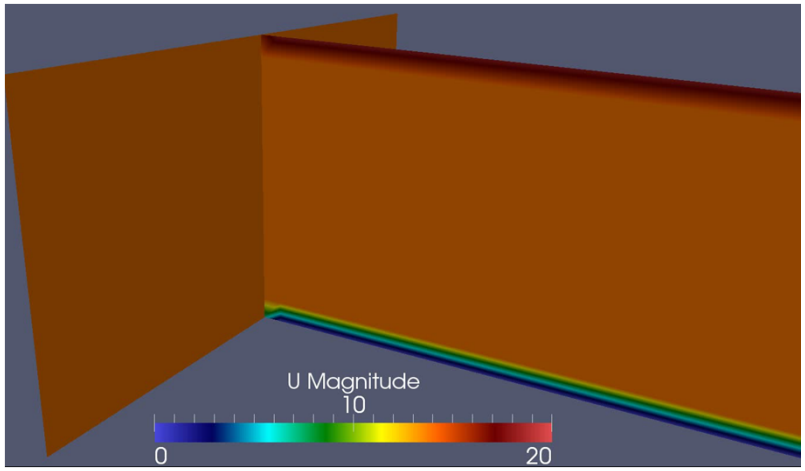
Decomposition of wind velocities in longitudinal, lateral, vertical direction:

$$U(x,y,z,t) = \overline{u}(z) + u(x,y,z,t)$$
$$v(x,y,z,t)$$
$$w(x,y,z,t)$$

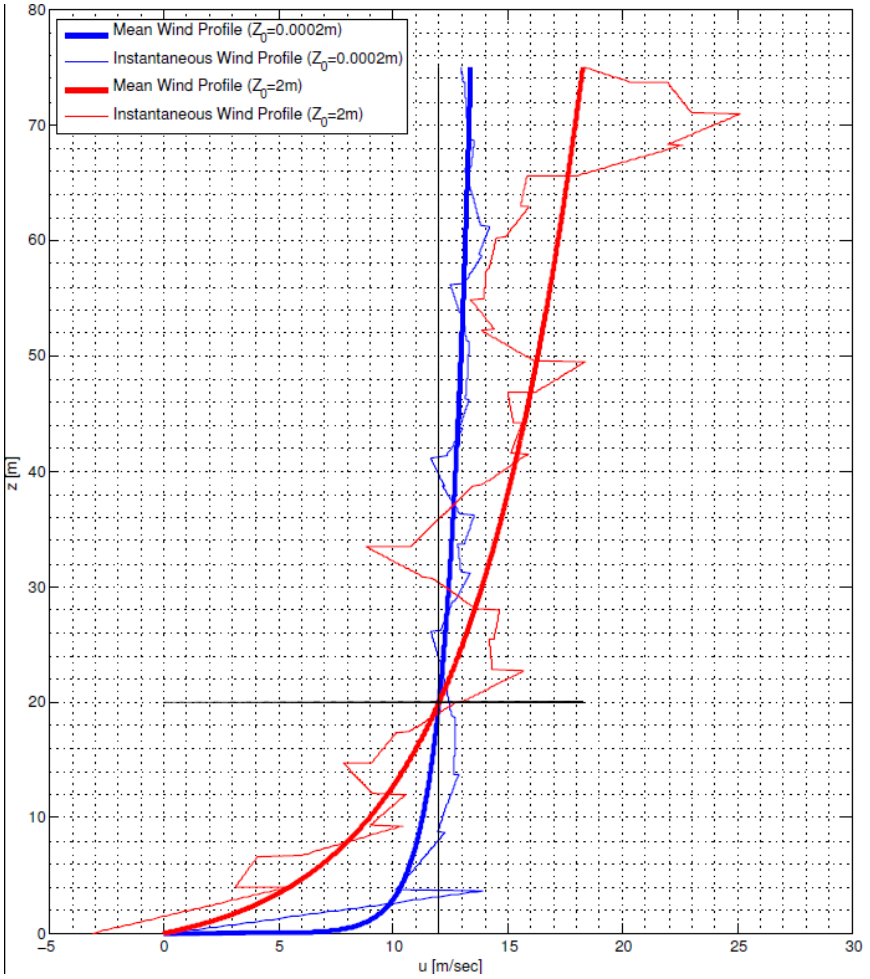
Site-specific wind field and gustiness

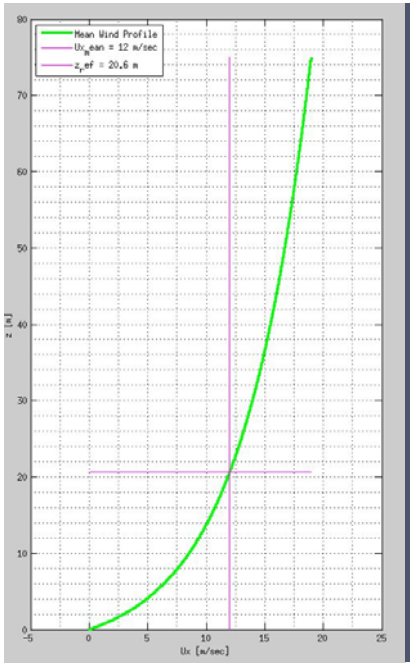


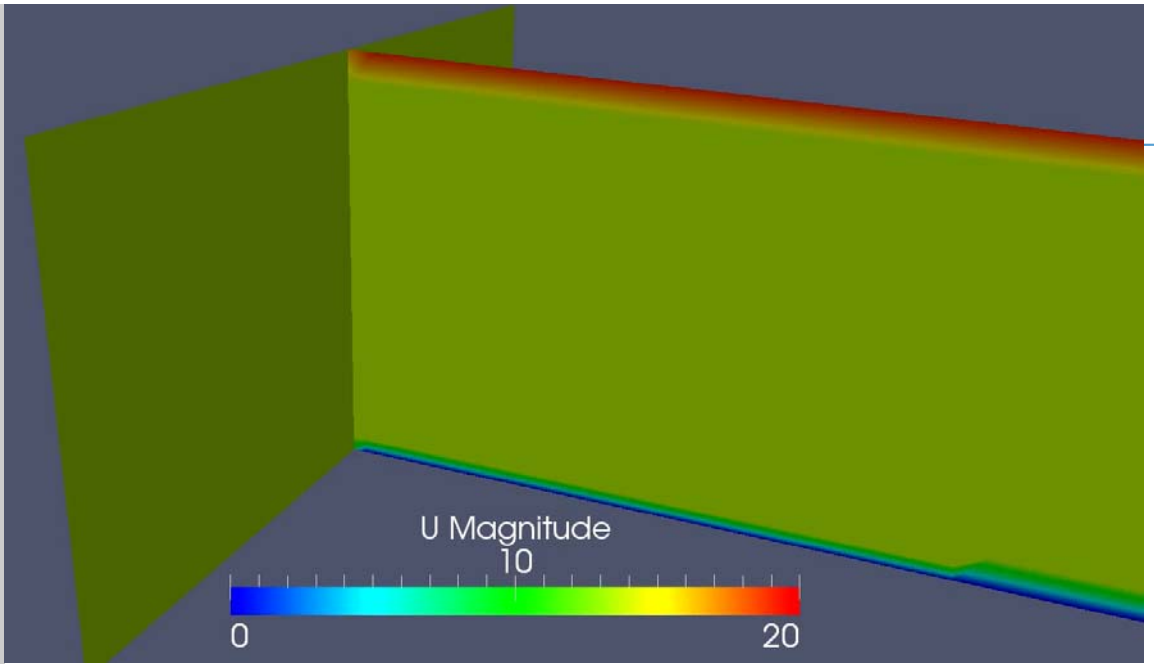
open sea



city



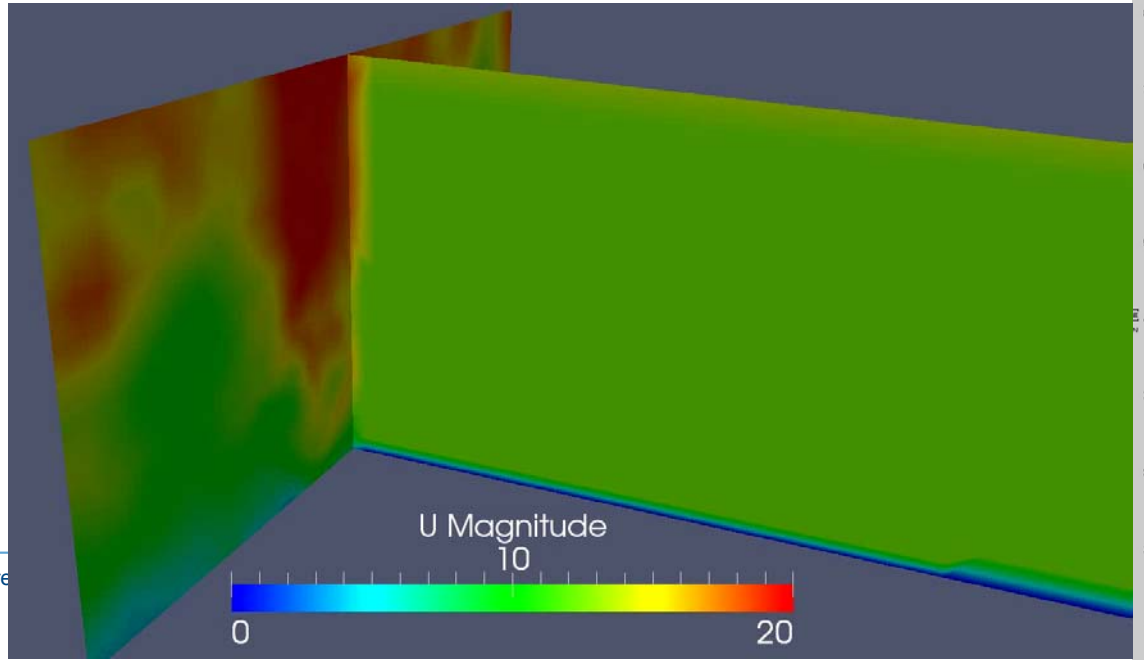


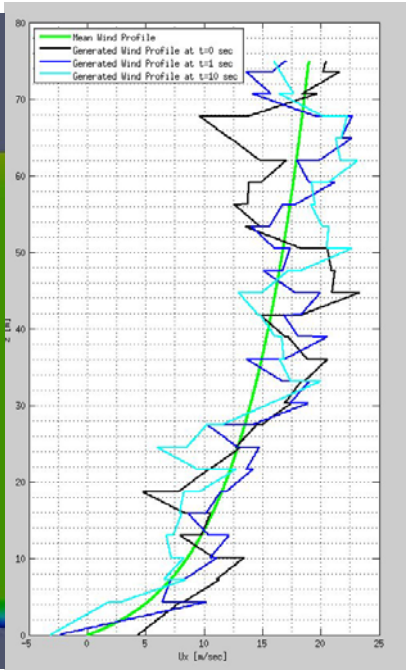


Logarithmic wind inflow profile

Proper wind field modeling at inlet

Fluctuating wind inflow profile





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

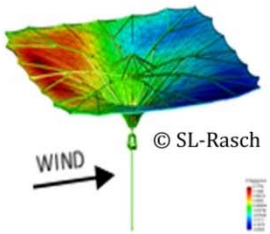
u

w

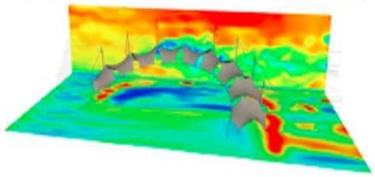
v

(here according to J. Mann)

