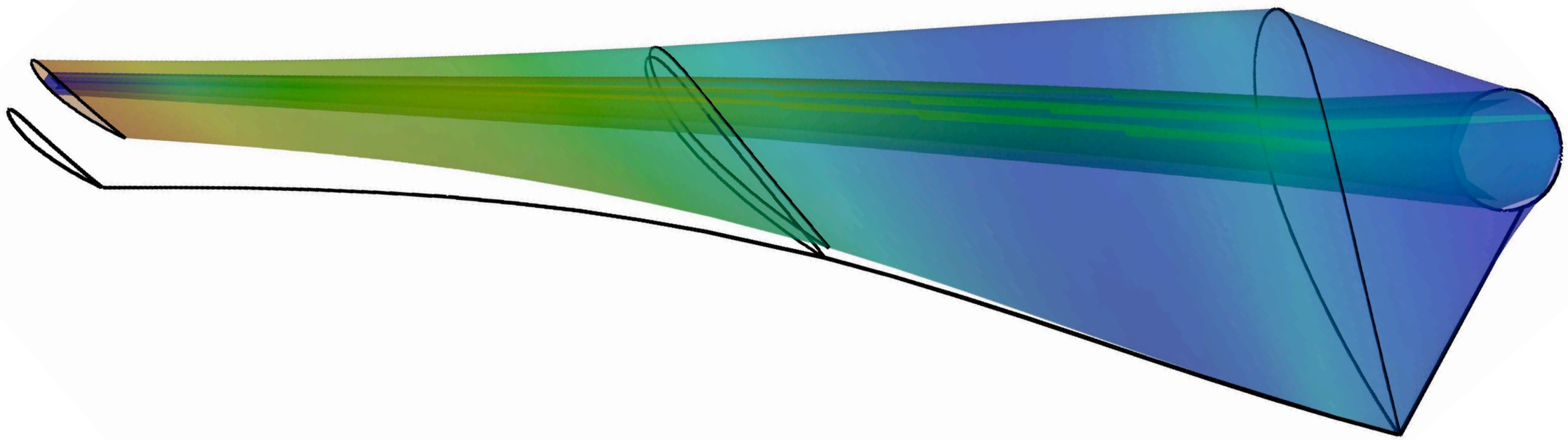
Towards Optimal Aeroelastic Tailoring of Wind Turbine Blades



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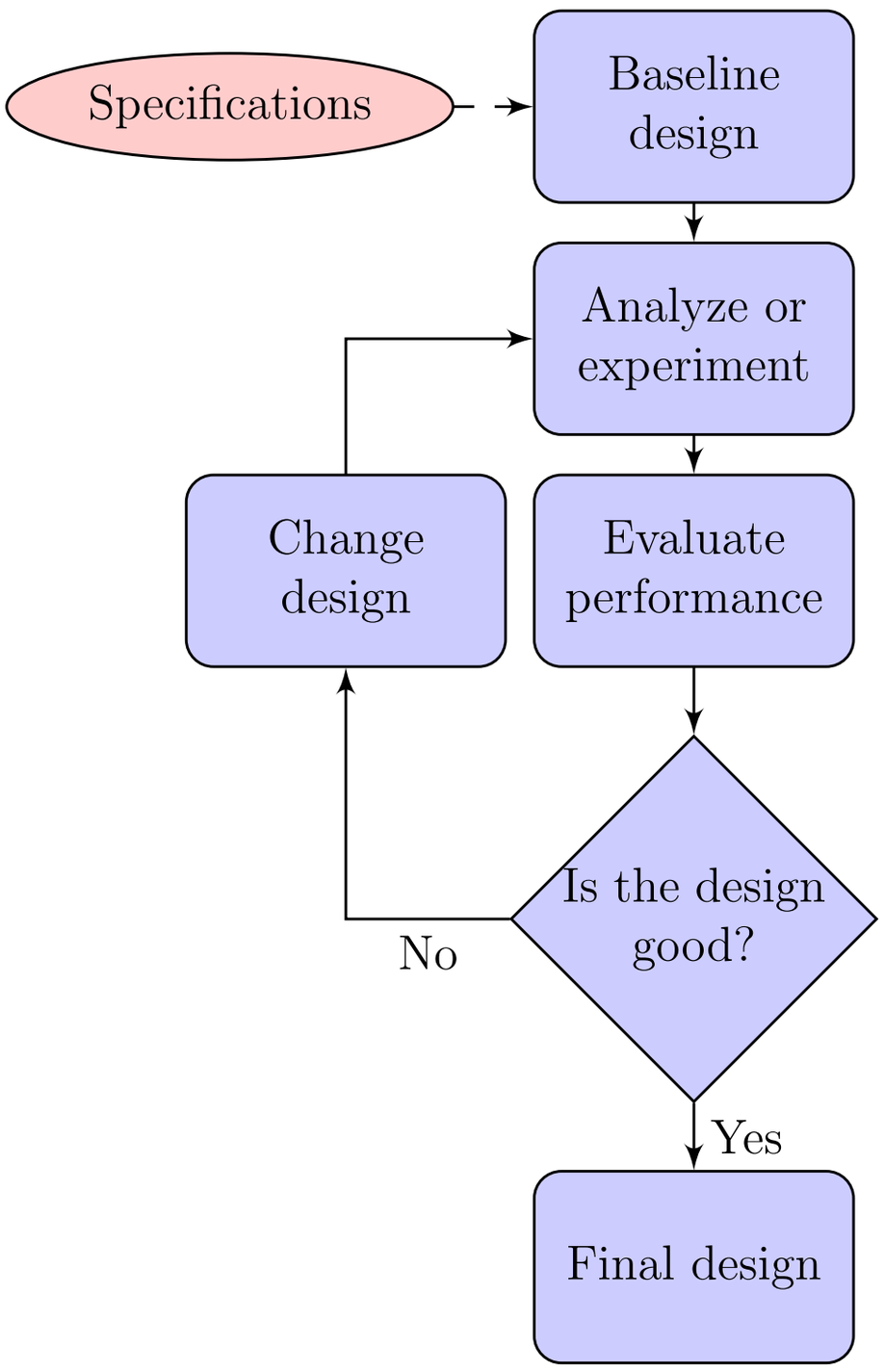
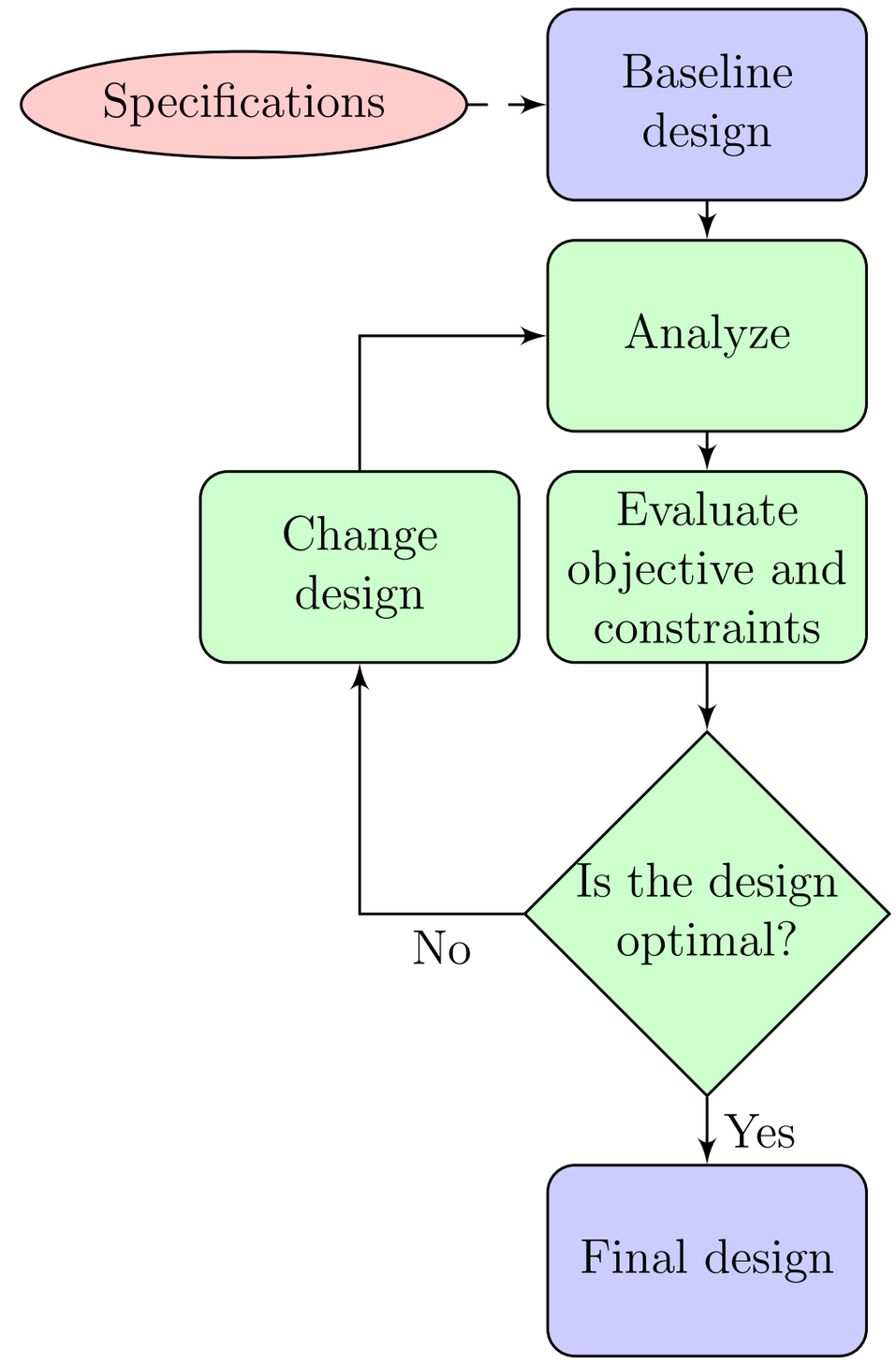
2nd NREL Systems Engineering Workshop
Broomfield, CO, Jan 29, 2013

What is Multidisciplinary Design Optimization – MDO?

Conventional design



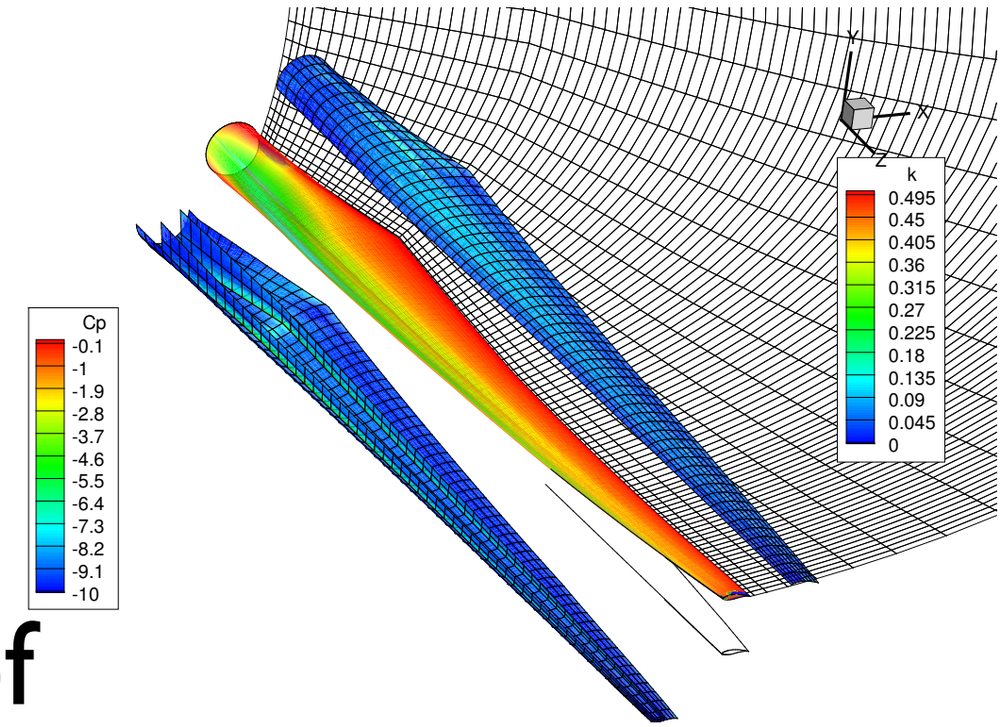
Optimal design



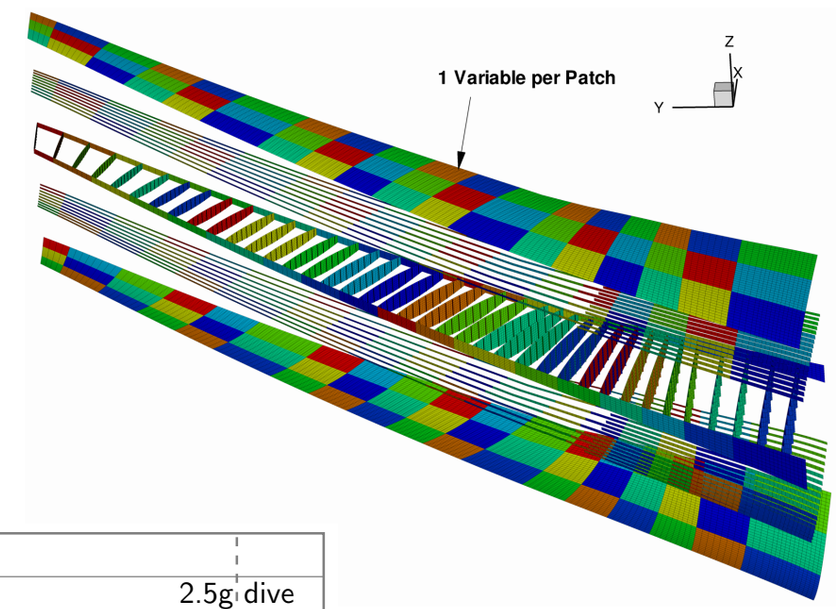
[Martins and Lambe, *AIAAJ* 2013]

MDO Challenges:

1. Multiple highly coupled systems

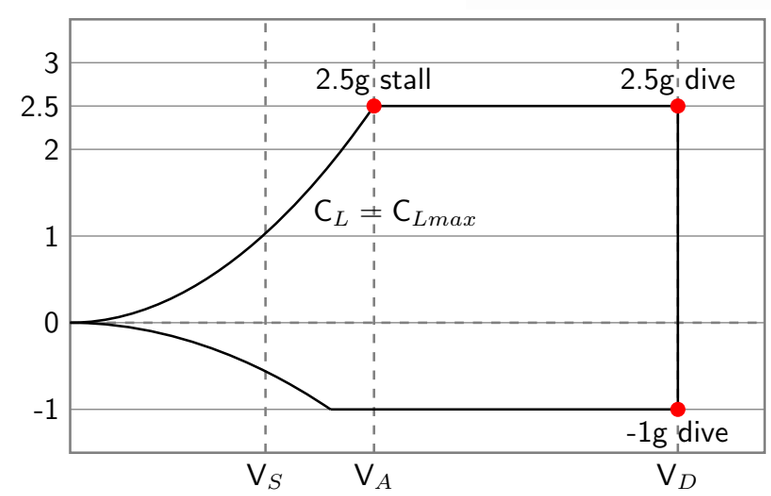


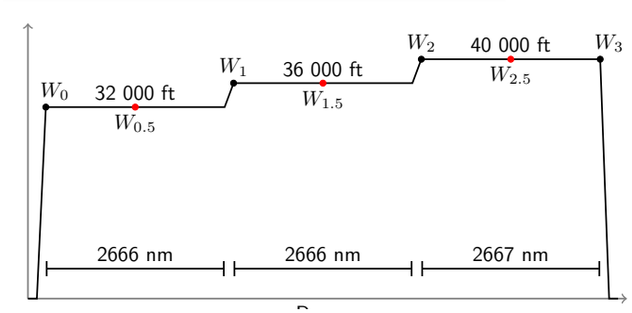
2. High computational cost of analysis



3. Large numbers of design variables, design points and constraints

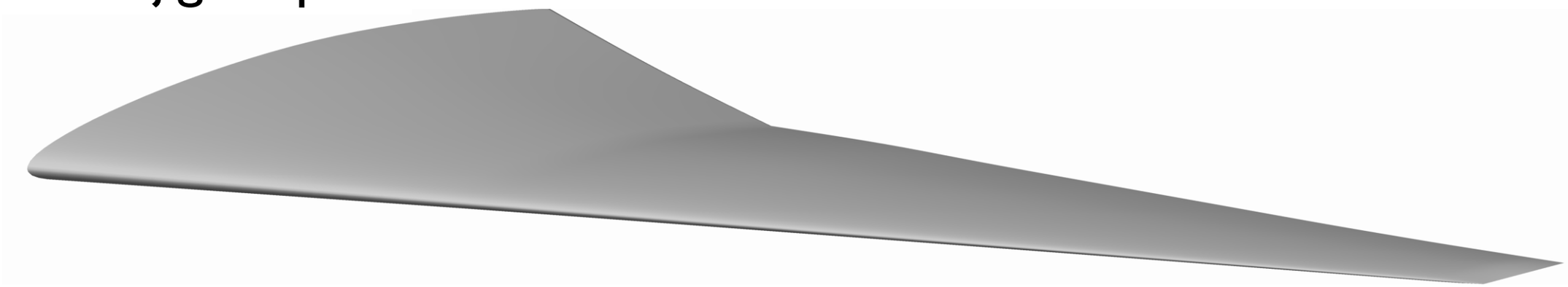
4. Relevant problem formulation



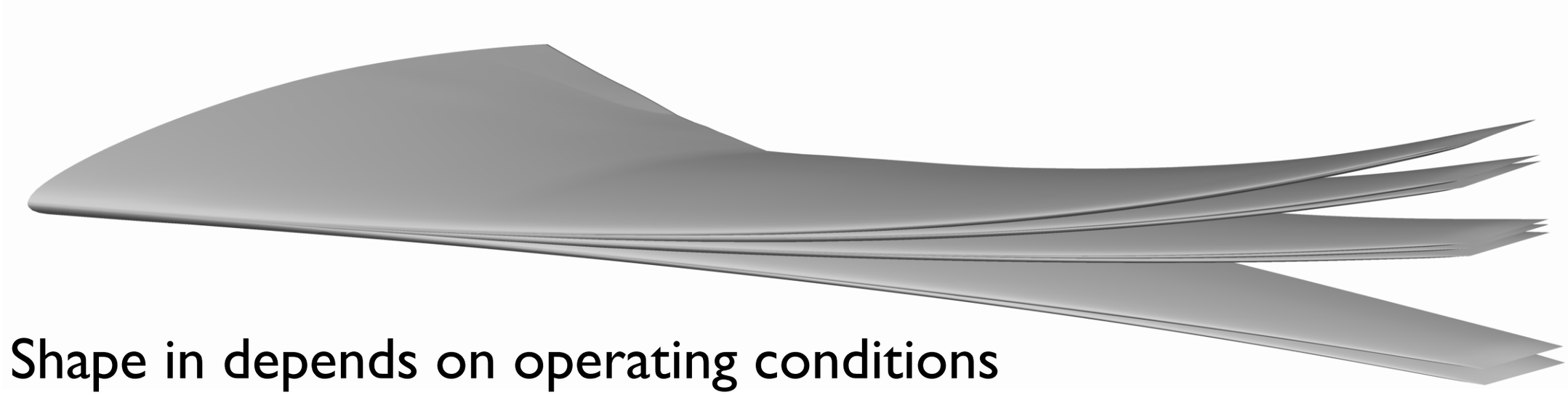


Aerostructural coupling is particularly important in lifting surface design

One jig shape



Many shapes in operation



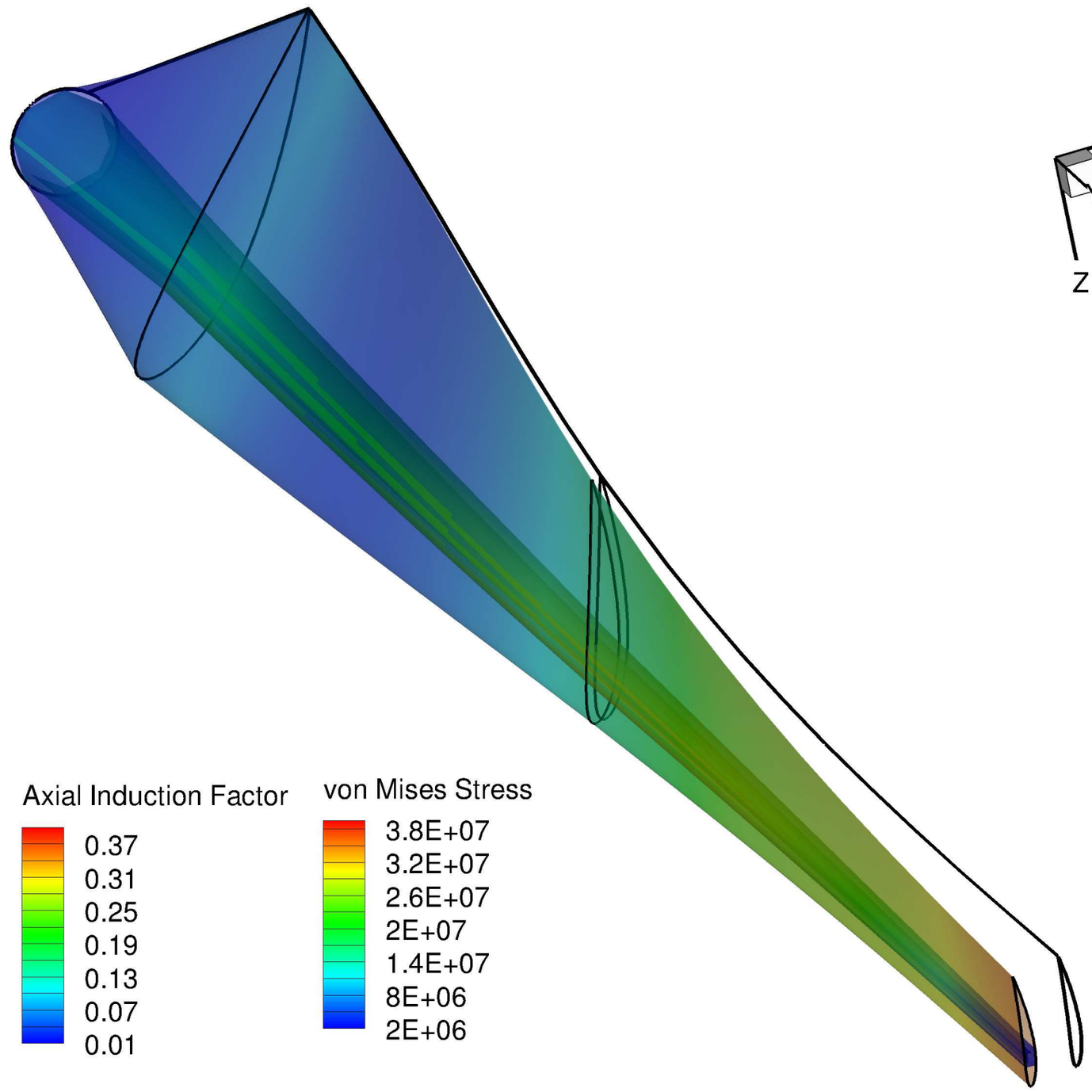
- Shape in depends on operating conditions
- Can result in poor performance if not accounted for...
- ...but can also be used to our advantage—aeroelastic tailoring

Aerostructural Optimization of a Wind Turbine Blade Considering Site-Specific Winds

[Kenway and Martins, AIAA 2008-6025]

Aerostructural Analysis

- BEM aerodynamic analysis with Prandtl correction and post-stall
- Structural analysis uses beam finite elements
- Aerodynamics and structures are coupled to obtain an aerostructural solution corresponding to a deflected blade
- The annual energy production (AEP) is computed based on aerostructural solutions for the various wind speeds

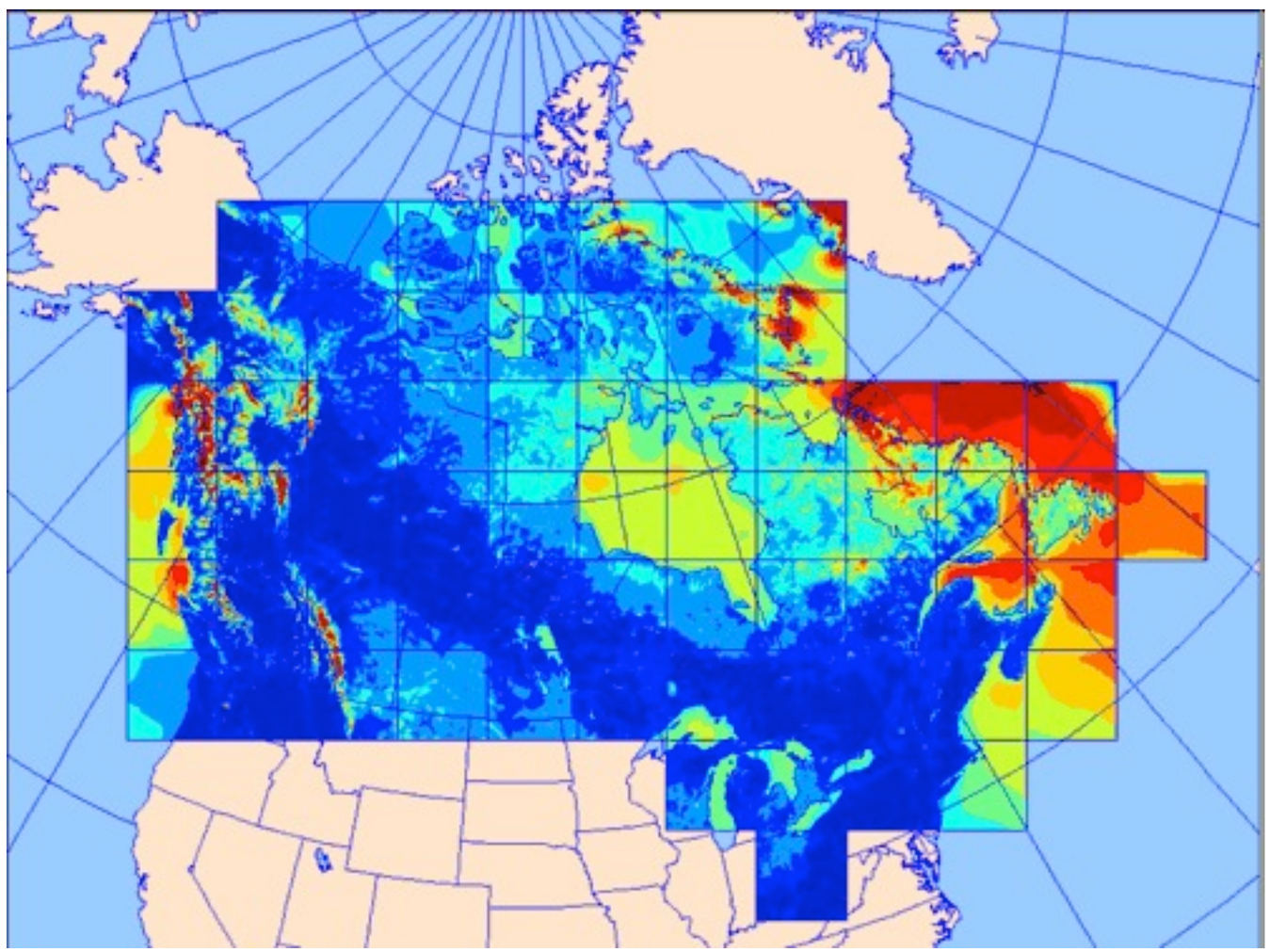


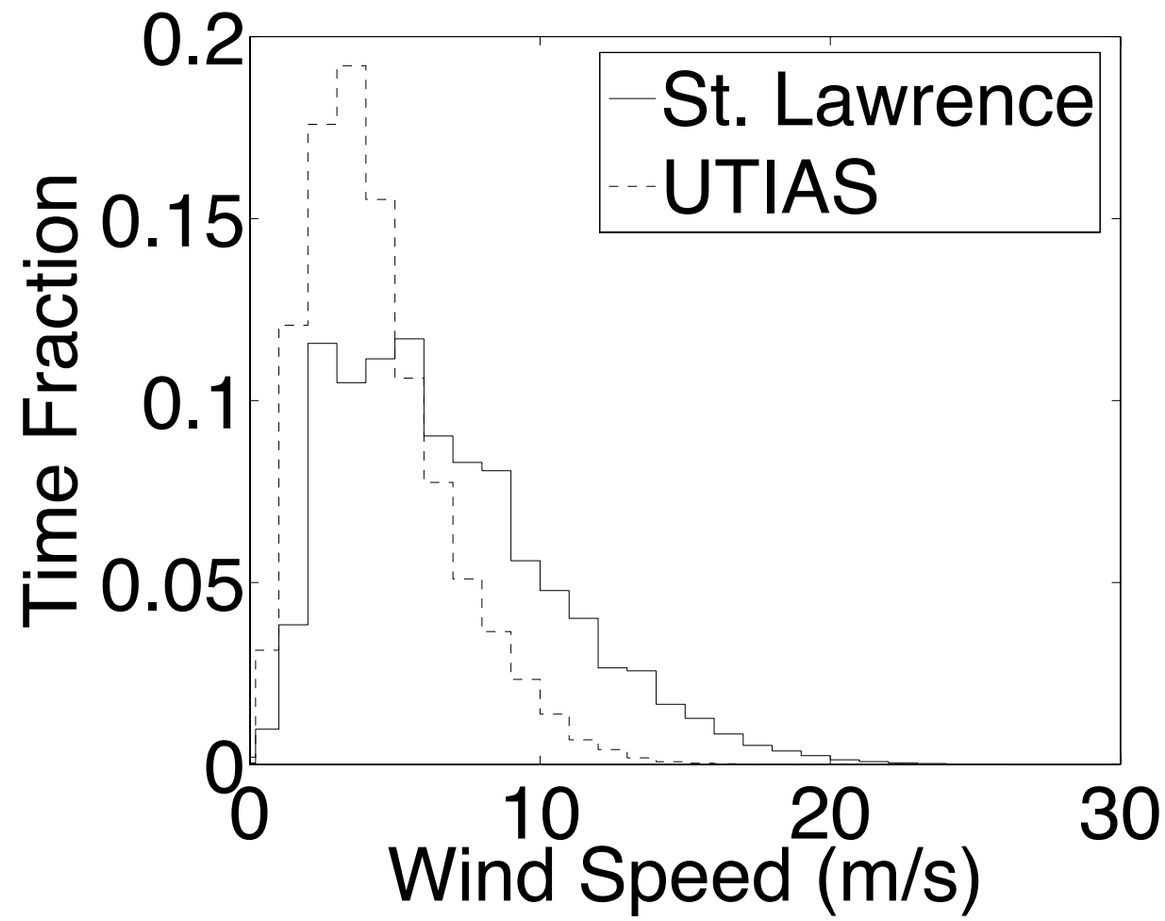
Design Case: Small Urban Wind Turbine

- Wes5 Tulipo
- 5 kW power
- 5 m diameter
- 3 blades, fixed pitch
- Variable speed

