Durable structure reinforcements for ram-air kites

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Who am I?

Marie Curie PhD student within AWESCO network

- Background in Aerospace Engineering from TU Delft and DTU
- Started PhD at SkySails GmbH in Hamburg until their insolvency in April 2016
- Uni Freiburg is new employer since July 2016
- Using office of SkySails Group in Hamburg to continue my research

Motivation

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REINFORCEMENTS

Ram-air kites

Structural layout

- **Canopy** – the kite's skin
- **Ribs** – internal structure which defines aerodynamic shape and stiffness
- **Bridles** – connecting lower canopy with tether, also used for steering
- **KCU** (Kite control unit) – steering, wind speed measurement, IMU, etc.
- **Inlet** – Hole at leading edge for inflation
- **Tether** – attached to ground station or vehicle/pilot

Ram-air kites for Airborne Wind Energy

- + Cheap, lightweight, easy to storage
- - Durability issues due to UV light exposure, fatigue, and storage
- - Lower CL/CD compared to rigid wings
- - Difficult to model due to large deformations

What are reinforcements?

Structural support to strengthen highly loaded areas

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- Example: 400m2 kite produces approximately 400kN tether force
  - The load acting on the centre rib is roughly 40kN (2 SUVs)
  - Fabric thickness is 1 mm
- Use fabric tape to direct loads from the top canopy to the bridle points

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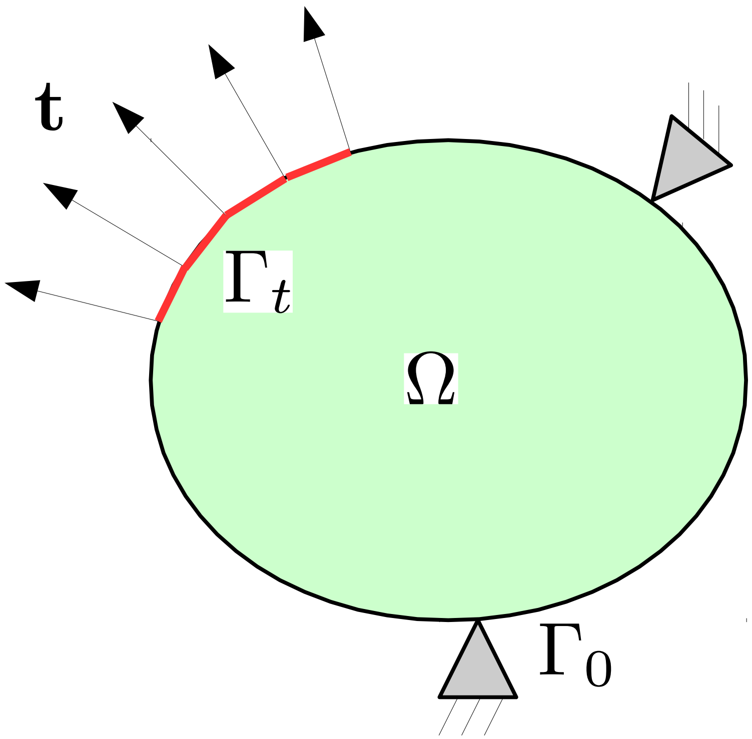
How to model the structure

Strong equilibrium form of an elastostatic body

$$\begin{aligned}\nabla \cdot \sigma - \mathbf{b} &= \mathbf{0} \quad \text{in} \quad \Omega \\ \mathbf{u} &= \mathbf{0} \quad \text{on} \quad \Gamma_0 \\ \sigma^{\mathbf{T}} \mathbf{n} &= \mathbf{t} \quad \text{on} \quad \Gamma_t\end{aligned}$$



Kinematics

$$\epsilon = \nabla \cdot \mathbf{u}$$

Constitutive relations

$$\sigma = \mathbf{C}\, \epsilon$$

How to model the structure

Weak equilibrium form of an elastostatic body

$$\Pi = \int_\Omega \nabla \cdot \sigma^{\mathbf{T}} \mathbf{u} \, dV - \int_\Omega \mathbf{b}^{\mathbf{T}} \mathbf{u} \, dV$$

Variational principle of total potential energy

$$\delta\Pi = \mathbf{0}$$

Applying Green's Theorem

$$\int_\Omega \sigma^{\mathbf{T}} \delta\epsilon \, dV = \int_\Omega \mathbf{b}^{\mathbf{T}} \delta\mathbf{u} \, dV + \int_{\Gamma_t} \mathbf{t}^{\mathbf{T}} \delta\mathbf{u} \, dS$$