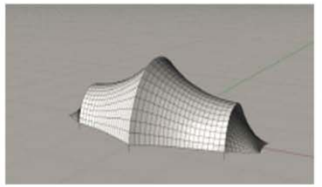
28m umbrella structure

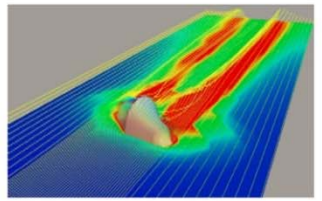


Wind load simulation of the Olympic stadium in Munich

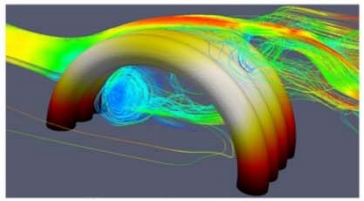


Simulation of expedition tents

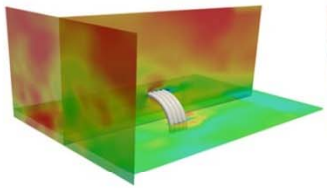


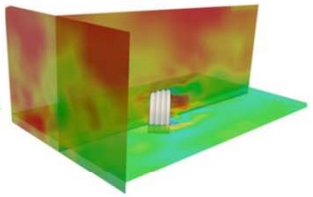


Hangar made out of membrane tubes



© Buildair





Numerical wind tunnel (WT)

WT inlet

$U = U_{given}$

wind

z

y

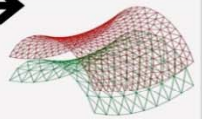
x

fluid domain and its own solver

mapping between wind generator mesh and WT domain inlet mesh

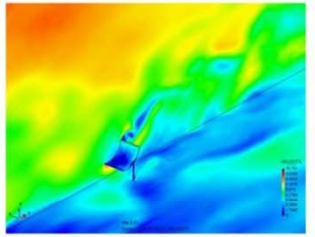
mapping between meshes

investigated structure with the respective structural solver

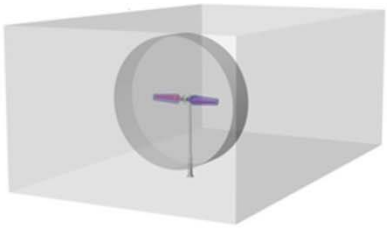


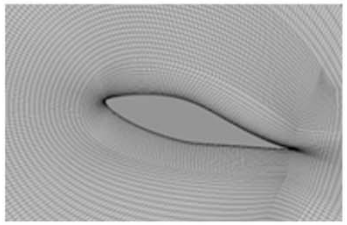
Solar throughs

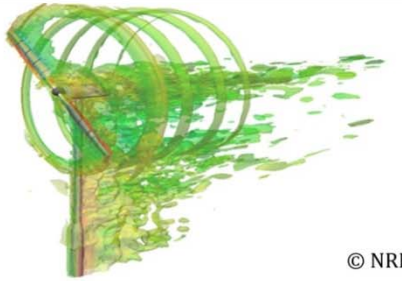
© Abengoa



Wind turbine FSI







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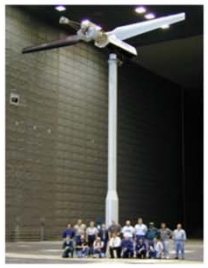


CARAT++ Structural solver

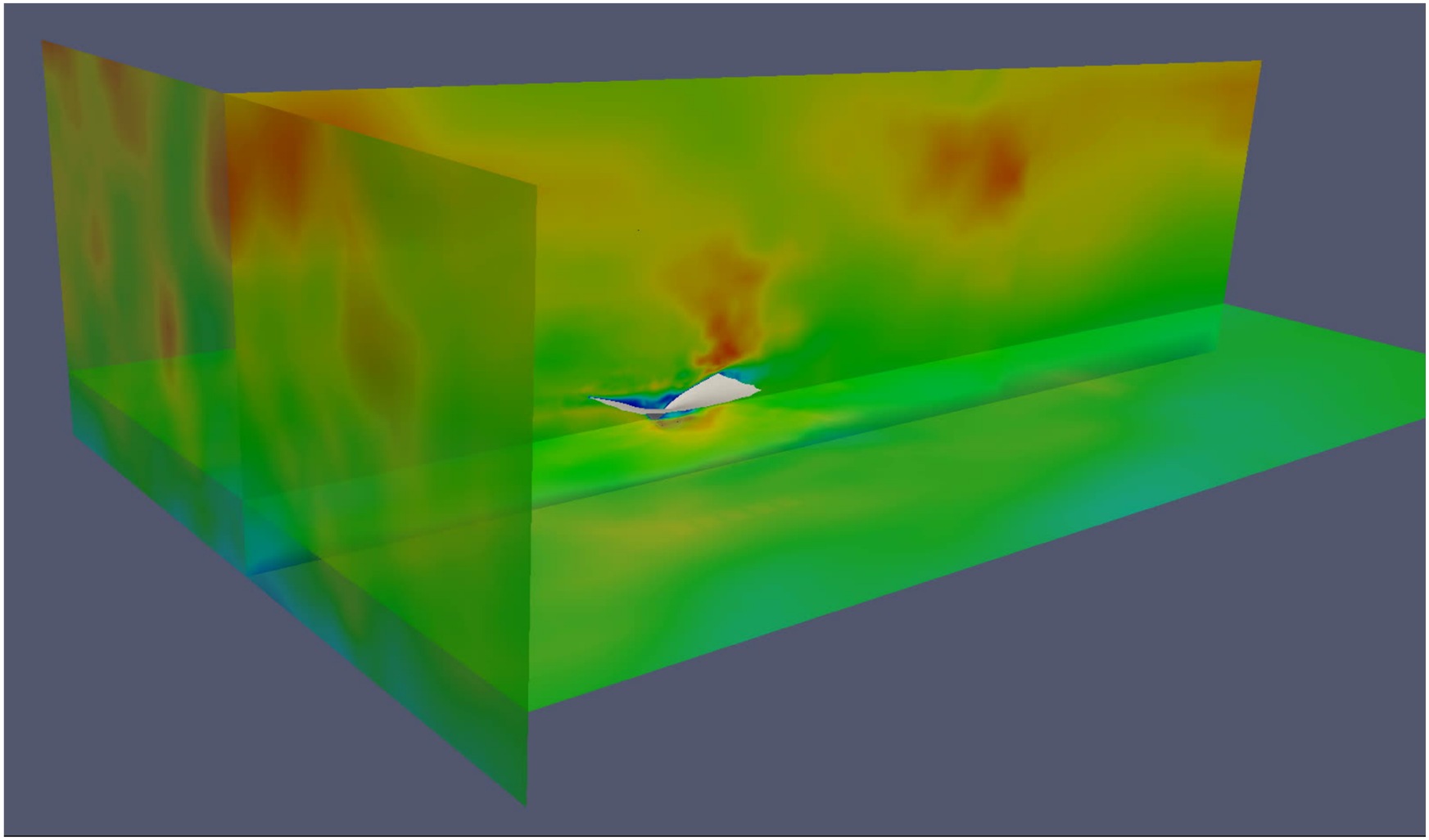
EMPIRE Coupling tool

Static TUM

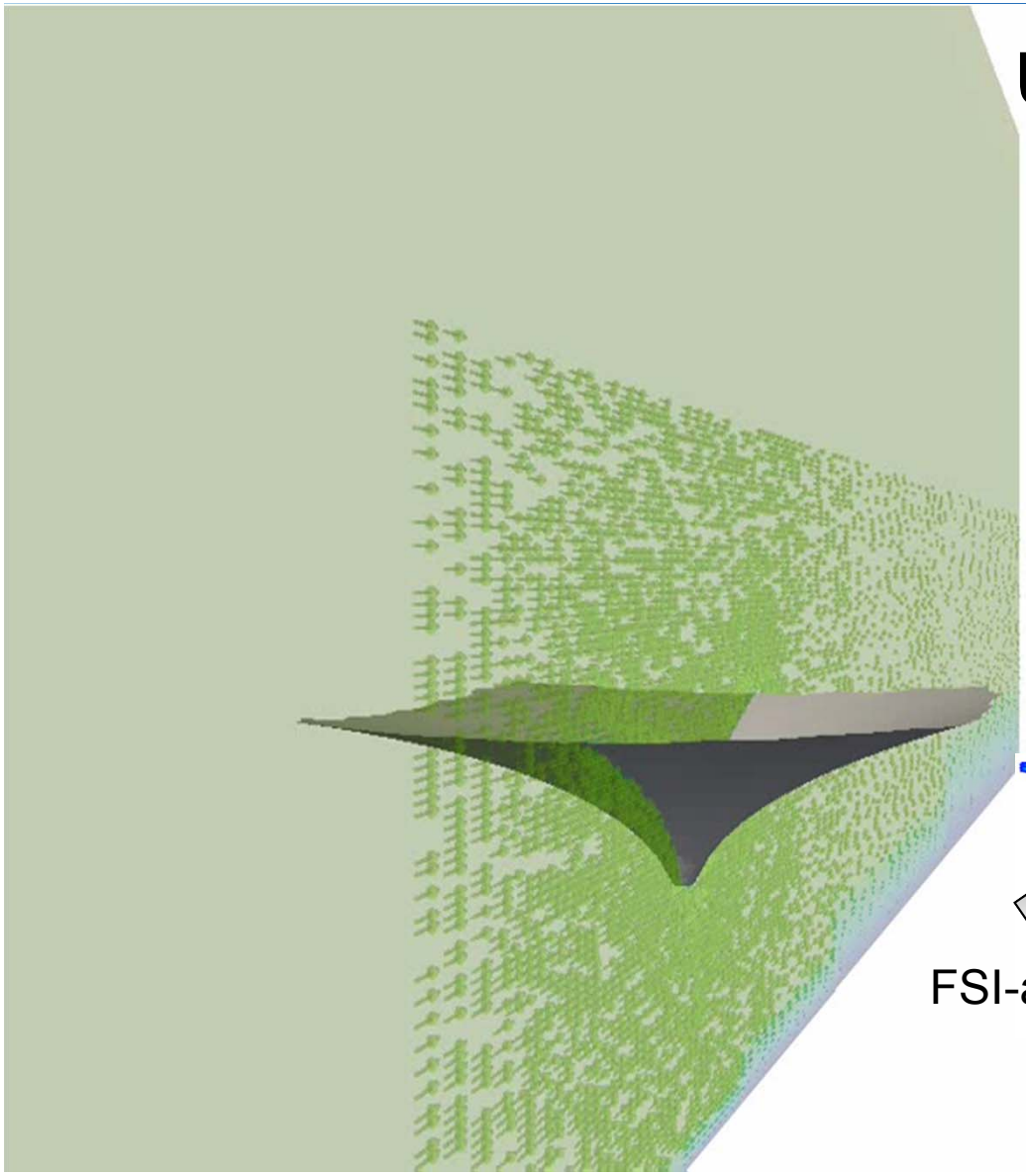
confidential results

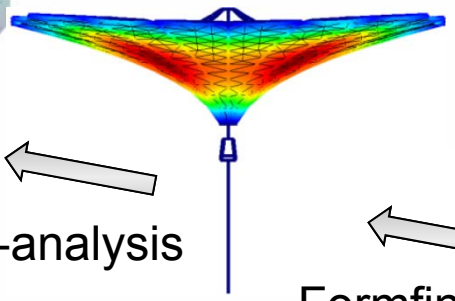
confidential results

FSI of large umbrella structures in ABL-flow

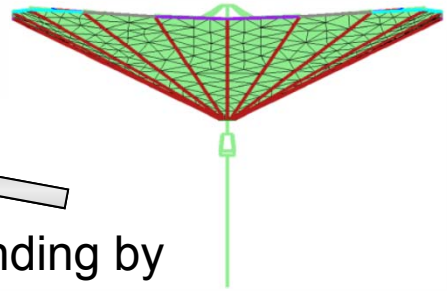


Umbrella motion in wind





FSI-analysis



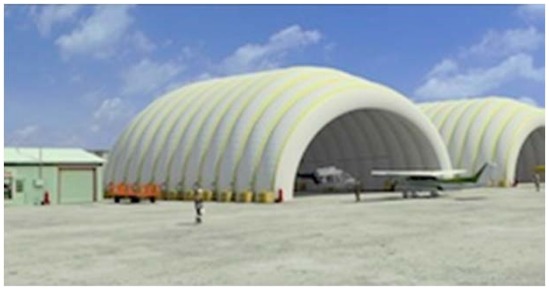
Formfinding by
updated reference strategy