Site-Specific Wind Distributions

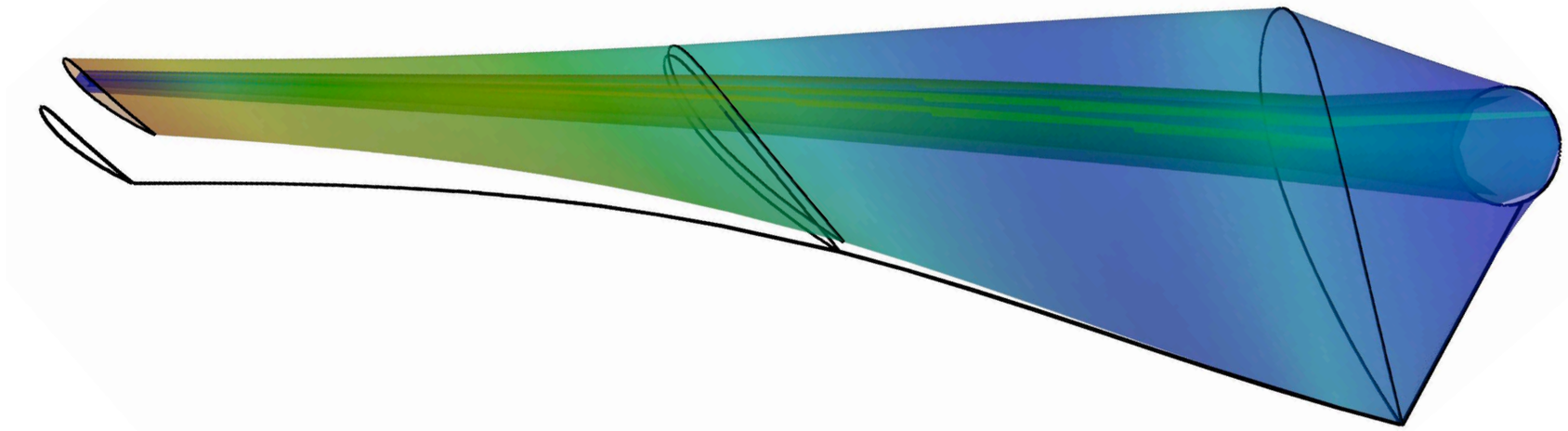
- Canadian Wind Energy Atlas gives wind velocity distributions for the whole country
- Two sites:
  - UTIAS, Toronto
  - St. Lawrence, Newfoundland

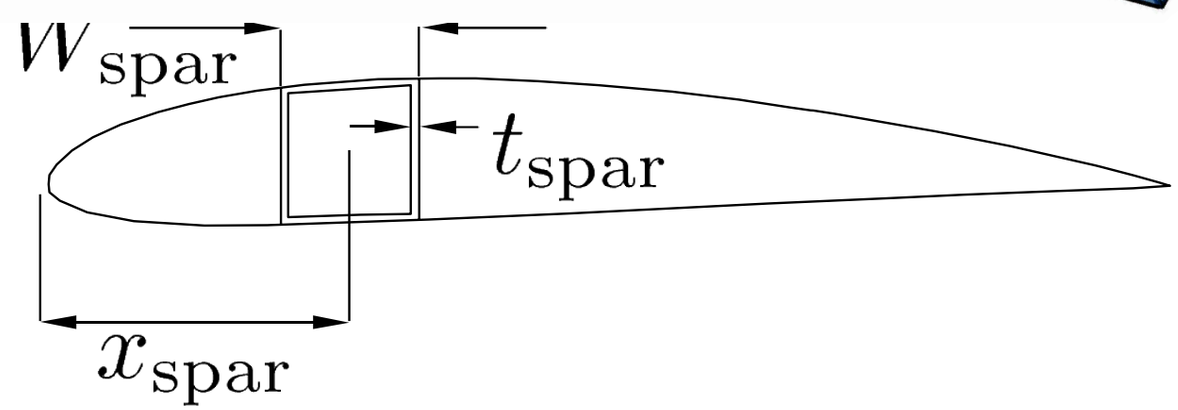




Design Variables

- Chord distribution
- Twist distribution
- Spar thickness
- Spar width
- Airfoil thickness
- Rotation rate





Design Variable	Count	Lower Limit	Upper Limit
Chord	4	.05 m	.40 m
Twists	4	-75 deg	75 deg
W_{spar}	4	4%	30%
t_{spar}	4	0.3 mm	10mm
t_{foil}	3	6%	20%
Ω	varies (12)	7.5 rad/s	14.7 rad/s

Design Constraints

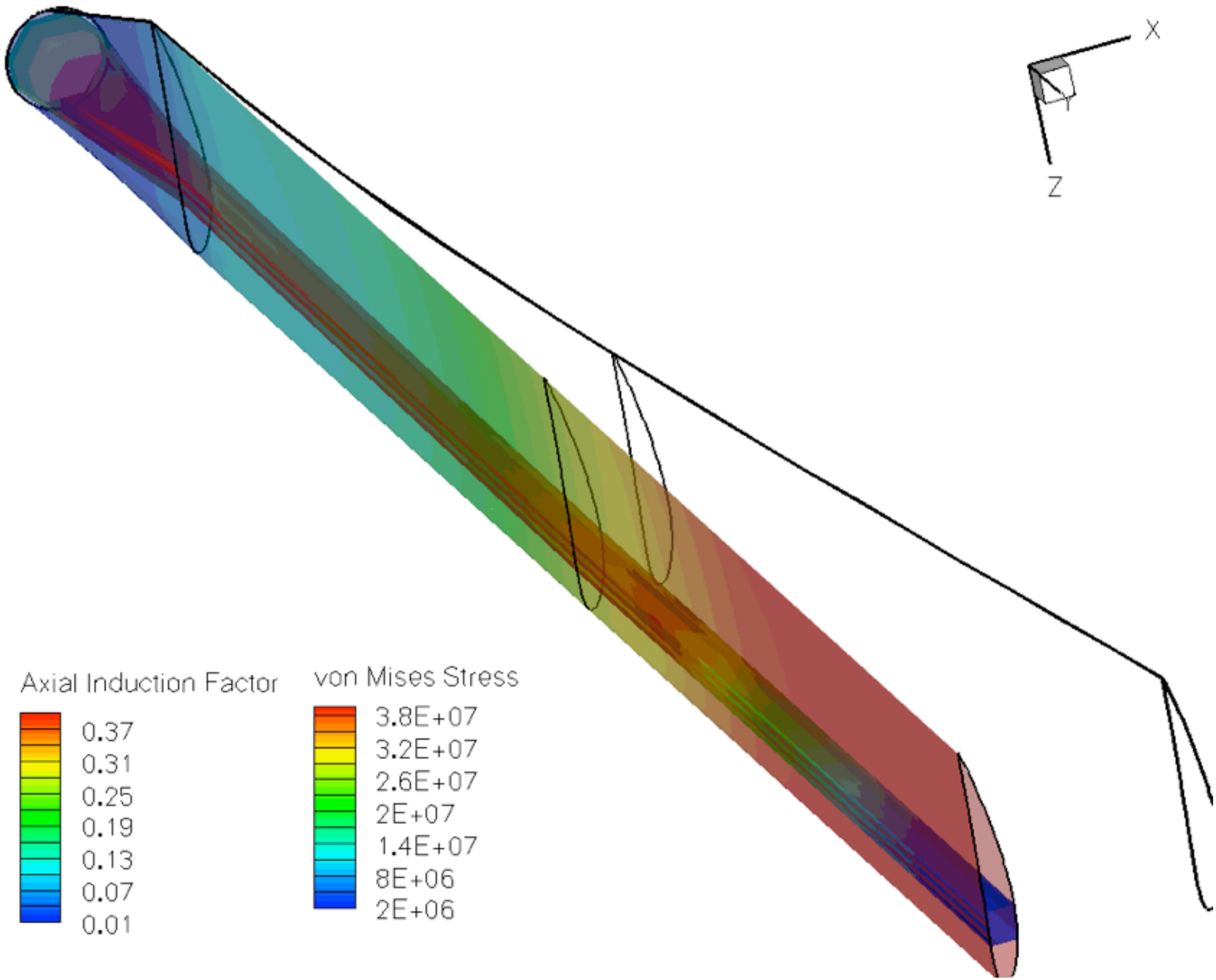
Stresses: Upper bound on von Mises stress for each finite element

Cost: This is constrained by setting upper bounds for spar mass and blade surface area

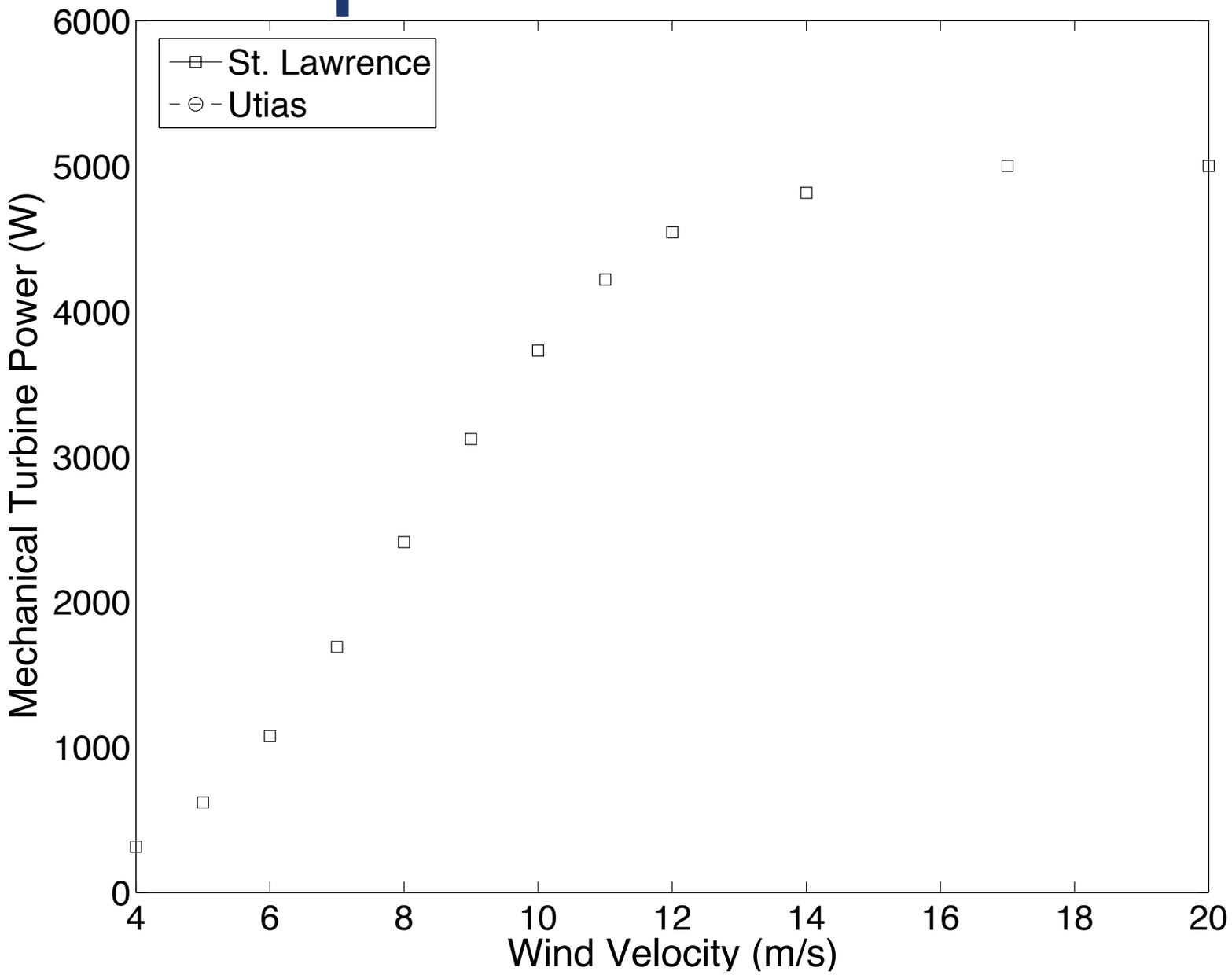
Maximum power: Power transmitted to the generator must not exceed its capacity

Geometry: Constrained to prevent non-physical geometries

Constraint	Minimum	Maximum
Stress	-	40MPa
Spar Mass	-	3.7kg
Surface Area	-	$0.83\mathrm{m}^2$
Power	-	5000 W
Geometry	0.5mm	-


X
Z
Axial Induction Factor
0.37
0.31
0.25
0.19
0.13
0.07
0.01
von Mises Stress
3.8E+07
3.2E+07
2.6E+07
2E+07
1.4E+07
8E+06
2E+06