How to model the structure

Finite element approximation with shape functions

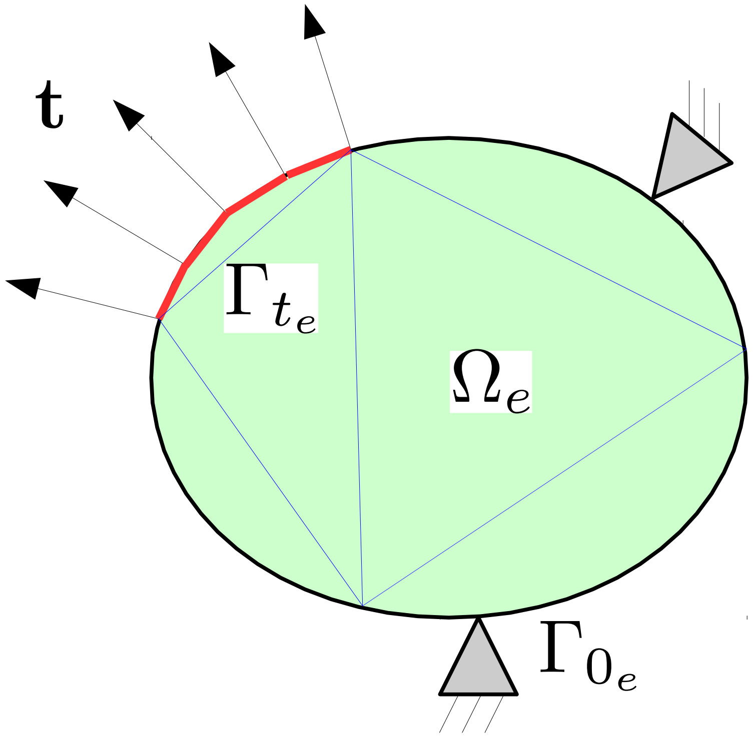
$$\mathbf{u}_e = \mathbf{N}\,\mathbf{d}_e$$

Static equilibrium equation

$$\mathbf{K}\mathbf{d} = \mathbf{F}_{\mathbf{ext}}$$

Dynamic equation of motion

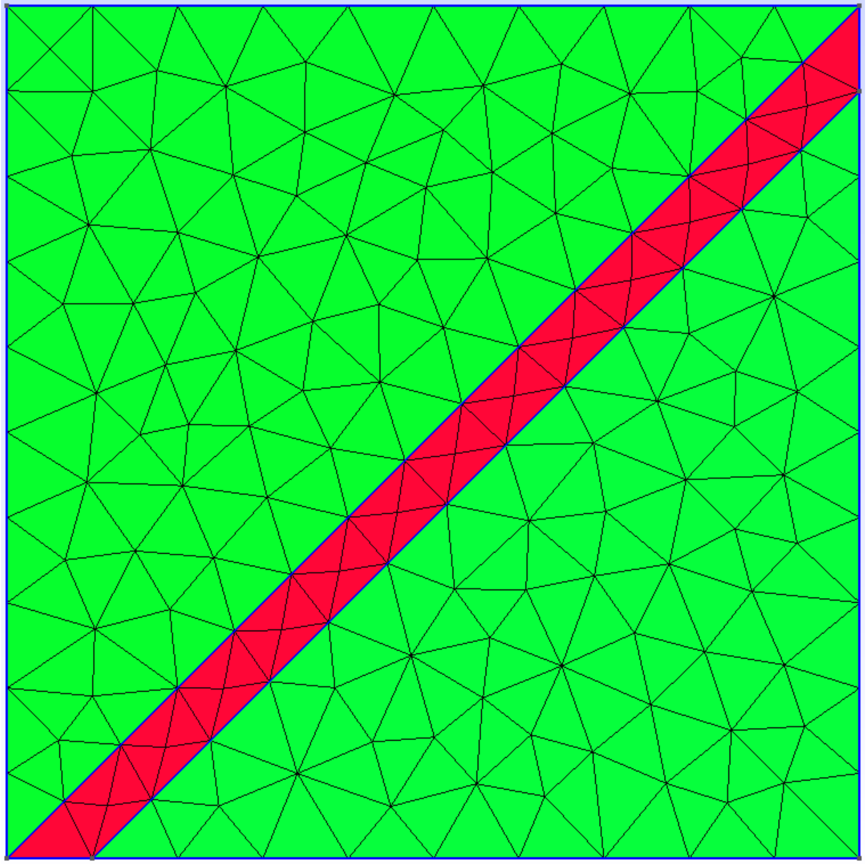
$$\mathbf{M}\ddot{\mathbf{d}} + \mathbf{C}\dot{\mathbf{d}} + \mathbf{K}\mathbf{d} = \mathbf{F}_{\mathbf{ext}}$$



How to model the reinforcements

Patch

- Introduce continuum elements with different material properties and/or thickness
- + Reinforcement has bending and shear resistance
- - more elements introduced
- - re-meshing required when reinforcements are moved