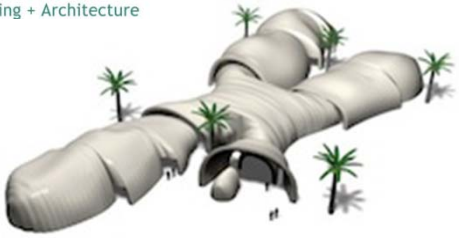
confidential results

confidential results

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



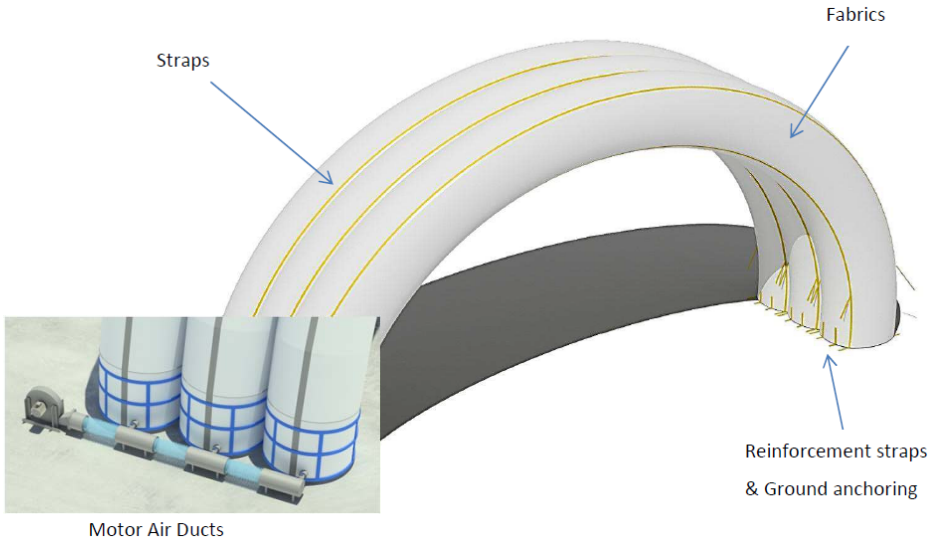


World‘s largest inflatable hangar (60m, Madrid)

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
- …

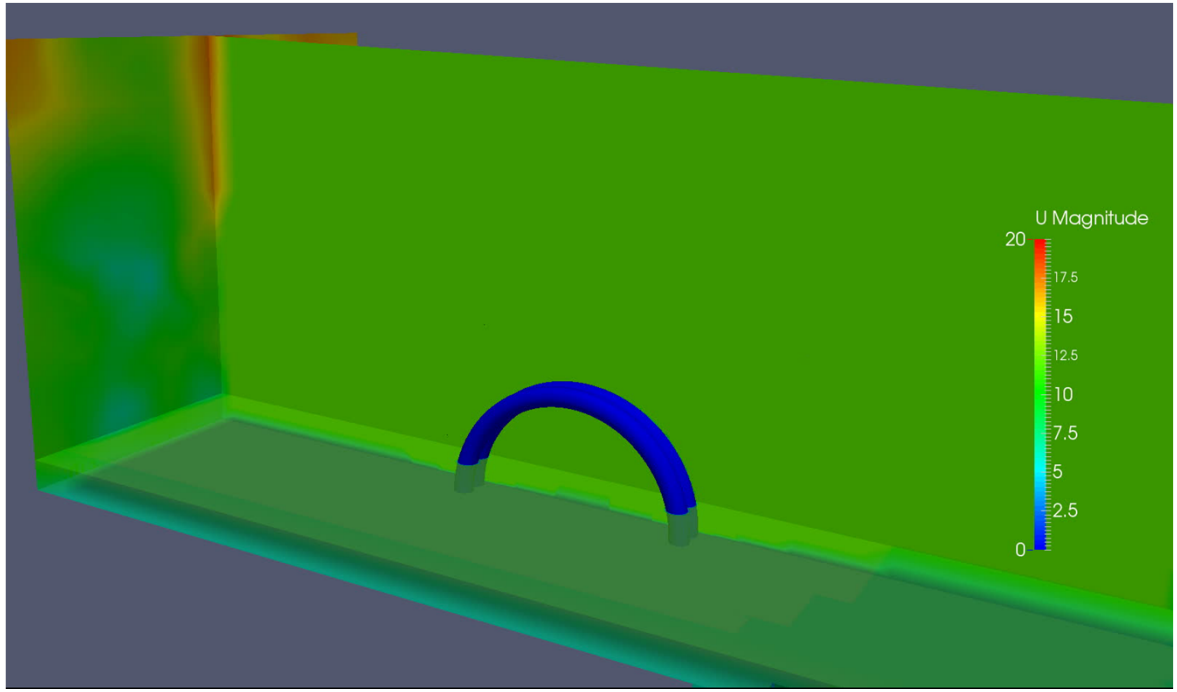
Flexible solar panels attached to the fabric



Components of a hangar prototype section

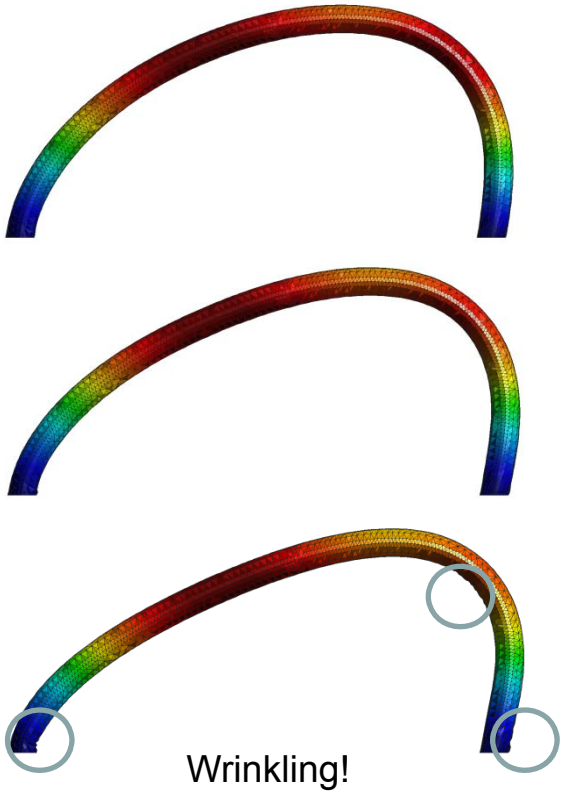
Ultra-lightweight structures with integrated photovoltaic solar cells: design, analysis, testing and application to an emergency shelter prototype

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



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

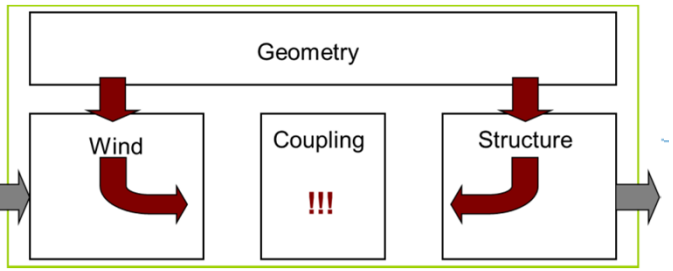
Geometrical nonlinear structural simulation of single tube:

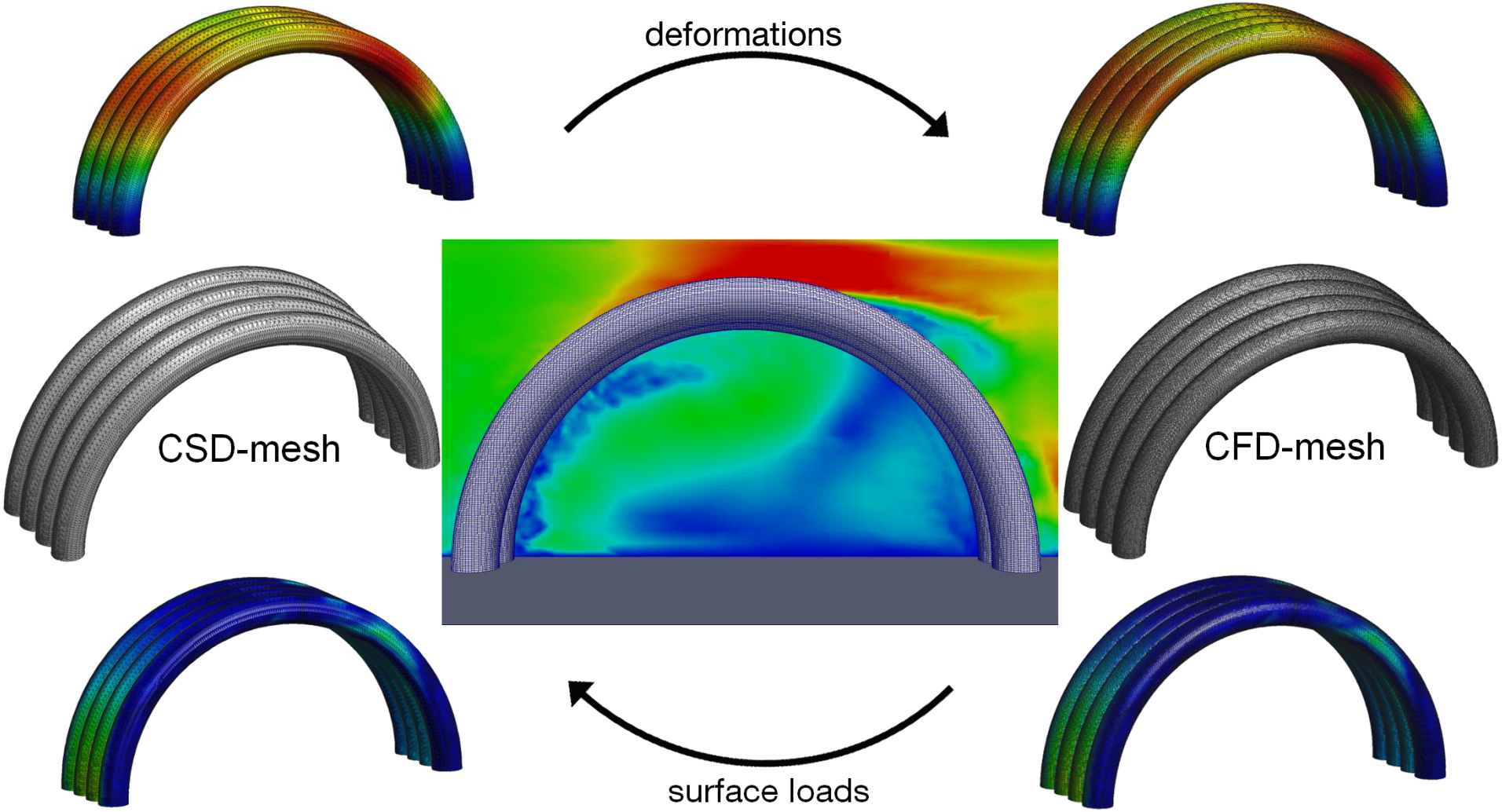


Wrinkling!