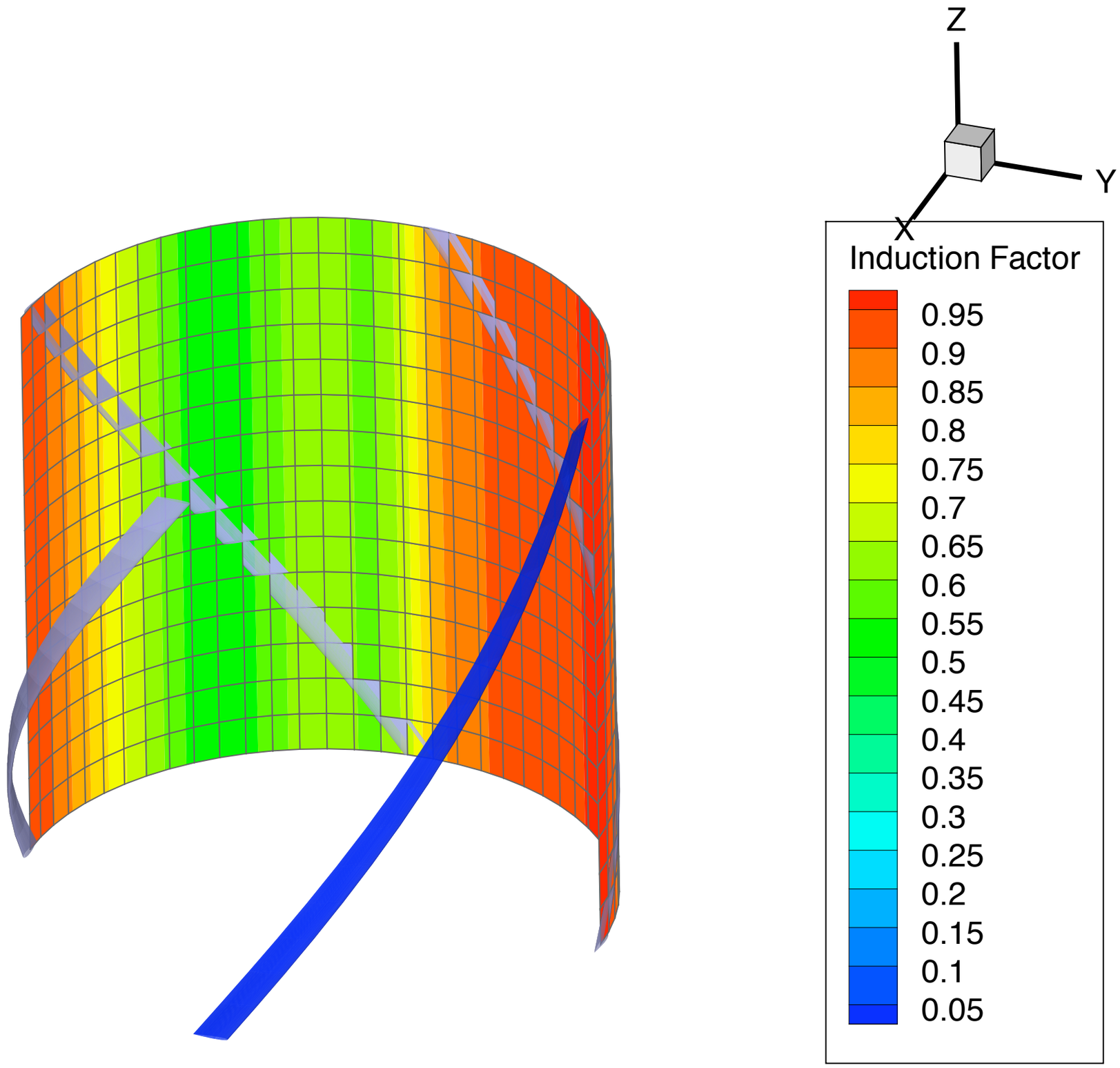
Power of Optimized Turbines



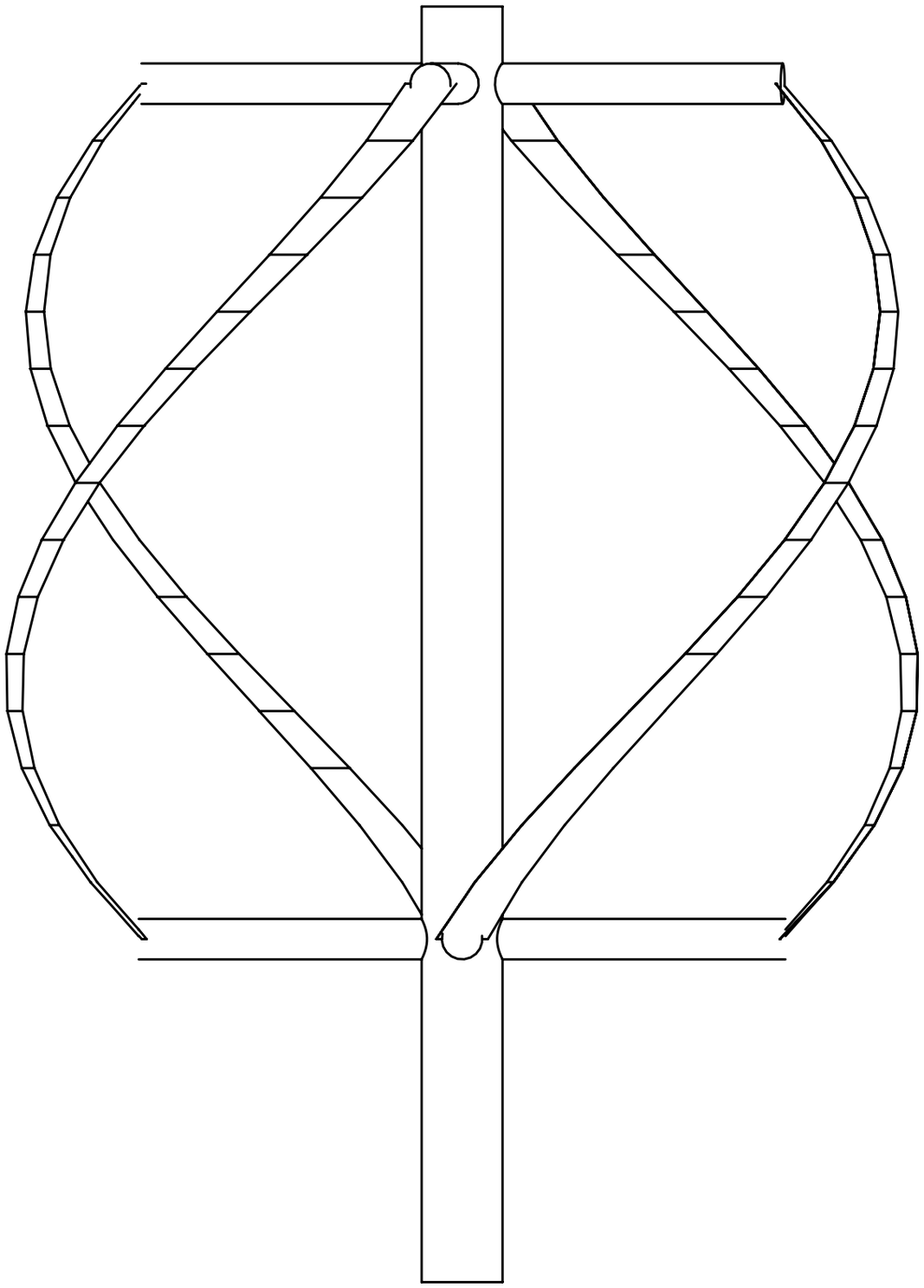
Location	$\bar{P}_{\mathrm{init}}$ (W)	$\bar{P}_{\mathrm{opt}}$ (W)	$\bar{P}_{\mathrm{other-opt}}$ (W)	Site-specific increase
St. Lawrence	1566.1	1984.5	1905.1	4.17%
UTIAS	660.2	853.3	826.0	3.31%

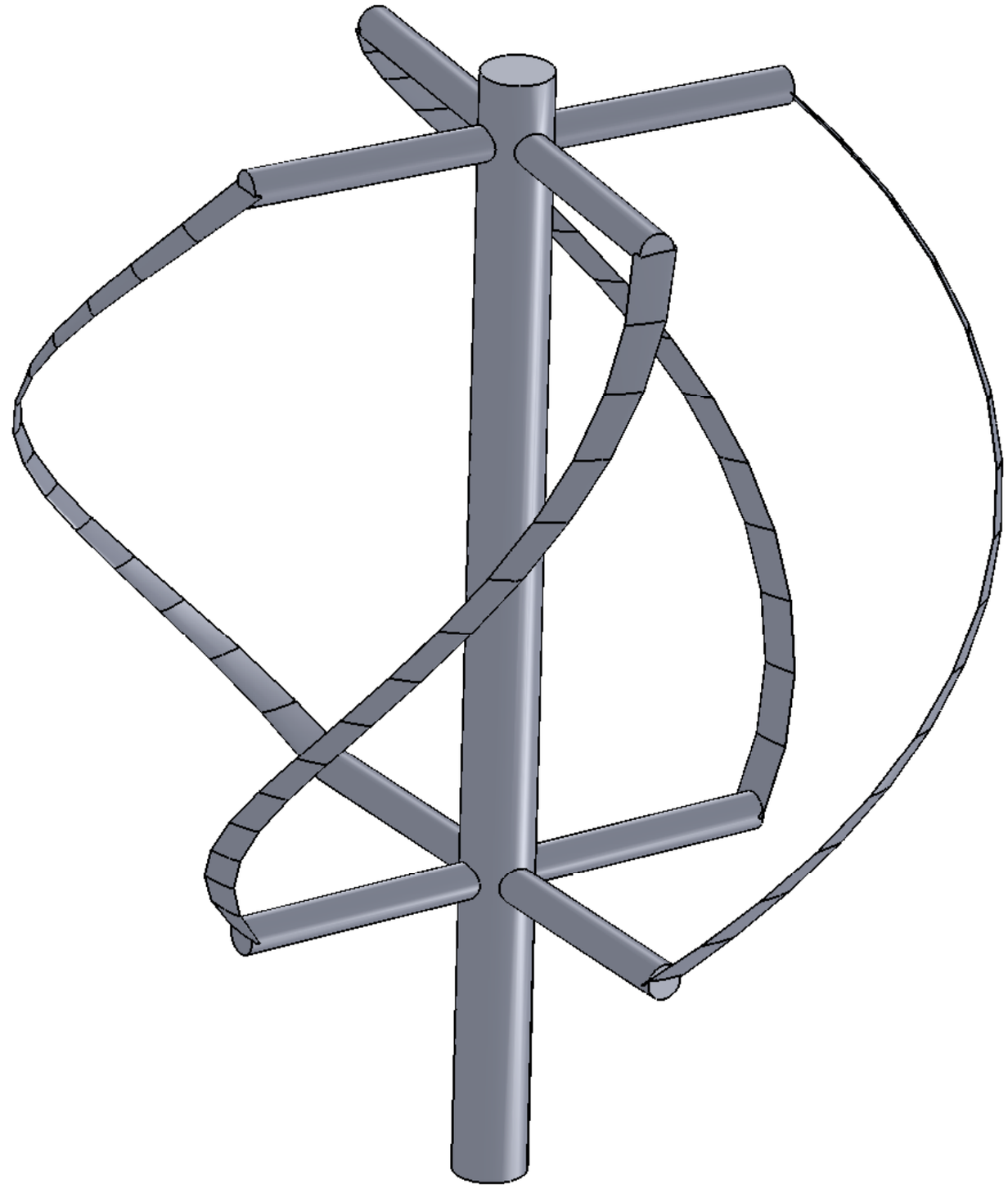
Design Optimization of an Urban Vertical-Axis Wind Turbine

Vertical Axis Urban Wind Turbine



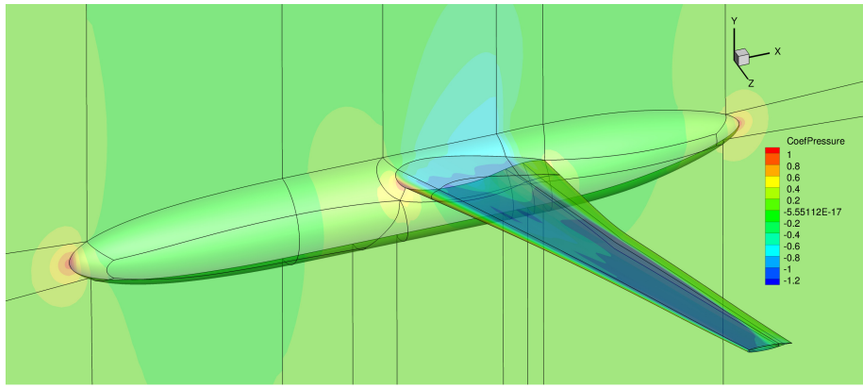
Vertical Axis Urban Wind Turbine



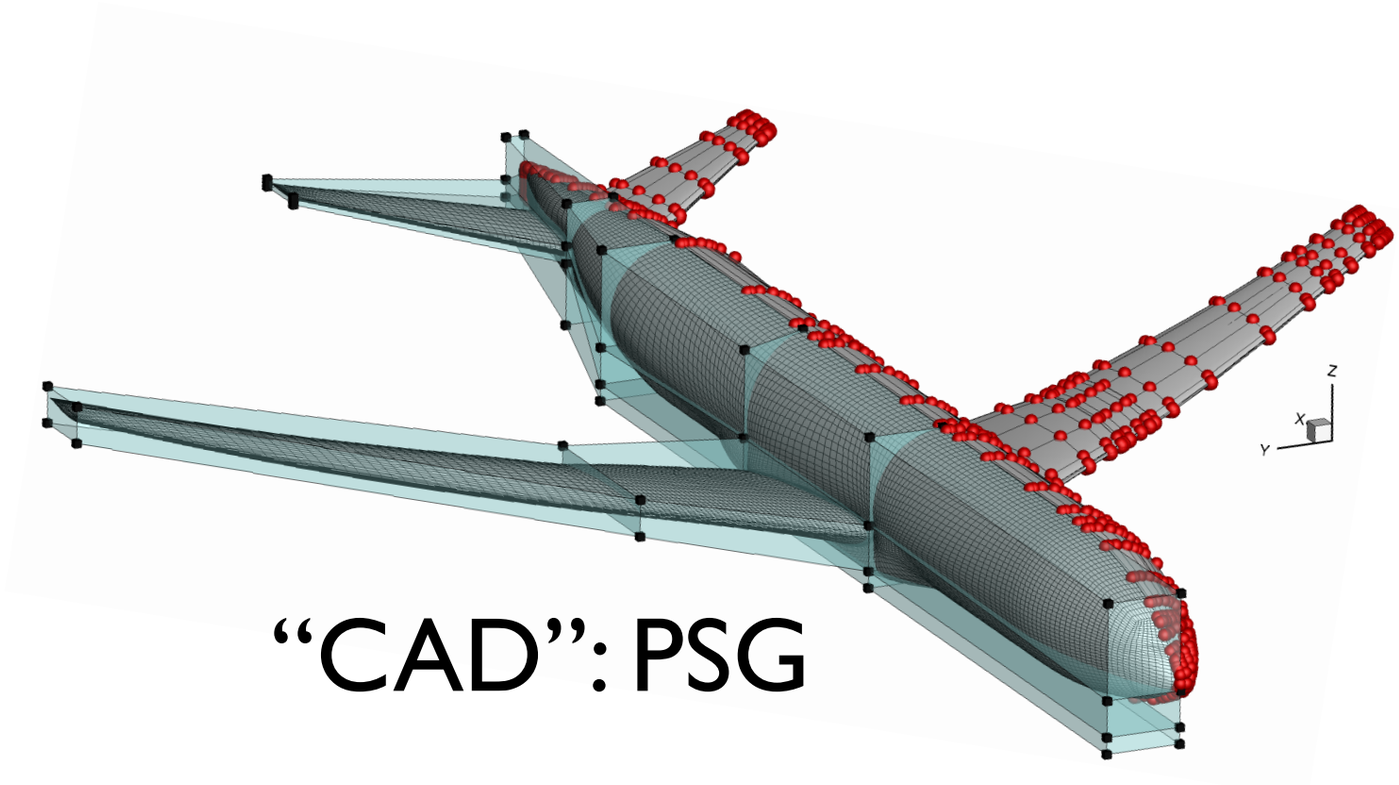


MDO for Aircraft Configurations with High-fidelity (MACH)