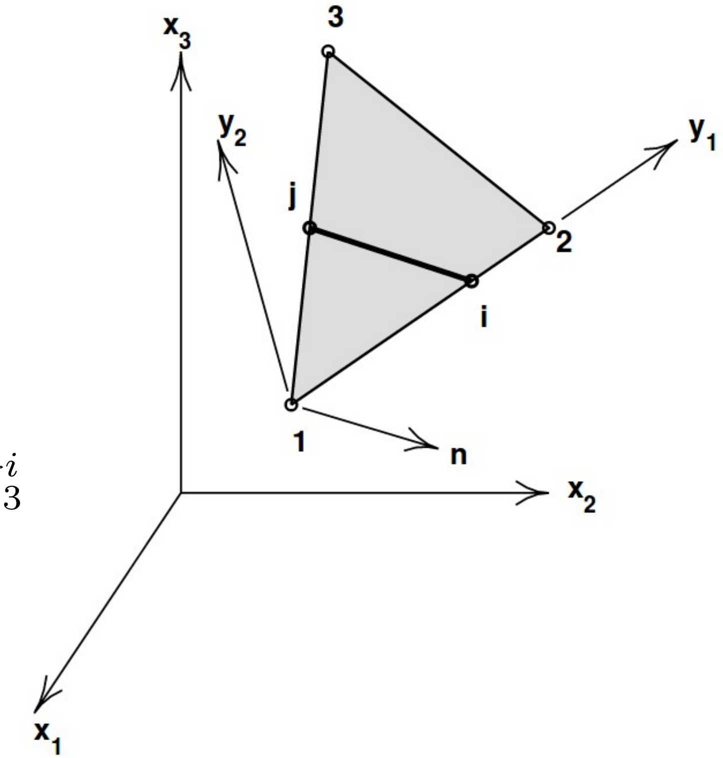
How to model the reinforcements

Truss element

- Introduce truss elements with different material properties and/or thickness (Taylor et al., 2005)

$$\mathbf{x}^i = \xi_1^i\ \tilde{\mathbf{x}}^1 + \xi_2^i\ \tilde{\mathbf{x}}^2 + \xi_3^i\ \tilde{\mathbf{x}}^3$$

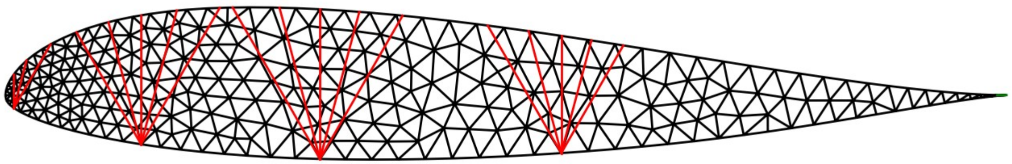
$$\xi_2^i = \frac{||\mathbf{X}^i - \mathbf{X}^1||}{||\mathbf{X}^2 - \mathbf{X}^1||} \quad ; \quad \xi_1^i = 1 - \xi_2^i \quad ; \quad \xi_3^i$$



- + no re-meshing
- + no additional degrees of freedom
- - reinforcements have no bending and shear resistance
- - might cause instabilities if reinforcement stiffness is too high

How to model the reinforcements

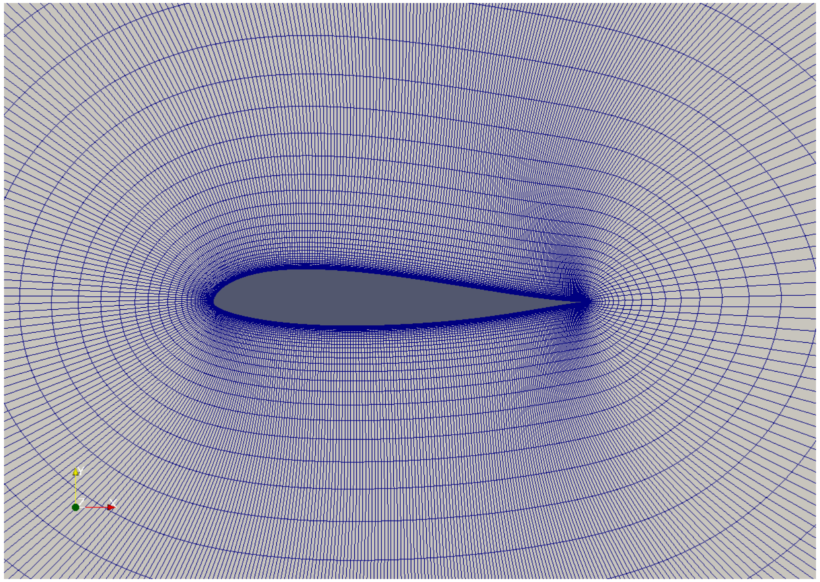
Reinforcement applied to the rib structure



How to model the flow

Computational Fluid Dynamics (CFD)