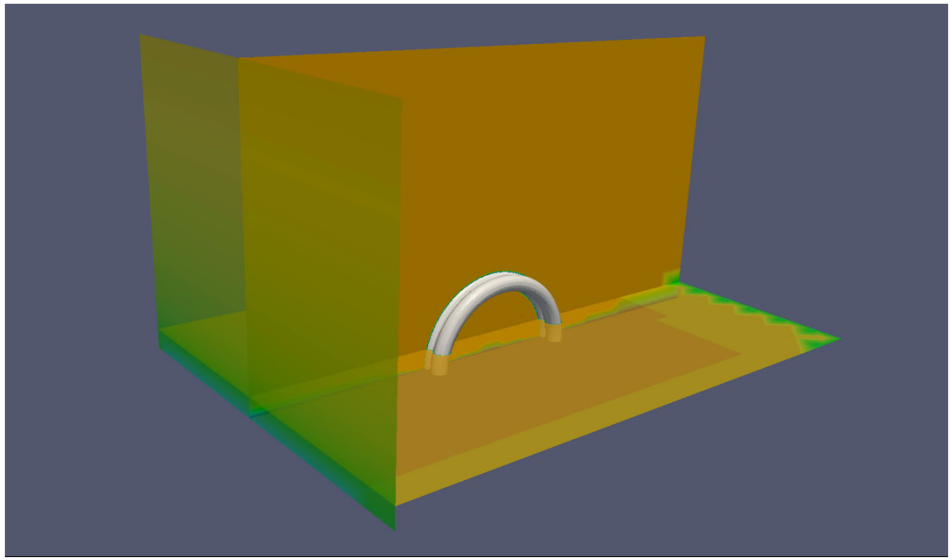
⇒ potential local wrinkling
⇒ nonlinear structural behavior
⇒ significant deformations are expected
⇒ simulation of fluid-structure interaction

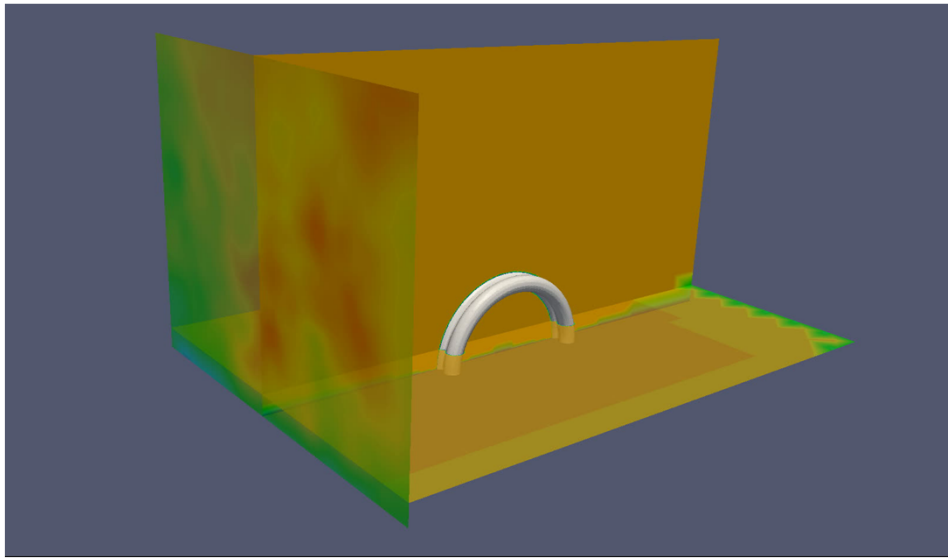
Wind-structure interaction

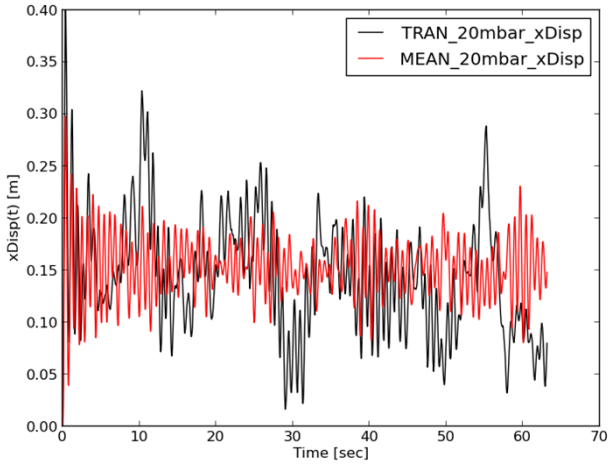


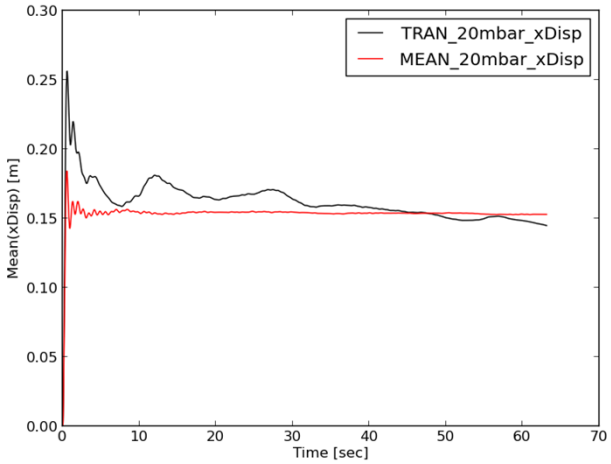


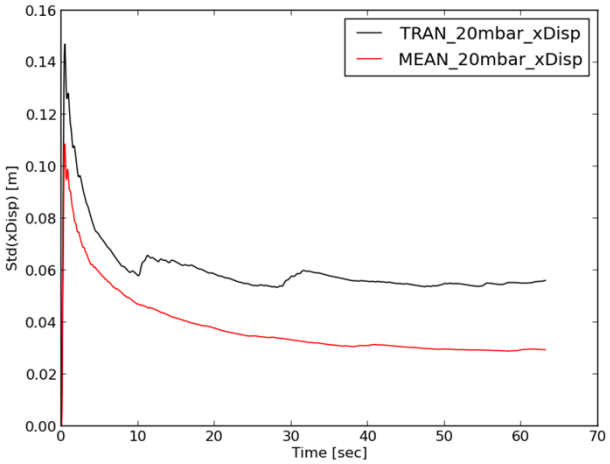
Importance of ABL inlet for transient load evaluation



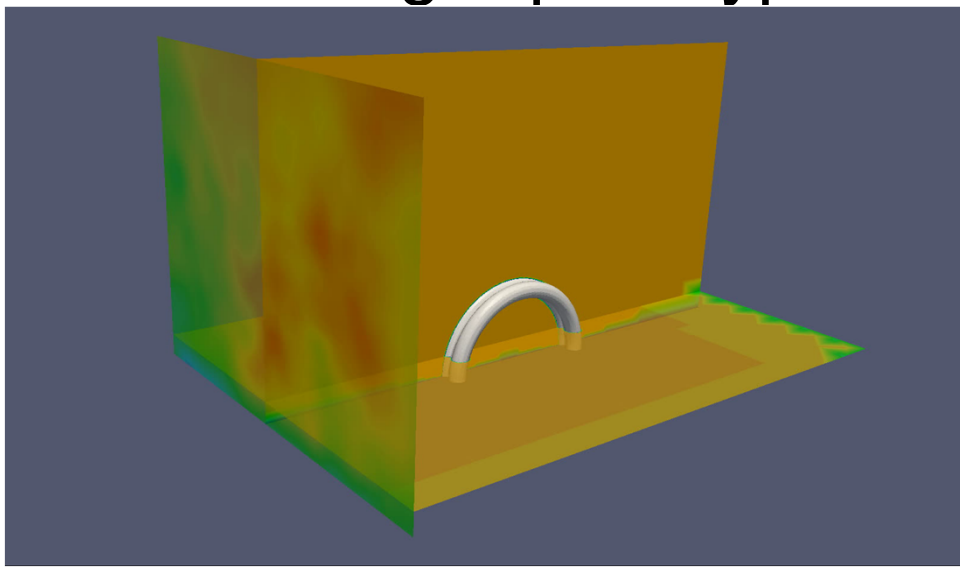


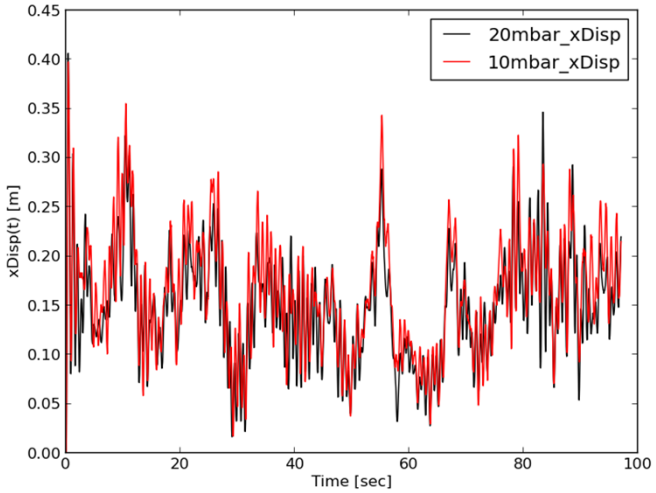


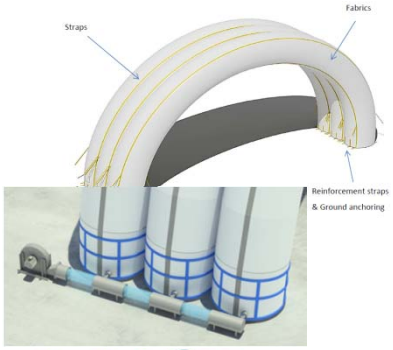




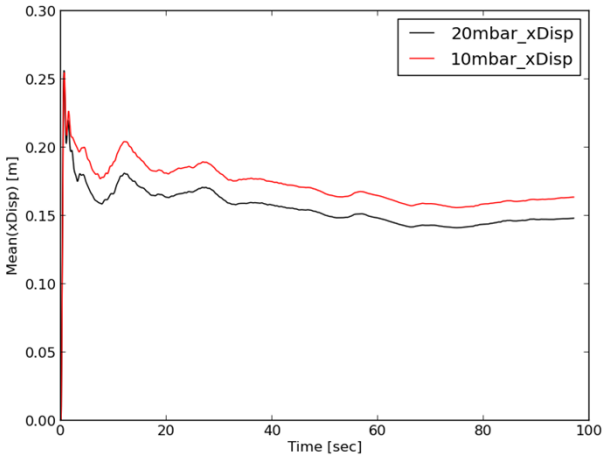
FSI of hangar prototype for various pressures

