# Shape Optimization and Mesh Regularization

for

# Fluid-Structure Interaction Wind engineering problems

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# Outline

- Structural Design
- Design workflow
  - Geometry
  - Form-finding, Mesh regularization
  - FSI analysis
  - Sensitivity
- Summarizing example
- Next steps

# Motivation


## Aim:

Design and improvement of light weight structures

## Characteristics:

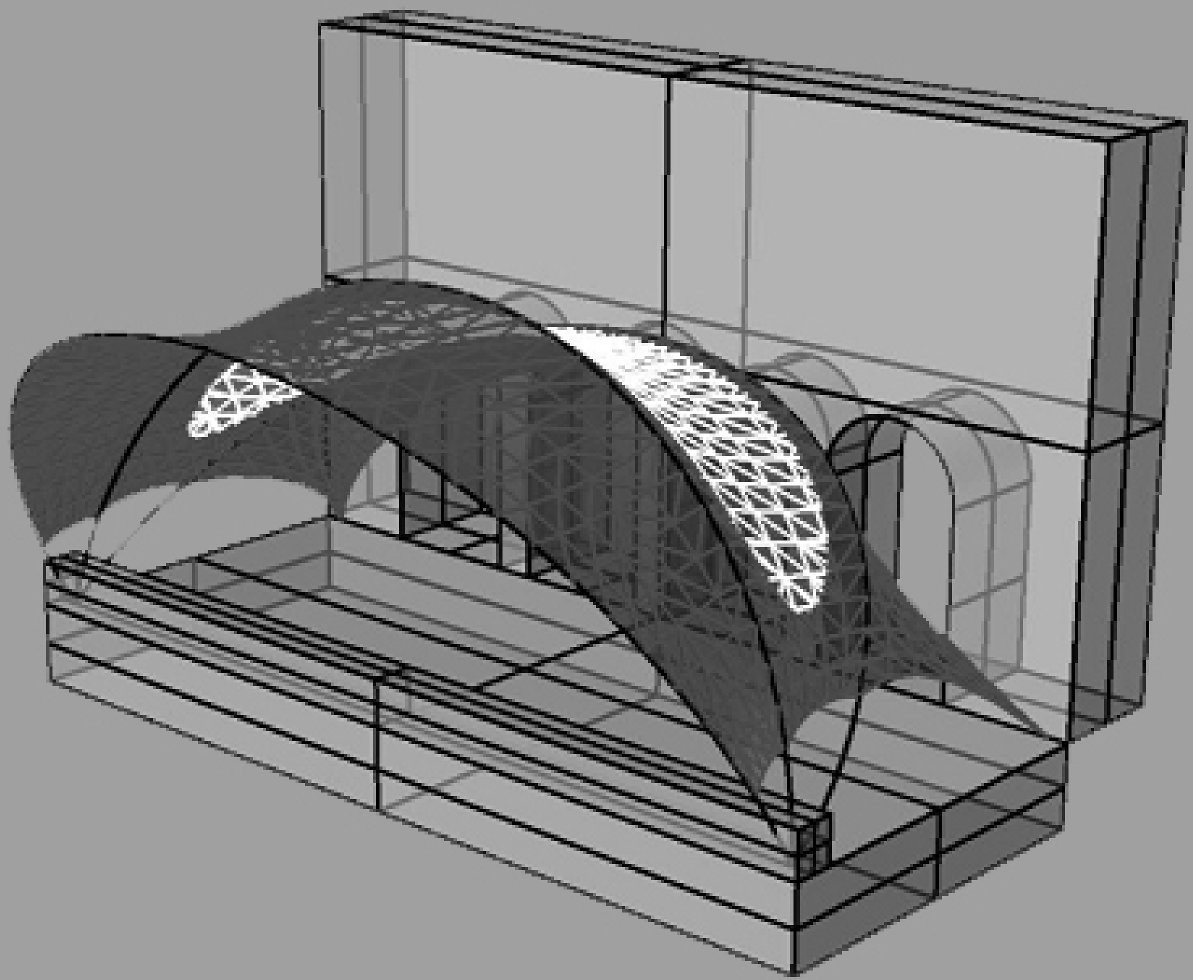
Thin and slender structures – complex geometries

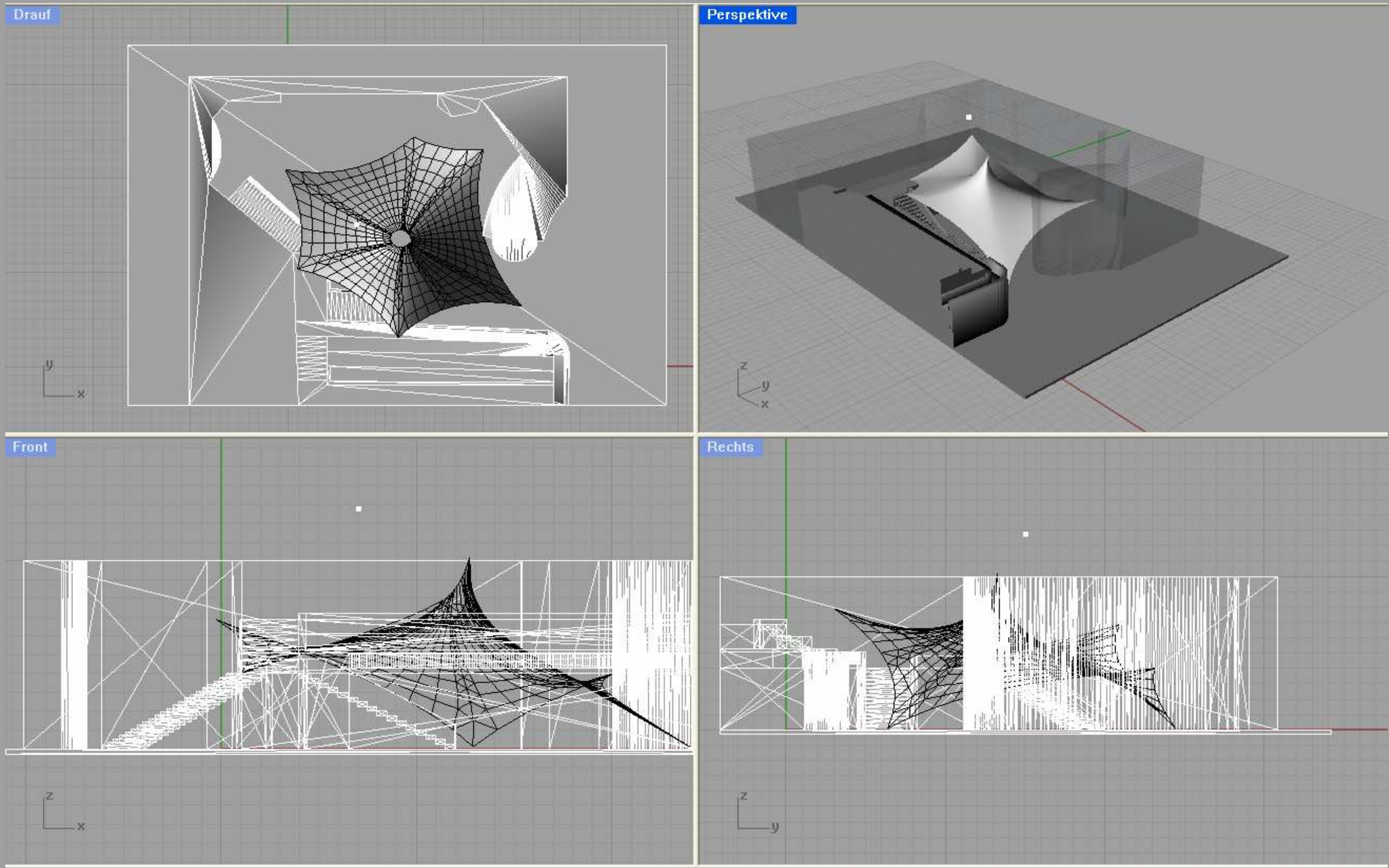
Highly turbulent Atmospheric wind around the structure

Strongly coupled fields

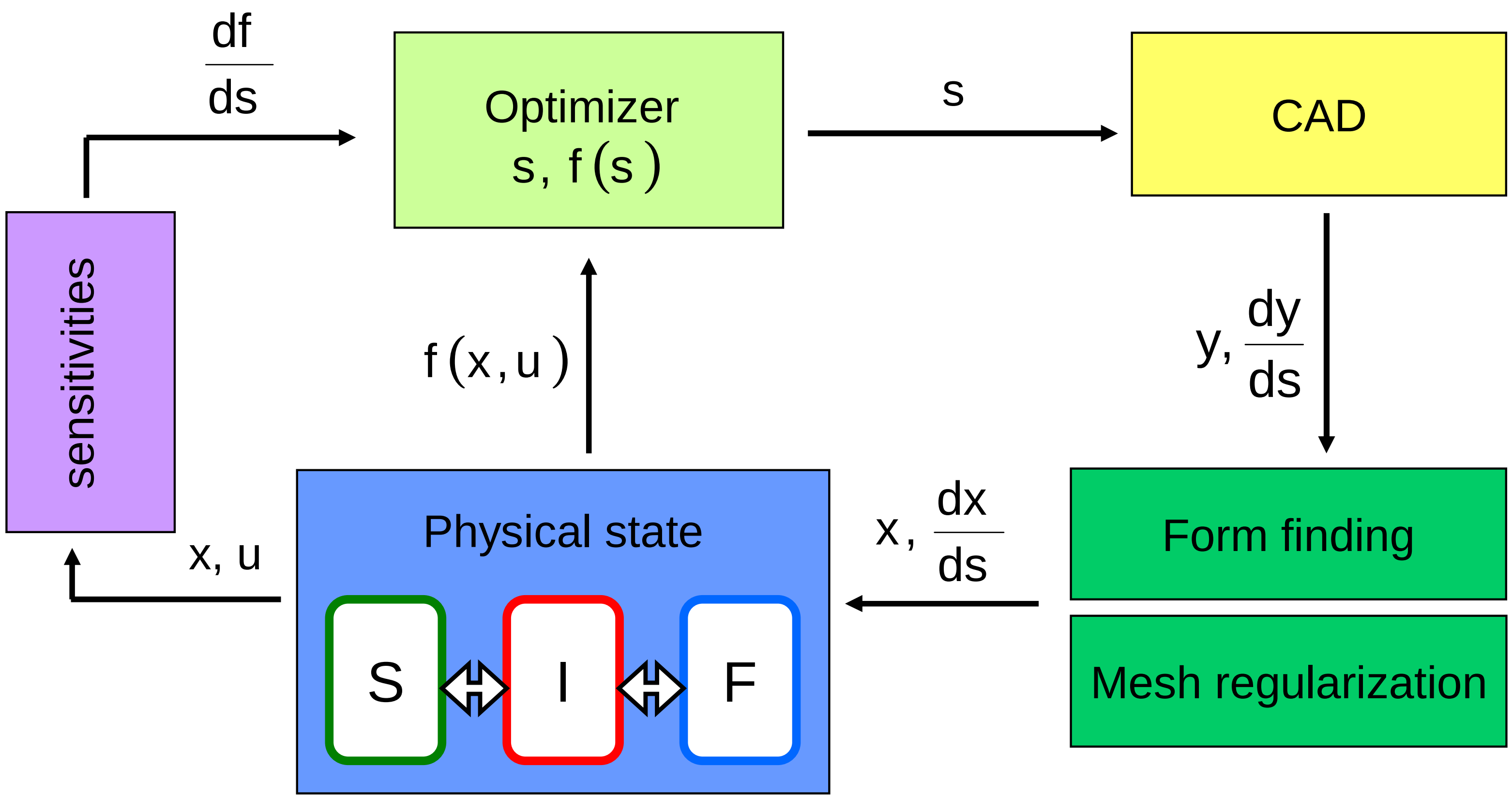
# Problem type

[Frei Otto, München 1999]



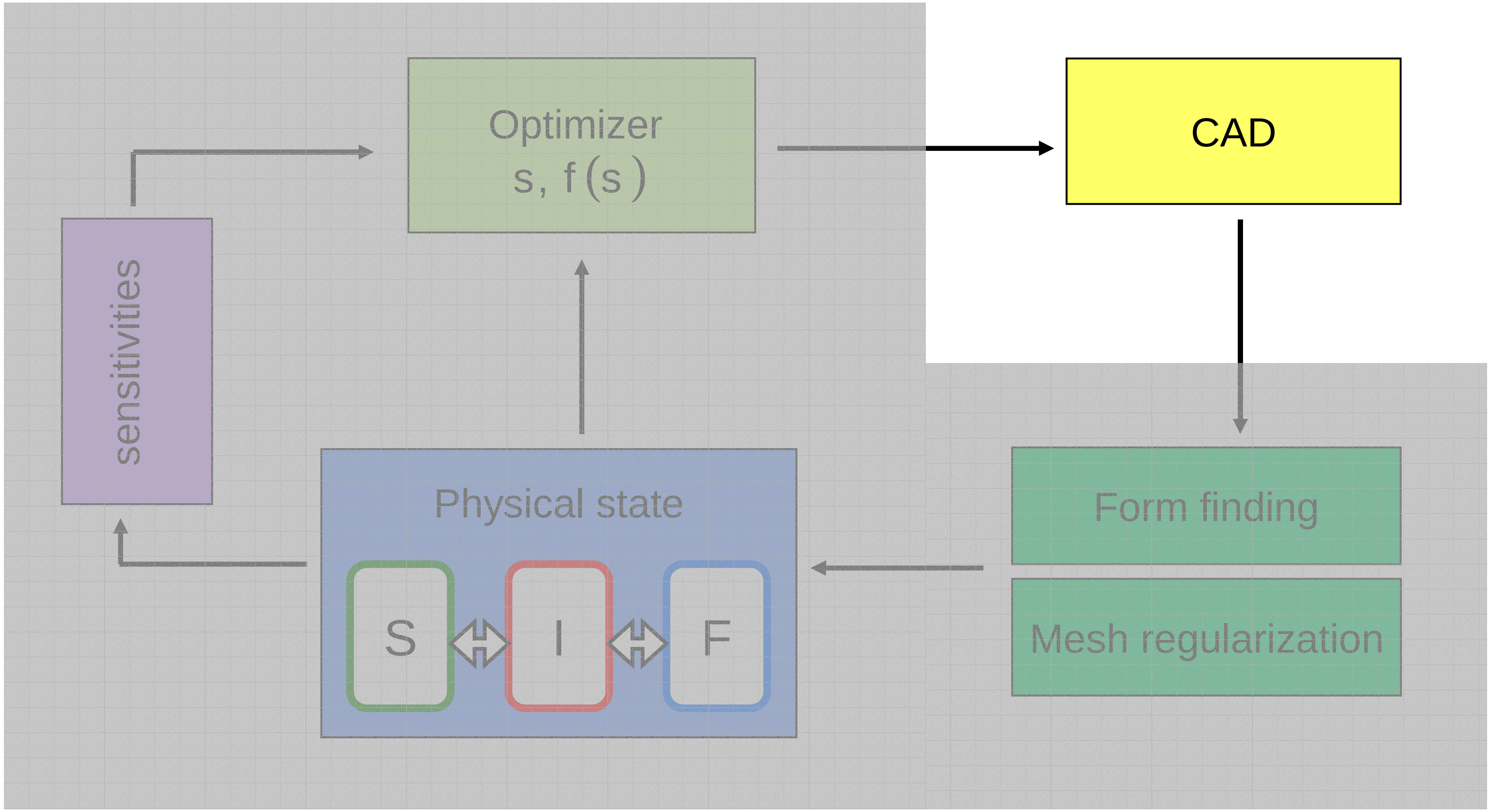

Drauf
Perspektive
Front
Rechts

# Design optimization workflow

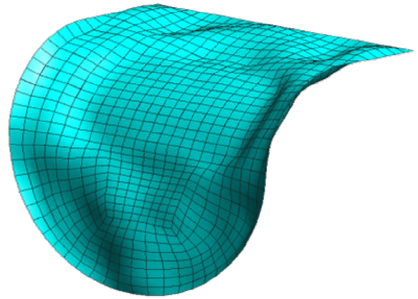



$$\frac{df}{ds} = \frac{df}{dx}\frac{dx}{dy}\frac{dy}{ds}$$

# Design optimization work flow

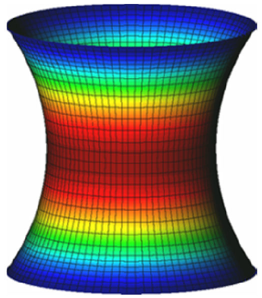


# CAD - Structural shape representation



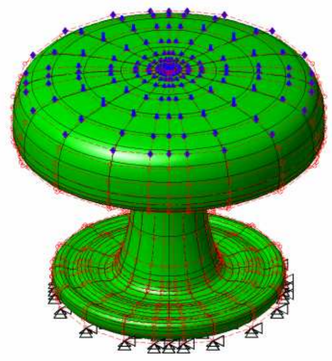
## FE-base design

- Design variables: FE nodes



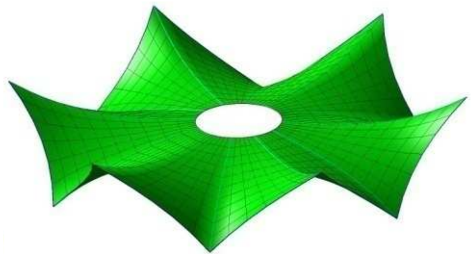
## CAD-base design (CAGD)

- Design variables: Geometry parameters



## Isogeometric design

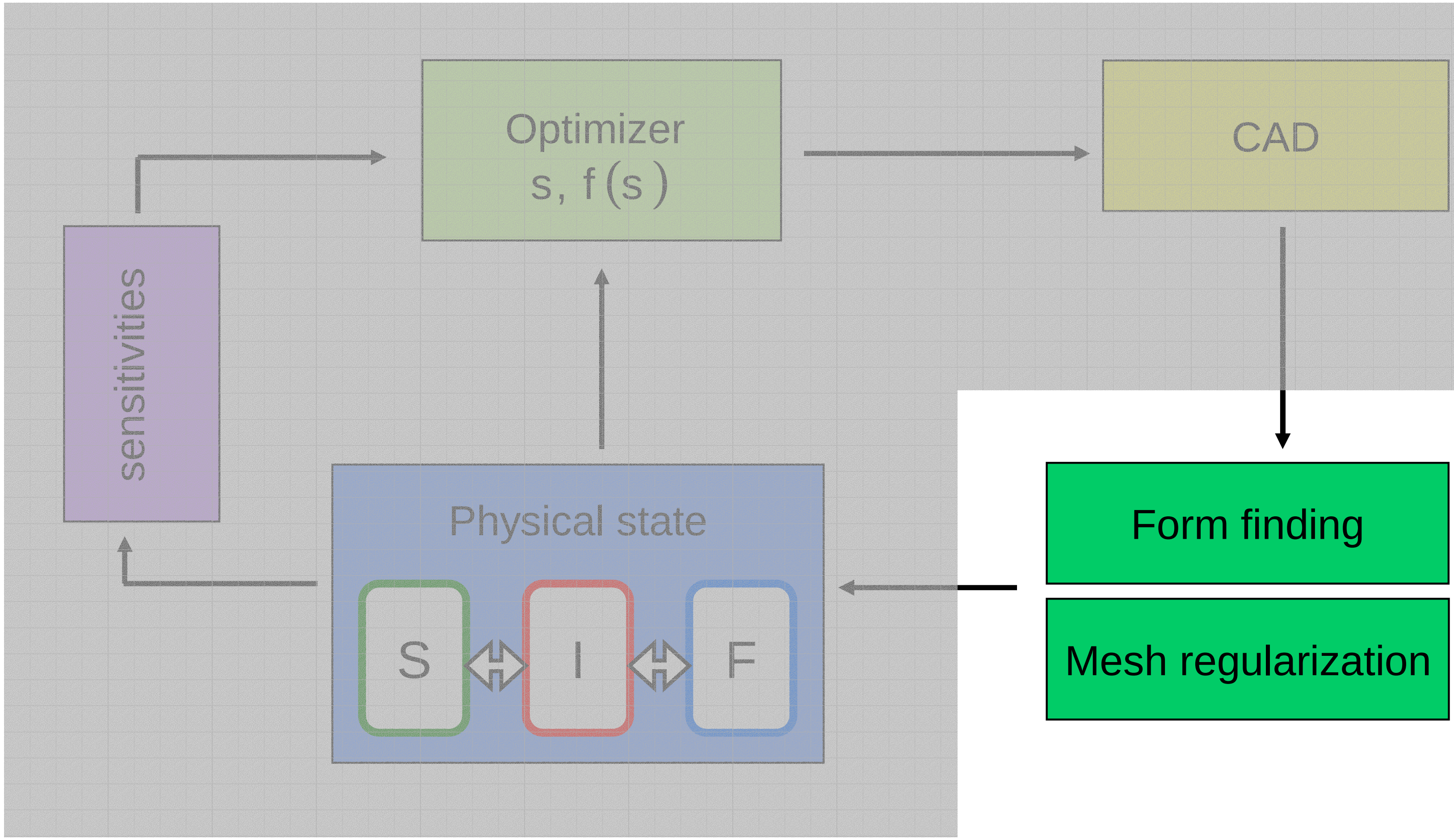
- Design variables: NURBS parameters



## Mechanical criteria

- Design variables: supports, Pre-stress, etc.