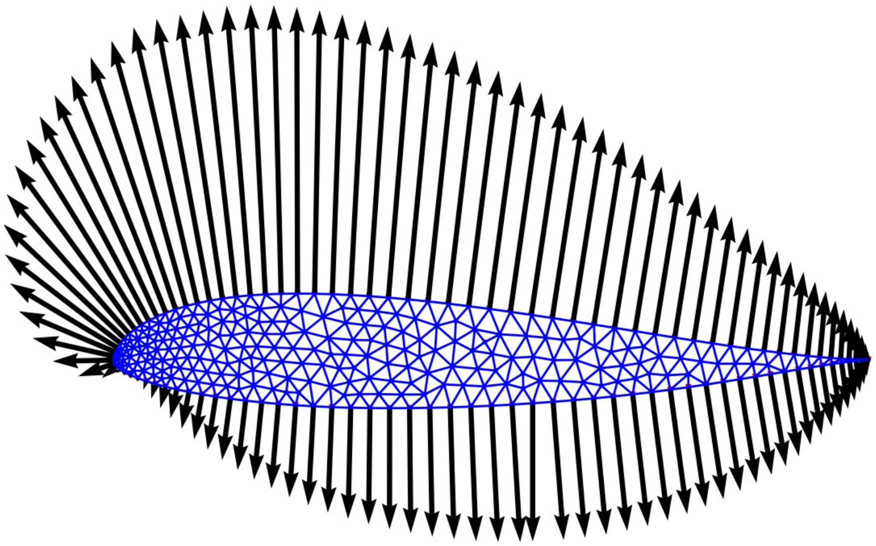
- Solve the Navier-Stokes equations with, e.g. finite volume approach
  → Obtain pressure and fluxes in each finite volume
- Kites fly at larger Reynold's number (Re > 1e6) and eddies cannot be resolved
  → turbulence model required
- Kites fly at large angle of attack to maximise tether force
  → flow separation can be expected



How to model the flow

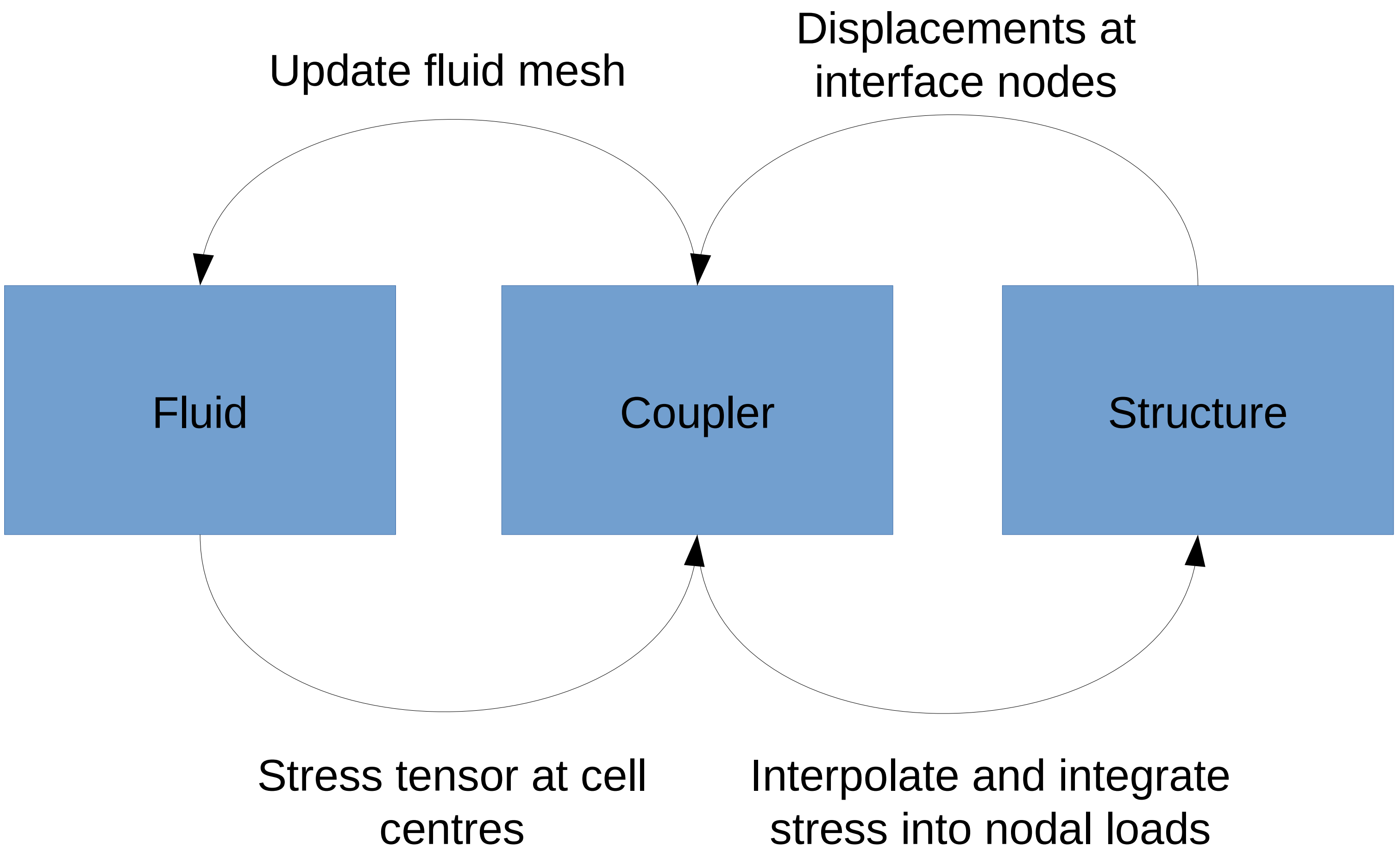
Computational Fluid Dynamics (CFD)

- From the fluid mesh integrate pressure to nodal forces
- Alternative to CFD is potential flow (panel method) which is much faster but has its limitations