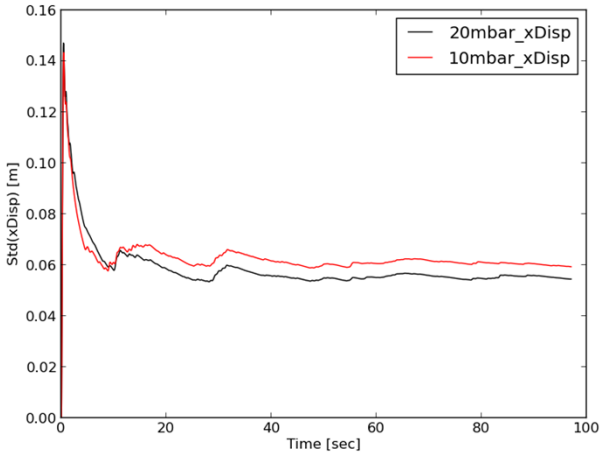






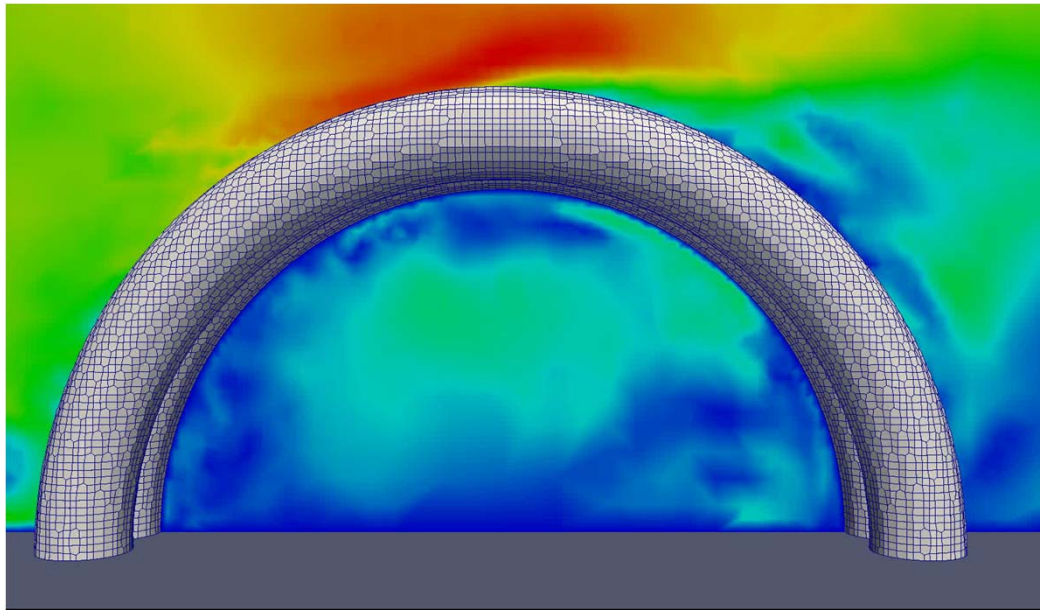
Build air
Engineering + Architecture





Further pressure reduction…

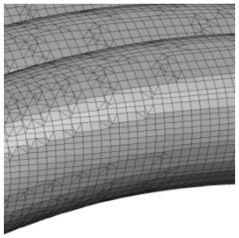
→ need to optimize energy consumption: required p for sufficient stiffening?
→ evaluation of „limit states“ for safe operation: e.g. p=5 mbar

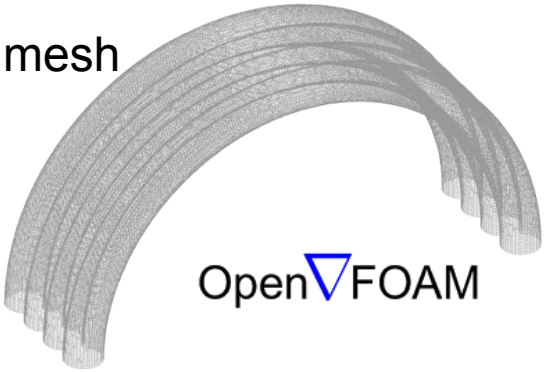


→ local wrinkling
→ severe mesh distortion at surface and end of simulation …

CFD-solvers: interface tracking vs. Interface capturing

→ OpenFOAM, FVM: ALE body-fitted mesh





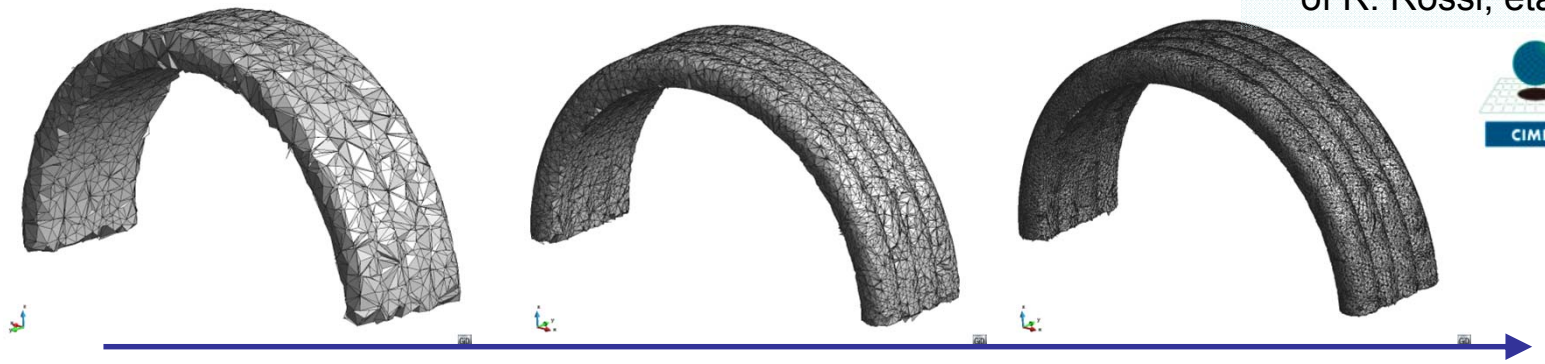
→ KRATOS, FEM: - ALE body-fitted mesh

KRATOS MULTI-PHYSICS

→see contributions of R. Rossi, etal.

uLites

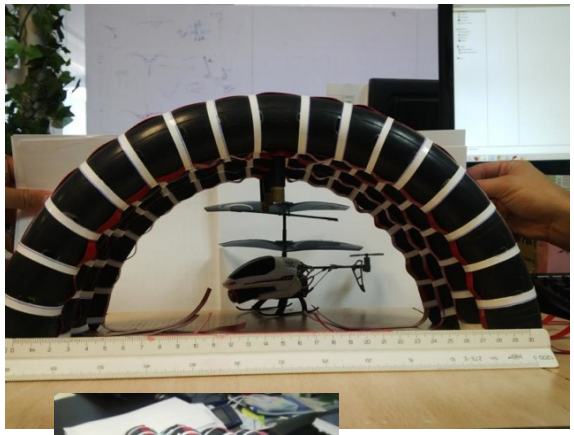
- fixed embedded mesh



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

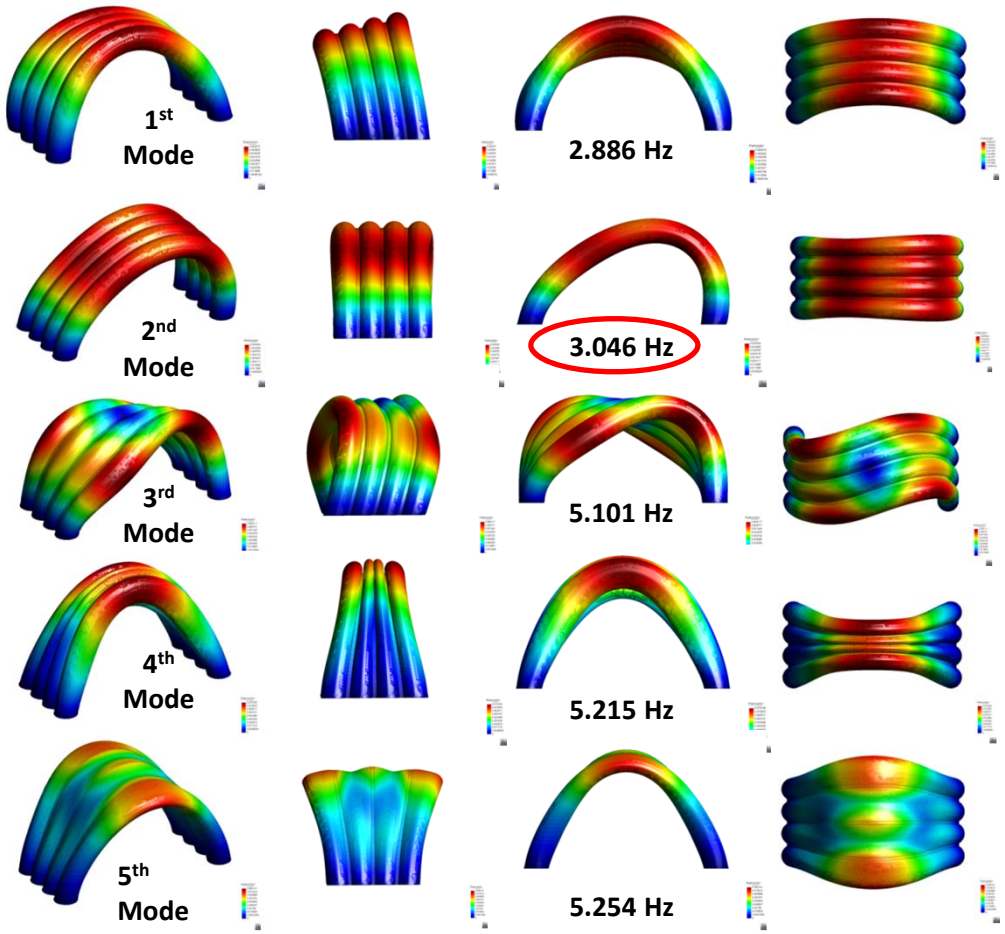


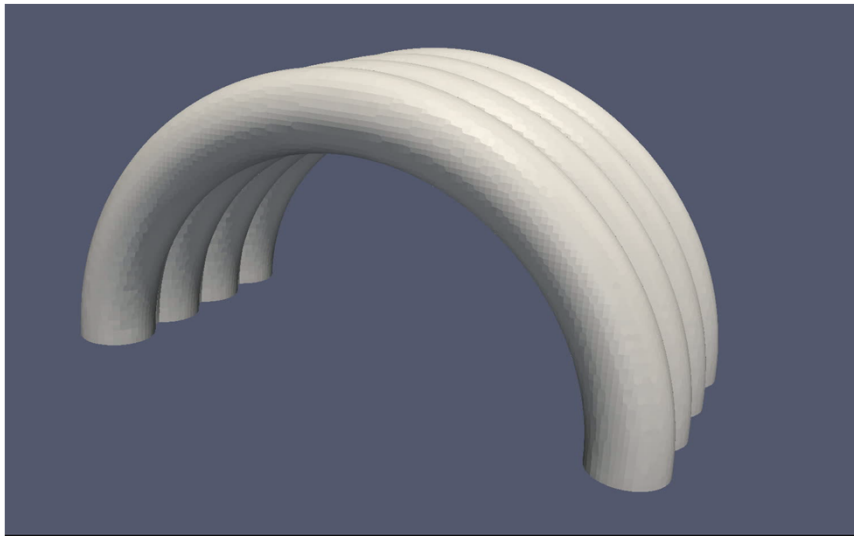
???

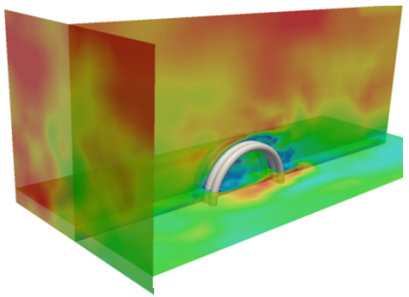
???