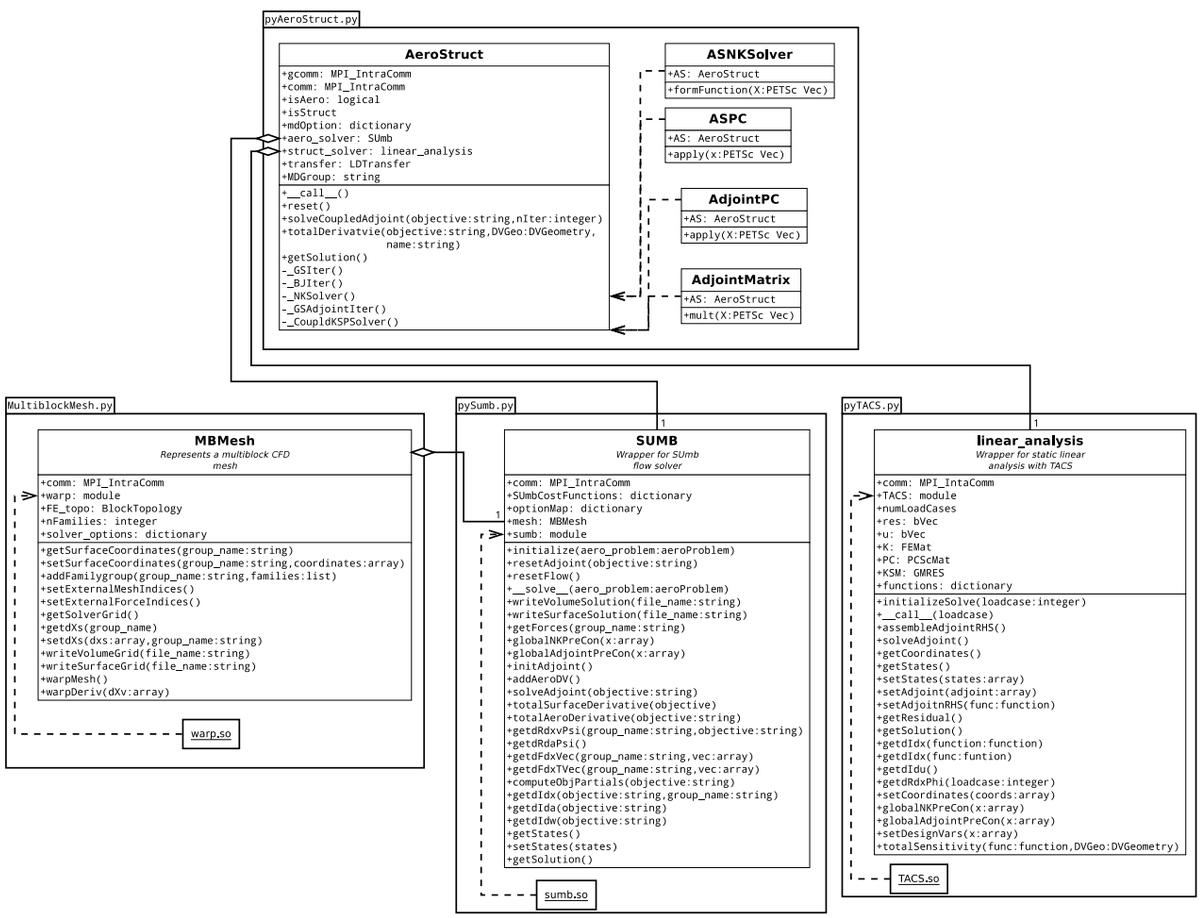
MDO for Aircraft Configurations with High-fidelity (MACH)

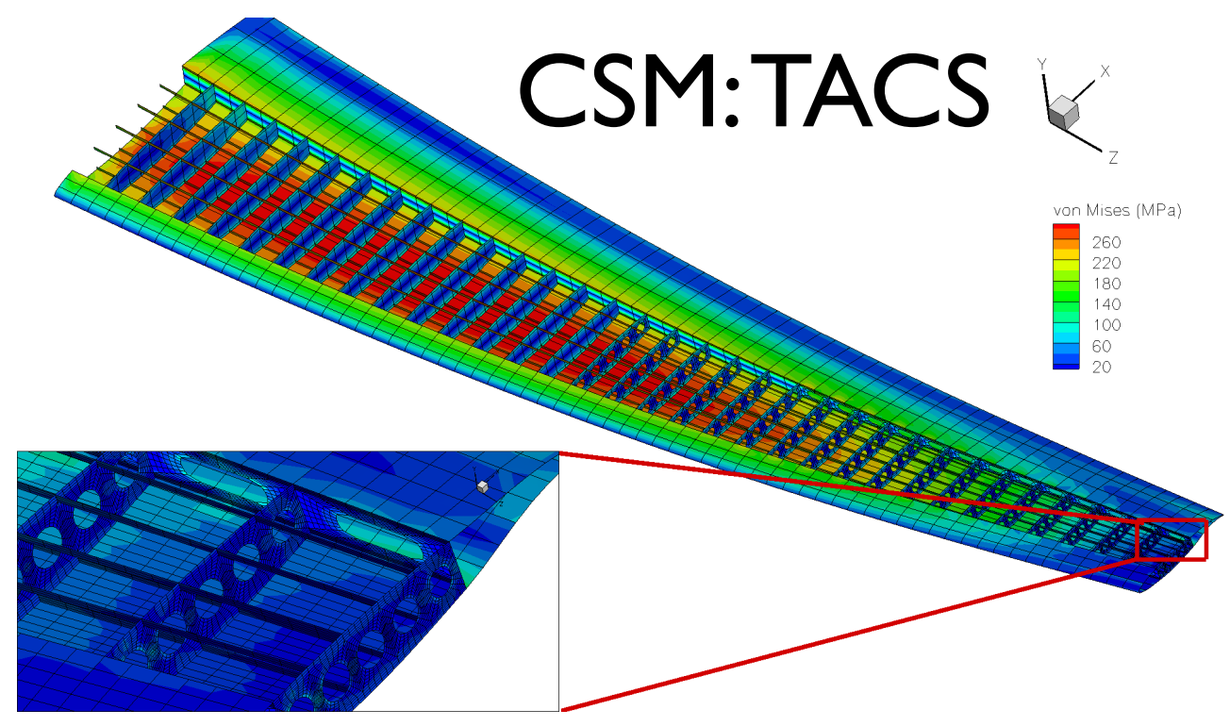


CFD: SUmb



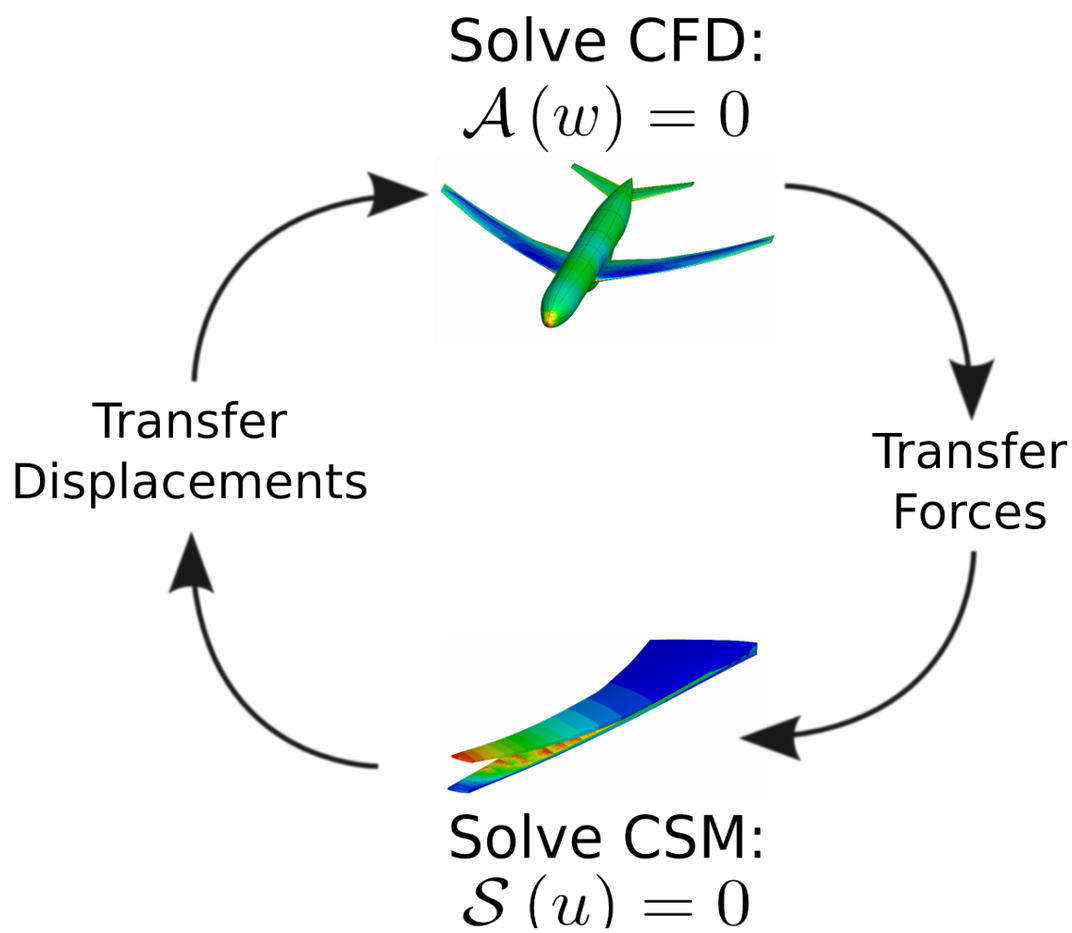
"CAD": PSG





CSM: TACS

Fully coupled aerostructural analysis



$\mathcal{A}$: Aerodynamic residuals
w: Aerodynamic states
$\mathcal{S}$: Structural residuals
u: Structural states

Two available methods:

- A nonlinear block Gauss–Seidel method with Aitken acceleration
- A coupled Newton–Krylov method

$$\begin{bmatrix} \frac{\partial \mathcal{A}}{\partial w} & \frac{\partial \mathcal{A}}{\partial u} \\ \frac{\partial \mathcal{S}}{\partial w} & \frac{\partial \mathcal{S}}{\partial u} \end{bmatrix} \begin{bmatrix} \Delta w \\ \Delta u \end{bmatrix} = - \begin{bmatrix} \mathcal{A}(w) \\ \mathcal{S}(u) \end{bmatrix}$$

The coupled adjoint is the key to efficient MDO with large numbers of design variables

Adjoint equations for the aerostructural system

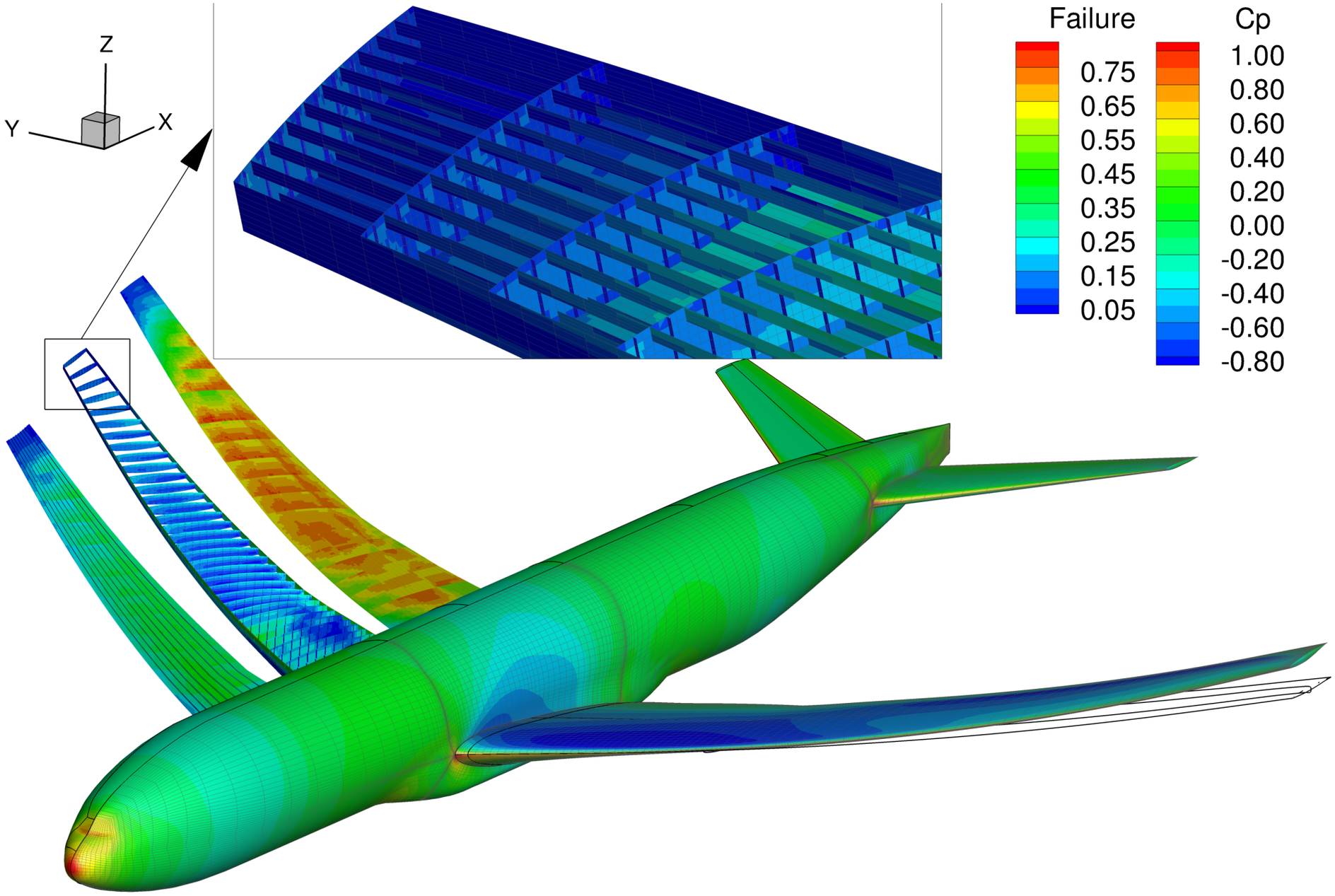
$$\begin{bmatrix} \dfrac{\partial \mathcal{A}}{\partial w} & \dfrac{\partial \mathcal{A}}{\partial u} \\ \dfrac{\partial \mathcal{S}}{\partial w} & \dfrac{\partial \mathcal{S}}{\partial u} \end{bmatrix}^T \begin{bmatrix} \\ \phi \psi \end{bmatrix} = \begin{bmatrix} \dfrac{\partial I}{\partial w} & \dfrac{\partial I}{\partial u} \end{bmatrix}^T$$

Total derivatives

$$\frac{\mathrm{d}I}{\mathrm{d}x} = \frac{\partial I}{\partial x} - {}^T \left(\frac{\partial \mathcal{A}}{\partial x} \right) - \phi^T \left(\frac{\partial \mathcal{S}}{\partial x} \right)$$