How to couple both models

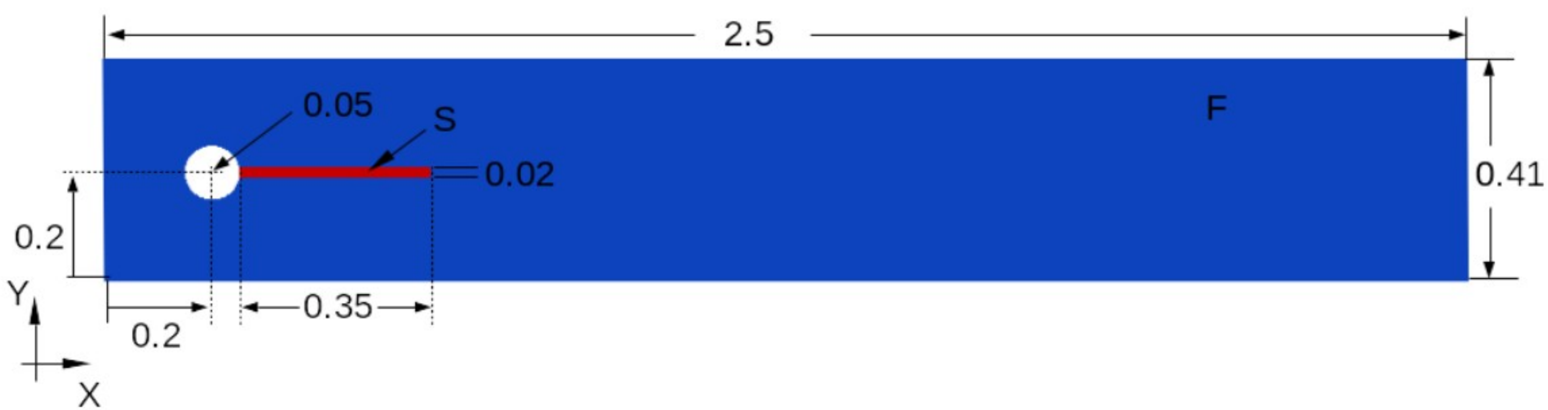
Partitioned Fluid-Structure Interaction (FSI)



Hron-Turek benchmark

Waving flag (Hron & Turek, 2006)

- Virtual wind tunnel with parabolic inflow conditions
  - Re = 200
  - Density ratio = 1
  - E = 1.6 MPa