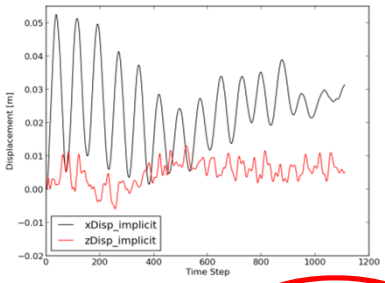
Predict Eigenfrequencies of 4-tubes prototype

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





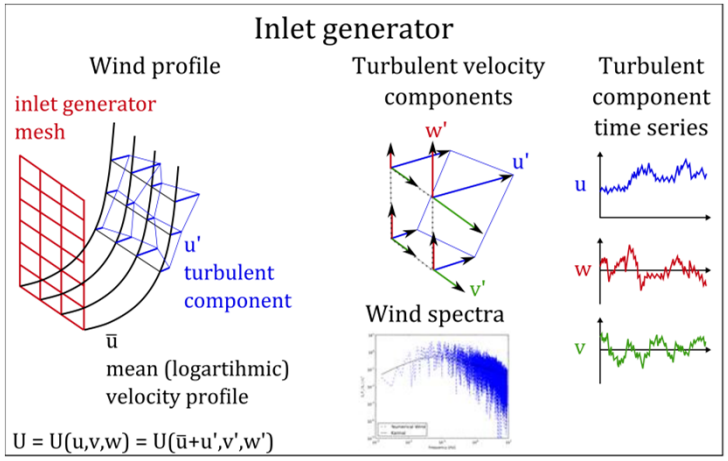


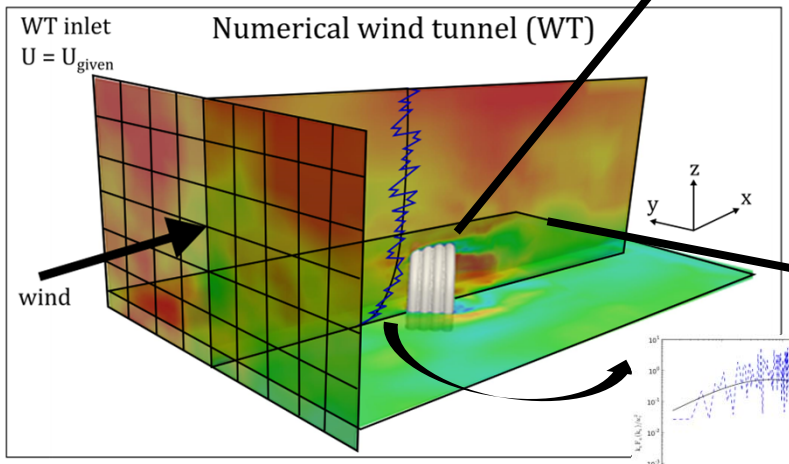


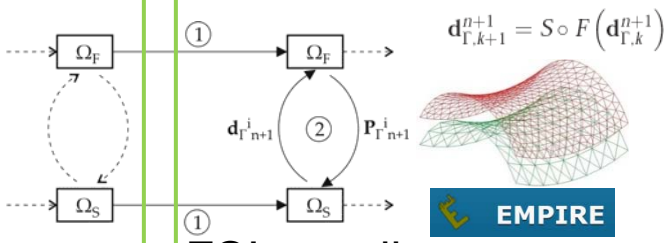
→ 2nd Eigen-frequency from FSI ≈ 1.25 Hz

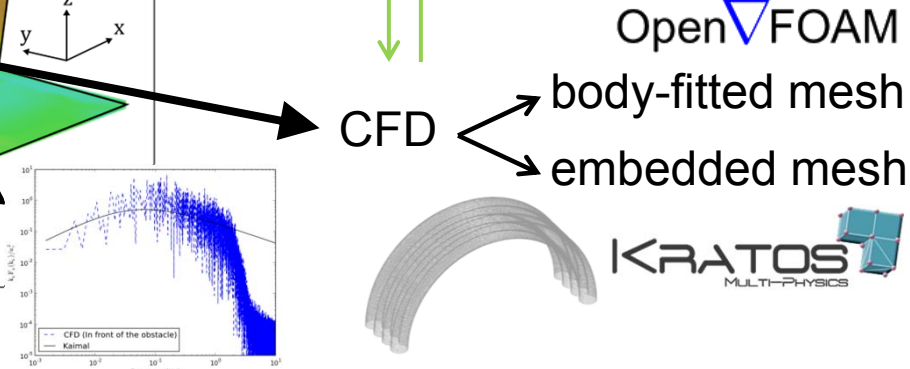
→ significant coupling effects

Systematic, stepwise validation concept:









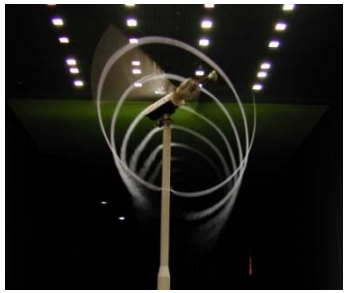
confidential results

confidential results

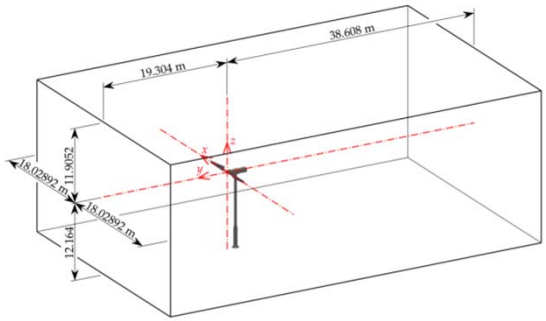
confidential results

Co-Simulation of wind turbines

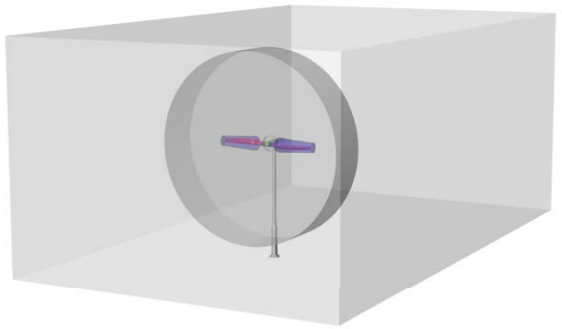
- goal: multi-field simulation with flow, structure, control, i.e. coupling of fields and signals
- Use of model turbine: available data for validation

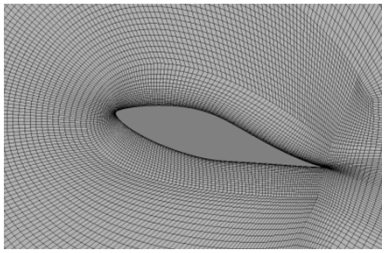


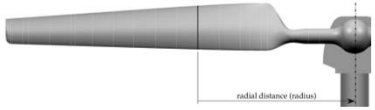
NREL-Phase VI-Experiment:
10 m diameter test turbine
in NASA Ames wind tunnel

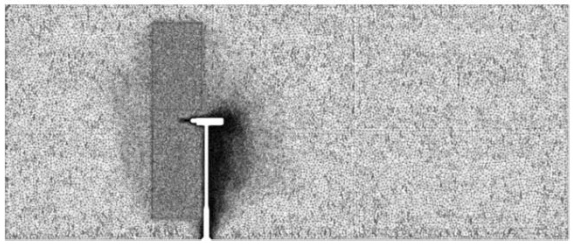


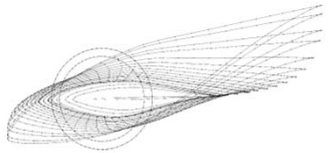
complex blade geometries and
special meshing of the flow domain



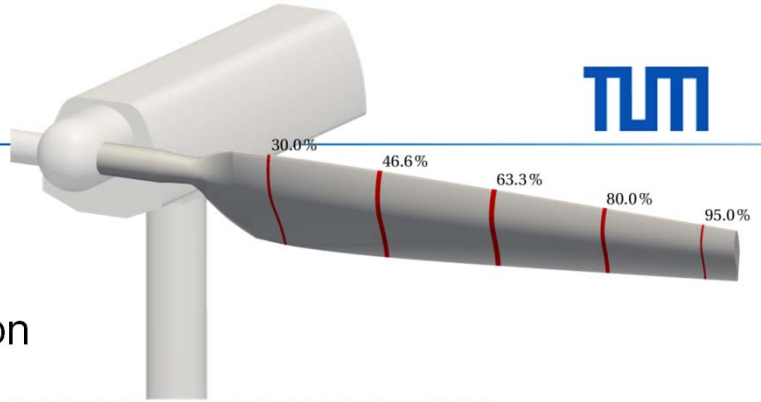






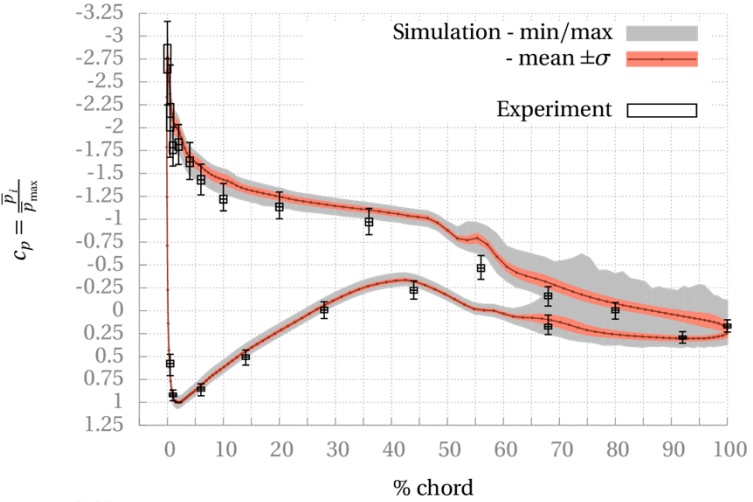


Stefan Sicklinger, in cooperation with Abaqus

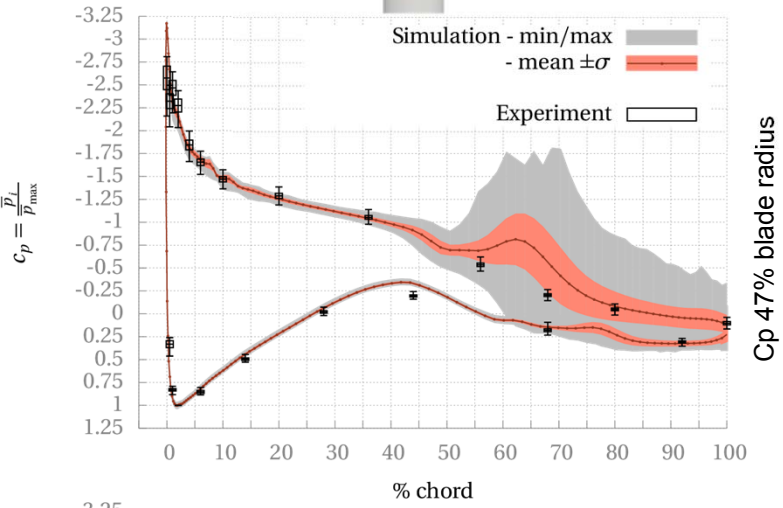


CFD Model (cont'd)

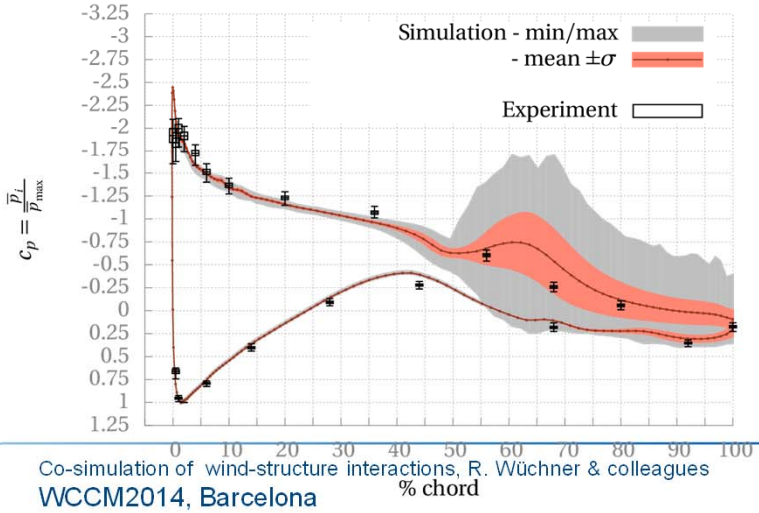
- Pressure Coefficient – Measurement vs. Simulation