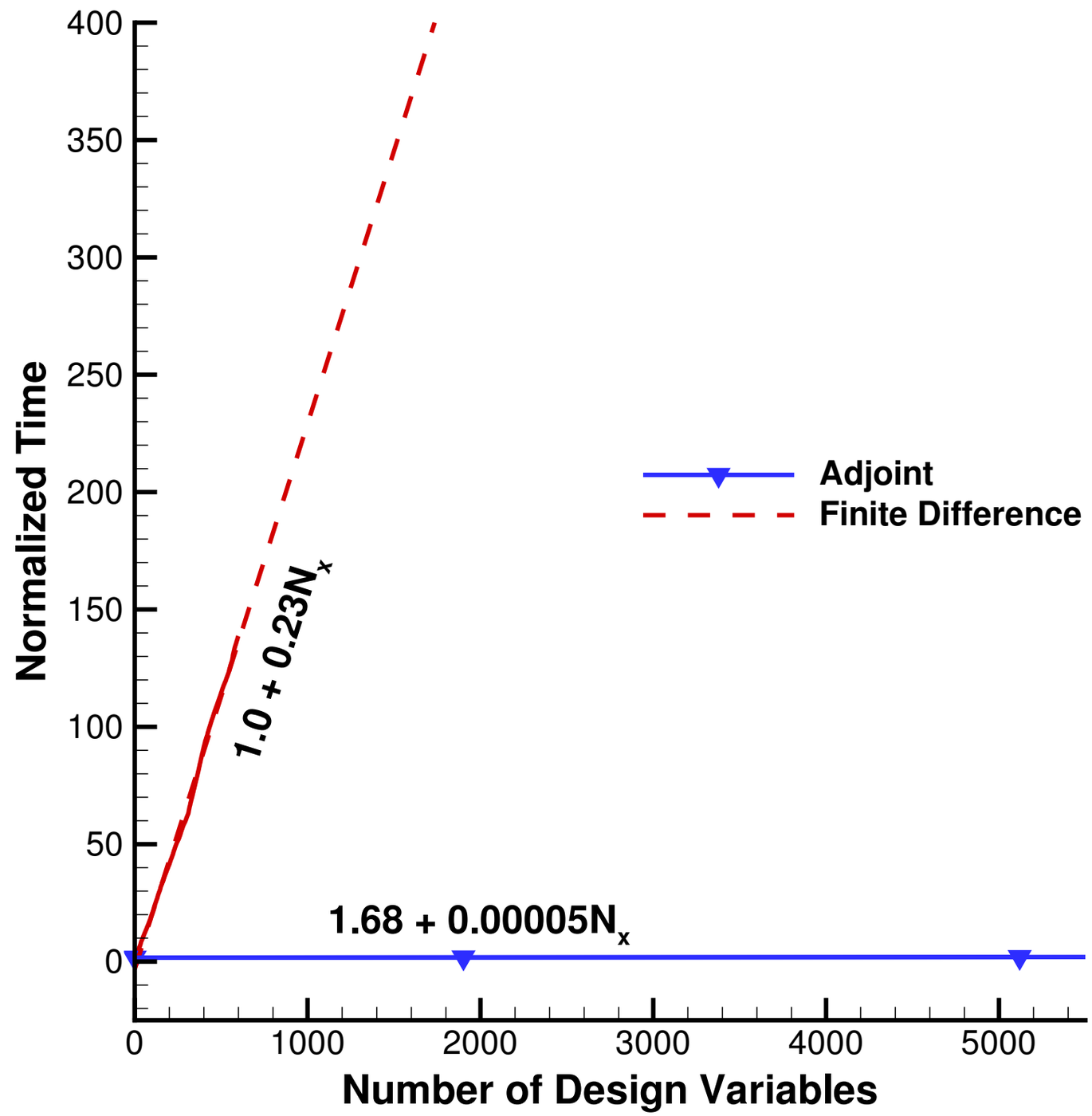
[Kenway, Kennedy and Martins, AIAAJ, 2013]

Aerostructural Model



- NASA Common Research Model (CRM) from DPW4
- 2 million cells in CFD mesh
- Includes a structural model with 300 thousand DOFs

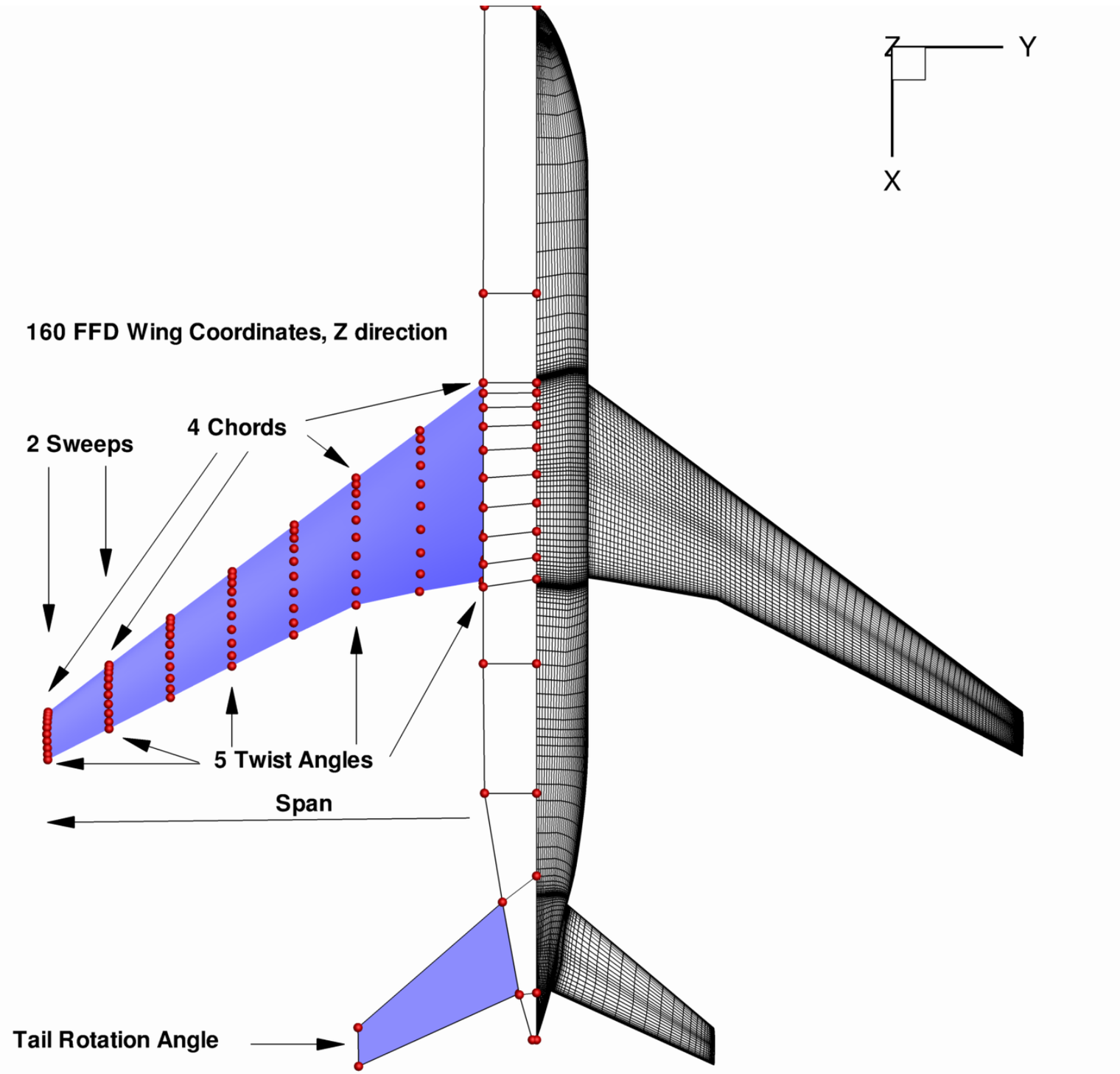
The coupled adjoint is the key for correct and efficient gradients



- 2M CFD cells
- 300k CSM DOFs
- 56 processors
- 1 aerostructural solution = 5.5 min

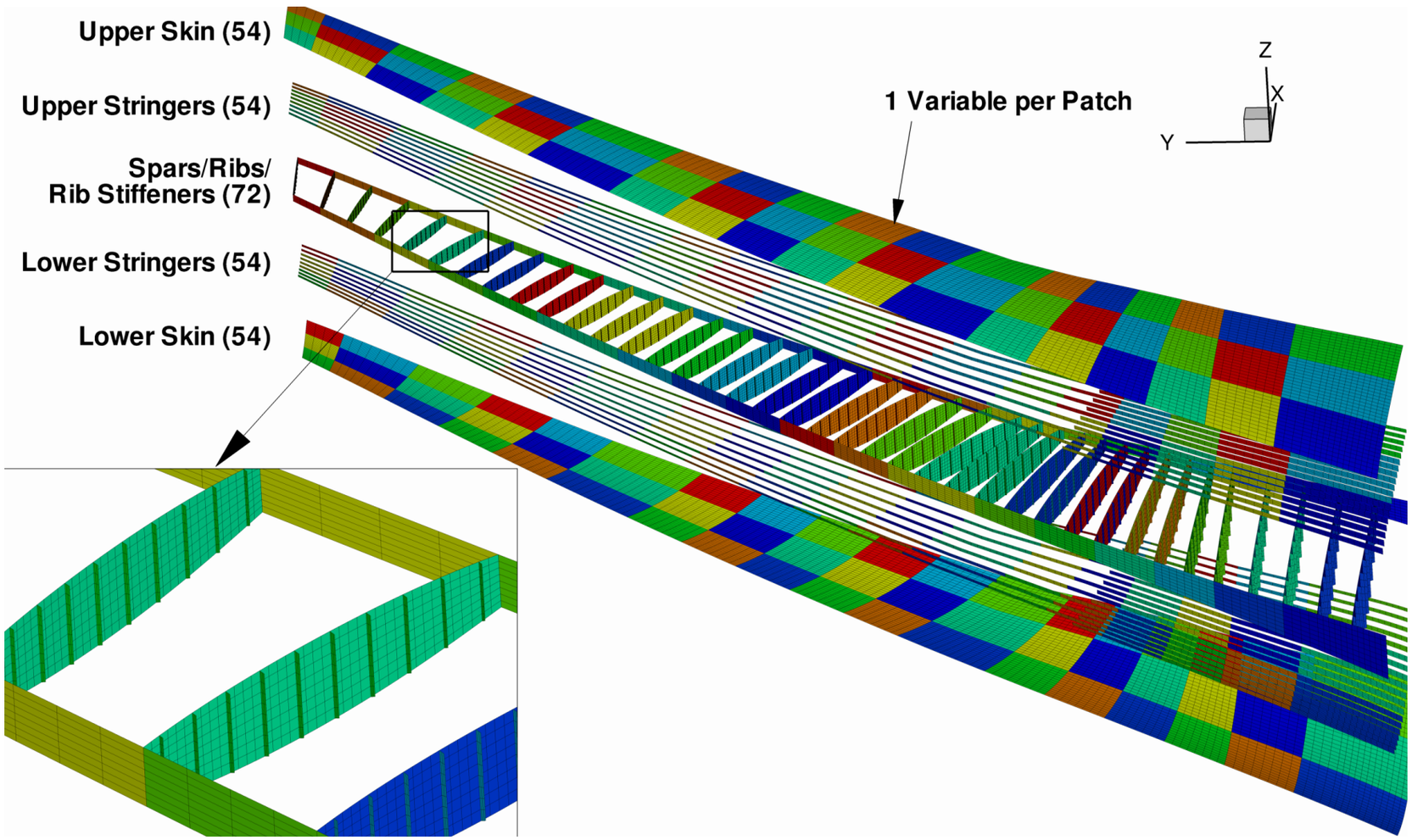
[Kenway, Kennedy and Martins, *AIAA Journal*, 2013 (forthcoming)]

“Aerodynamic” shape variables also affect the structure directly

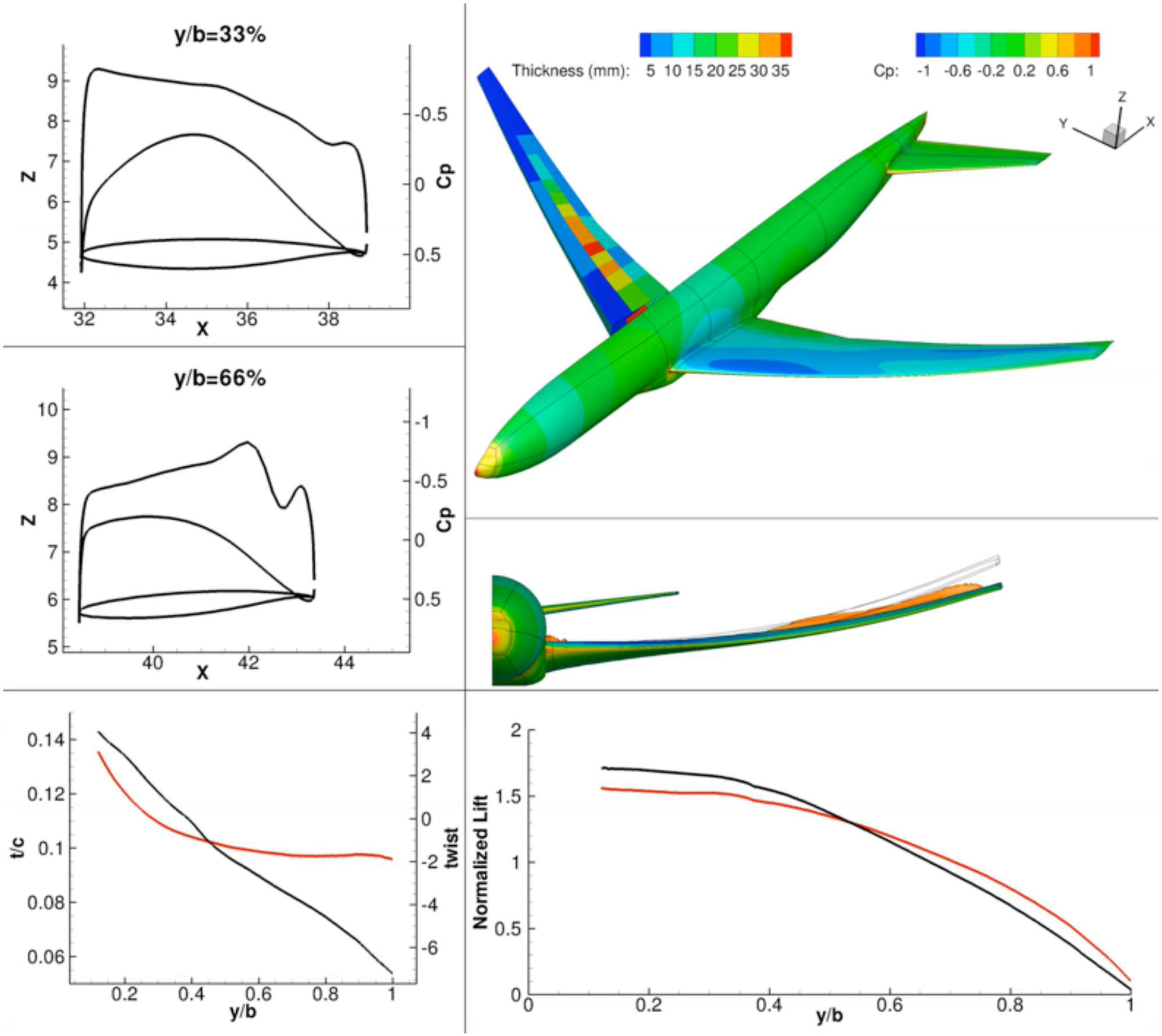


- 12 global geometric design variables
- 160 local shape design variables
- 2.1 million cell CFD mesh
- 1 angle of attack and 1 tail rotation angle for each operating condition

Structural sizing patchwork



- 288 thickness design variables
- 300 000 structural degrees of freedom
- 476 total design variables



[Kenway and Martins, Journal of Aircraft, 2013 (forthcoming)]