- Mesh motion and interface interpolation with radial basis functions
- Parabolic inflow conditions and slight asymmetry to induce vortex shedding



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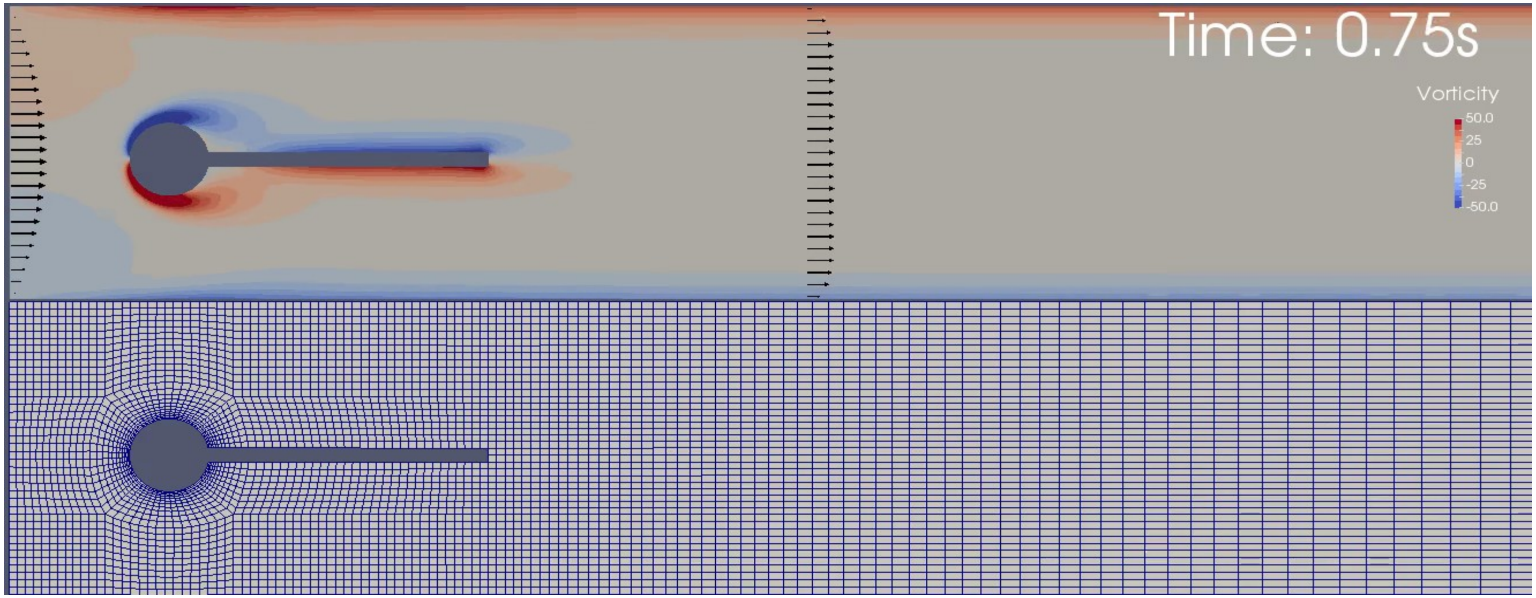
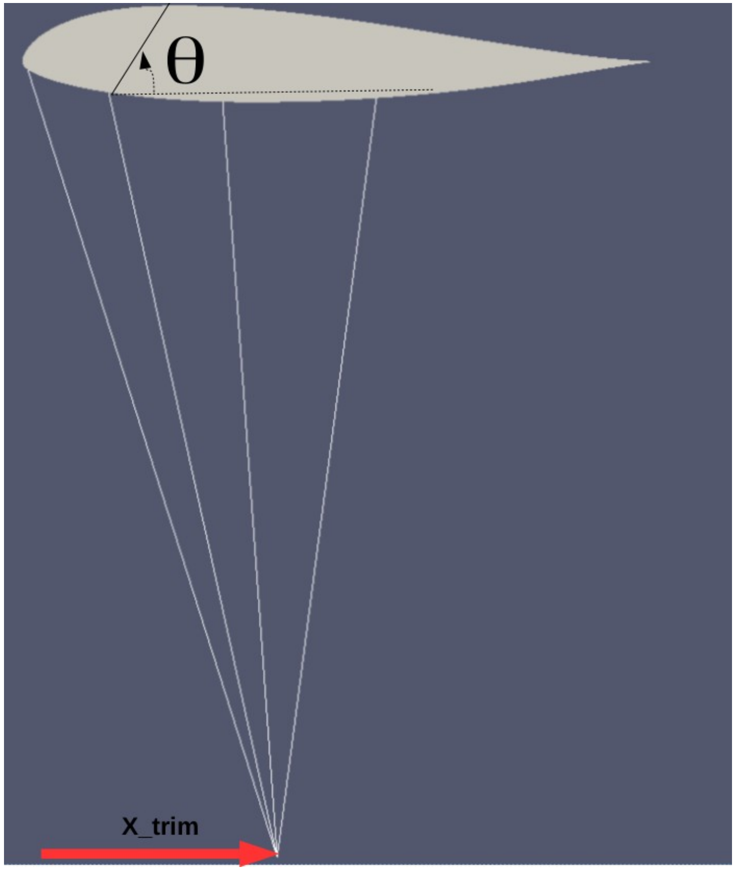