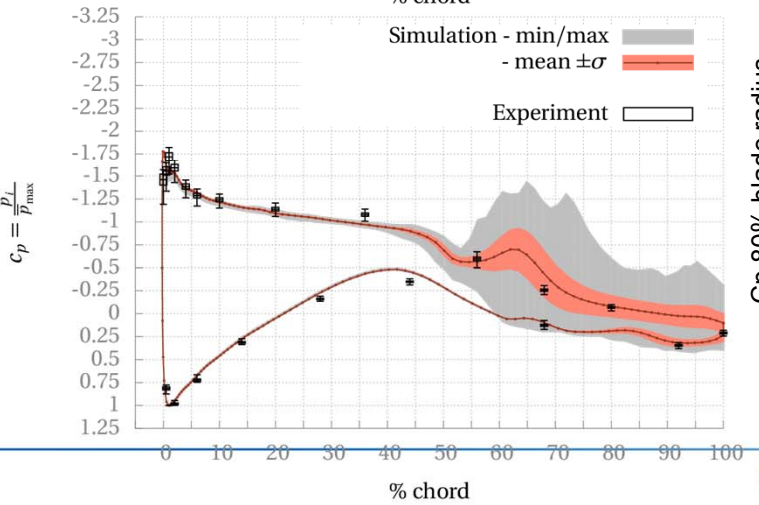
Cp 30% blade radius



Cp 47% blade radius



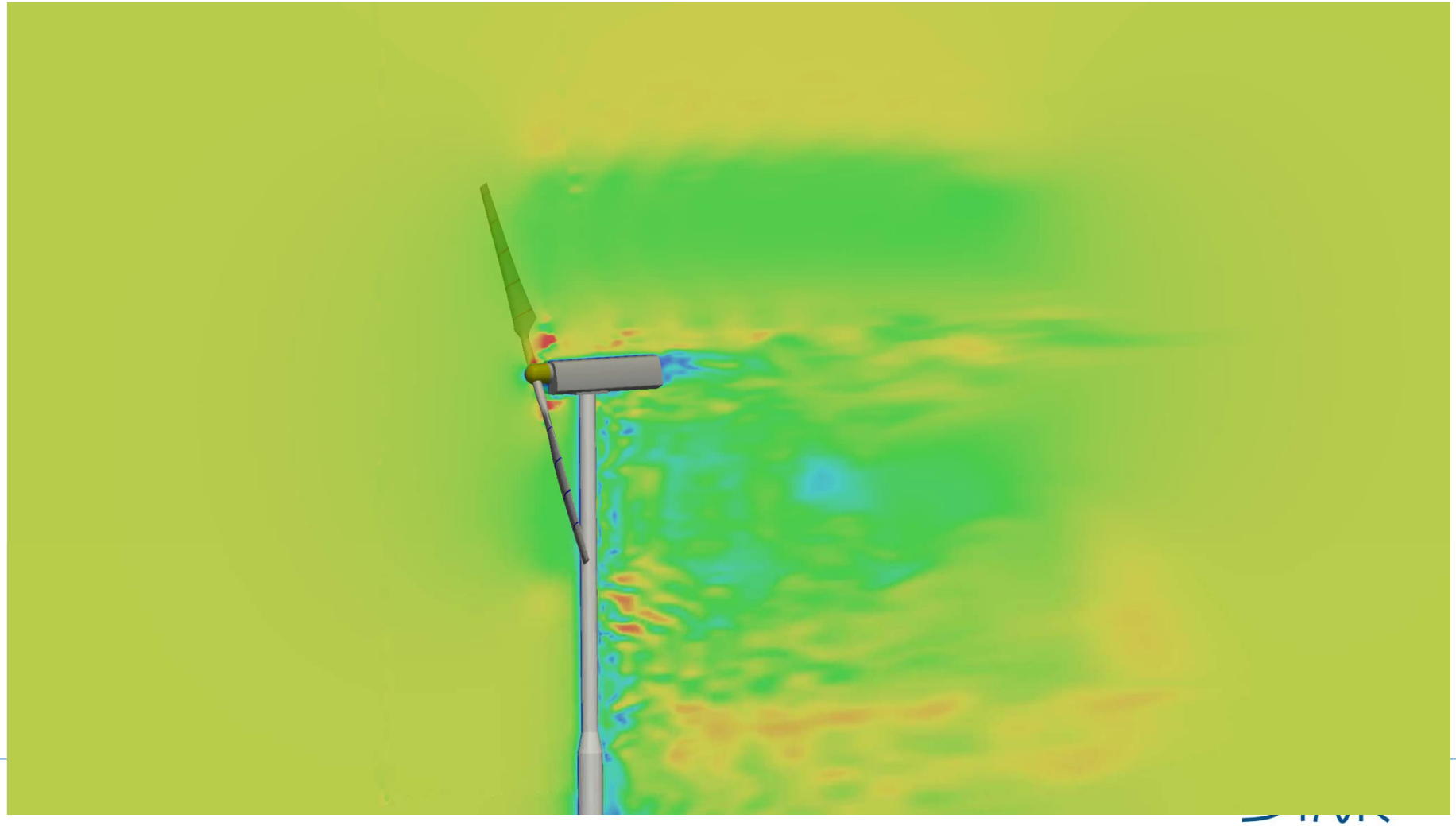
Cp 63% blade radius



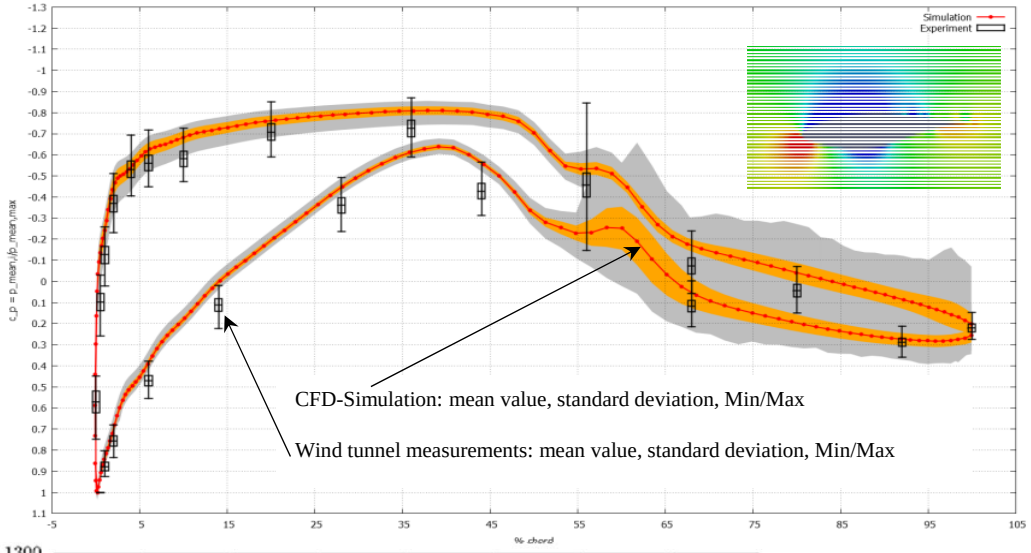
Cp 80% blade radius

NREL’s Unsteady Aerodynamic Experiment Phase VI (cont'd)

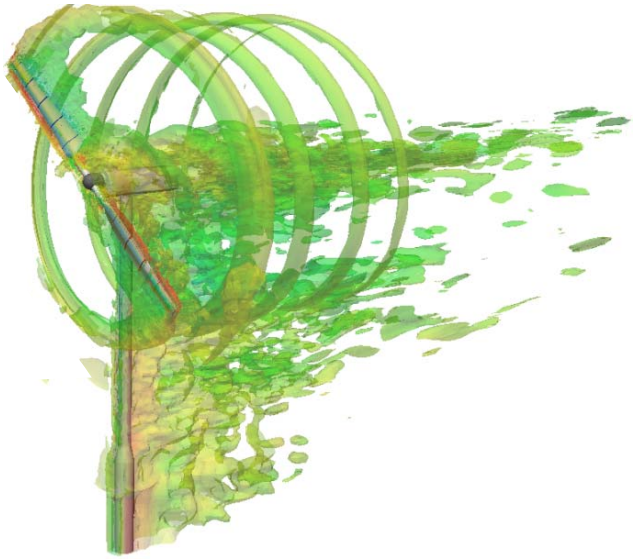
Results – Velocitiy Sideview – 5 m/s Inlet Velocity