# Design optimization work flow



# Membrane structures and Form finding

(Bltezinger, Ramm 1999)

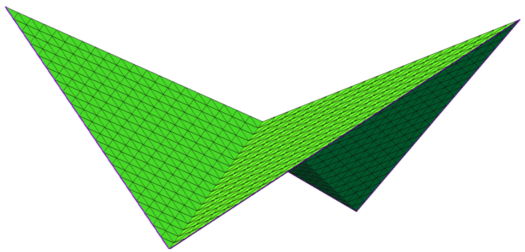
Minimal surface: principle of virtual work

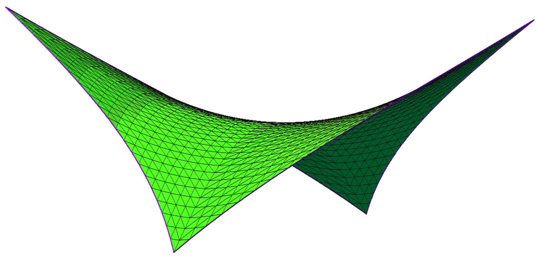
$$\delta W = \int_{v} \boldsymbol{\sigma} : \delta \mathbf{e} \, dv = \int_{V} \mathbf{S} : \delta \mathbf{E} \, dV = 0$$

$$\mathbf{S} = \det \mathbf{F} \mathbf{F}^{-1} \boldsymbol{\sigma} \mathbf{F}^{-T}$$

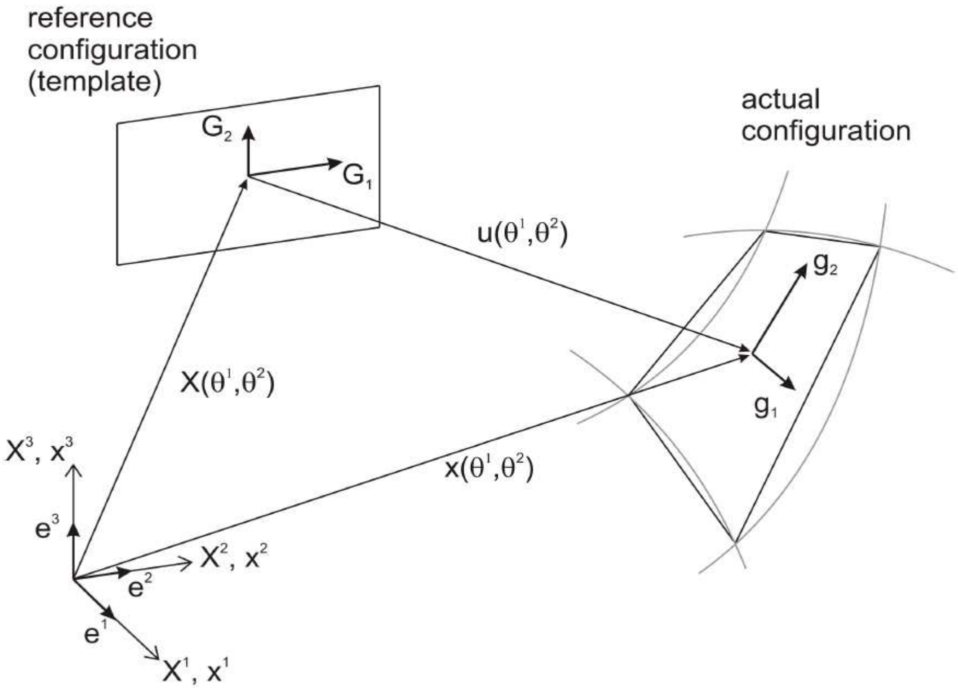
**“artificial”** 2nd Piola-Kirchhoff surface stress **S** instead of Cauchy $\sigma$

→ control of tangential shape variation





# Mesh regularization



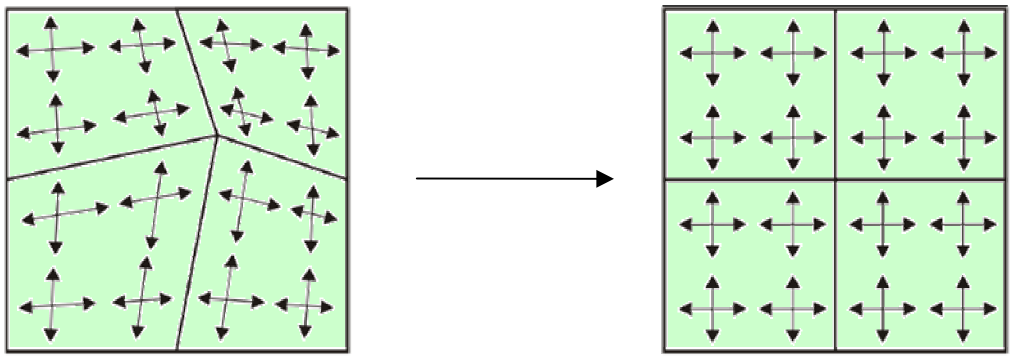

„Pre-stress“
Element size control

$$\delta W = \int_{\Omega} (S : \delta E)\, dV = 0$$

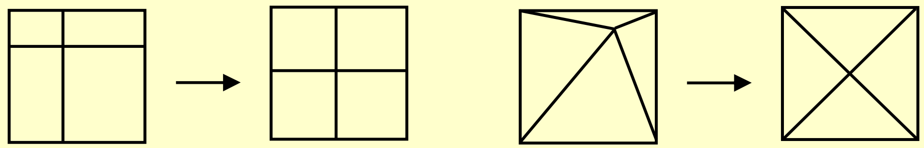
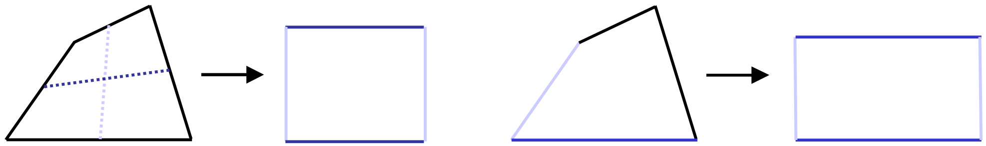
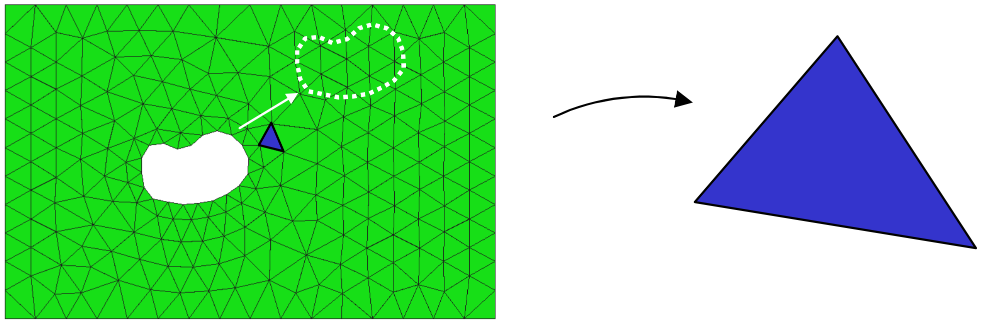
stiffness matrix of problem:

$$\frac{\partial r_i}{\partial u_j} = \int_{\Omega} (S : \frac{\partial^2 E}{\partial u_i \partial u_j})\, dV = \int_{\Omega} (S^{\alpha\beta} (g_{\alpha,i} \cdot g_{\beta,j})\, dV$$

$$G_a = \frac{\partial X}{\partial \theta^a} \qquad g_a = \frac{\partial x}{\partial \theta^a}$$



# Mesh Regularization - Templates

| template | | applications: examples |
|---|---|---|
| squares<br>equilatera<br>l triangles |  | noise filtering |
| shearless template |  | mesh quality improvement |
| predefined<br>(initial template) |  | bulk motion<br>moving boundaries |

# Mesh Regularization - Templates

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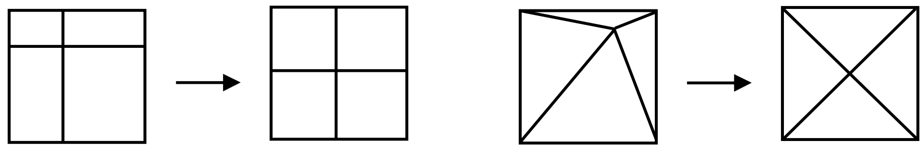
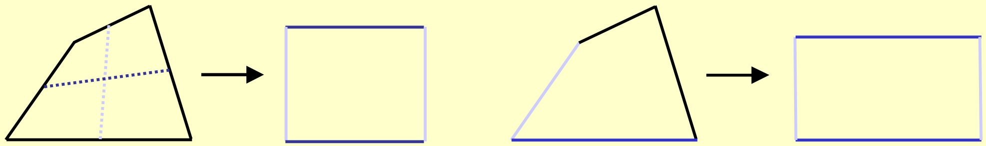
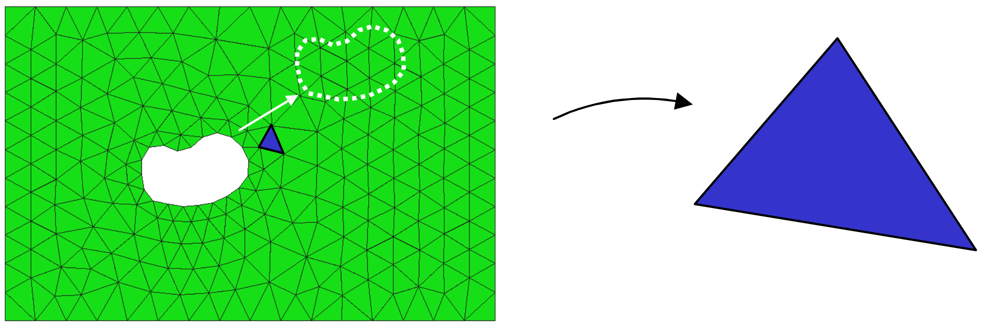
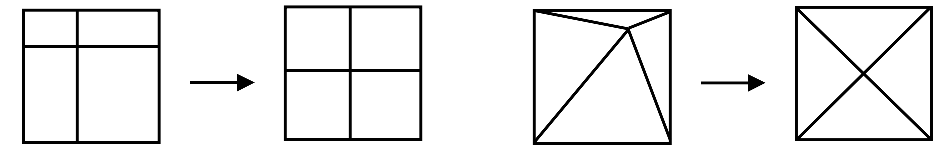
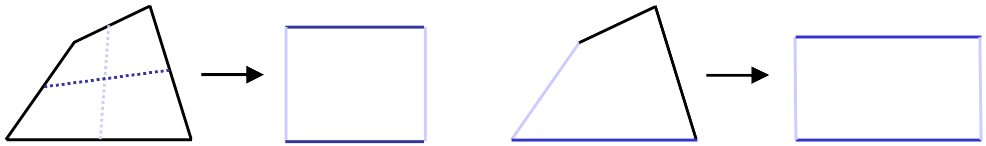
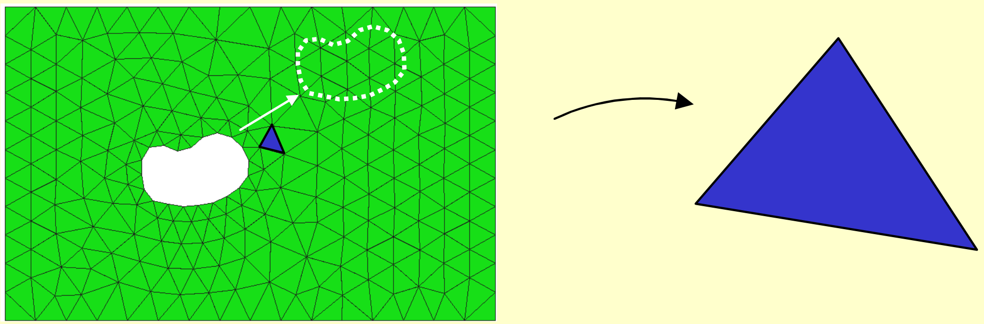
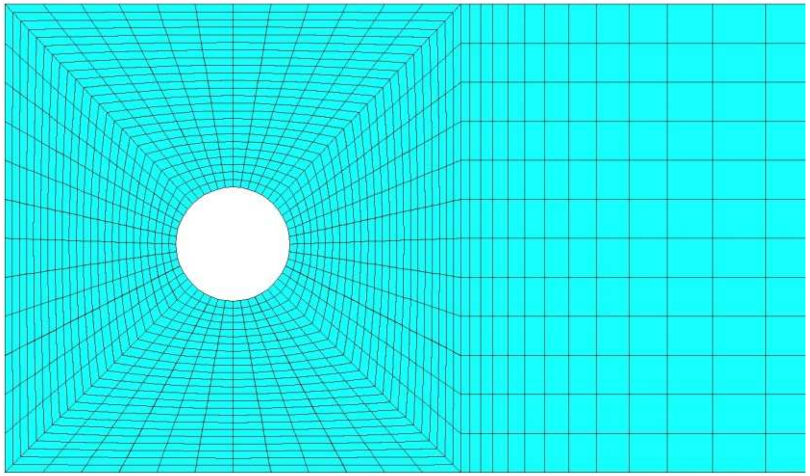
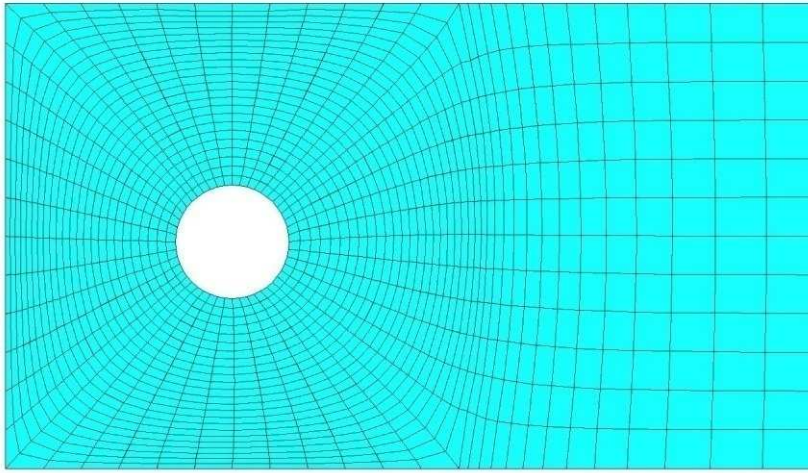
| squares<br>equilatera<br>l triangles |  | noise filtering |
| shearless template |  | mesh quality improvment |
| predefined<br>(initial template) |  | bulk motion<br>moving boundaries |

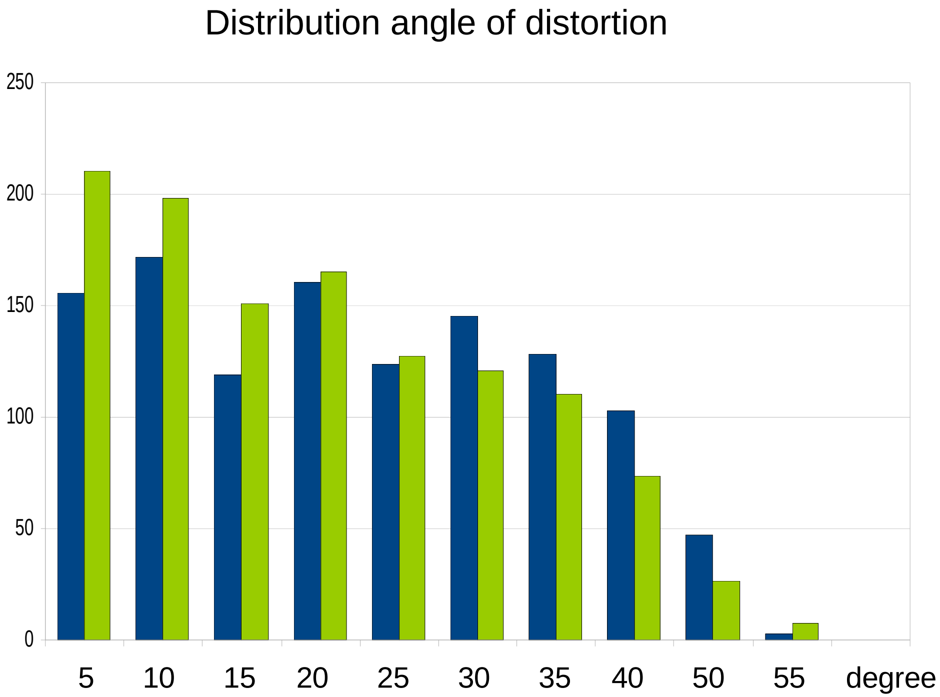
# Mesh Regularization - Templates

| template | | applications: examples |
|---|---|---|
| squares<br>equilateral triangles |  | noise filtering |
| shearless template |  | mesh quality improvement |
| predefined<br>(initial template) |  | bulk motion<br>moving boundaries |

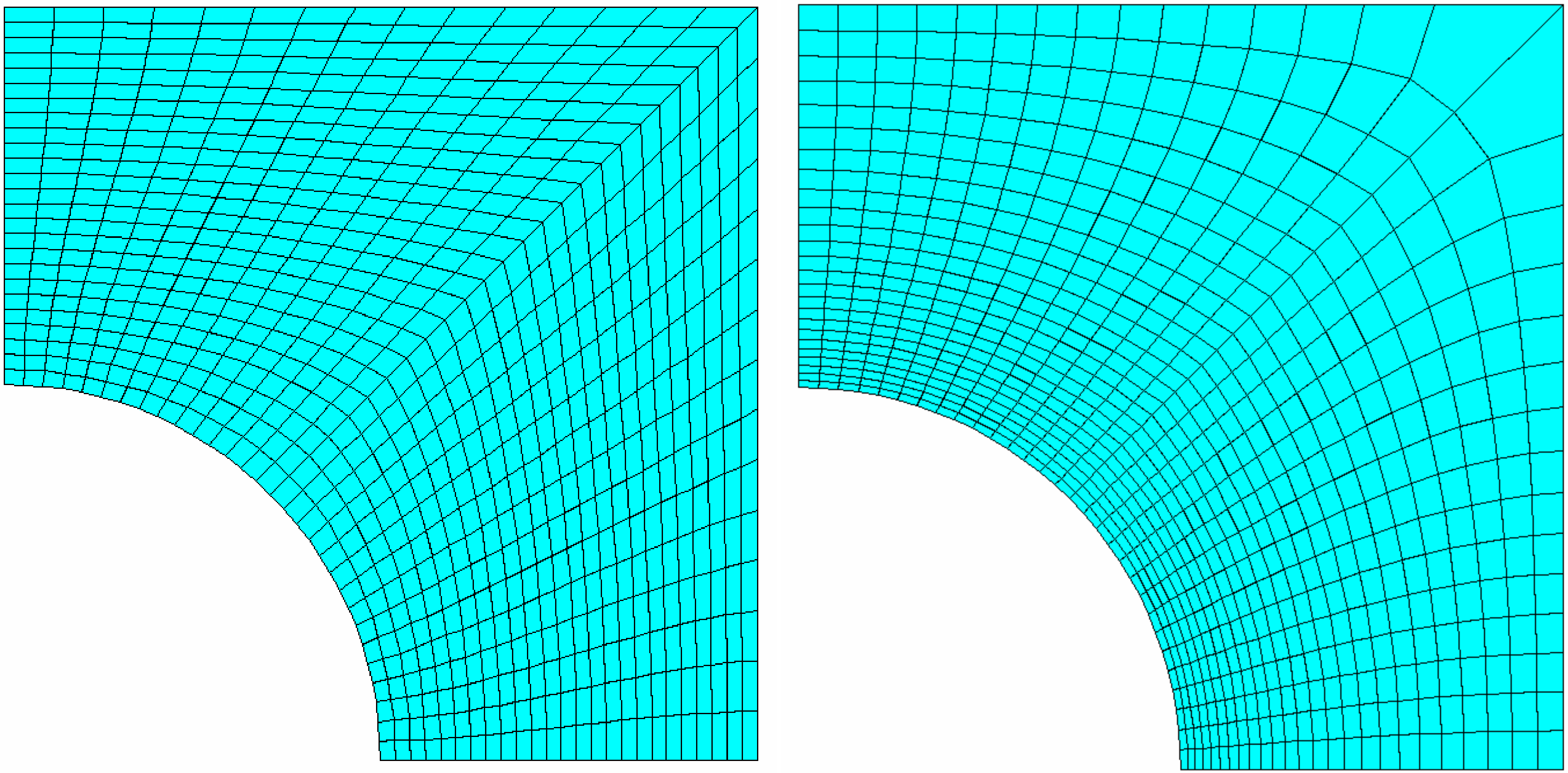
# Applications – mesh quality improvement