Reinforcement optimisation

For the first publication:

- 2D reinforcement layout optimisation
- How to get from 3D to 2D?
  - Assume constant pressure over single kite cell
  - Add internal pressure
- Static loads only
- Trim kite in each iteration by finding X_trim such that moment is zero
- What to optimise?



Reinforcement optimisation

Optimisation statement

$$\underset{\theta,\alpha}{\text{maximise}} \quad f(\theta, \alpha) = C_r(1 + E^2)$$

$$\text{subject to} \quad C_m = 0$$

$$\theta_{min} \leq \theta \leq \theta_{max}$$

$$\alpha_{min} \leq \alpha \leq \alpha_{max}$$

$$\text{with } \; Cr = \sqrt{(C_l)^2 + (C_d)^2} \quad ; \quad E = C_l / C_d$$

Reinforcement optimisation

Optimisation statement 2

$$\max_{\theta,\alpha} \quad f(\theta,\alpha) = \beta\, C_r(1+E^2) + (1-\beta)\, 1/(\mathbf{u^T K u})$$

$$\text{subject to} \quad C_m = 0$$

$$\theta_{min} \leq \theta \leq \theta_{max}$$

$$\alpha_{min} \leq \alpha \leq \alpha_{max}$$

$$\sigma_{\mathrm{VM}} \leq \sigma_{\mathrm{VM}_{\mathbf{max}}}$$

$$\text{with} \;\; Cr = \sqrt{(C_l)^2 + (C_d)^2} \quad ; \quad E = C_l/C_d$$

Reinforcement optimisation

Questions

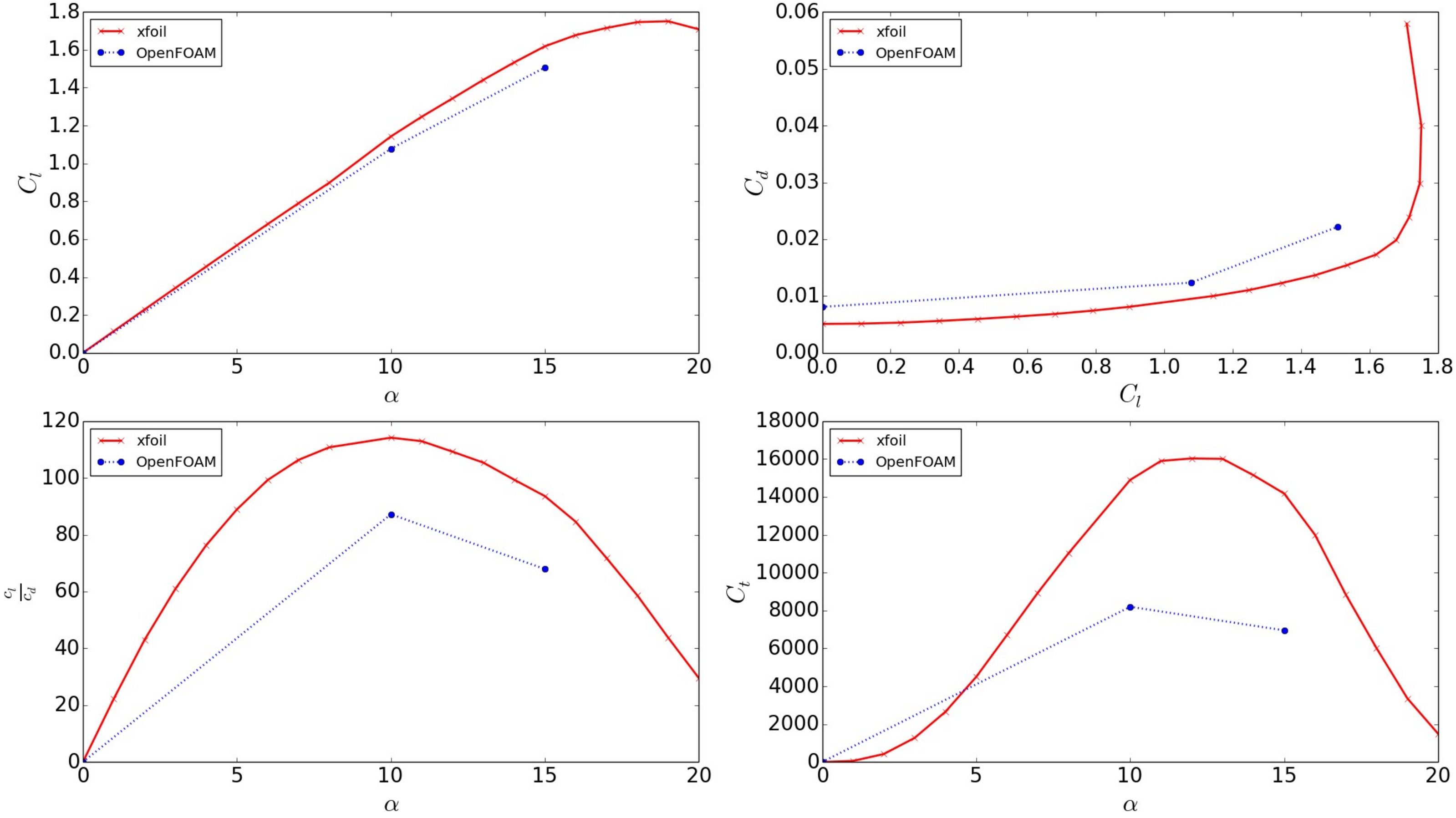
- What solver can be used?
- Gradient or non-gradient based?
- How to parameterise the design variables?

Question time

Thank you for your attention!