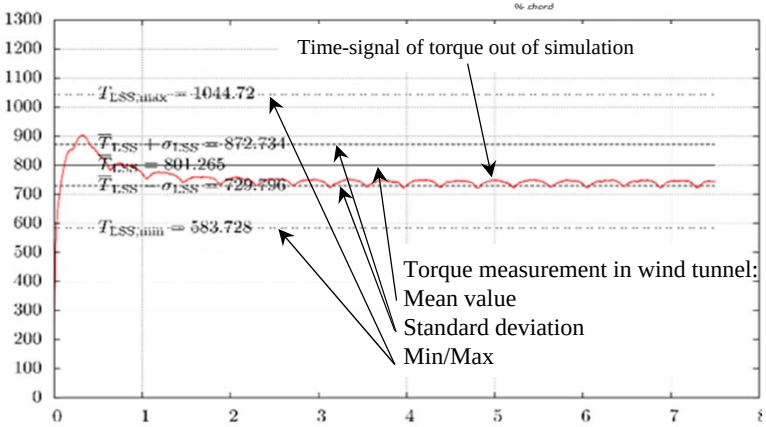


Comparison of simulation and wind tunnel measurements



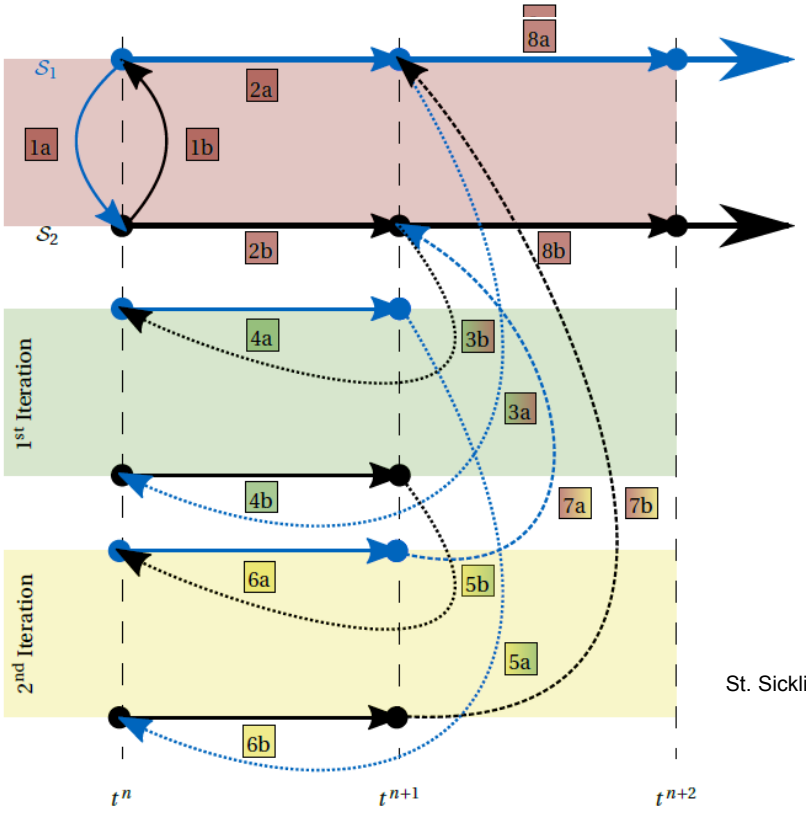
C_p-distribution
around a profile



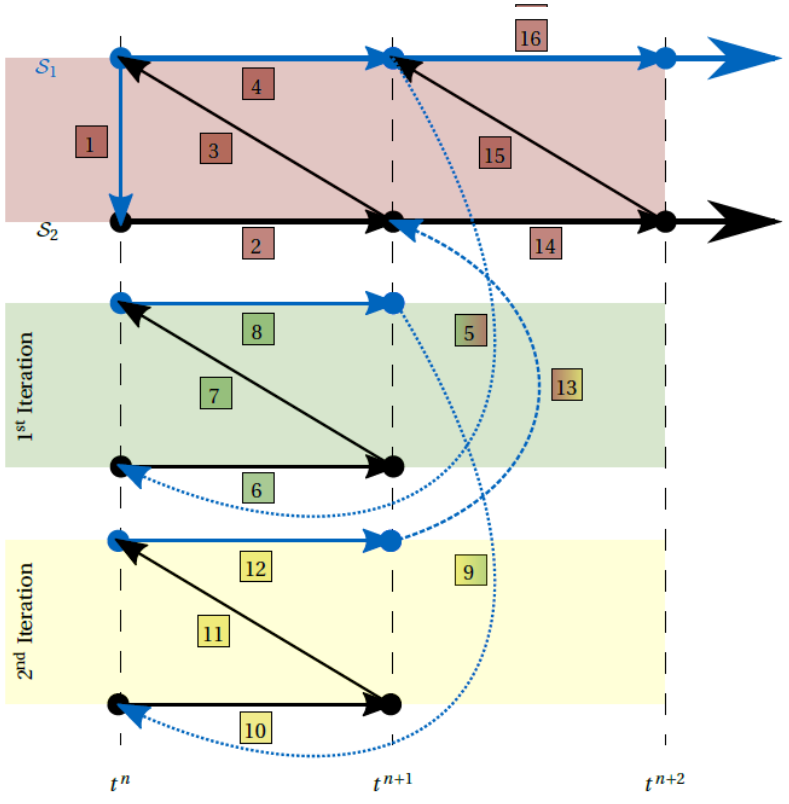


torque
at rotor

Coupling of more than two codes: communication pattern



St. Sicklinger

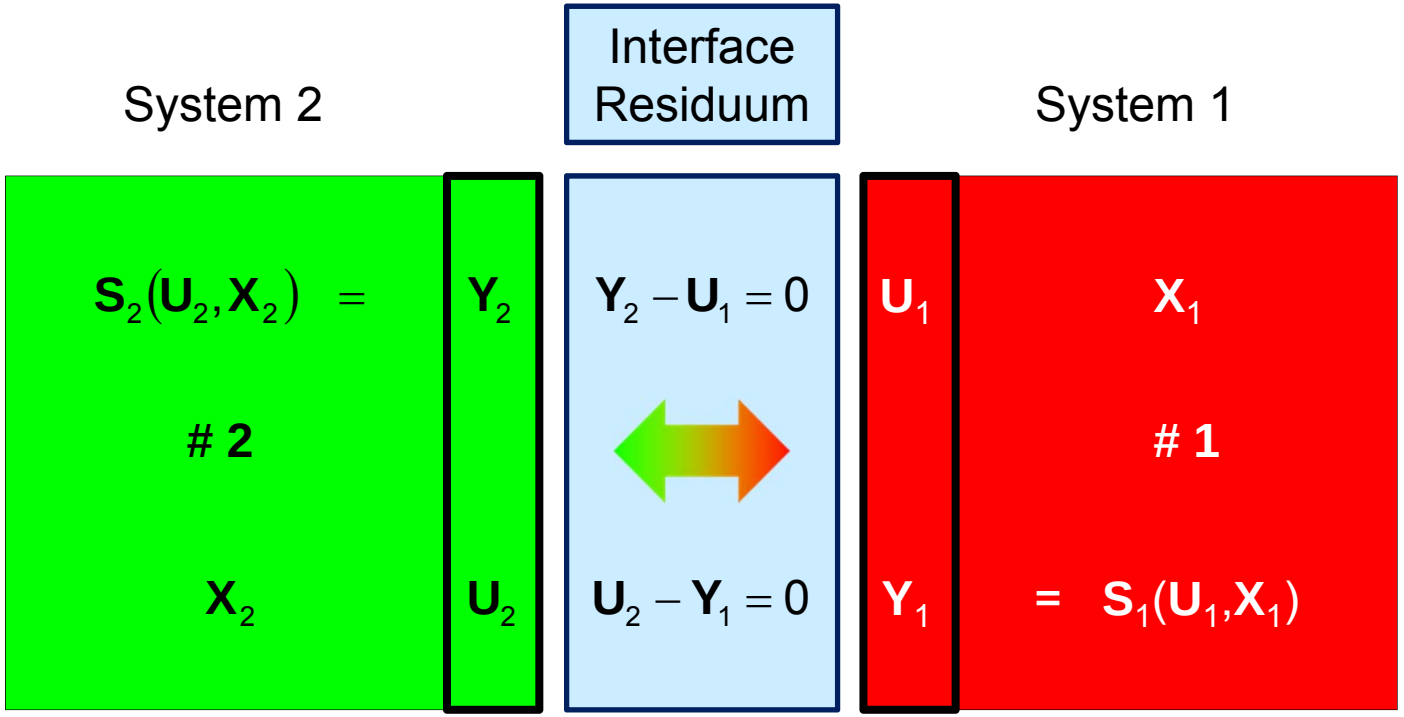


Jacobi iteration pattern (2 it.)
-> no data flow dependency in time step

Gauß-Seidel iteration pattern (2 it.)
-> subsystem need to wait for each other

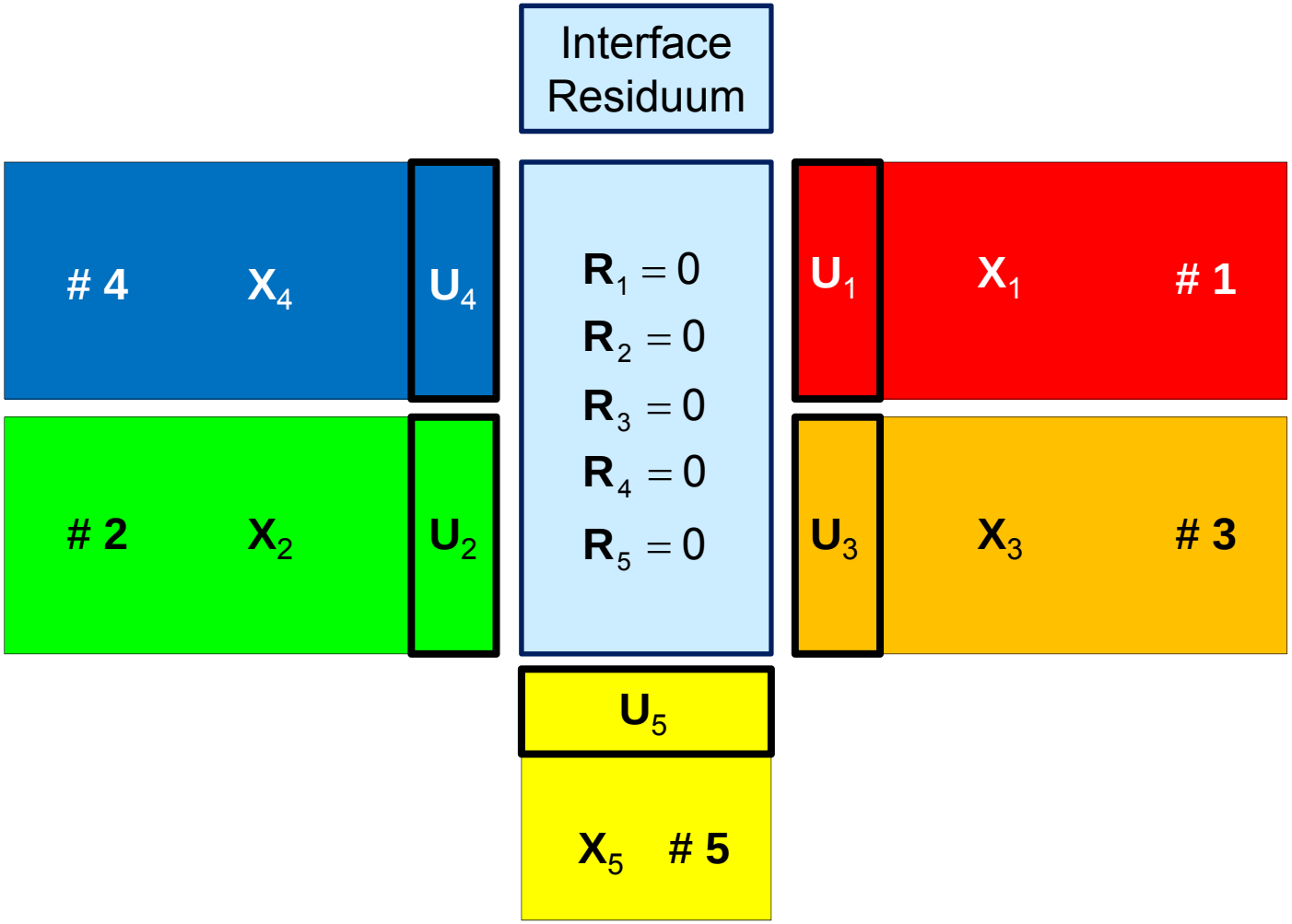
Solution of the coupled system

Co-Simulation	IJCSA (new) *	Monolithic
Stability issues	Robust & accurate	Robust & accurate
Re-using existing tools	Re-using existing tools	Cannot use existing simulation tools



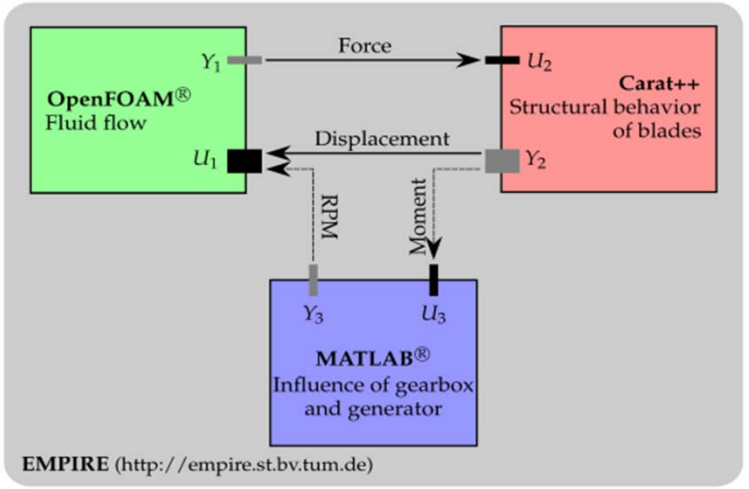
* Sicklinger S., Belsky V., Engelmann B., Elmqvist H., Olsson H., Wüchner R., Bletzinger K.-U. (2014). Interface-Jacobian based Co-Simulation: *International Journal of Numerical Methods in Engineering. (DOI: 10.1002/nme.4637)*

Solution of the coupled system



Simulation of emergency brake maneuver

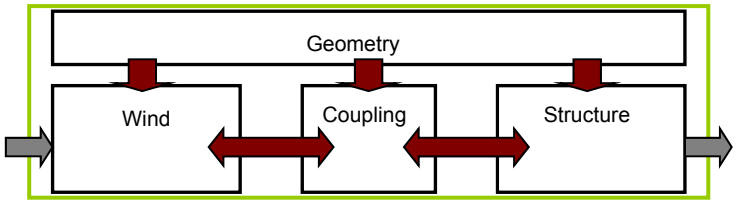
partitioned software-environment
for Co-Simulation:



Stefan Sicklinger

confidential results

confidential results



Summary and outlook

- 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!
  → modeling aspects of virtual wind tunnel

- Coupling: modular software framework and co-simulation
  → non-matching grids:
  FSI simulations with ALE-based and embedded solvers, isogeometric analysis
  → coupling algorithms: coupling of fields and signals

- Validation is indispensable for predictive CWE:
  → but: impossible down-scaling of ultra-lightweight structures,
  → definition of wind tunnel campaign considering FSI (scaled ABL, Ulites project)