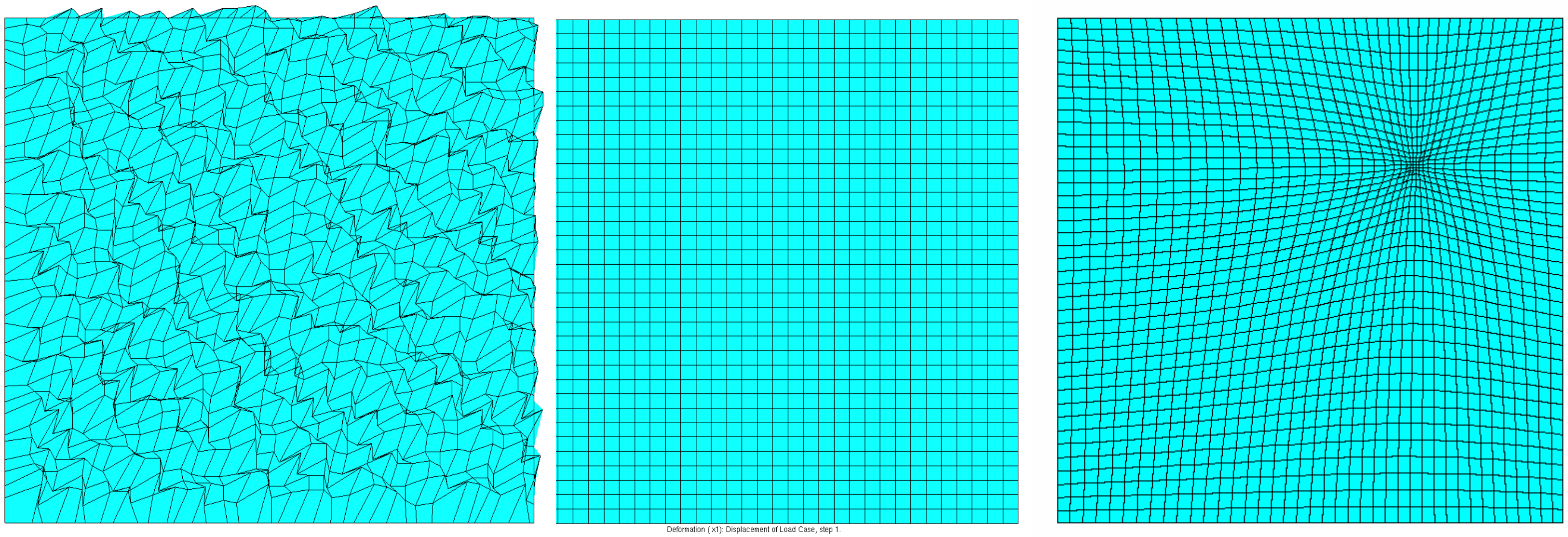


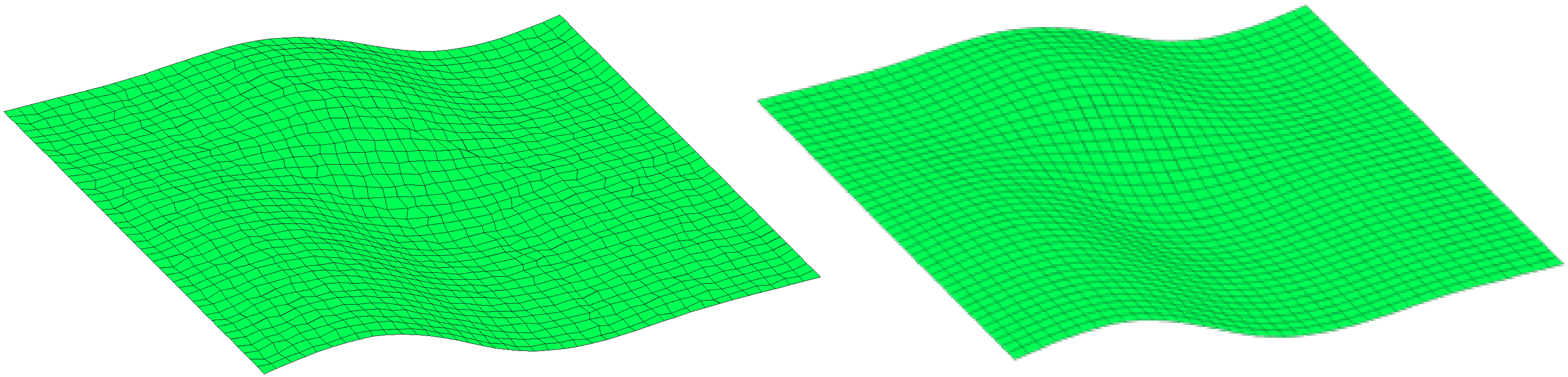
# Applications – Quality improvement



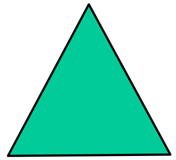
# Applications – noise smoothing

template

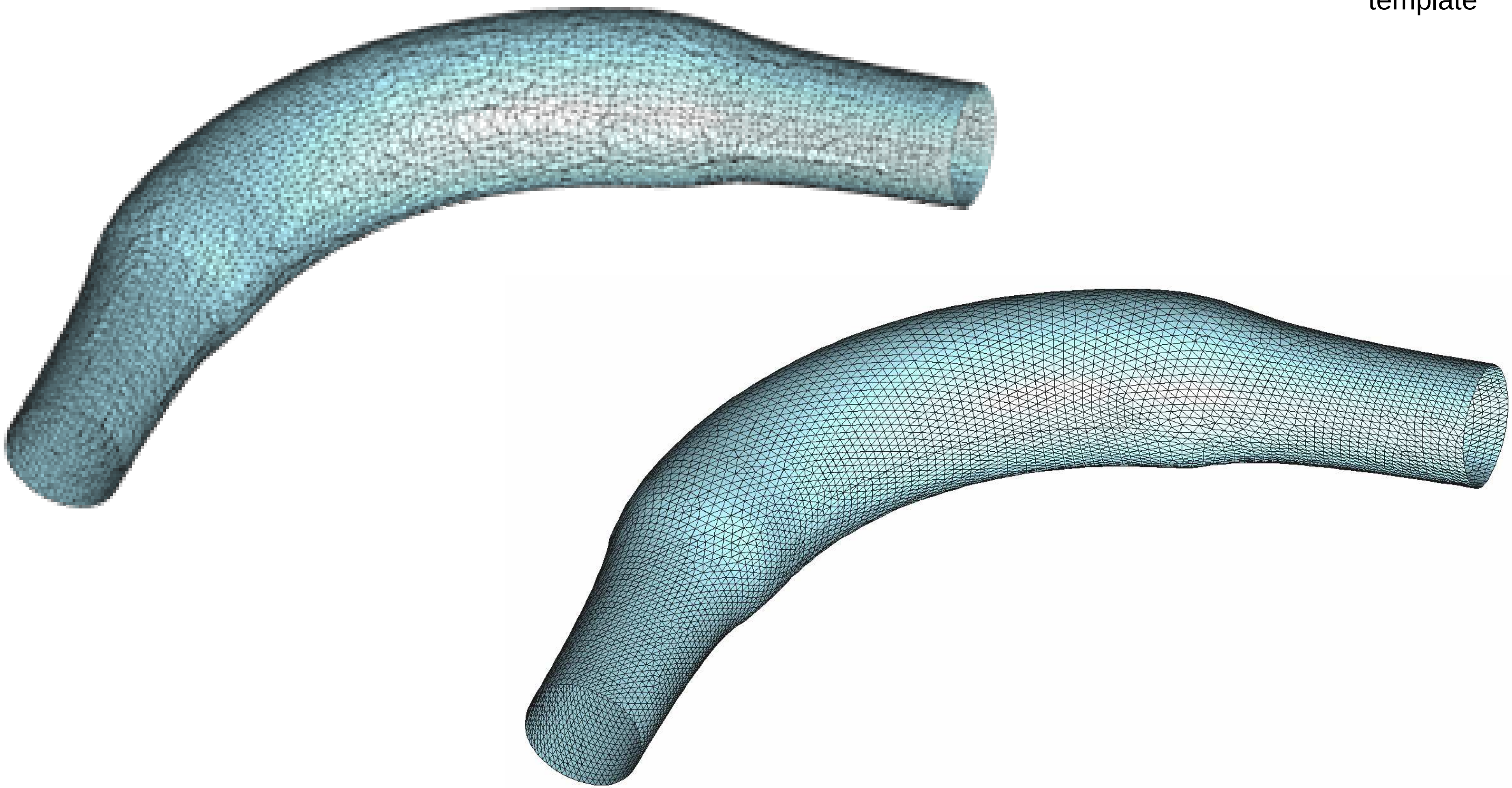


# Applications – noise smoothing



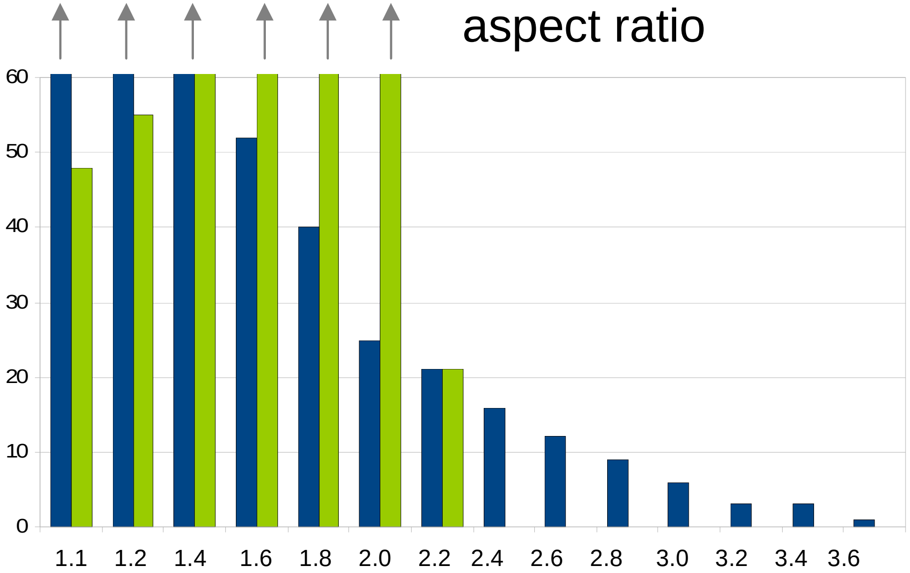
template

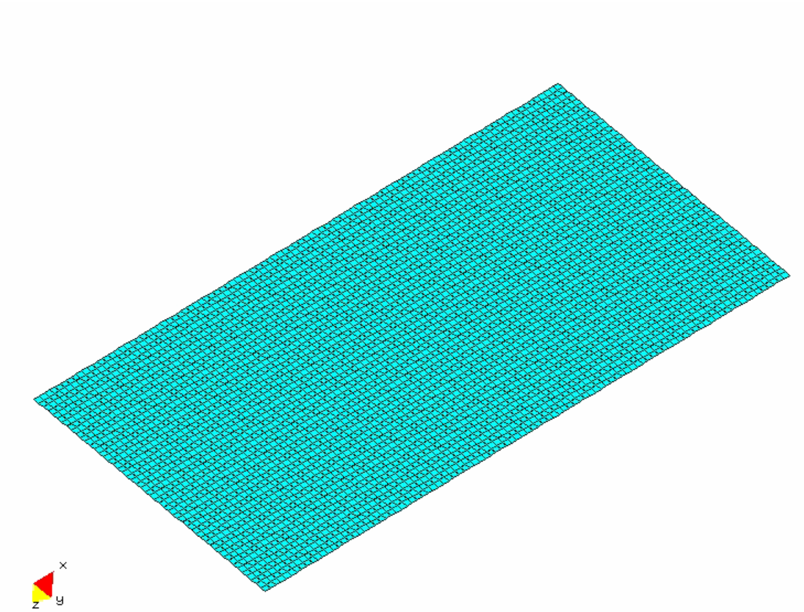


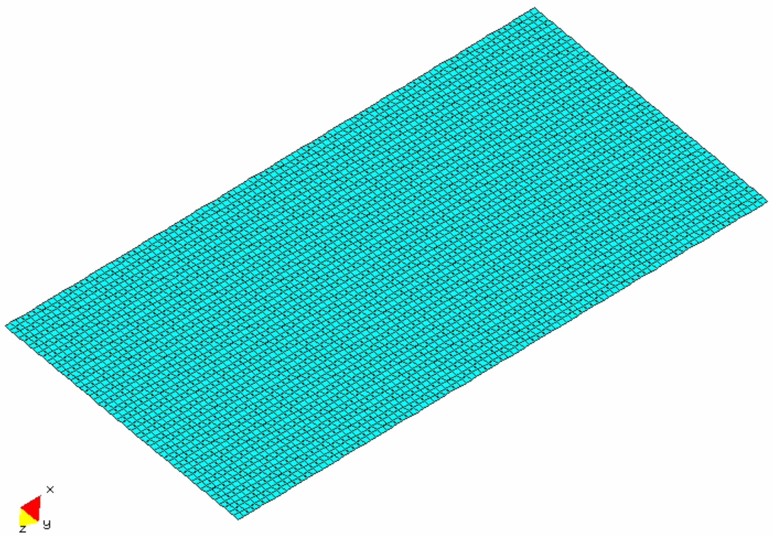
# Applications – large deformations

- surface deformations : curving

template

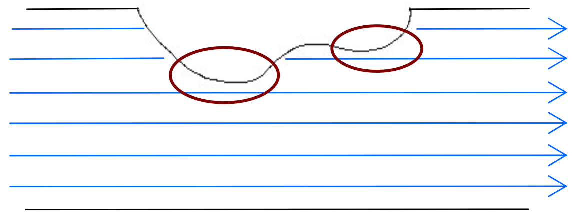


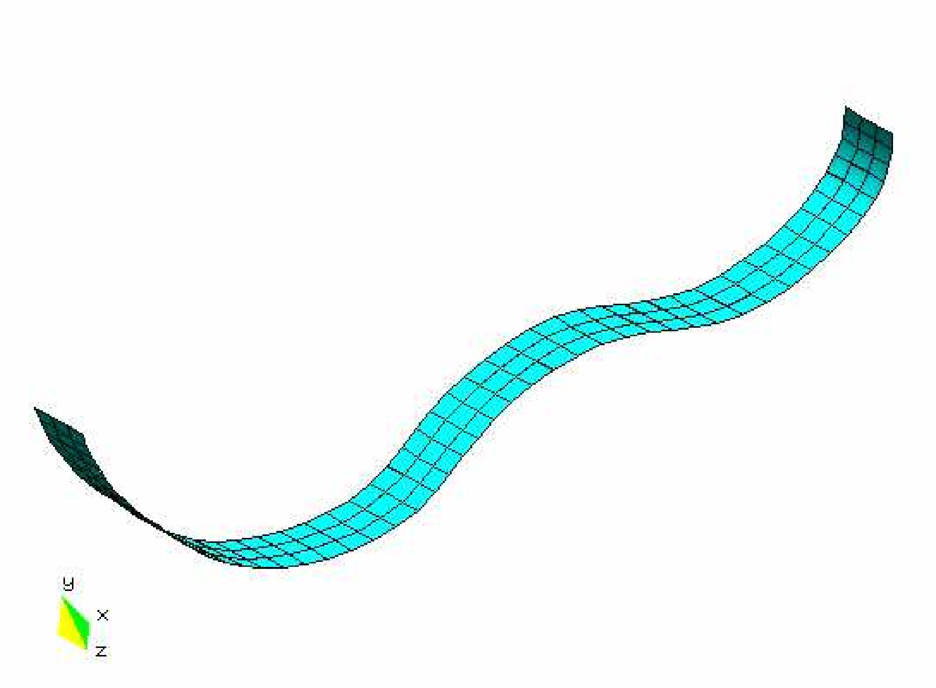



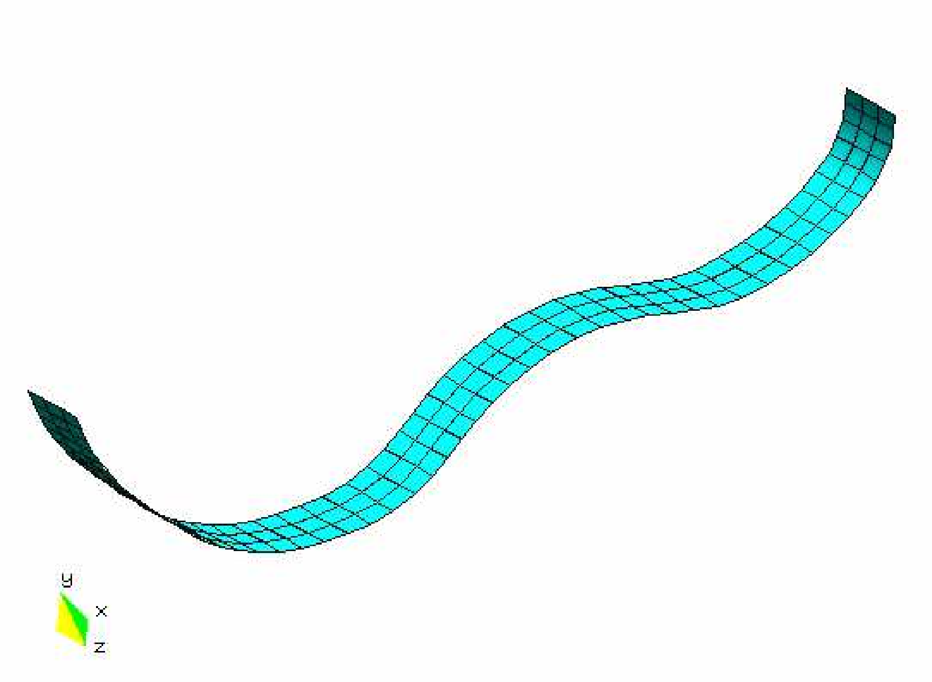


# Applications – large deformations

- surface deformations : flattening

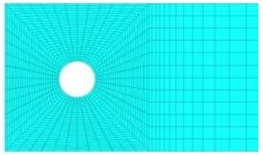




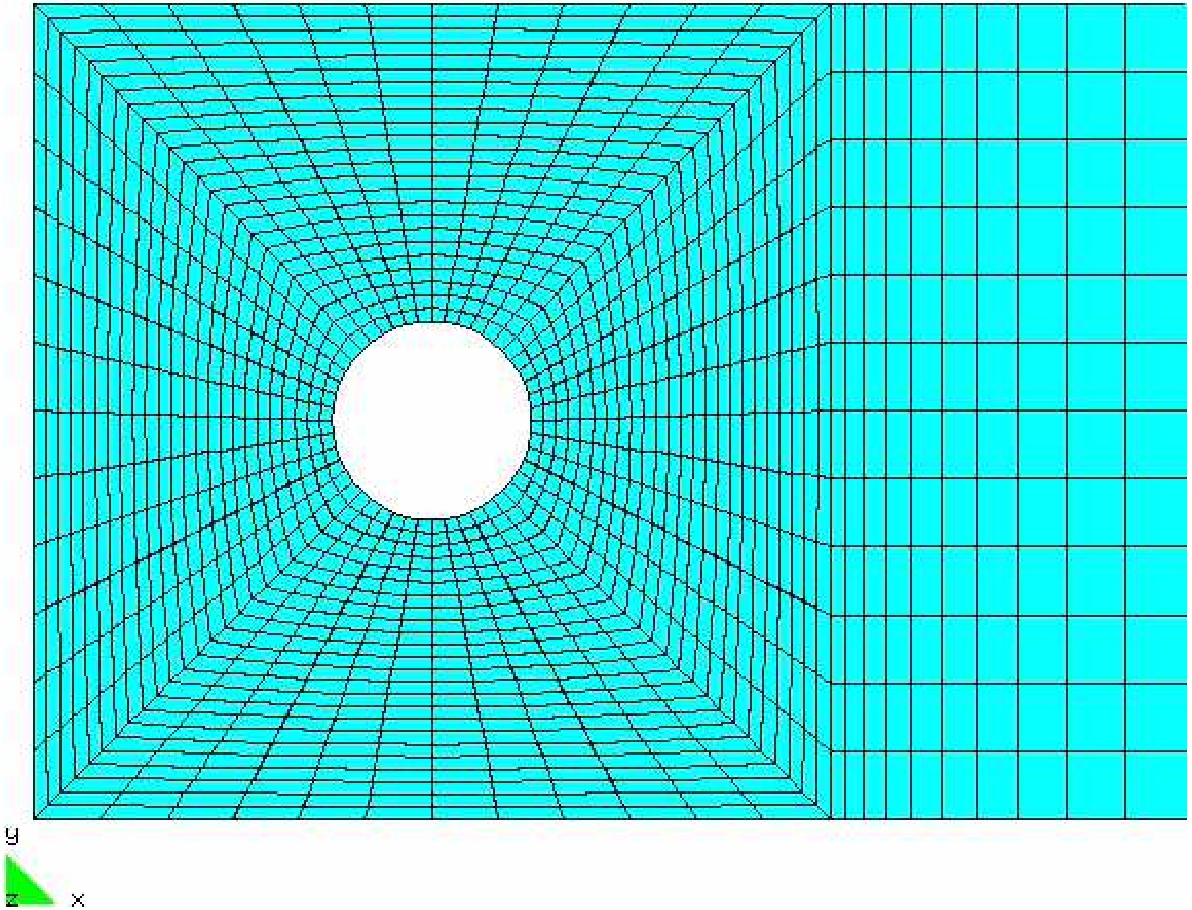



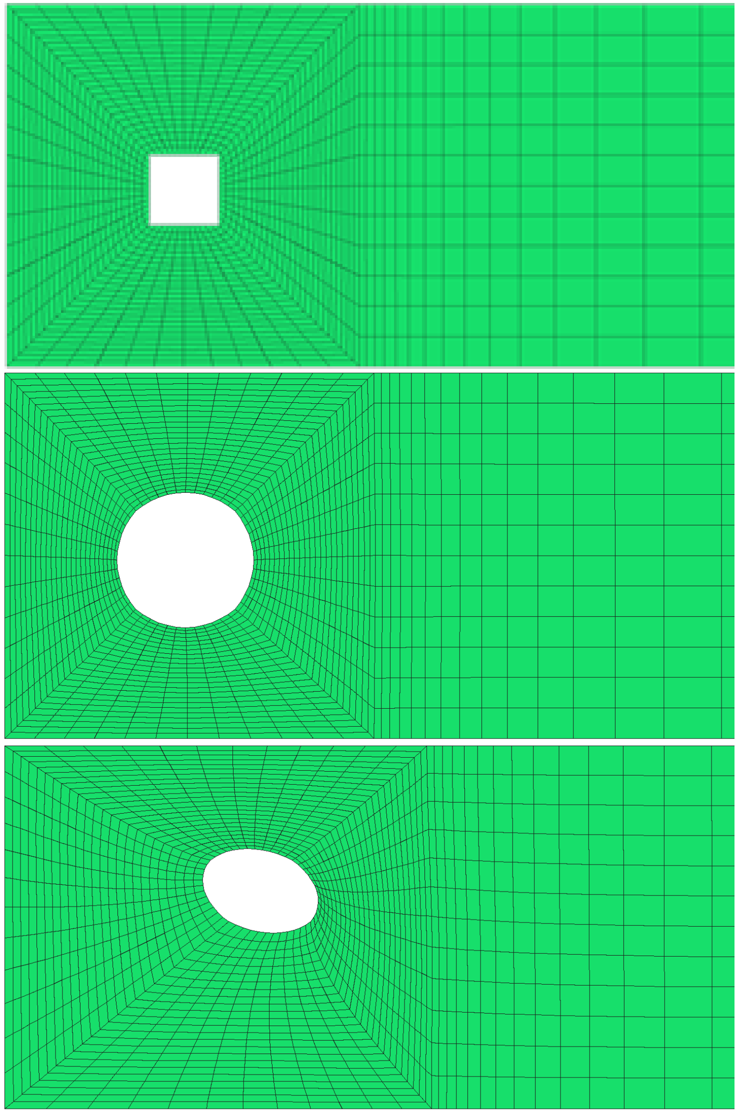
# Applications – large deformations

initial template

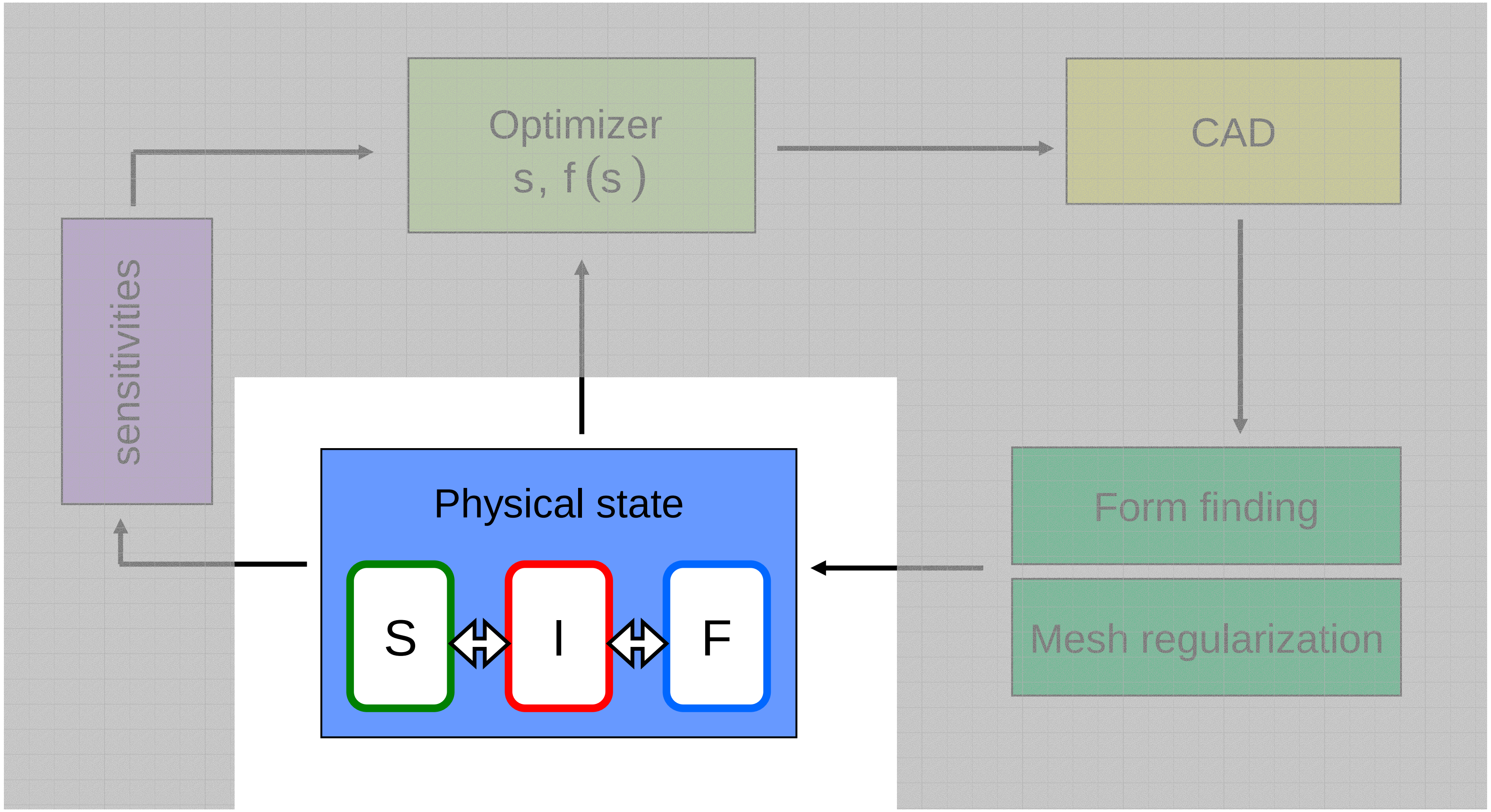


- volume deformations : bulk motion



# Design optimization workflow



# Partitioned FSI environment

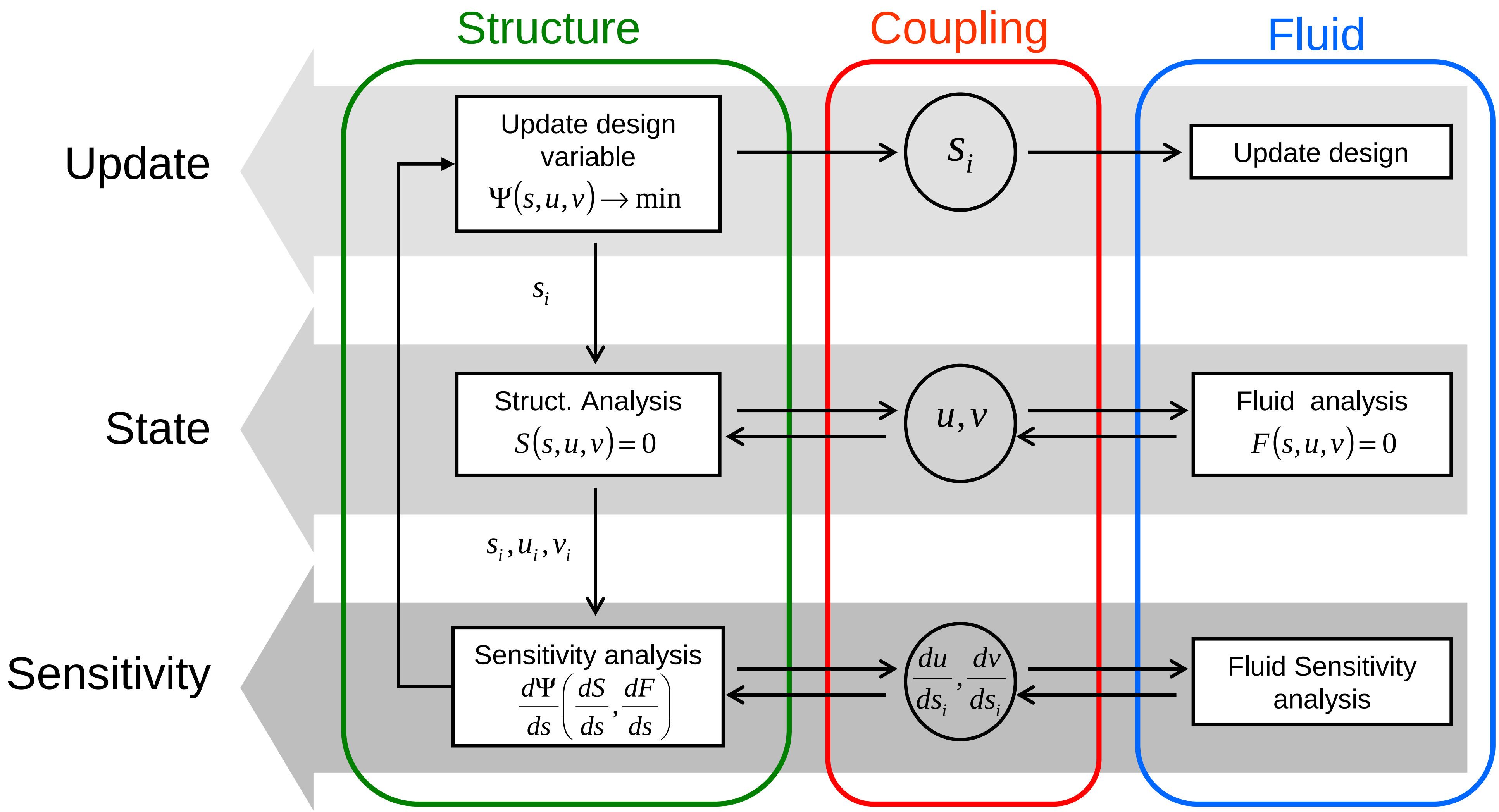
| Structure: | | Interface: | | Fluid: |
|---|---|---|---|---|
| Carat | ↔ | CoMA | ↔ | Open Foam |