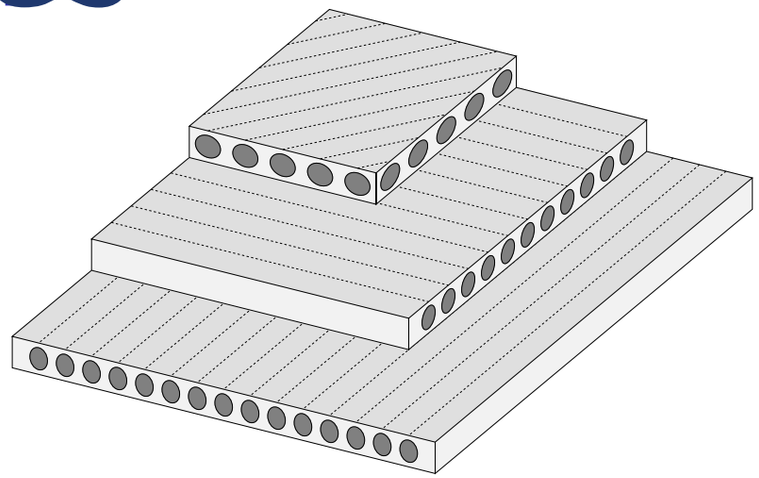
Click here to see the video

Composites

I have just one
word for you:

How to tackle 10^{75} possible lamination sequences

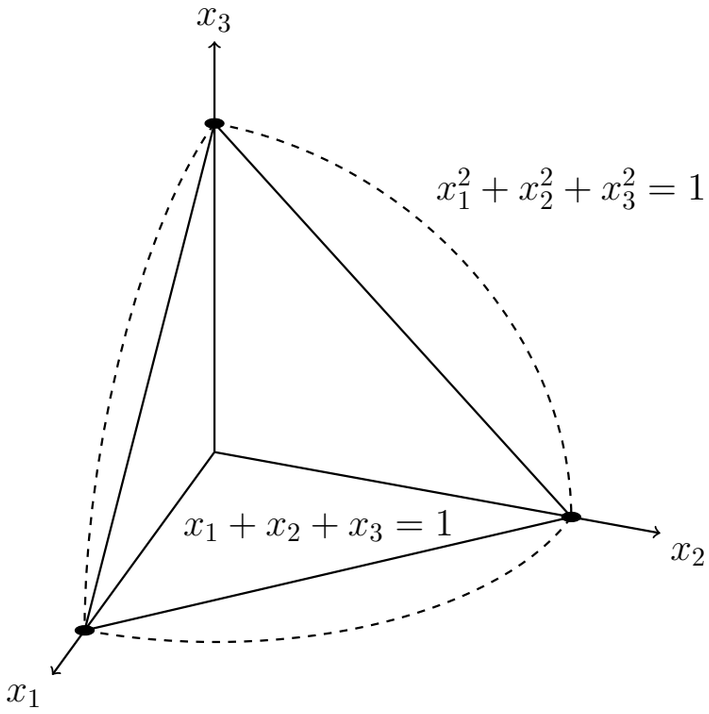
- Ply-identity variables x_i: weights on the different possible ply selections, $\{-45°, 0°, 45°, 90°\}$
- Only one ply-identity can be active in each layer



Use two simultaneous constraints:

1. Sum of weights is 1
2. Sum of the square of the weights is 1

- Spherical constraint introduces many local minima
- Enforce spherical constraints through the use of an exact penalty function



Manufacturing constraints:

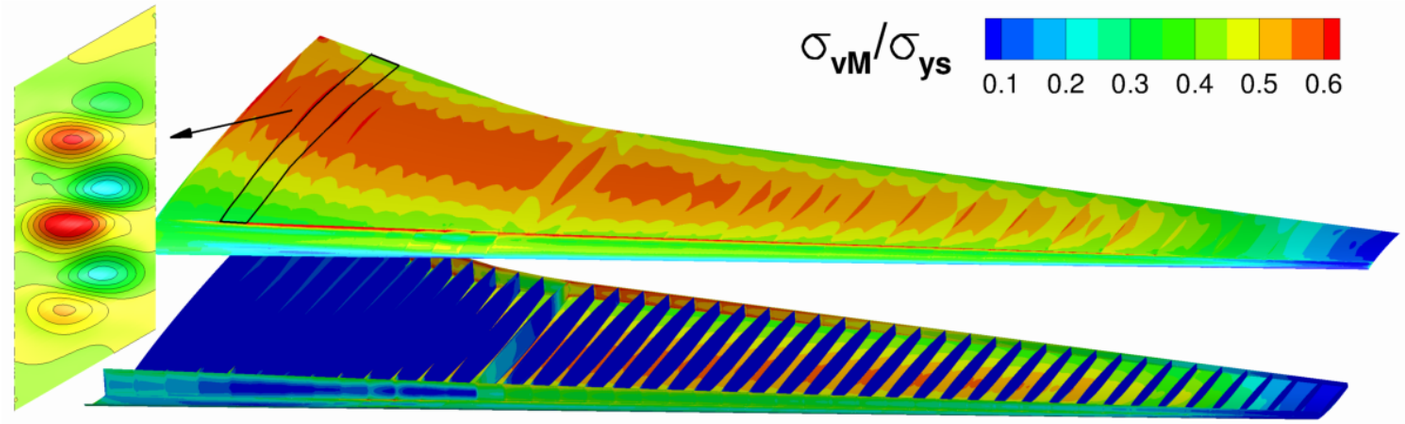
- Minimum 10% ply content in all laminates
- No more than four contiguous plies at the same angle

The design problem

- Design based on Boeing 777-200ER
- Baseline metallic wing: 29 133 kg
- Baseline composite wing: 18 131 kg

- Cruise Mach number: 0.84
- Design range: 8000 nm
- Payload: 40 000 kg
- OEW: 138 100 kg

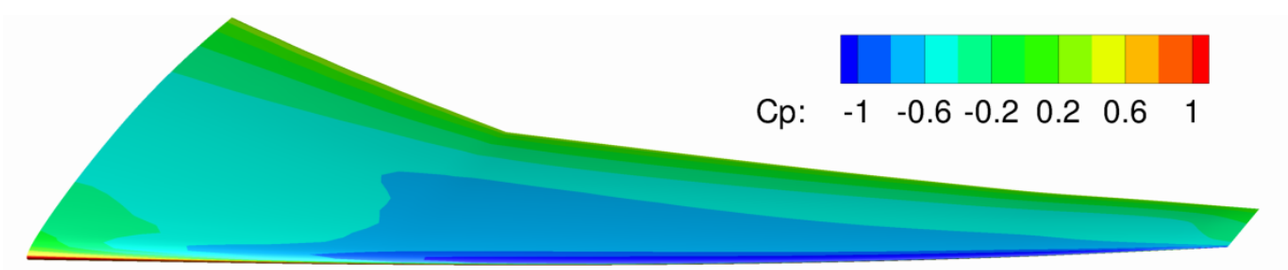
Finite-element structural model



- 44 ribs, 2 spars
- Global finite-element model: 900 000 DOF
- Finite-strip local models with discrete stiffeners
- Smeared stiffness for FE

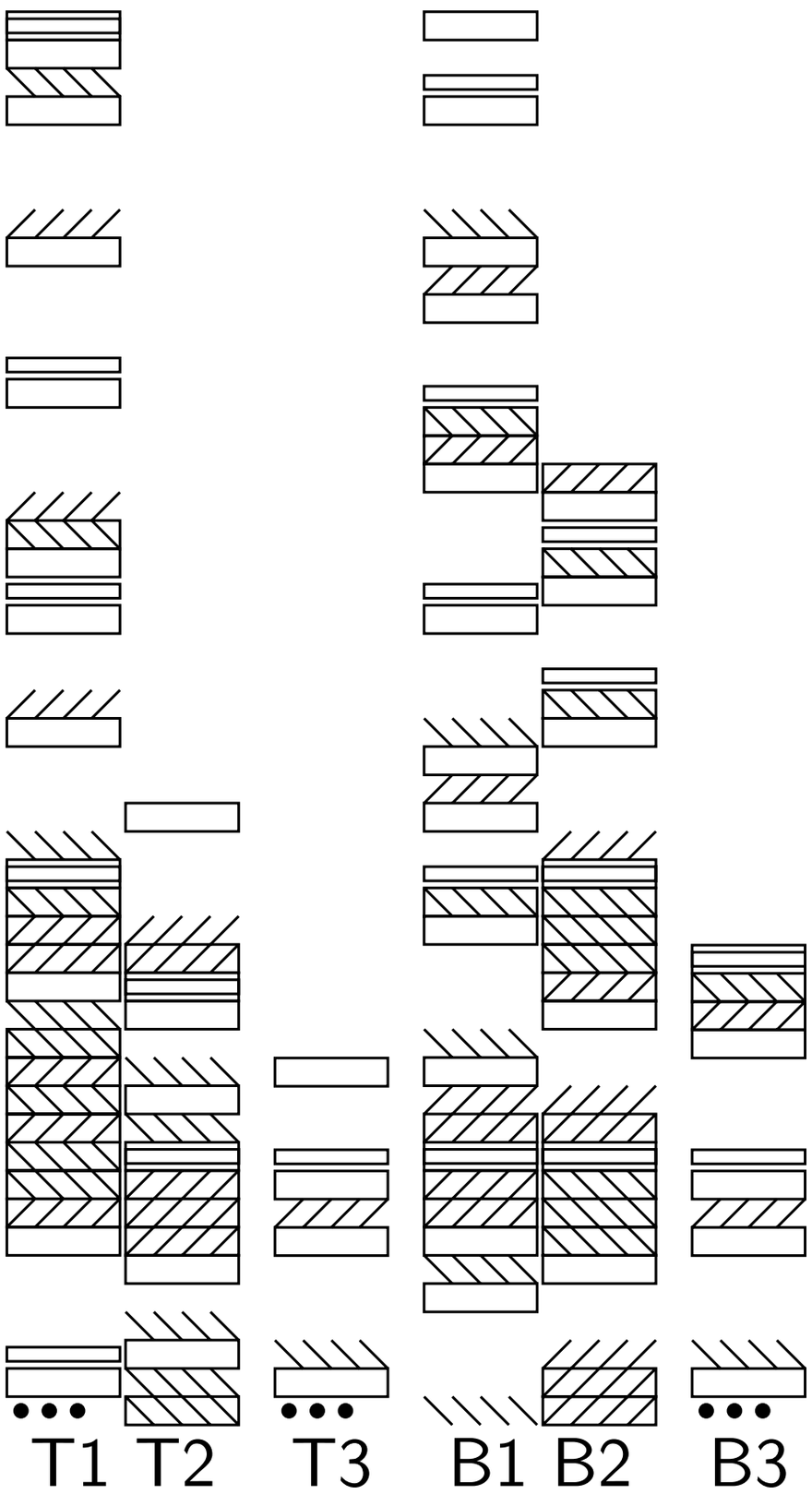
Three-dimensional panel method

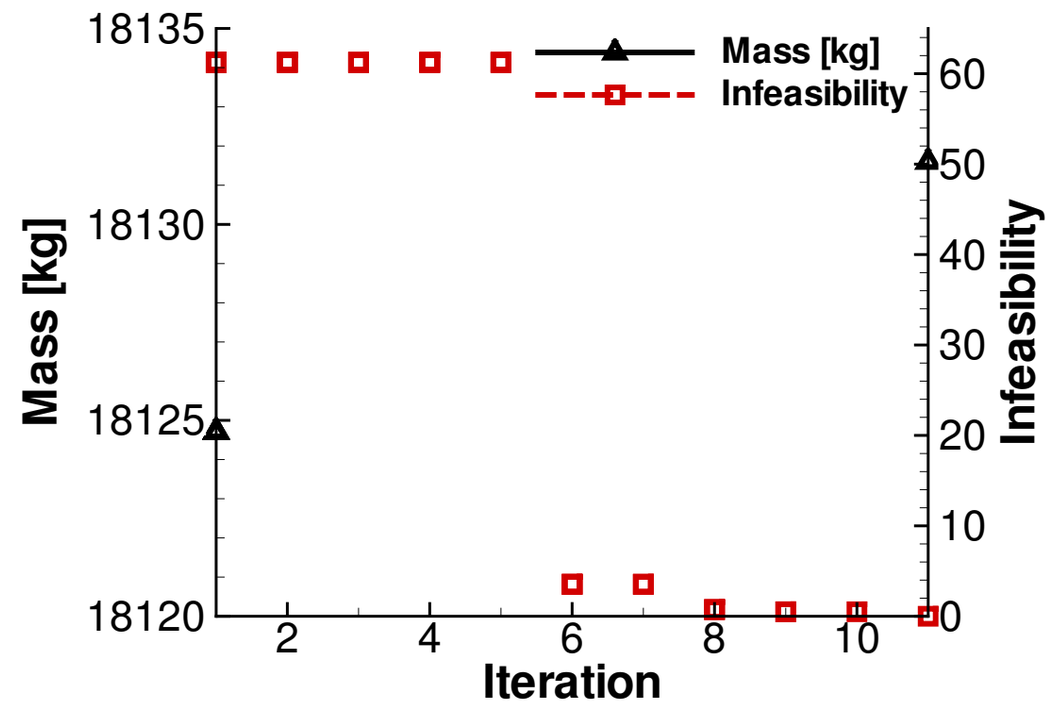
- 4200 surface panels
- Profile and wave drag corrections

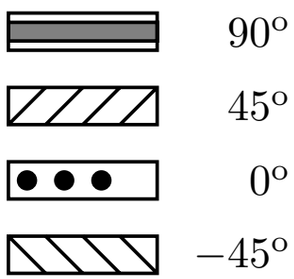


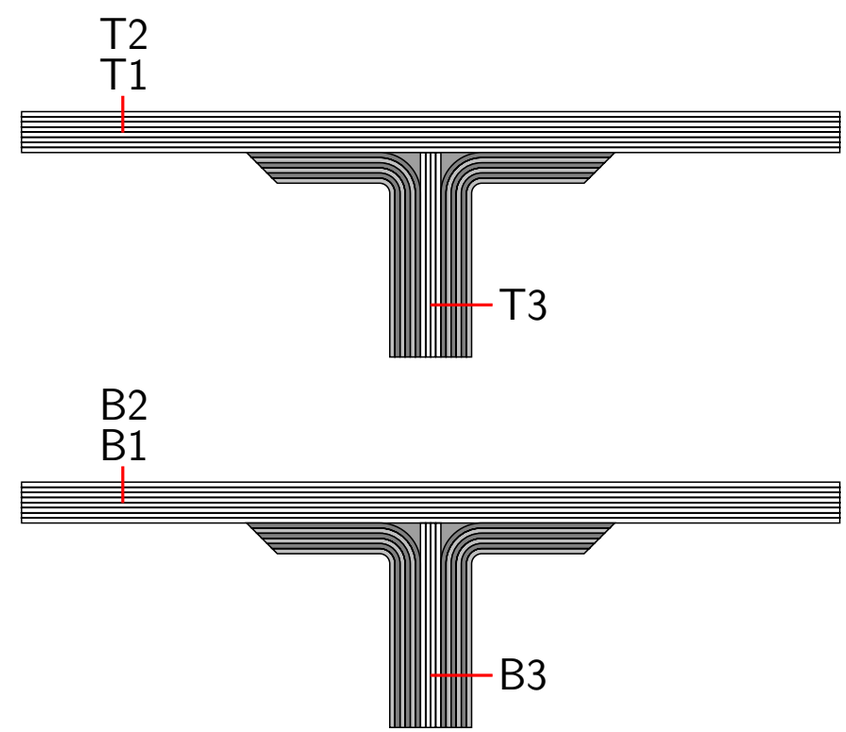
[Kennedy and Martins, *AIAA MAO*, 2012]