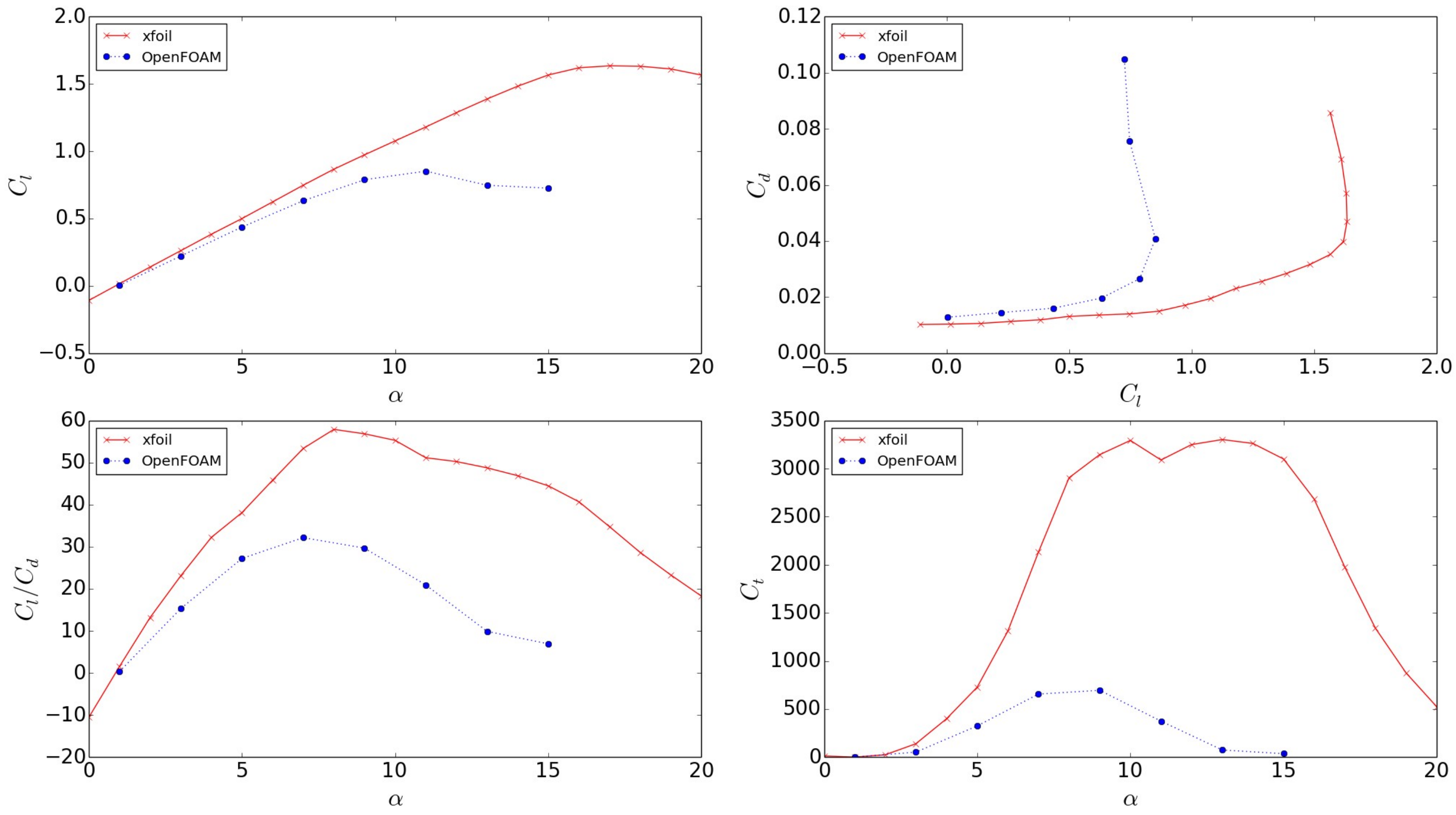
CFD vs. potential flow

Undeformed NACA0012 airfoil



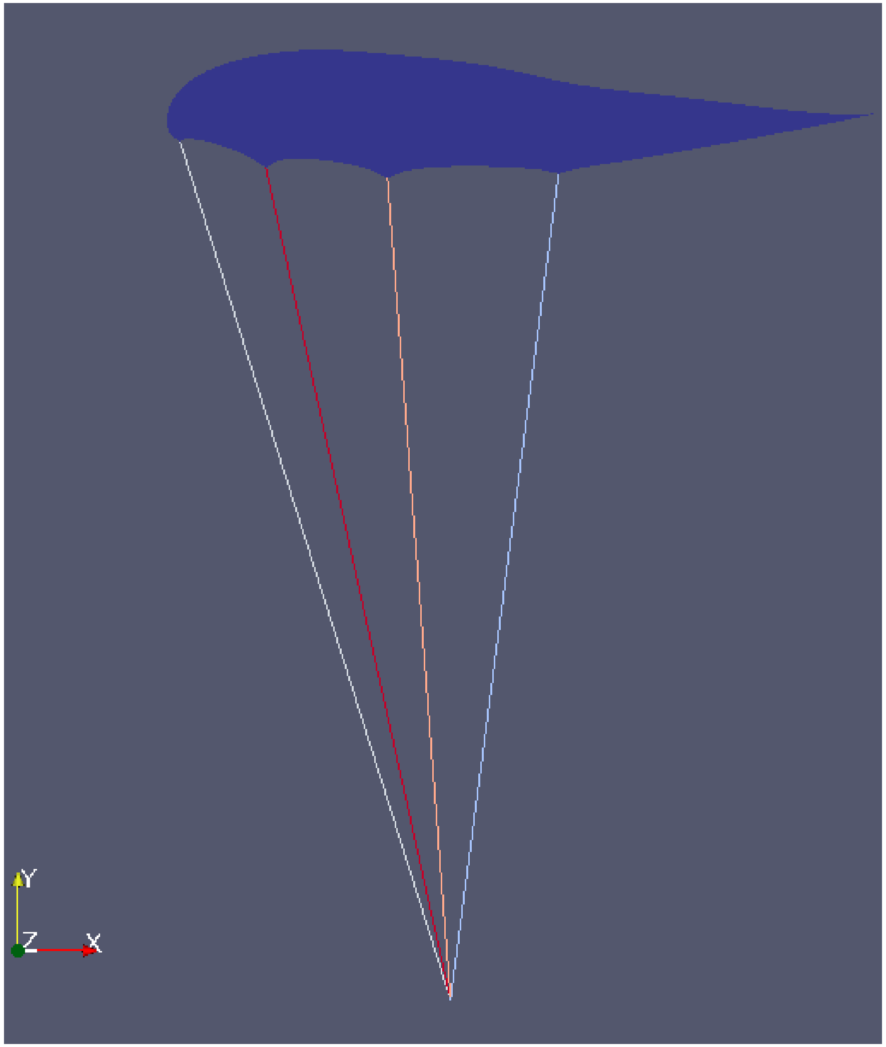
CFD vs. potential flow

Deformed mh92 airfoil



Reinforcement optimisation

No reinforcements



Reinforcement optimisation

With reinforcements