- C++ - in-house code
- FE based
- Geometrically nonlinear
- Generalized-$\alpha$ time integration
- Parallel computation

- C++ - in-house code
- Implicit / explicit
- Non-matching grids
  . Fix-point iteration
  . Vector extrapolation
  . Quasi-Newton (*Degroote 2009)*
- Parallel computation

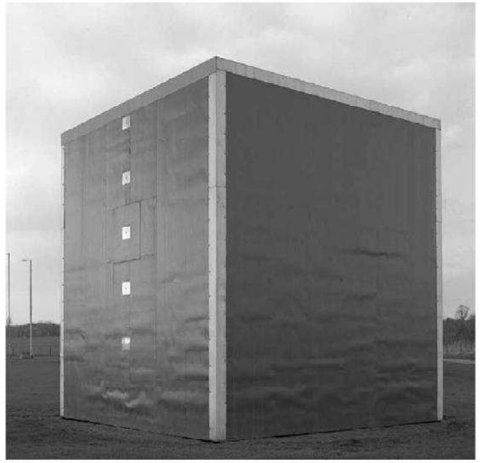
- C++ - Open source
- Finite Volume
- Mesh motion
- Parallel computation

# NAND optimization environment



# Validation example: Wind loads

- Silsoe Cube

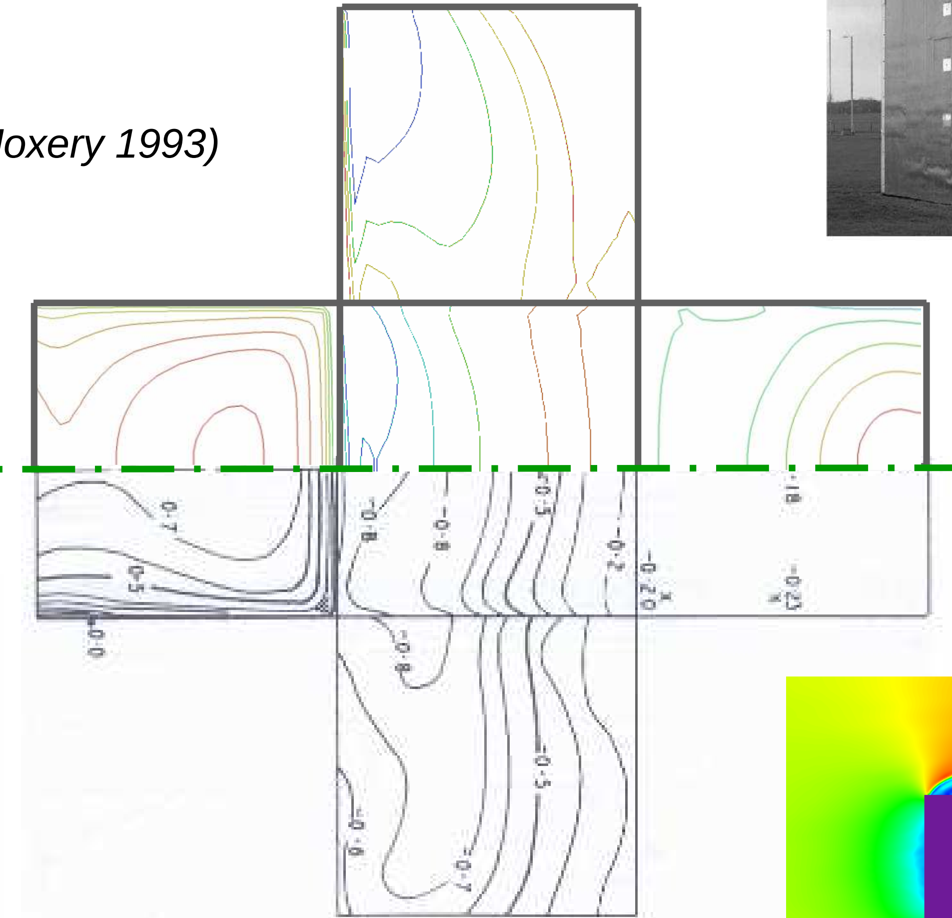


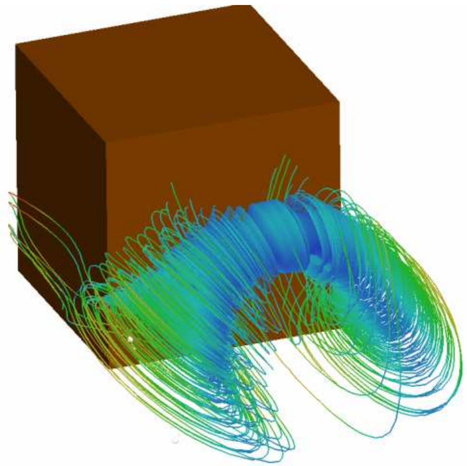
$$\bar{u}(z) = \frac{u^*}{\kappa} \ln\left(\frac{z+z_0}{z_0}\right)$$ *(Richards, Hoxery 1993)*

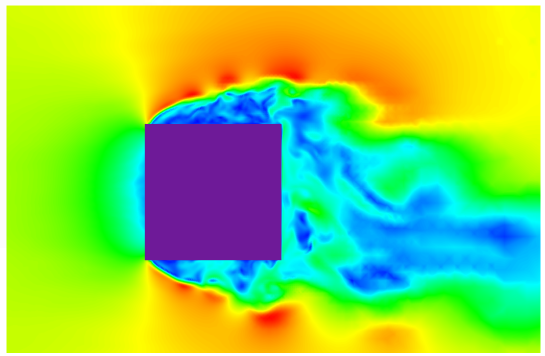
$$k = \frac{u^{*2}}{\sqrt{C_\mu}}, \qquad \varepsilon = \frac{u^{*3}}{k(z+z_0)}$$

$$u^* = \frac{\kappa\, u_{ref}}{\ln\left(\frac{z_{ref}}{z_0}\right)}$$

Simiu,Scanlan







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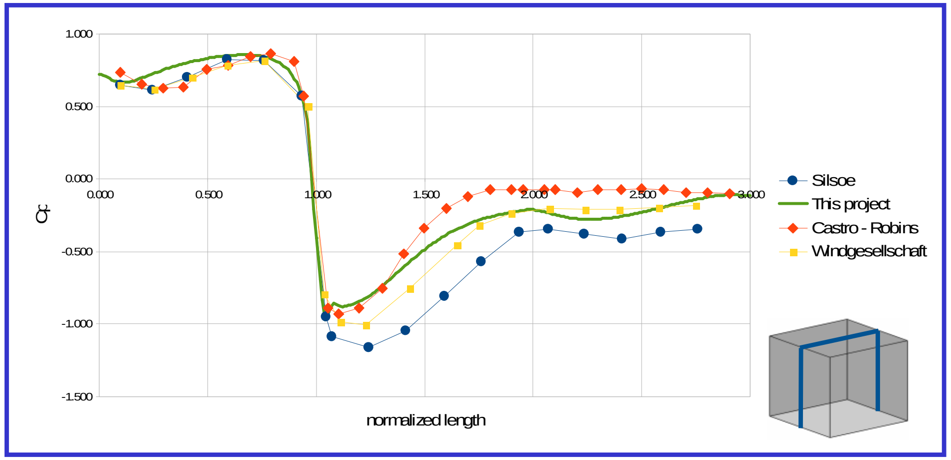
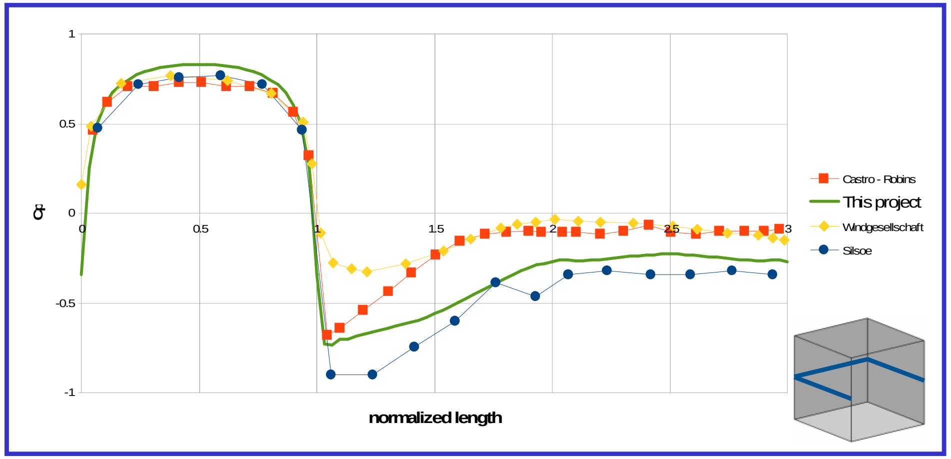
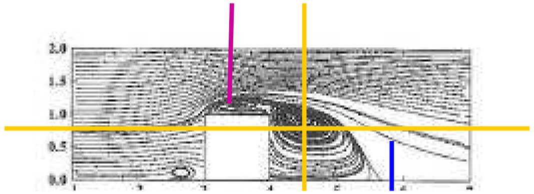


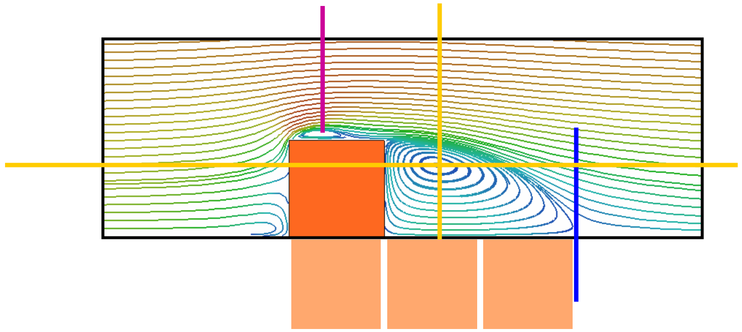




*(Richards, Hoxery 2001)*
*(Castro, Robins 1977)*
*(Hoelscher, Niemann 1998)*

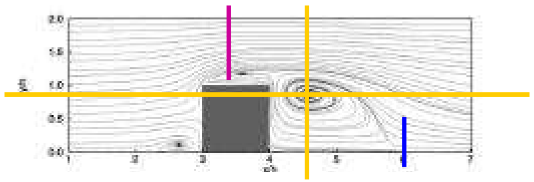
*(Hussain, Maratinuzzi 1996)*



Experimental – Hussain-Maratinuzzi, 1996



*(Icarrino 2003)*

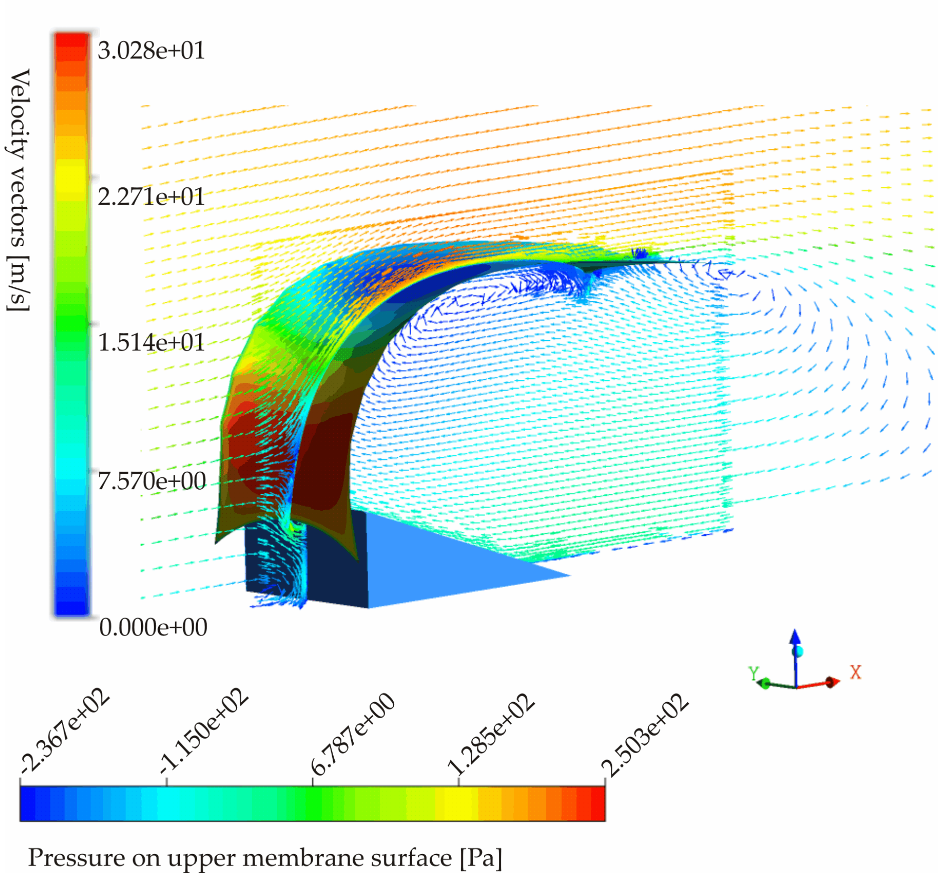


Unsteady RANS – Stanford 2001

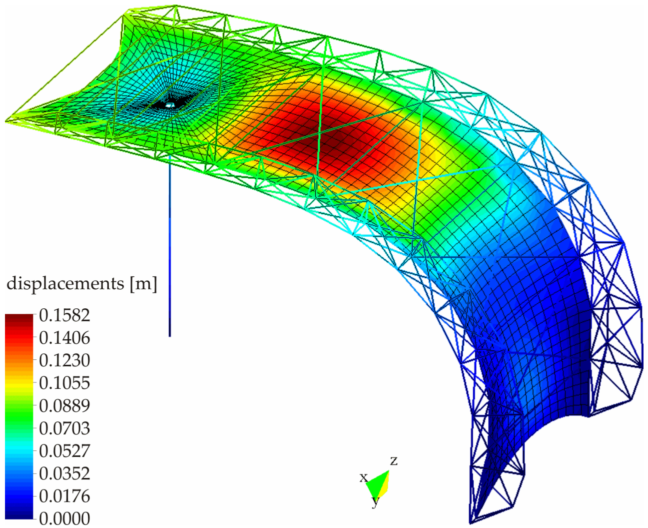
$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho U_\infty^2}$$

# FSI example

- Flexible structure subject to wind



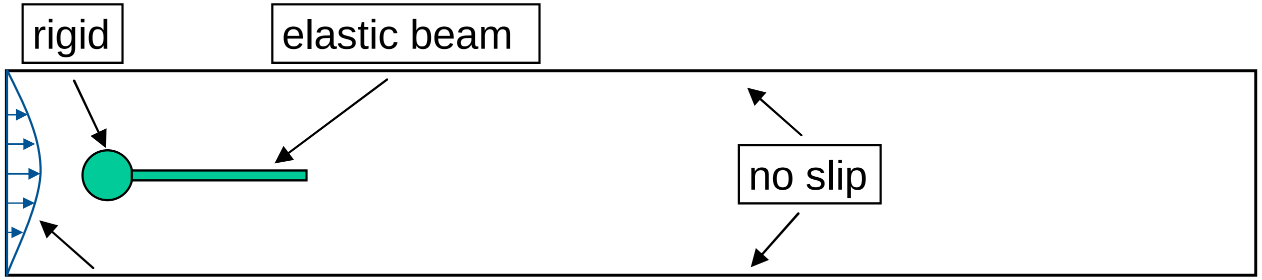

ARIES – mobile - © Gengnagel, 2006

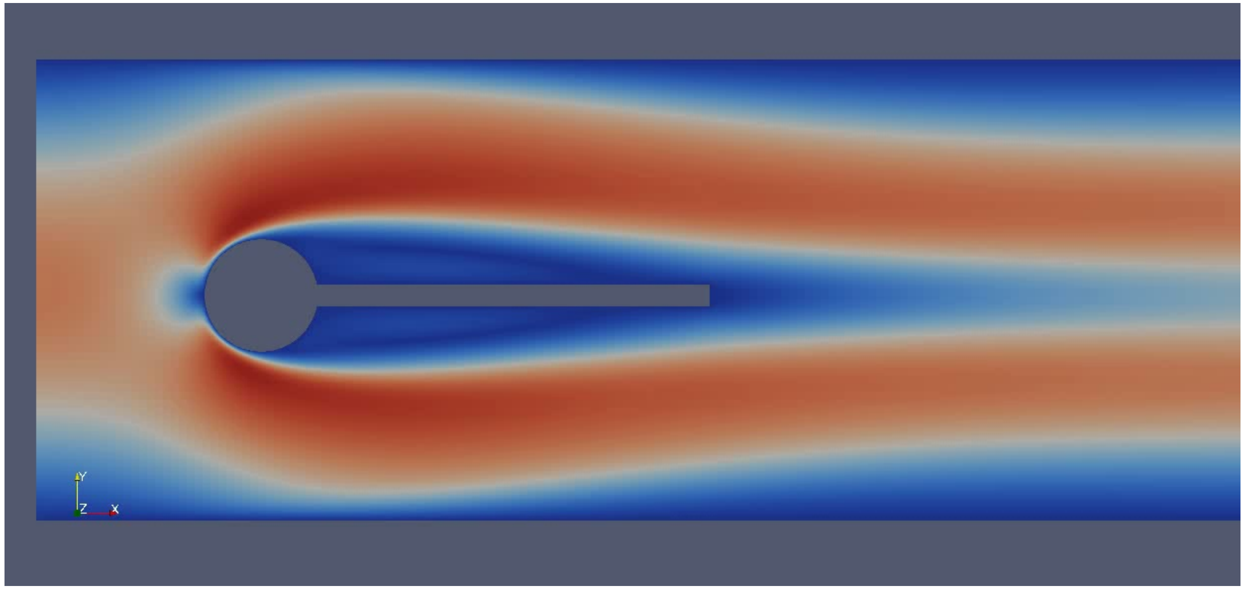


# FSI verification: DFG Benchmark

- Series of simulations for validation purposes:
    - Structure
    - Fluid
    - FSI

- Performed and compared by 11 Institutes

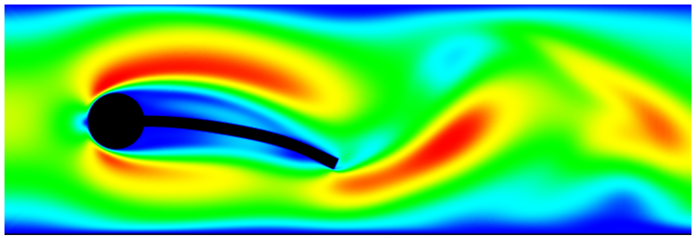


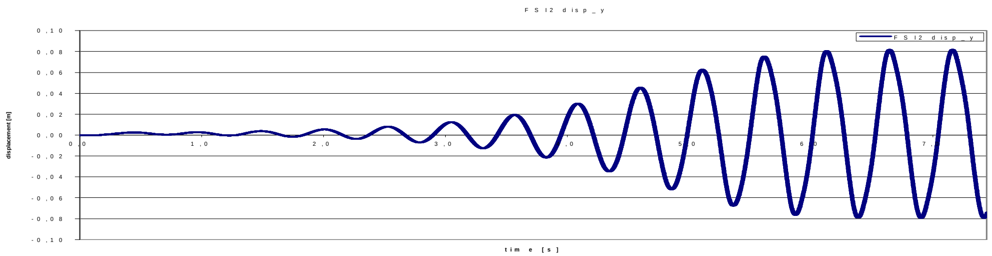



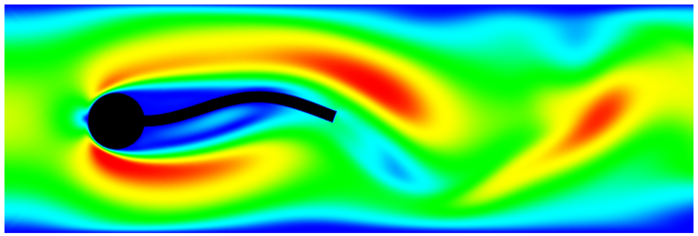
# FSI verification: DFG Benchmark

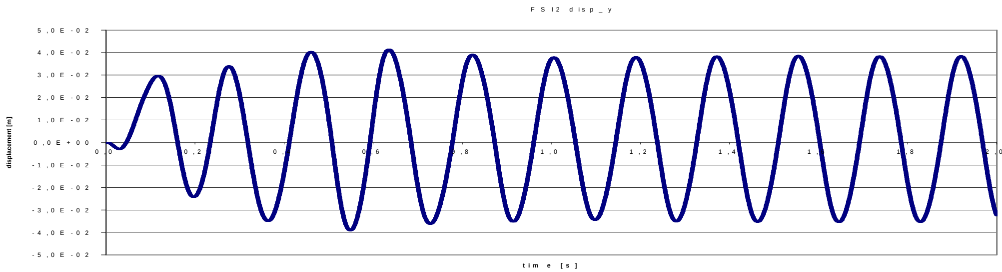
*(Turek 2006)*

| | *difference* | | *difference* | | *difference* |
|---|---|---|---|---|---|
| CSD 1 | 0.00 [%] | CFD 1 | 0.18 [%] | FSI 1 (Steady state) | 2.55 [%] |
| CSD 2 | 0.00 [%] | CFD 2 | 0.85 [%] | FSI 2 (Transient) | 3.45 [%] |
| CSD 3 | 0.45 [%] | CFD 3 | 1.72 [%] | FSI 3 (Transient – Strongly coupled) | 1.02 [%] |







# Coupling algorithm Quasi-Newton [1]

- Alternative to fixed-point iteration

Approximate new residual increment based on known increments:

$$\Delta \mathbf{R} = -\mathbf{R}^{\Gamma,k} \approx \sum_{i=1}^{k-1} \alpha_i^k \Delta \mathbf{R}^{\Gamma,i}$$

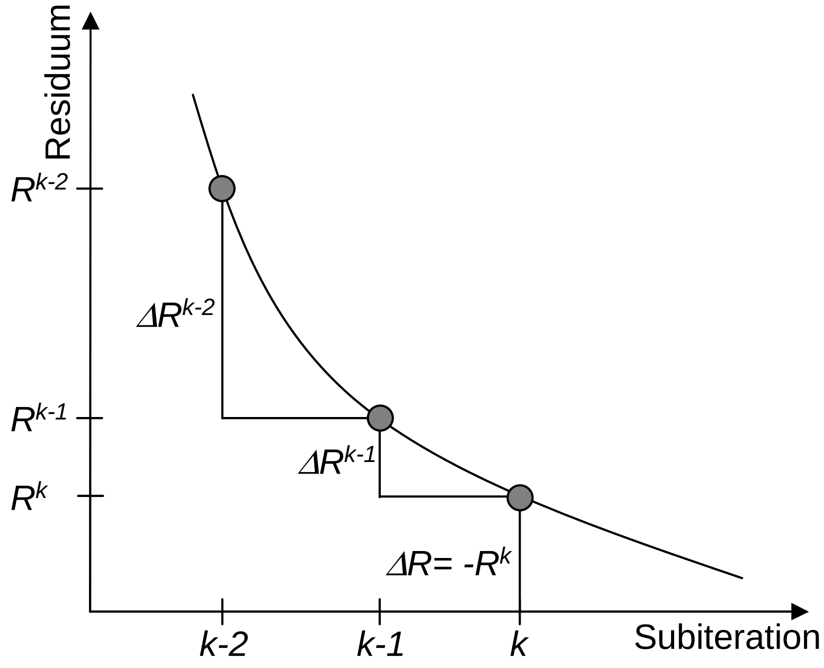
solve the EQS → linear coefficients $\alpha_i^k$

Determine new interface displacement increment:

$$\Delta \mathbf{d}^{\Gamma} = \sum_{i=1}^{k-1} \alpha_i^k \Delta \tilde{\mathbf{d}}^{\Gamma,i} - \Delta \mathbf{R}$$

Update the interface position:

$$\mathbf{d}^{\Gamma,k+1} = \mathbf{d}^{\Gamma,k} + \Delta \mathbf{d}^{\Gamma,k}$$



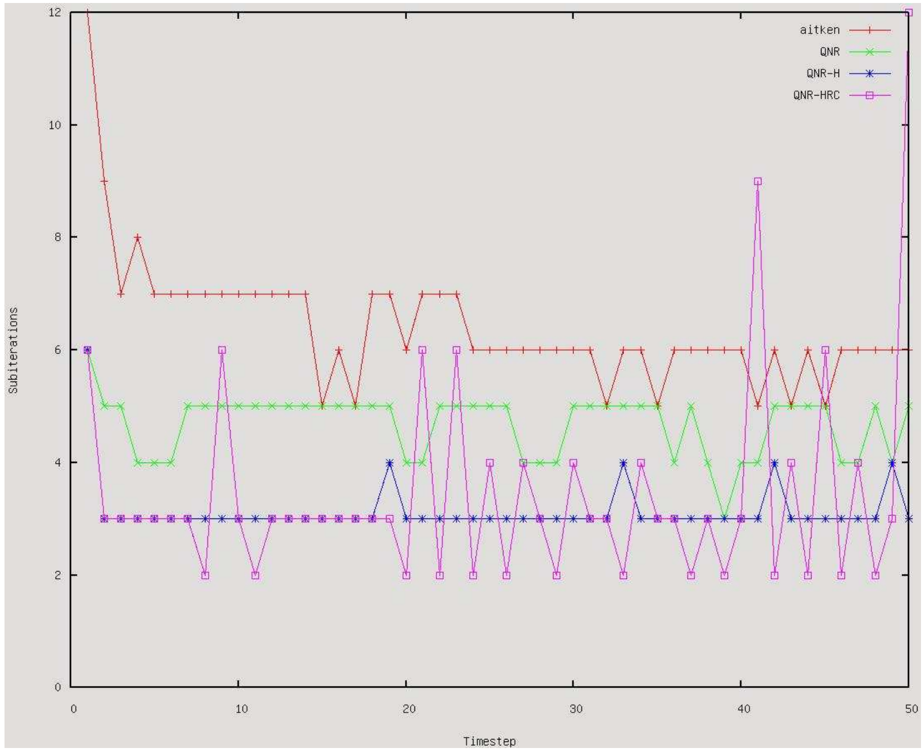

*[1]: Degroote, Bathe and Vierendeels: Performance of a new partitioned procedure versus a monolithic procedure in fluid-structure interaction, Computers & Structures, Vol 87, 2009*

# Comparison QNR vs. fixed Point – FSI2

***basic settings:***

- examine first 100 timesteps
- relative convergence criterion: $\varepsilon \le 1.0e^{-04}$
- timestep: =0.0005 [s]  (maxCo≈0.8)
- predictor: Newmark 2nd order

| Type | mean iter | Reduction [%] |
|---|---|---|
| Const. (ω=0.2) | 35 | +464.0 |
| Aitken | 6.4 | 0.0 |
| Basic QNR | 4.68 | -26.9 |
| QNR-H | 3.26 | -49.0 |
| QNR-HRC | 3.14 | -50.4 |

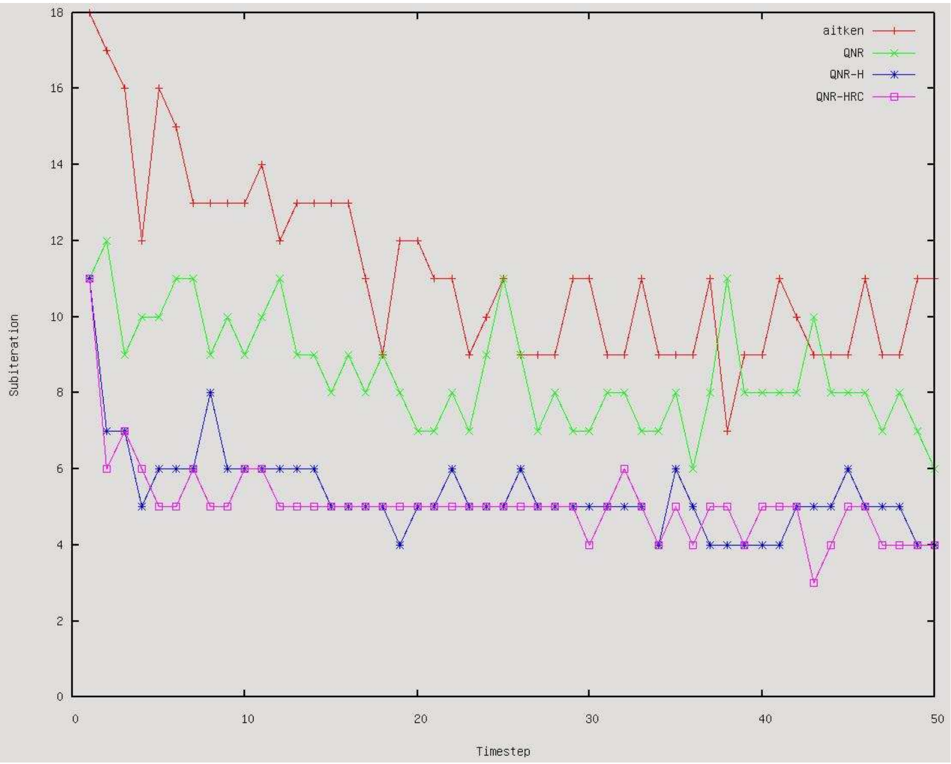


# Comparison QNR vs. fixed Point – FSI3

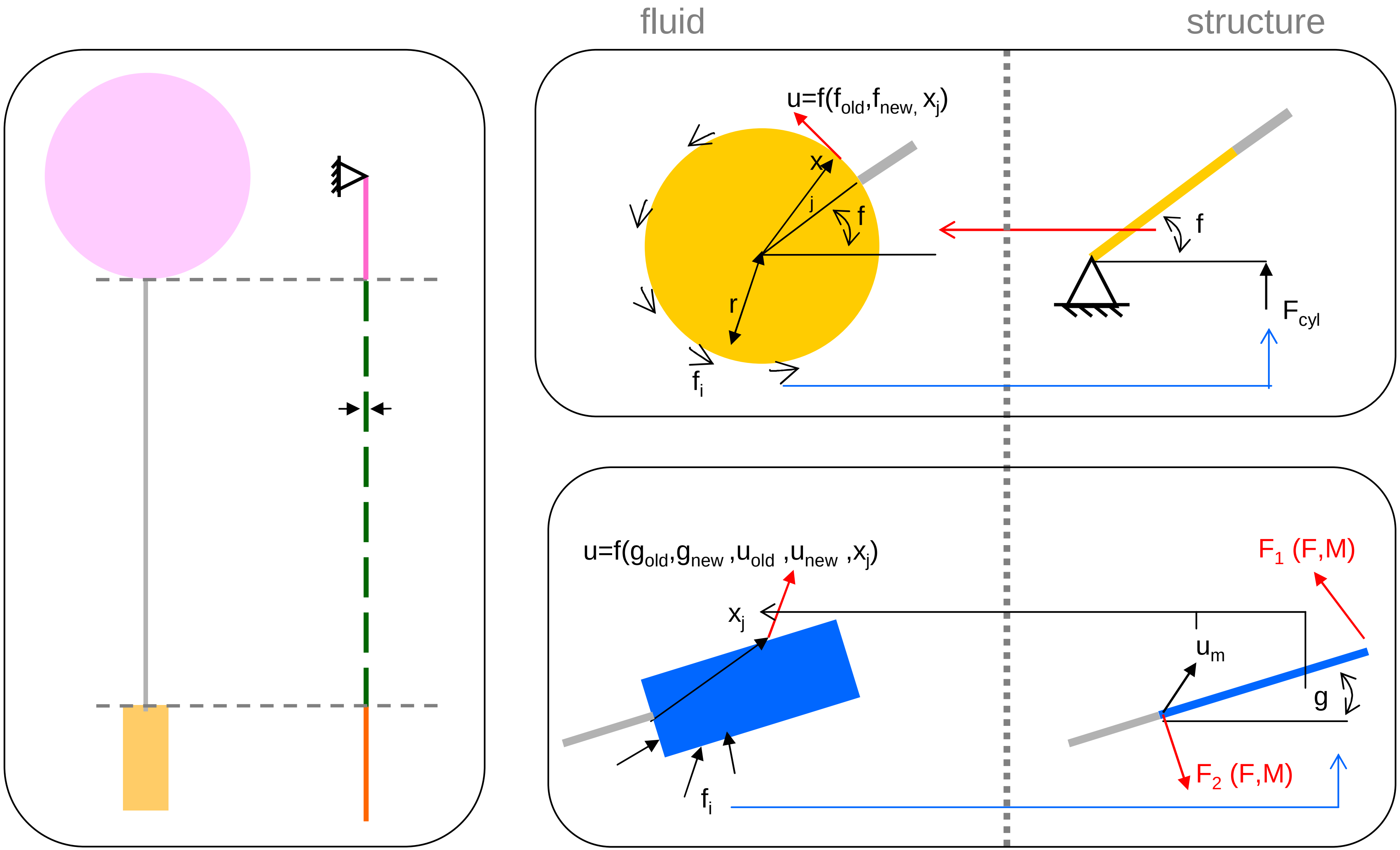
***basic settings:***

- examine first 100 timesteps
- relative convergence criterion: $\varepsilon <= 1.0e^{-04}$
- timestep: =0.0002 [s]  (maxCo≈0.4)
- predictor: Newmark 2$^{nd}$ order

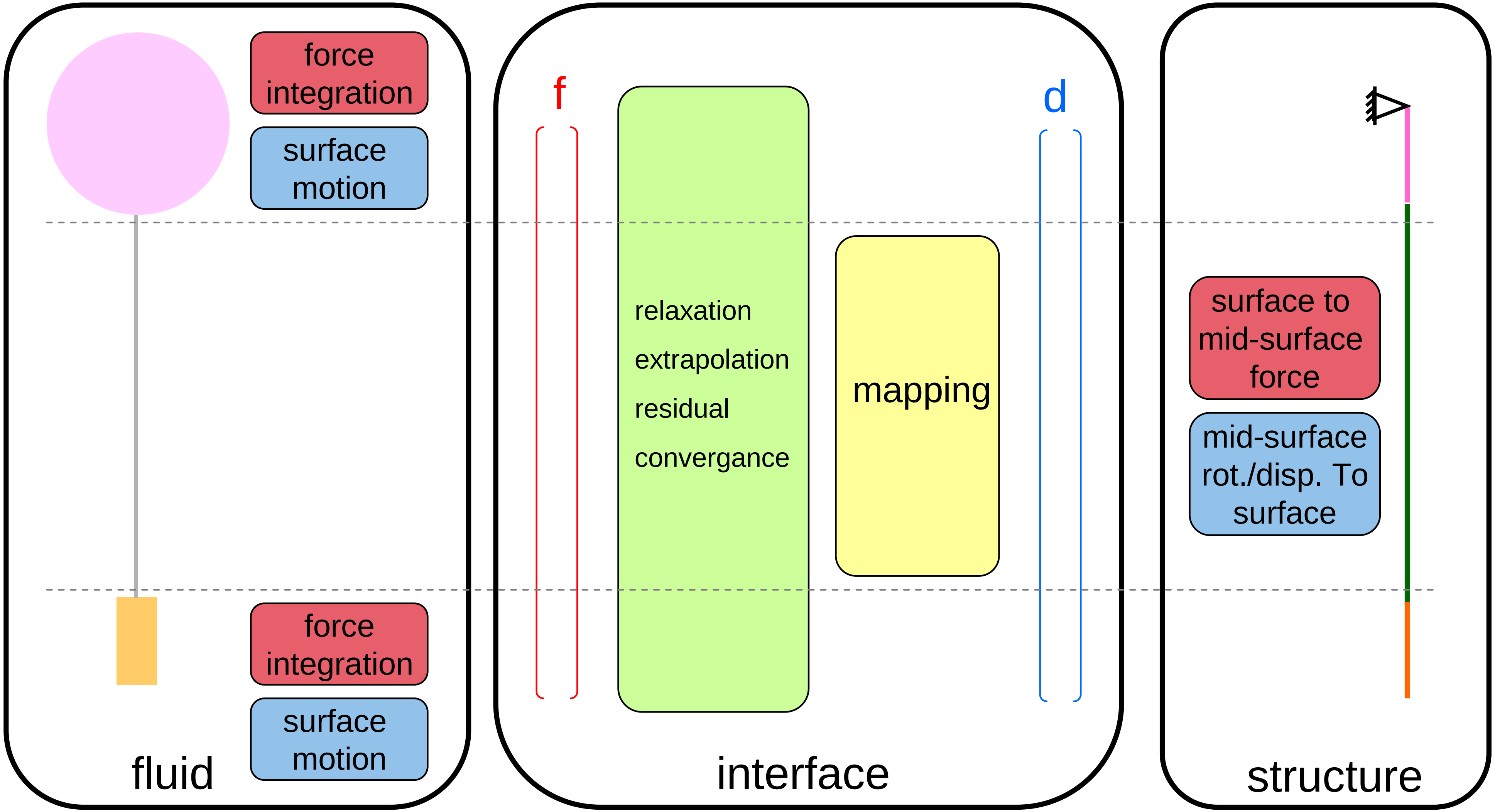
| Type | mean iter | Reduction [%] |
|---|---|---|
| Const. (ω=0.2) | - | - |
| Aitken | 11.2 | 0.0 |
| Basic QNR | 8.54 | -23.8 |
| QNR-H | 5.34 | -52.3 |
| QNR-HRC | 5.06 | -54.8 |



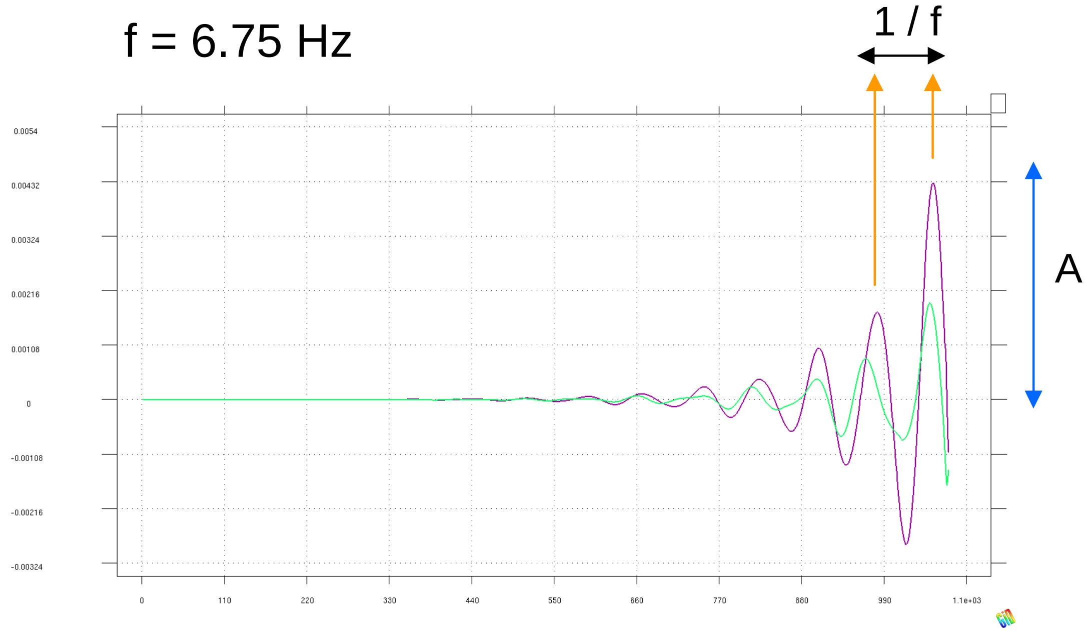
# Benchmarking – Experimental benchmark

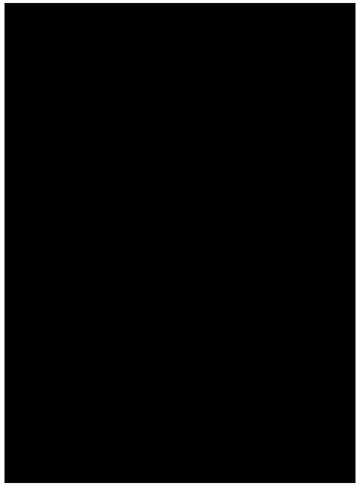


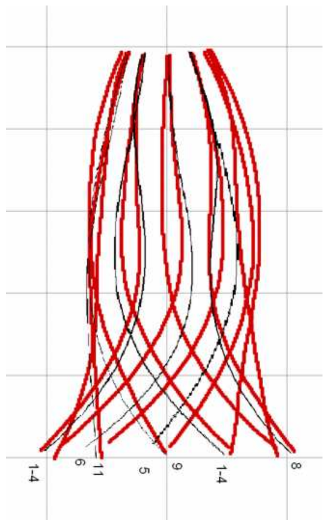
# Benchmarking – Experimental benchmark

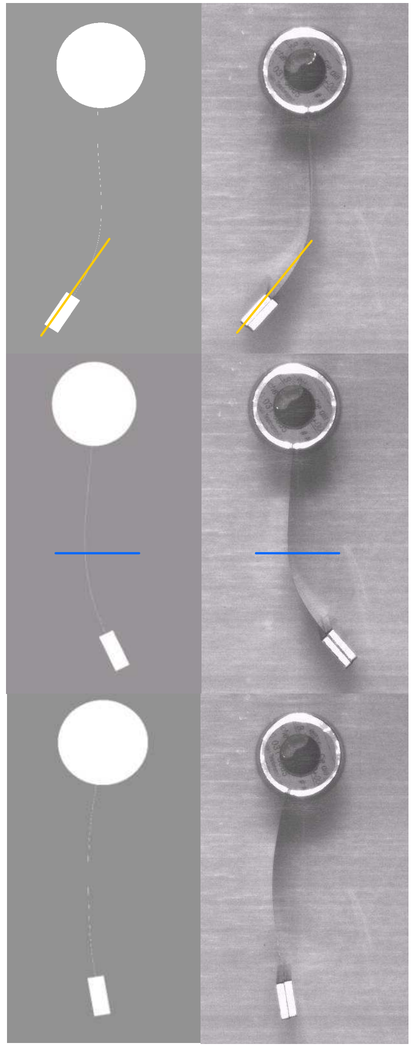


# Benchmarking – Experimental benchmark

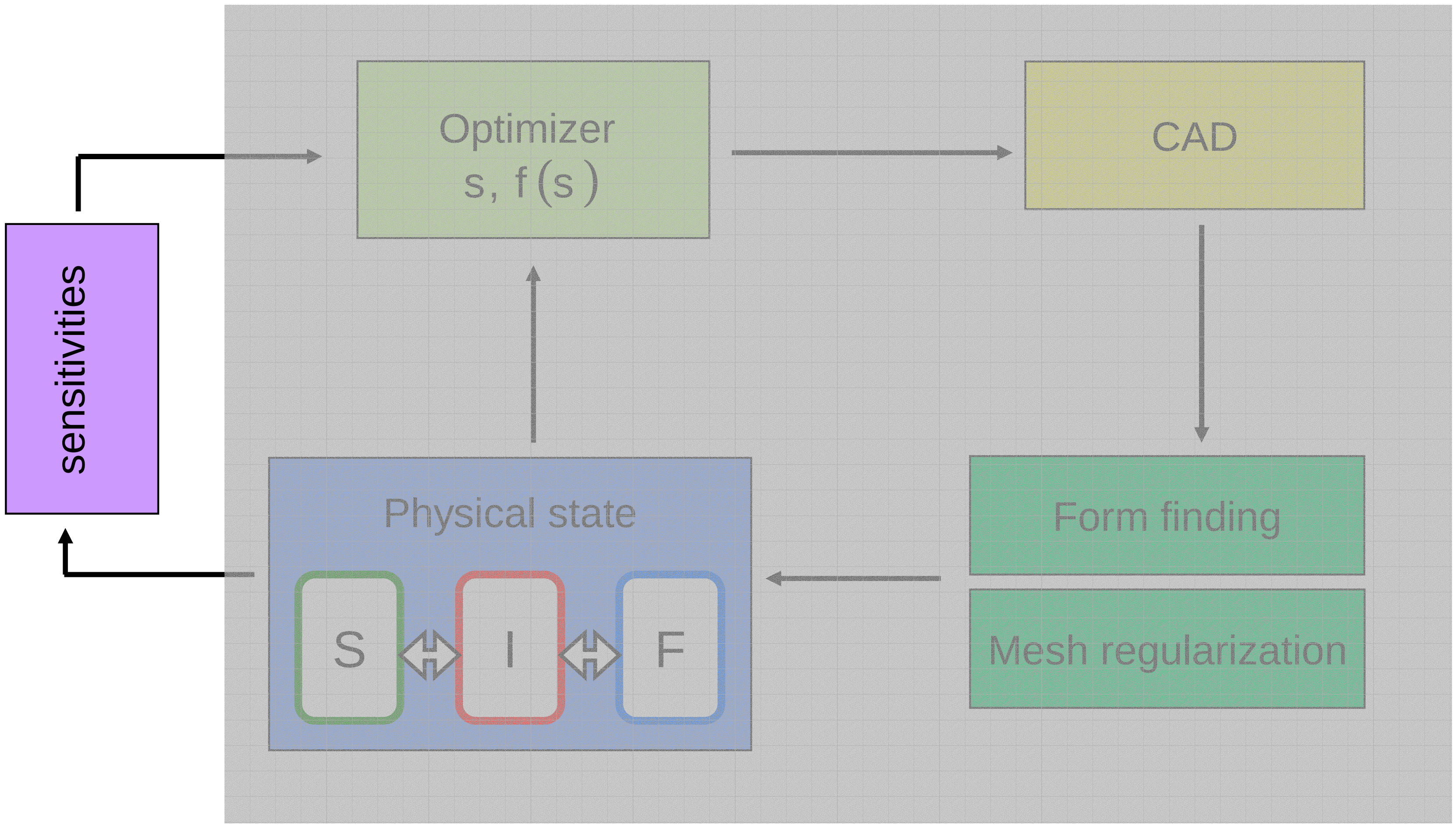




# Design optimization work flow



# Sensitivity Analysis

*(Sobieszcanski-Sobieski 1990)*

$$\begin{cases} S(u,v,s)=0 \\ F(u,v,s)=0 \end{cases}$$

State equations

$$\Psi = \Psi(u,v)$$

$$\frac{d\Psi}{ds} = \frac{\partial\Psi}{\partial u}\frac{du}{ds} + \frac{\partial\Psi}{\partial v}\frac{dv}{ds} + \frac{\partial\Psi}{\partial s}$$

Objective (target) function

$$\begin{cases} \dfrac{dS}{ds} = \dfrac{\partial S}{\partial u}\dfrac{du}{ds} + \dfrac{\partial S}{\partial v}\dfrac{dv}{ds} + \dfrac{\partial S}{\partial s} = 0 \\ \dfrac{dF}{ds} = \dfrac{\partial F}{\partial u}\dfrac{du}{ds} + \dfrac{\partial F}{\partial v}\dfrac{dv}{ds} + \dfrac{\partial F}{\partial s} = 0 \end{cases}$$

Sensitivity equations

$$\begin{bmatrix} \dfrac{\partial S}{\partial u} & \dfrac{\partial S}{\partial v} \\ \dfrac{\partial F}{\partial u} & \dfrac{\partial F}{\partial v} \end{bmatrix} \begin{bmatrix} \dfrac{du}{ds} \\ \dfrac{dv}{ds} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial S}{\partial s} \\ \dfrac{\partial F}{\partial s} \end{bmatrix}$$

Fluid-Structure coupled sensitivities

# Sensitivity Analysis - Algorithm

FSI

$$S(u_0, v_0, s_0) = 0 \qquad F(u_0, v_0, s_0) = 0$$

sensitivity

structure

$$\frac{du}{ds} = \left(\frac{dS}{du}\right)^{-1}\left(\frac{\partial S}{\partial v}\frac{dv}{ds} + \frac{\partial S}{\partial s}\right)$$

$$\frac{dv}{ds} \approx \frac{v_i - v_0}{\Delta s}$$

$$u_i = u_0 + \frac{du}{ds}\Delta s = u_0 + \Delta u$$

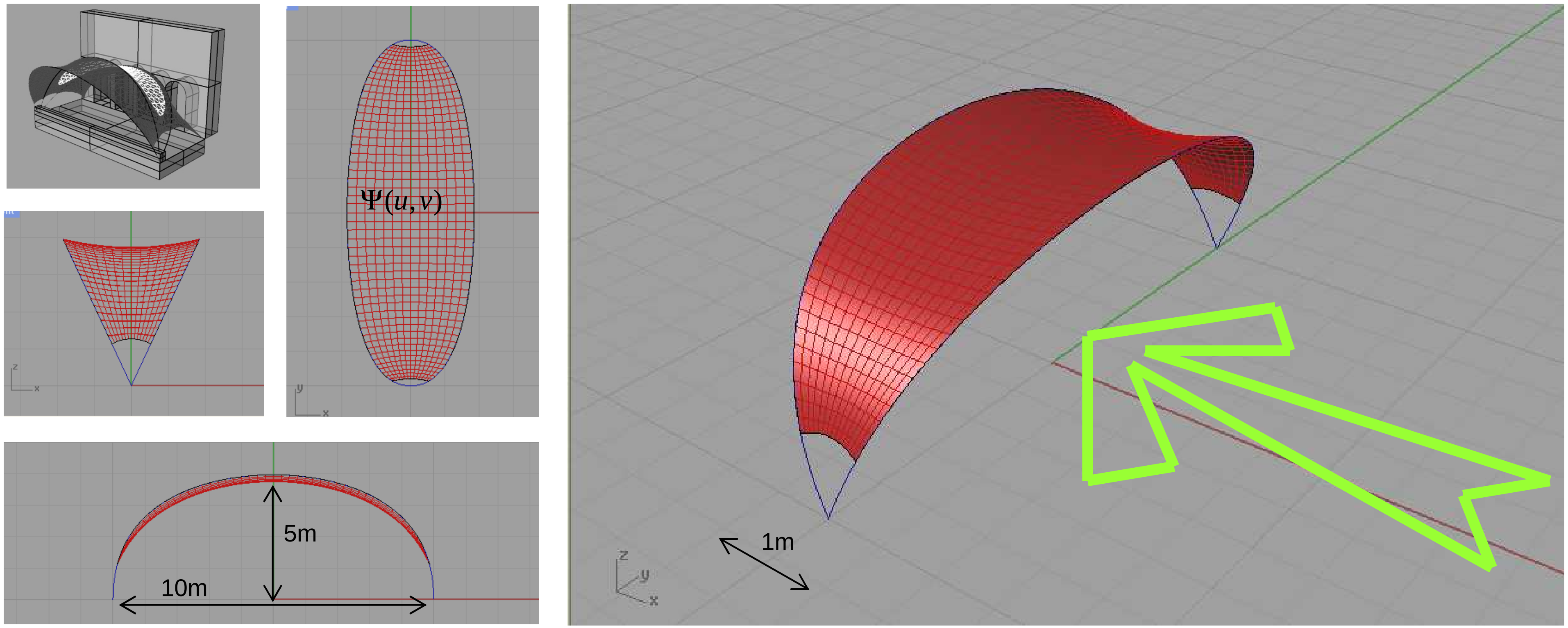
fluid

$$v_i = v(u_0 + \Delta u, z_0 + \Delta z)$$

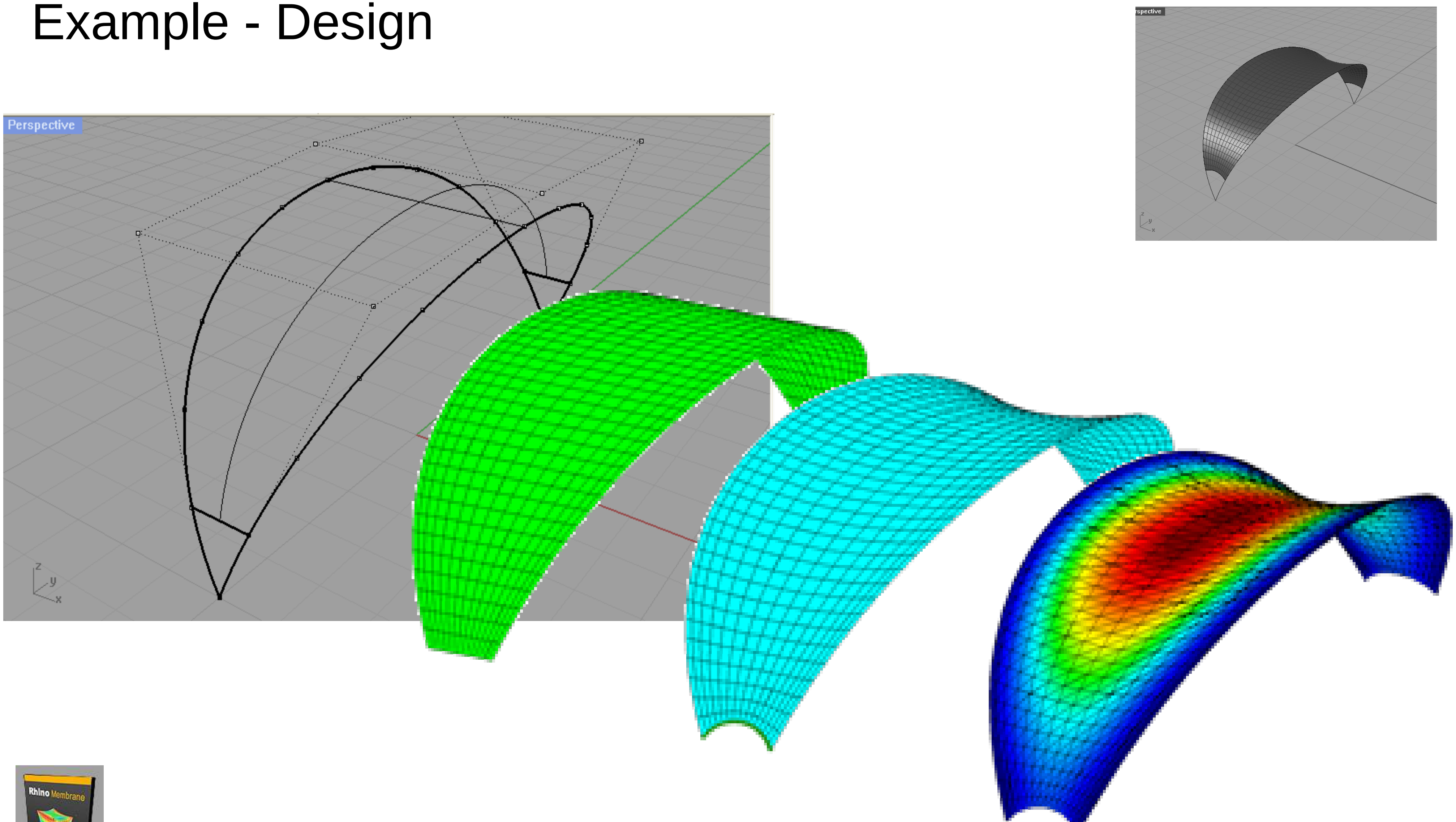
# Example – The Banana structure

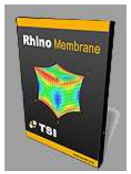
Design variable: Geometry of the supporting frames, NURBS

Objective: Multi objective design (lift and drag forces)



# Example - Design

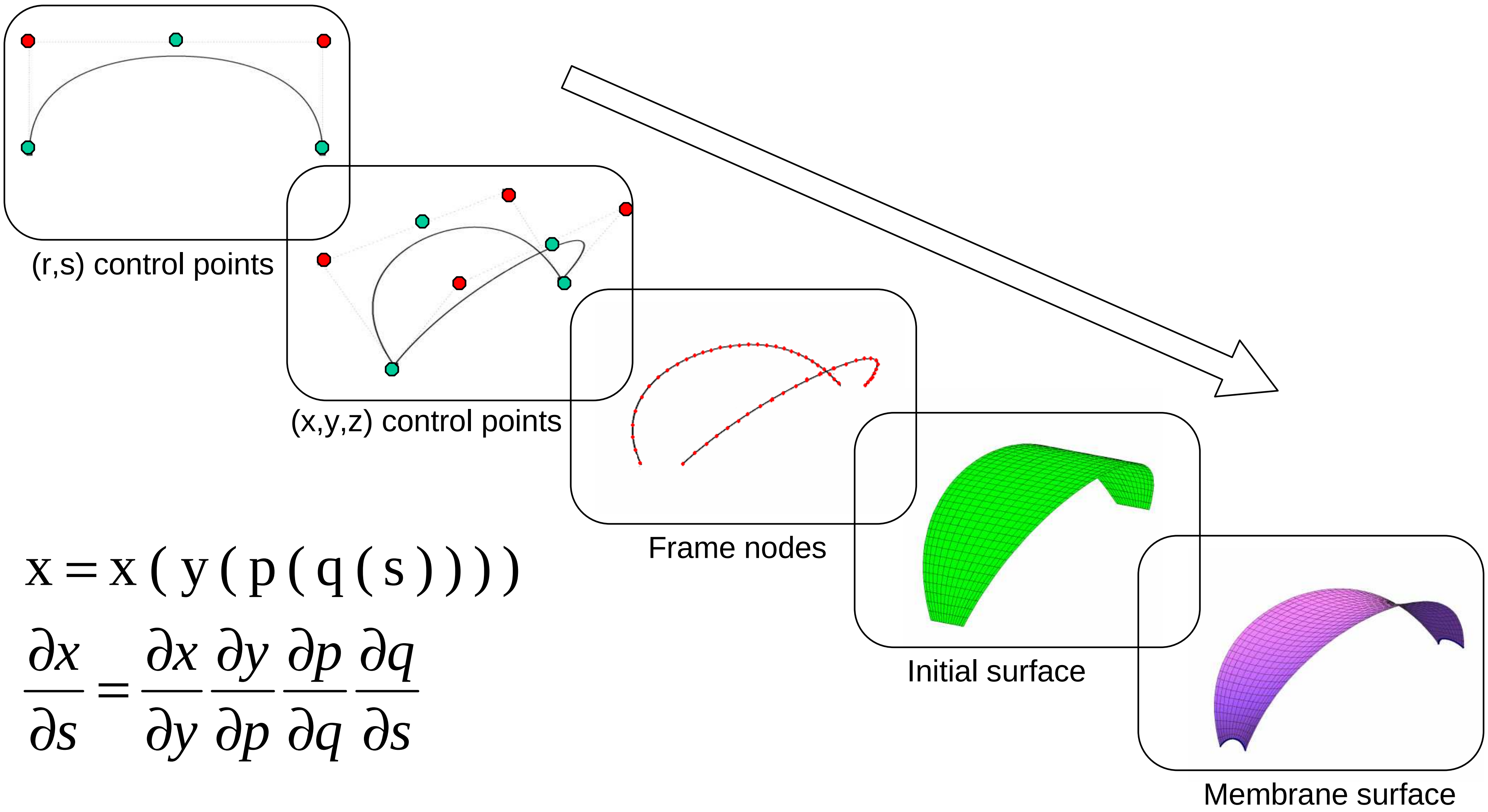



CAD - Rhino membrane

FE - Carat

# Example – Design and state variables

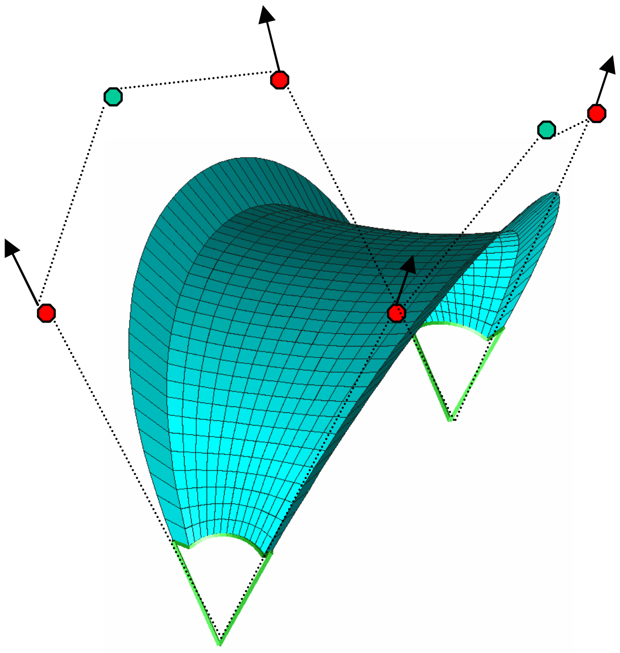



$$x = x(y(p(q(s))))$$

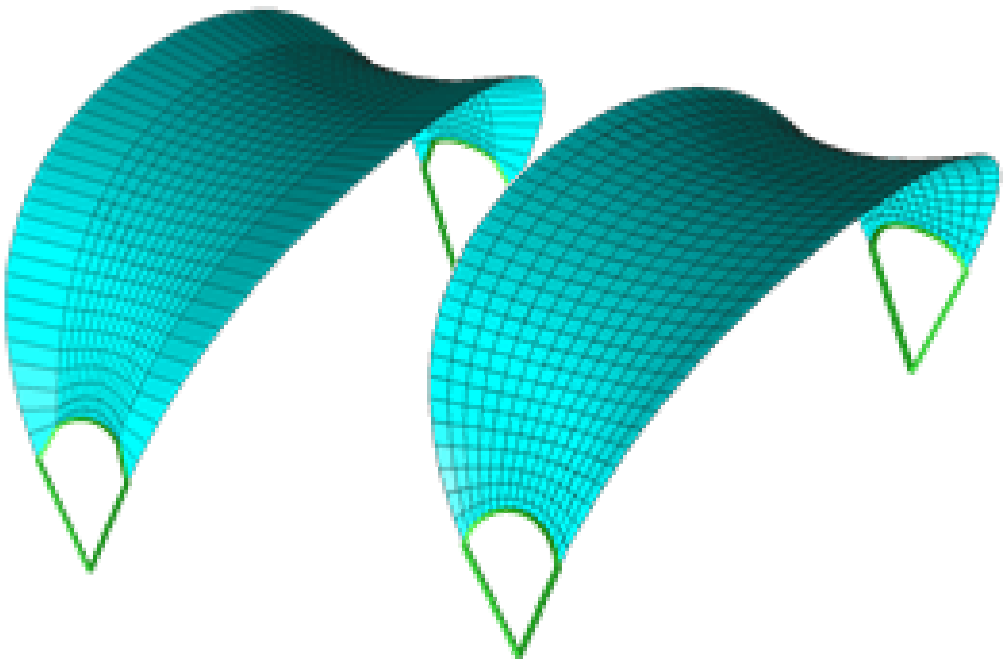
$$\frac{\partial x}{\partial s} = \frac{\partial x}{\partial y}\frac{\partial y}{\partial p}\frac{\partial p}{\partial q}\frac{\partial q}{\partial s}$$

# Example – Mesh regularization

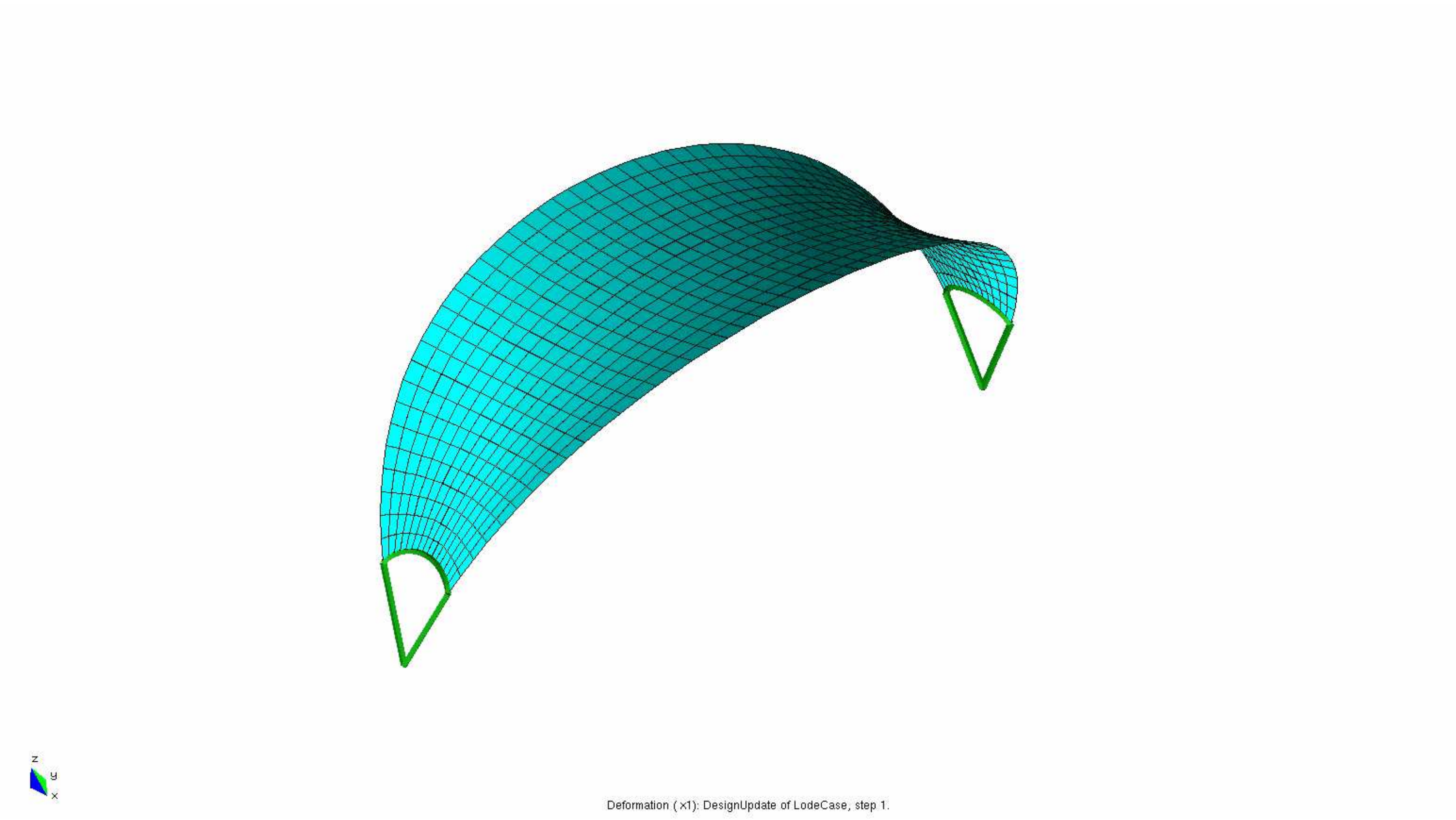
## Design update



## Mesh regularization



# Example – Design, geometry



# Example – Definition of the physical state

Structure:

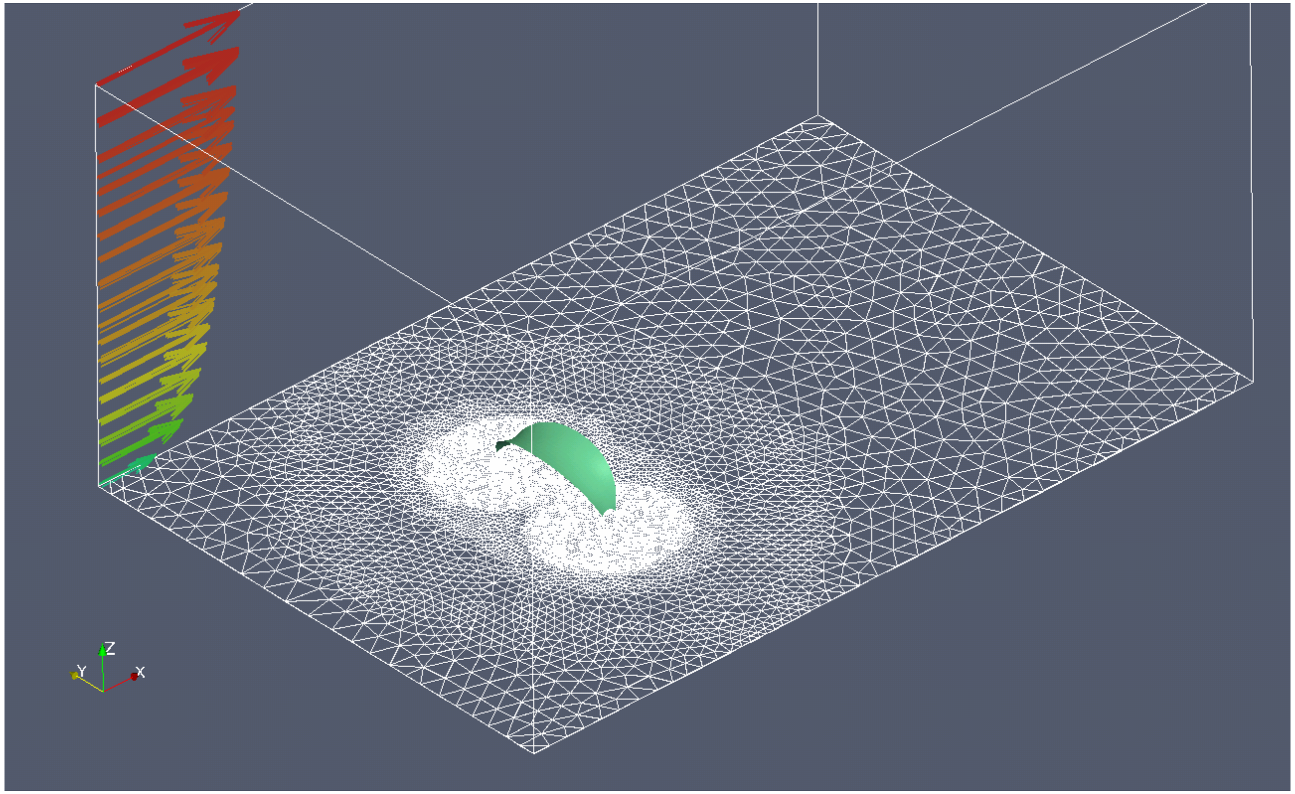
- membrane, cable
- static nonlinear

Fluid:

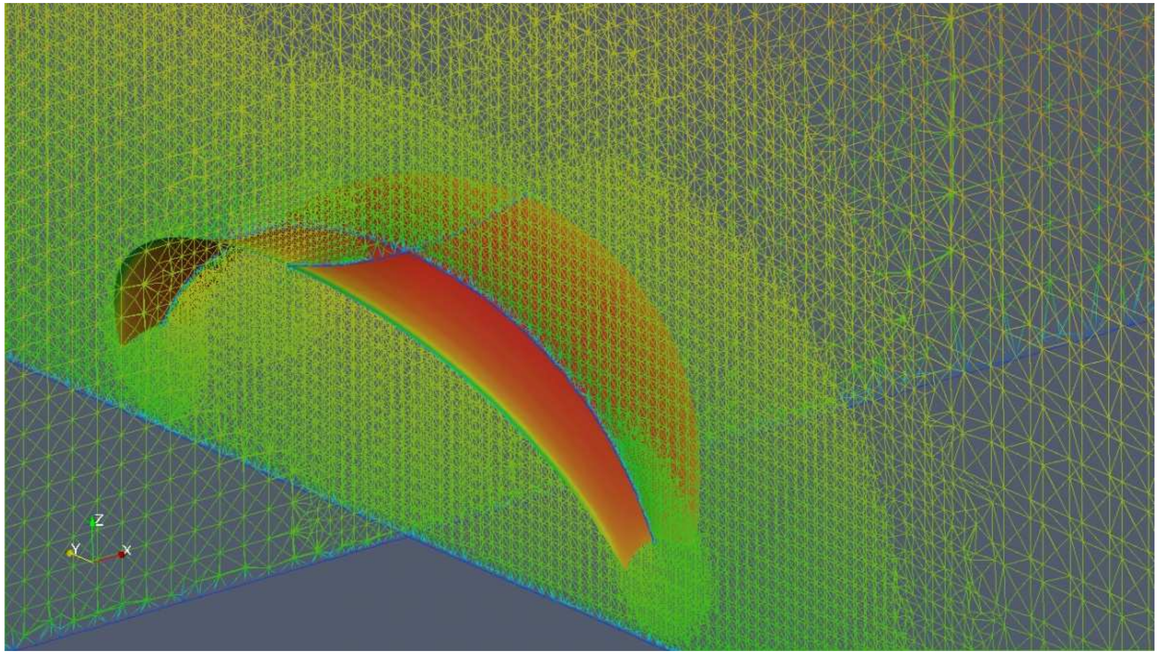
- RANS k-omega SST

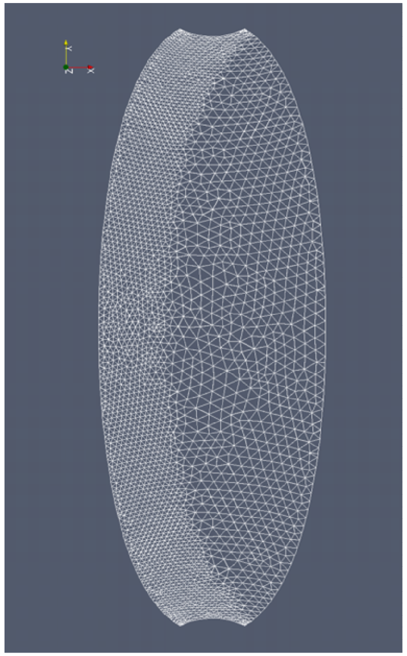
*(Menter 1994)*

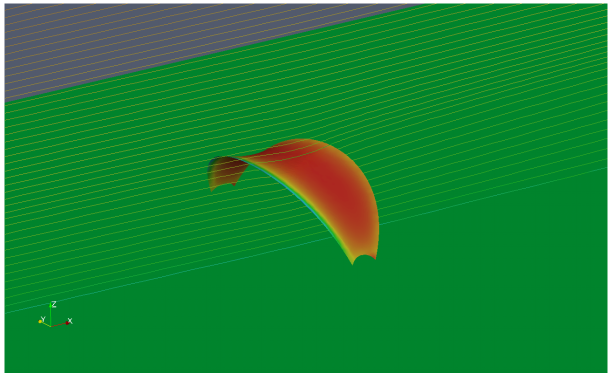
- ABL inlet
- small blockage

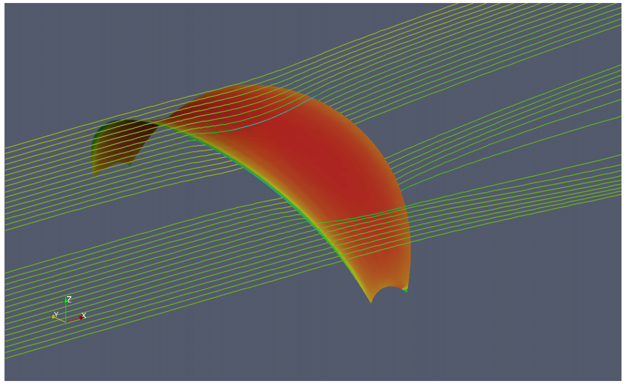


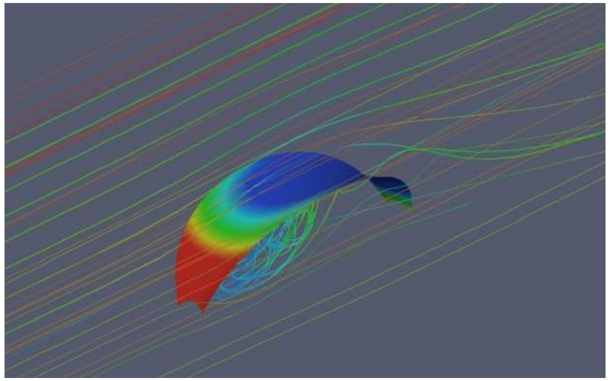
# Example – Fluid field



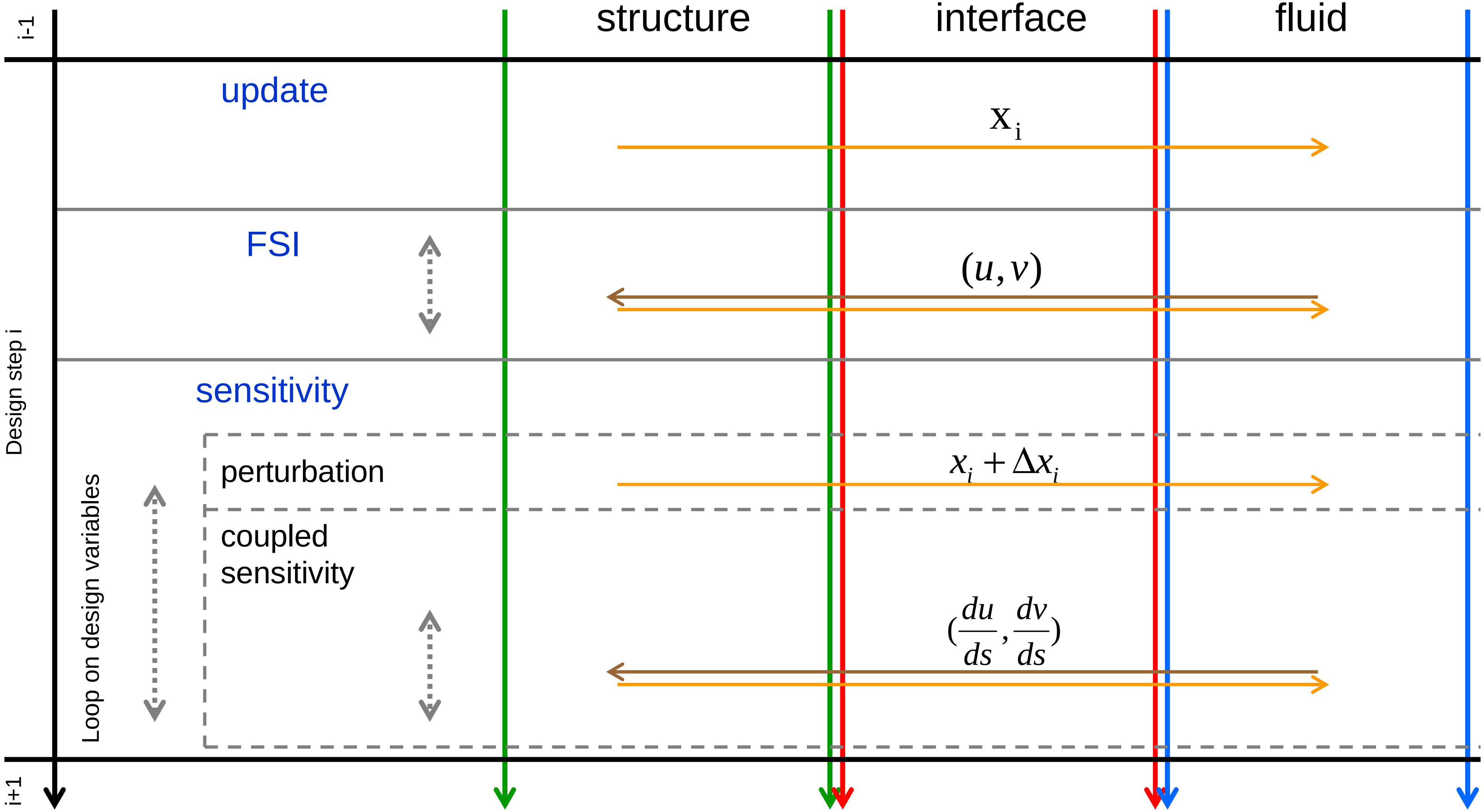






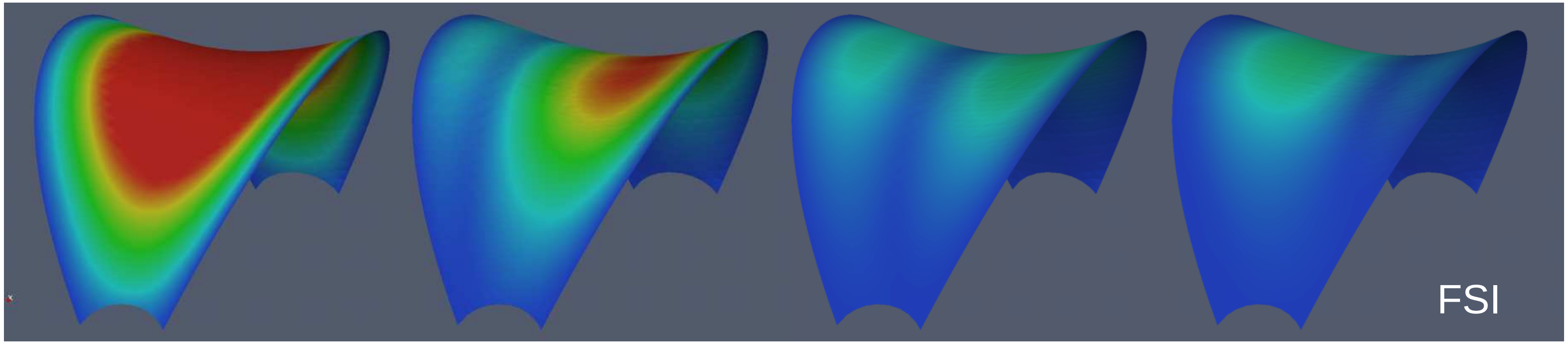


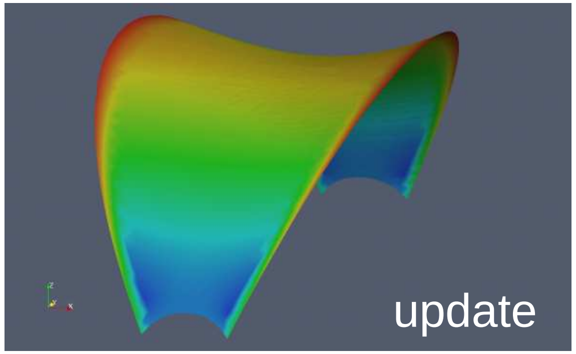
# Example – Design optimization loop

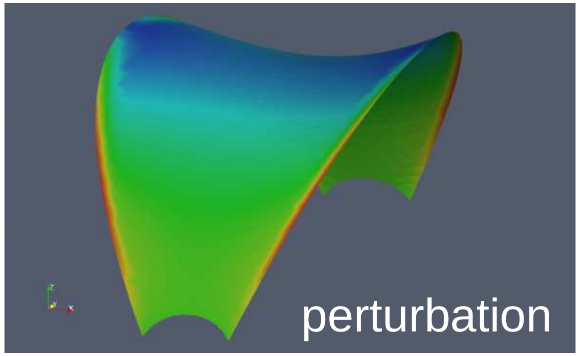


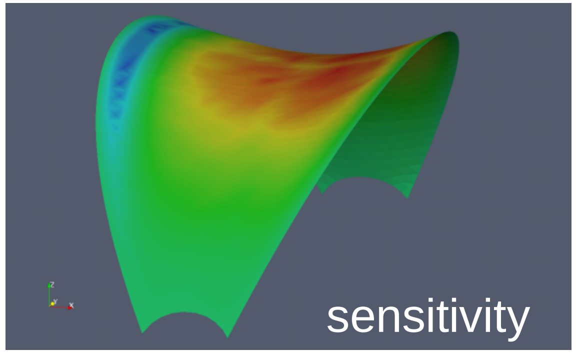
# Example – solution

Motion

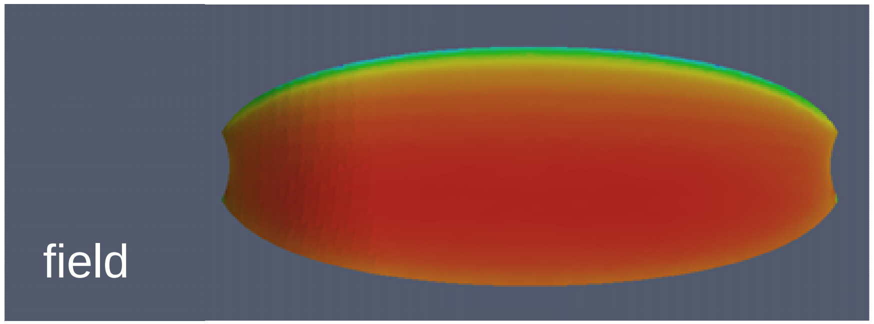


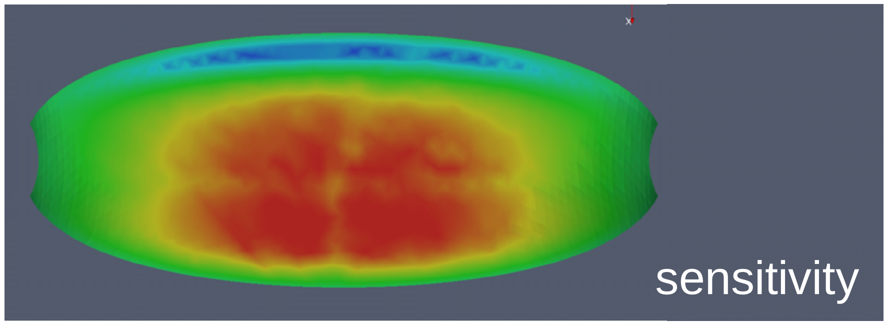



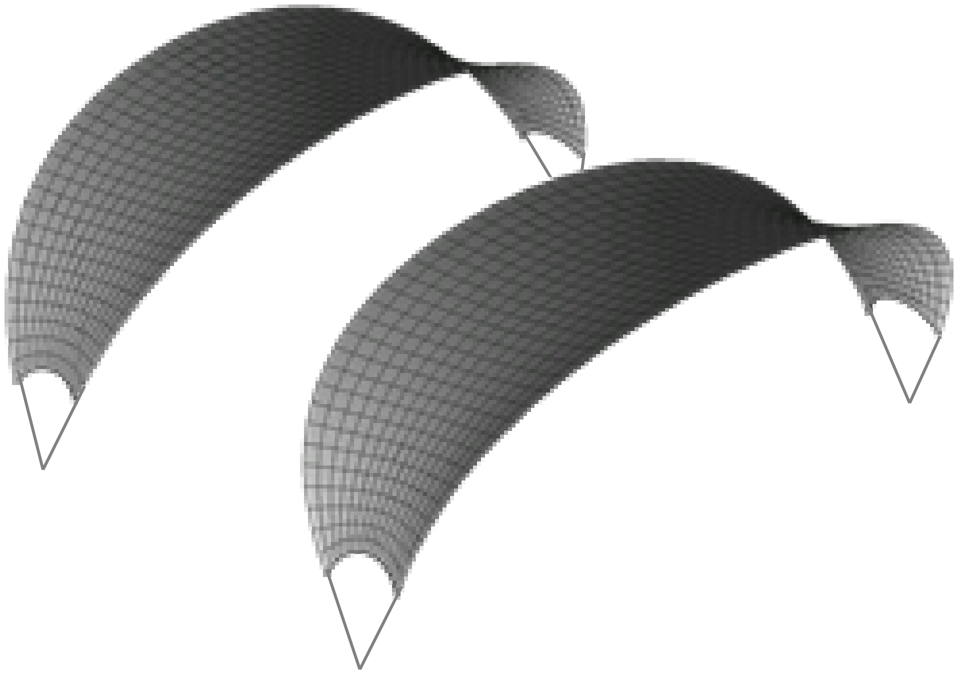

Pressure

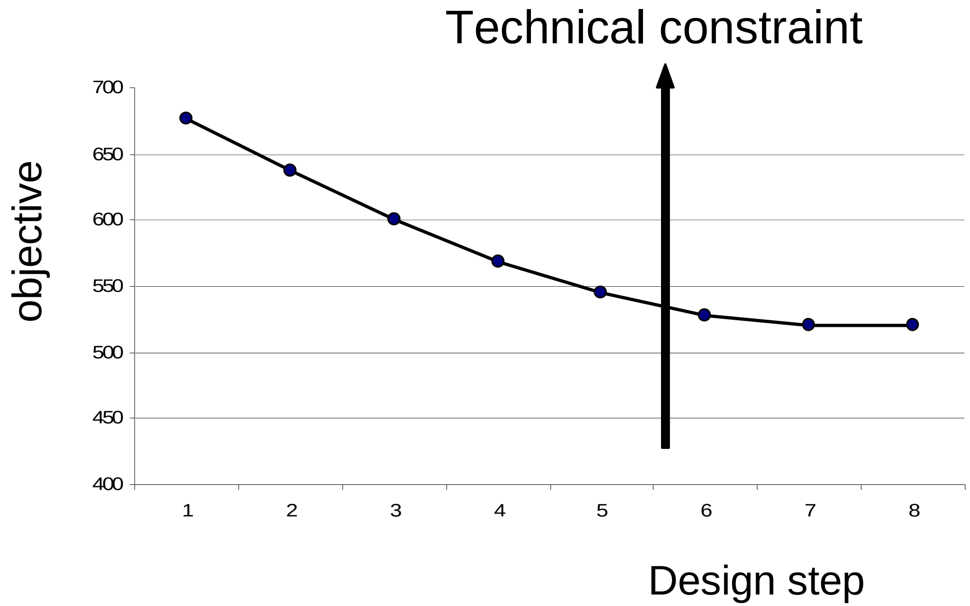


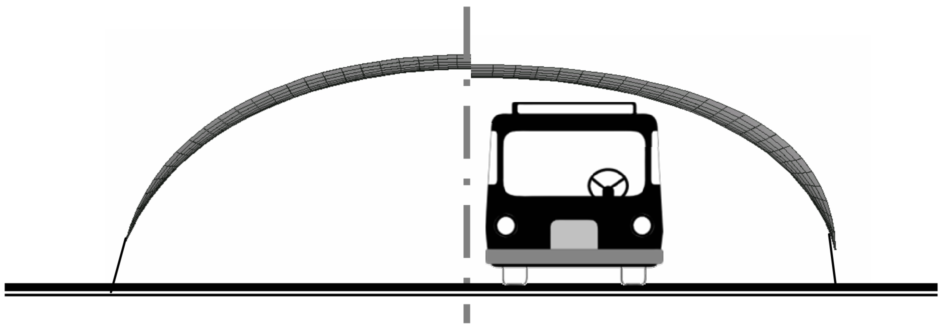



# Example – Results

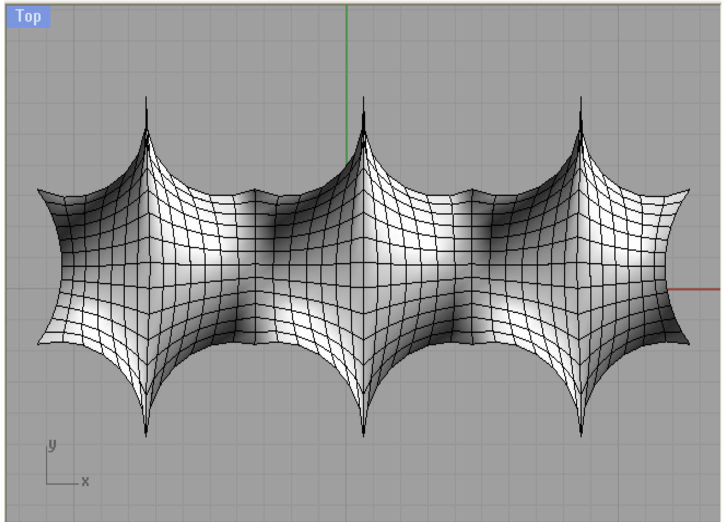
- Steepest decent
- Drag-lift target function
- Improved frame geometry





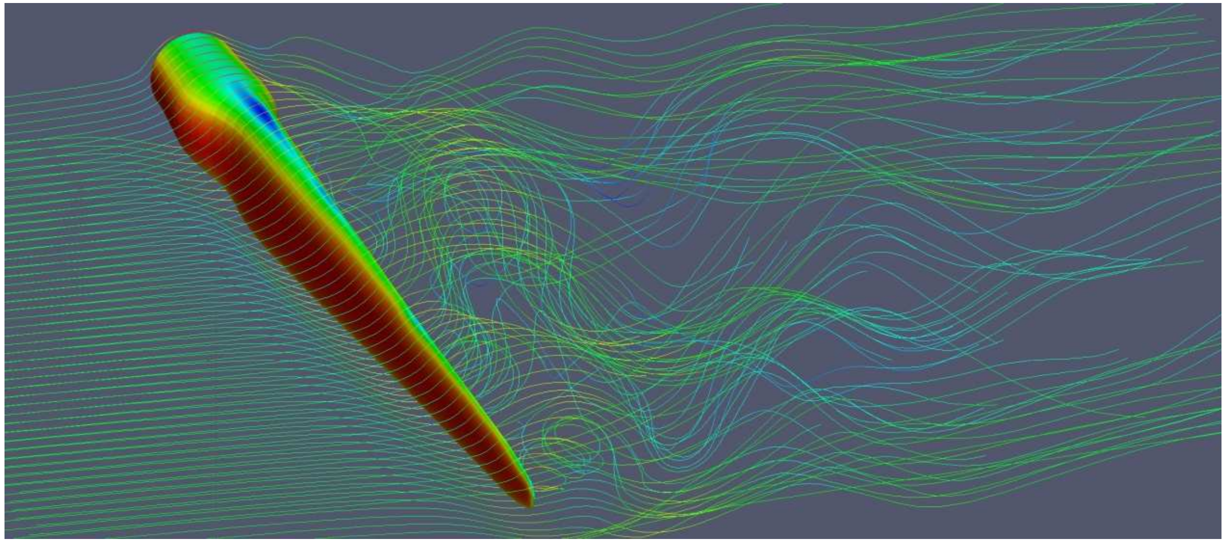
# Summary




- A modular design workflow
- Modules
    - Geometry and mesh
    - Physical state
        - Partitioned FSI
    - Sensitivity
- Application

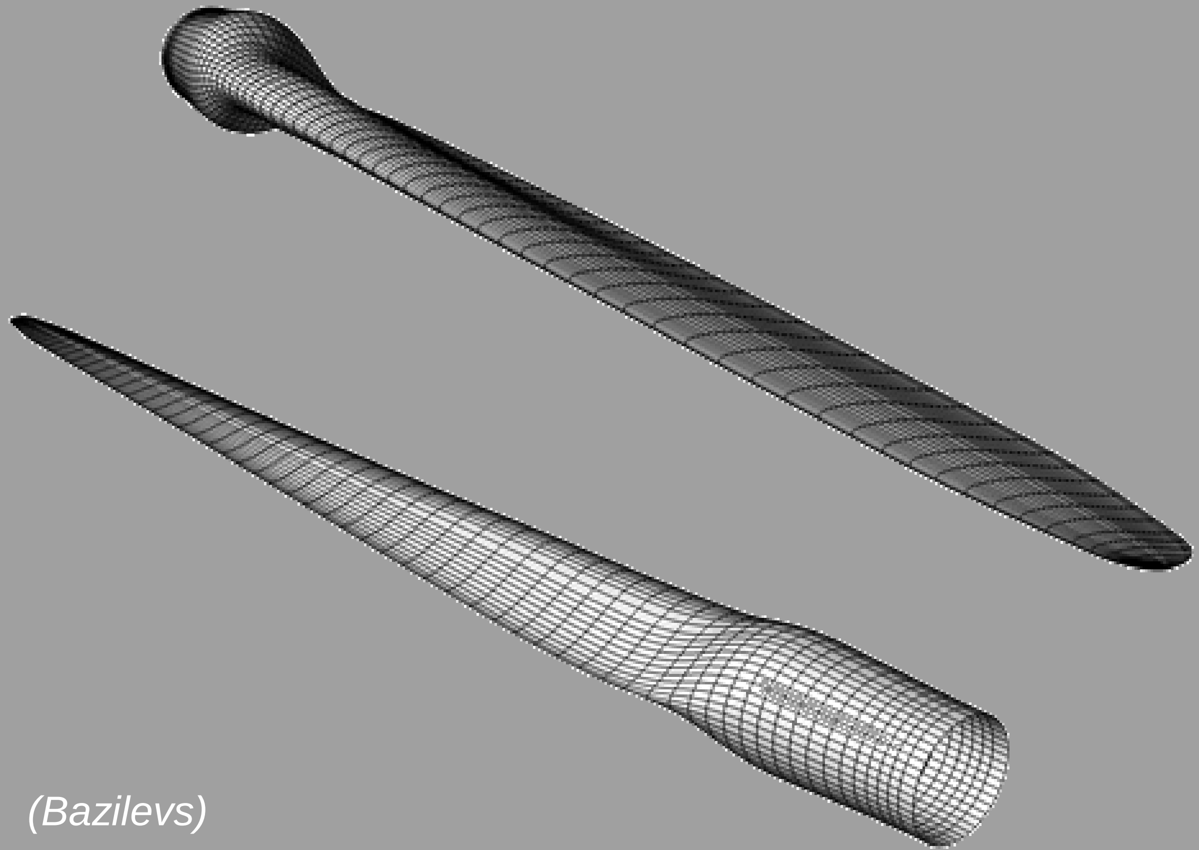
# Next step...

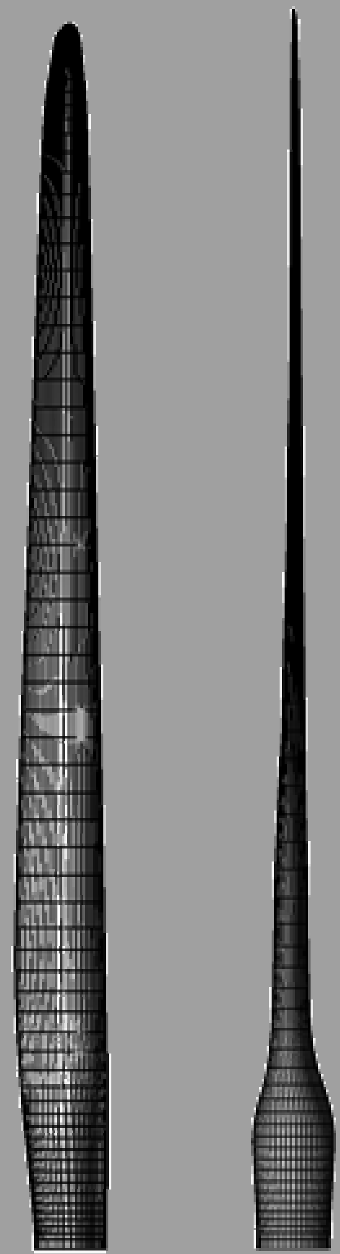
- More Complex geometry
- Rotating parts



# Next step...

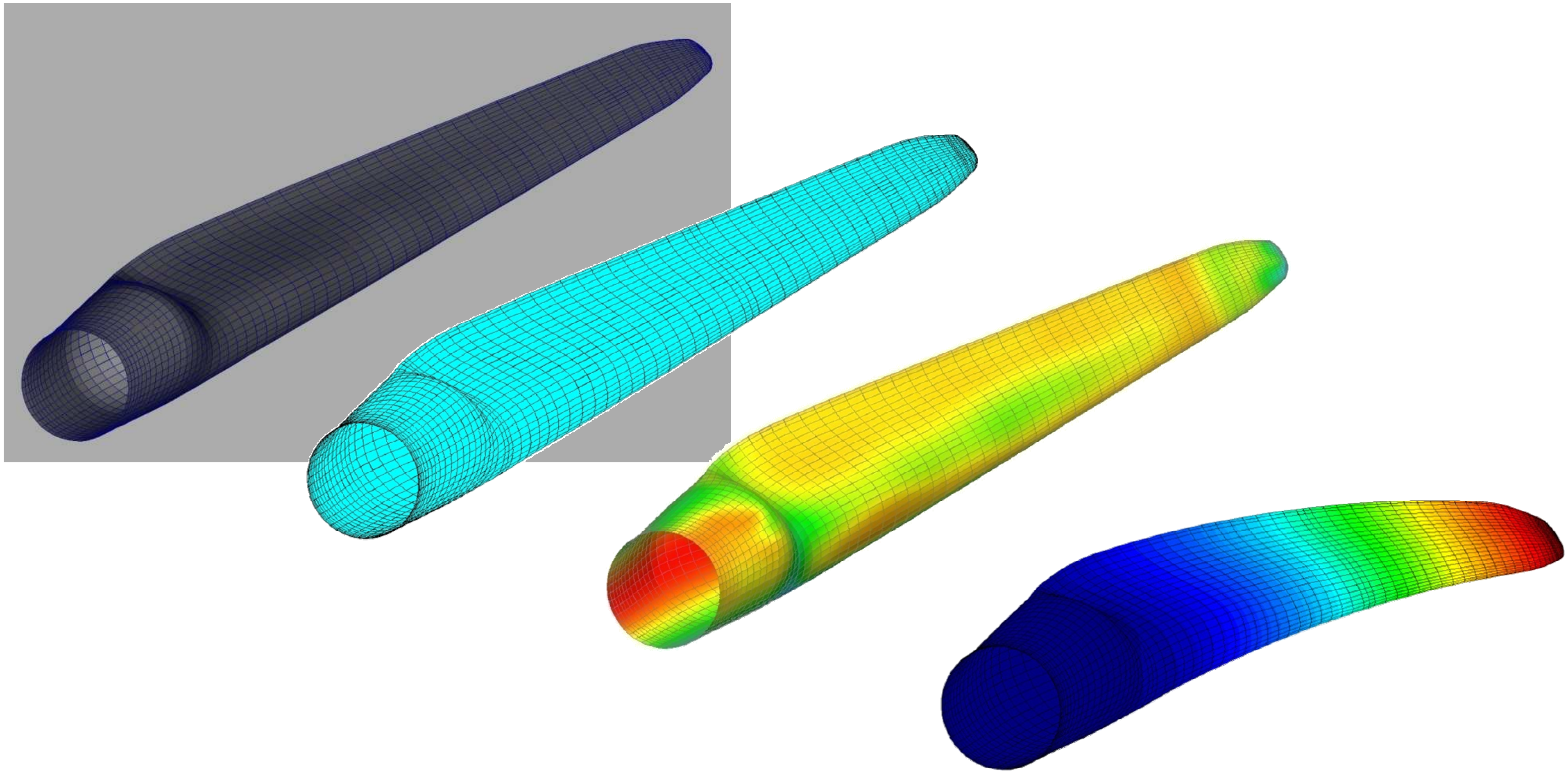
## Geometry





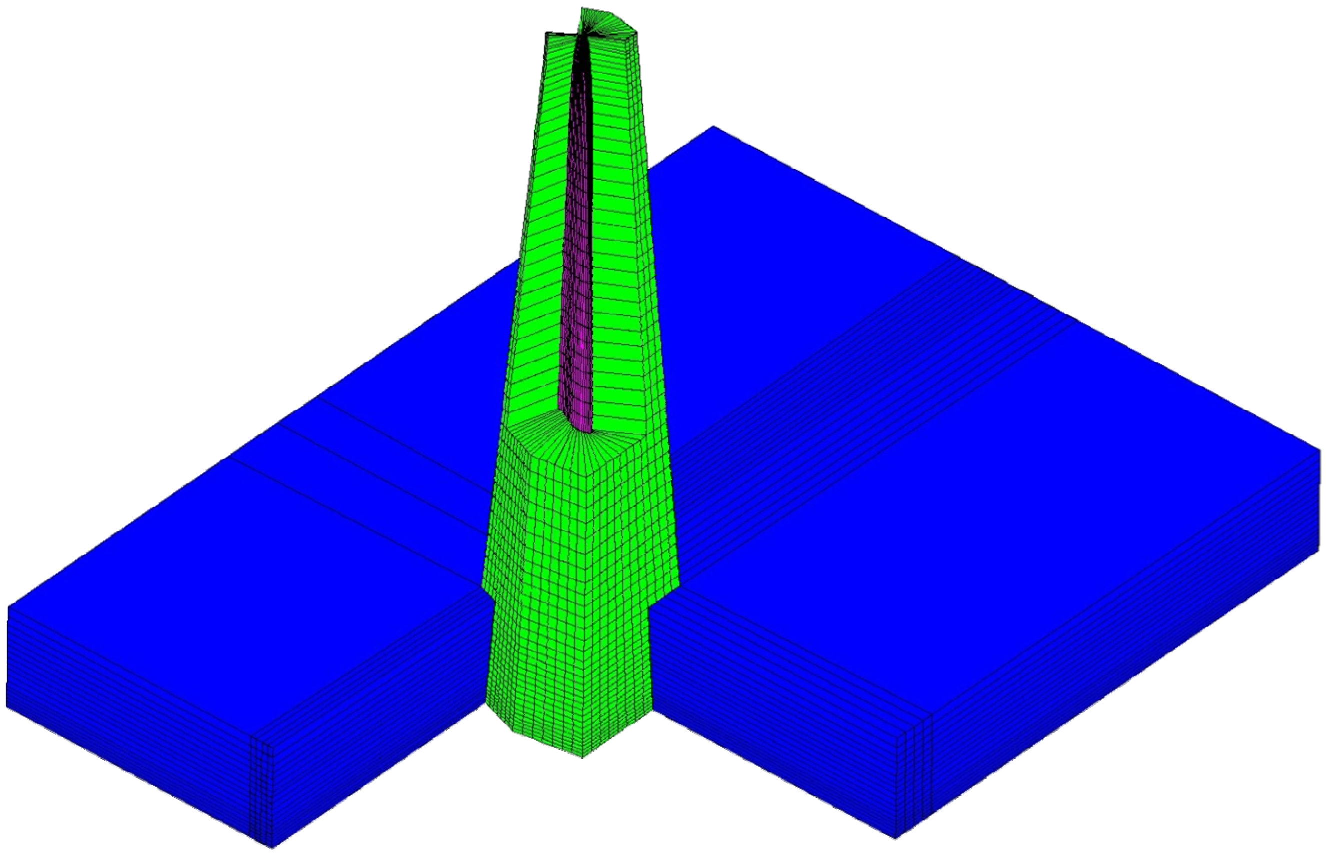
*(Bazilevs)*

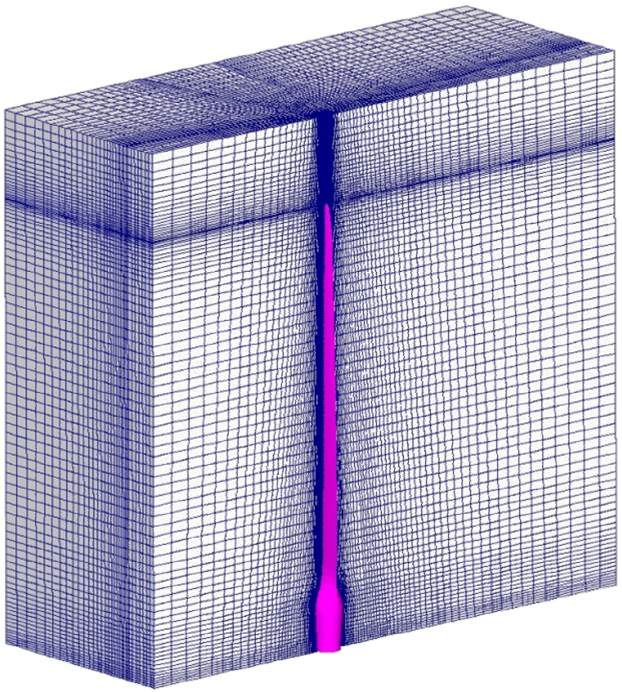
# Next step...

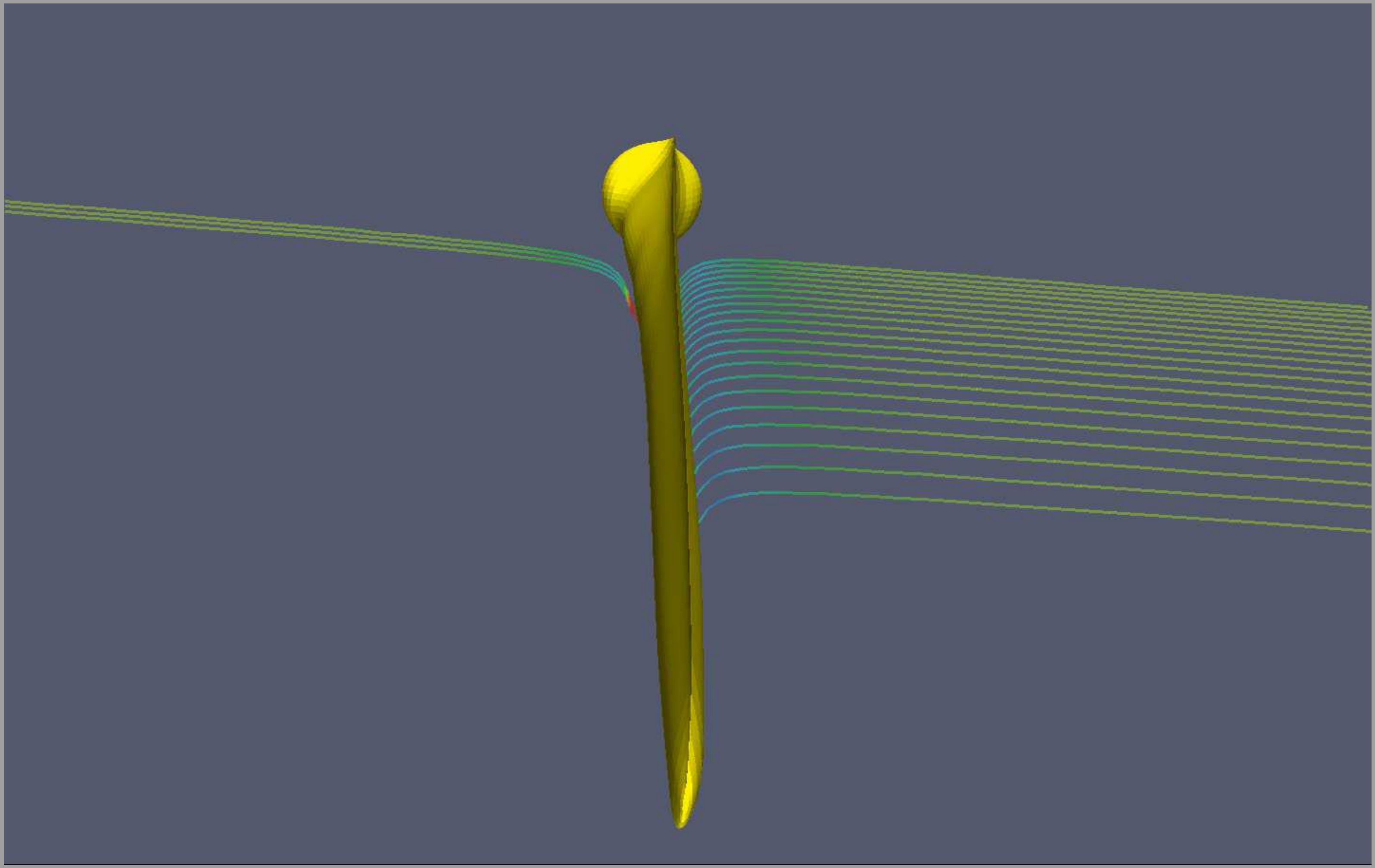


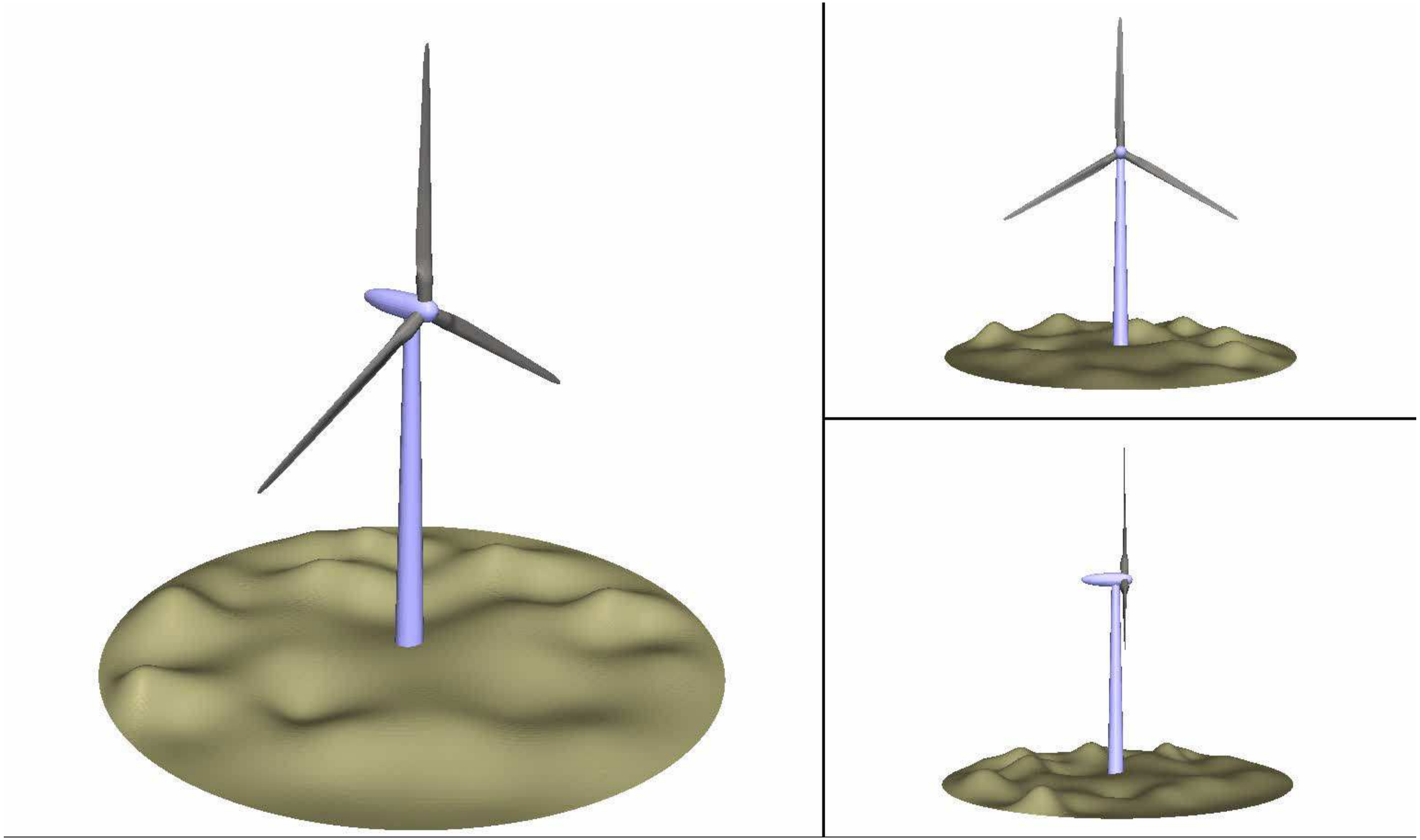
# Next step...

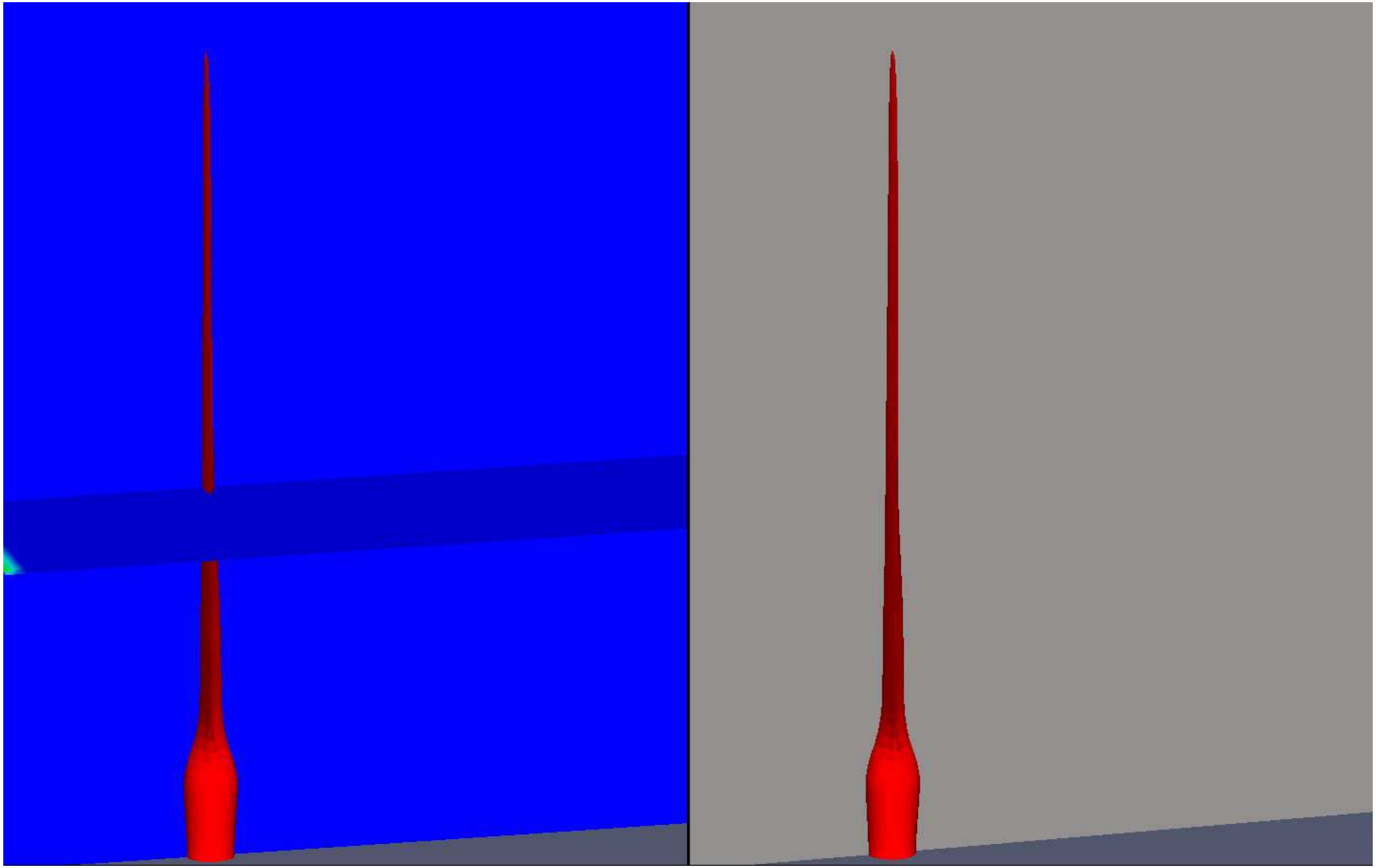
## Block-structured grid



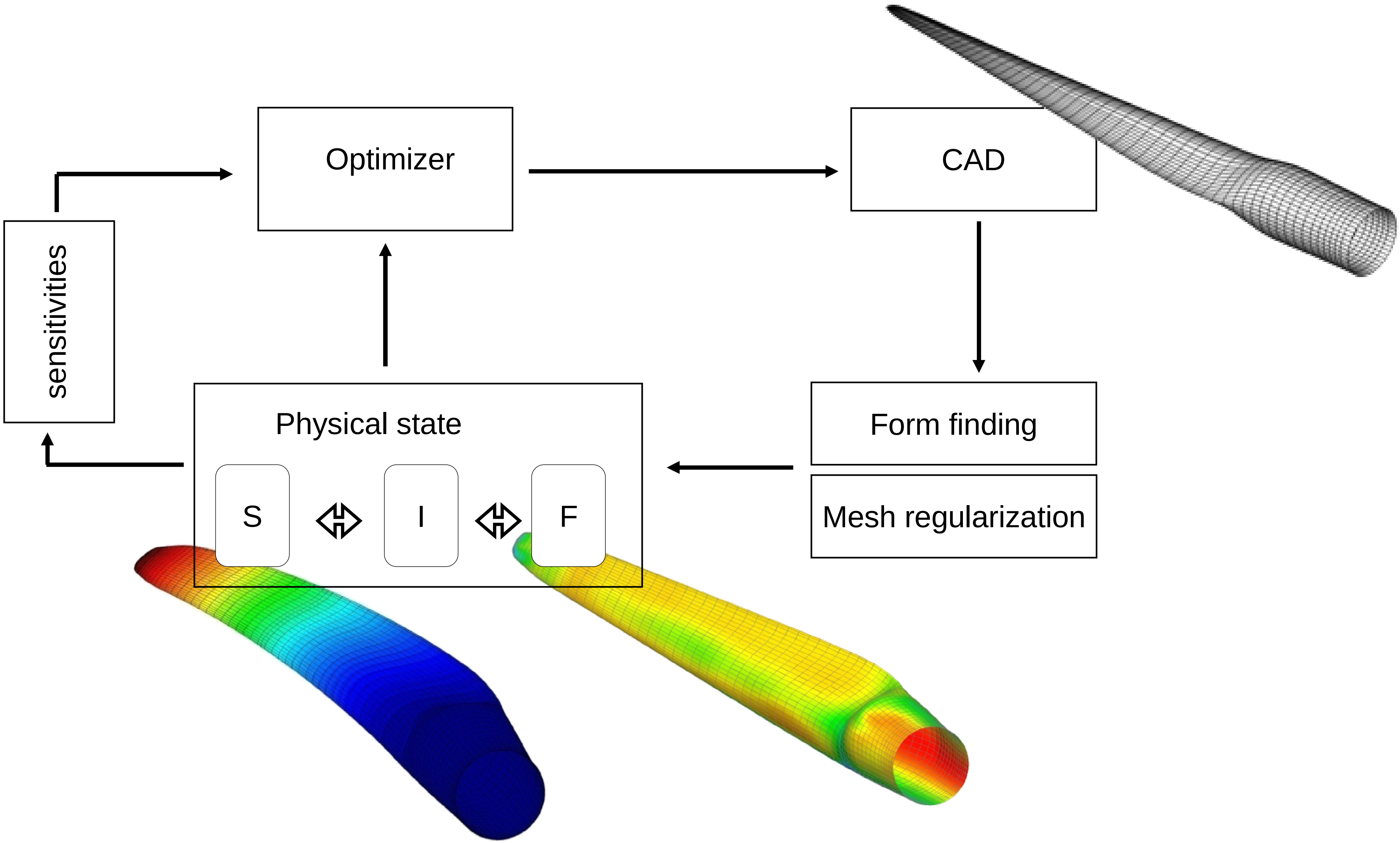








# Next step...


Optimizer
CAD
sensitivities
Physical state
S
I
F
Form finding
Mesh regularization

FLOWHEAD

Fluid Optimisation Workflows for Highly Effective Automotive Development Processes

[ http://flowhead.sems.qmul.ac.uk/ ]

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# Shape Optimization and Mesh Regularization

for

Fluid-Structure Interaction Wind engineering problems

# THE END

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