How these results stack up



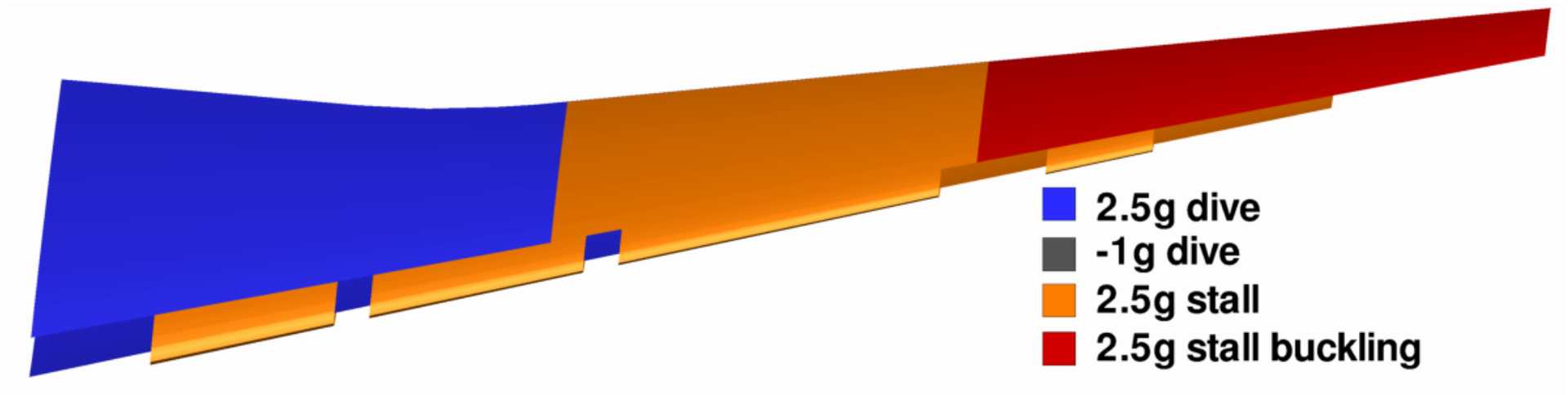




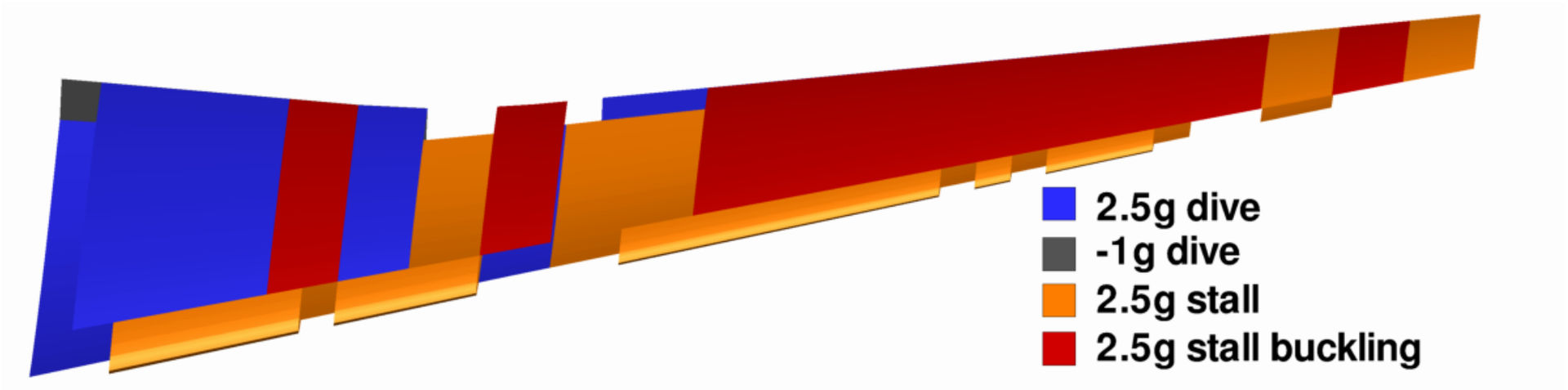


The active structural constraints

Metallic wing



Composite wing



- Only the 100% fuel load conditions are active
- Composite inboard buckling conditions: local buckling of the stiffeners

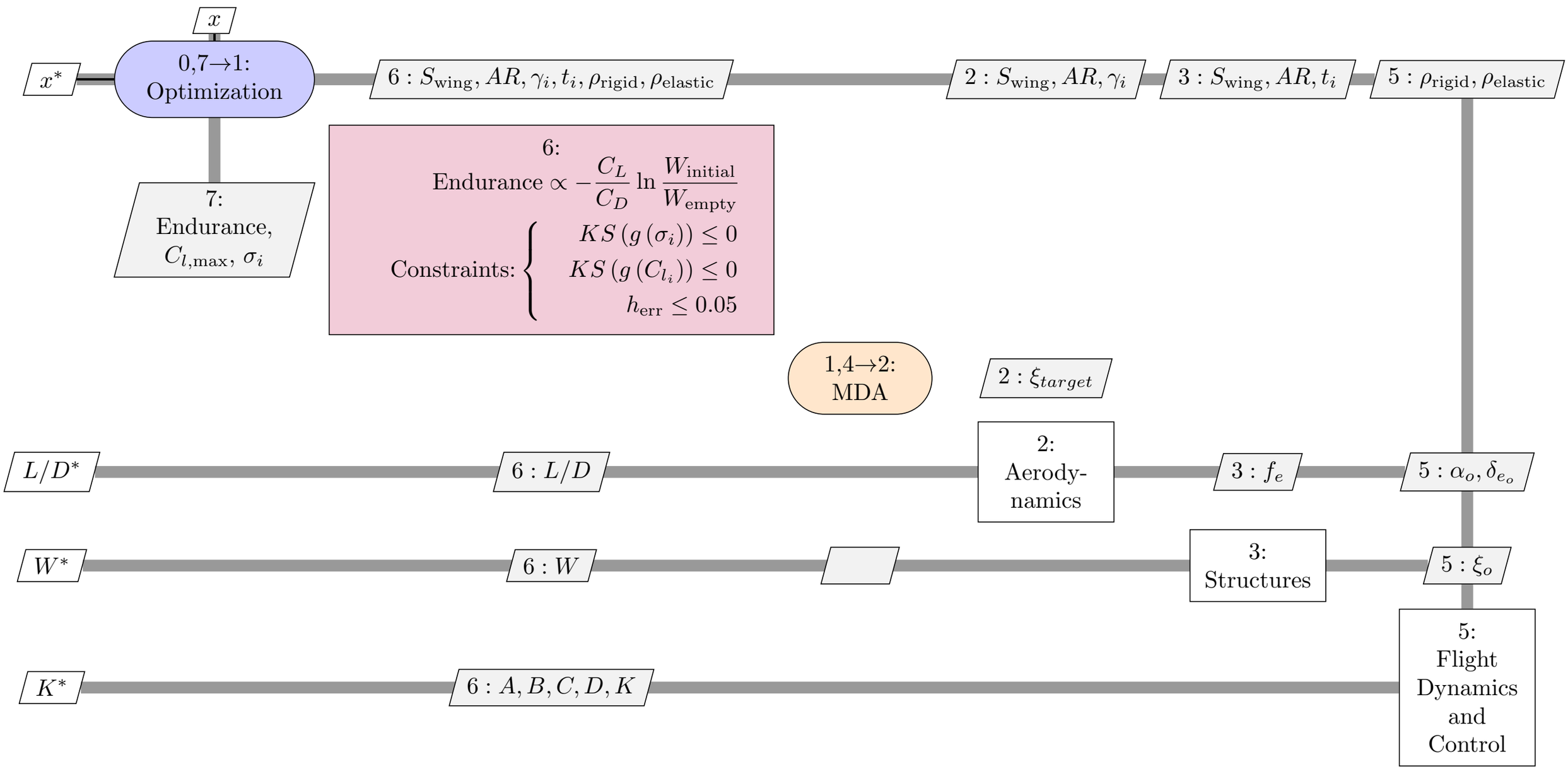
[Kennedy and Martins, *AIAA MAO*, 2012]

Why can't we just all work together?

Aerodynamic shape + Structural sizing + Control gains =

Aeroservoelastic Optimization

This aeroservoelastic optimization considers maneuver and gust loads



[Haghighat, Liu and Martins, *Journal of Aircraft*, 2012]

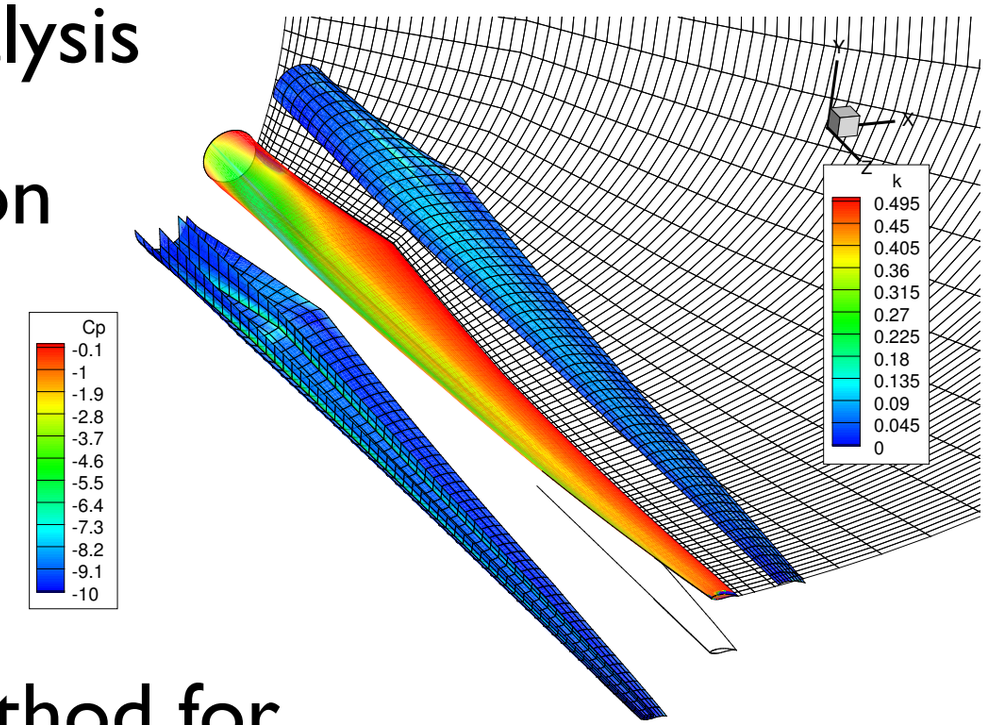
Aeroservoelastic optimum was significantly better than the aerostructural one...

Optimization results with and without load alleviation system.

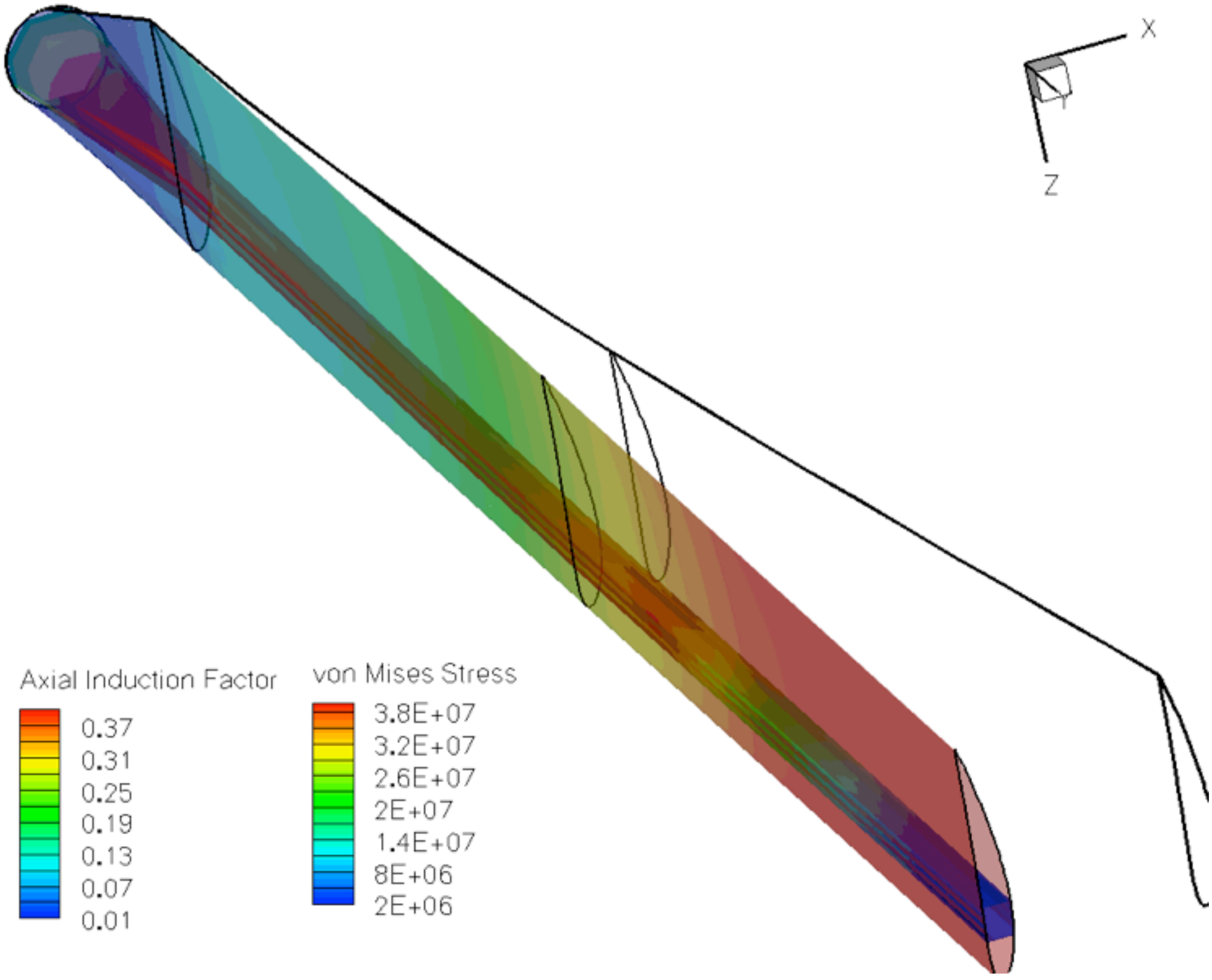
Load alleviation	Off	On	
S_{ref} (m^2)	219.18	191.47	14.5% smaller
AR	13.98	14.03	
L/D	34.29	34.37	
q_{elastic}	1499.95	1499.88	
q_{rigid}	90.63	75.71	
Wing mass (kg)	13,378	7,817	41.5% lighter
Endurance factor	31.90	38.83	21.7% higher

Current and Future Work

- Create a detailed FEM of an NREL turbine blade
- Implement a low-speed preconditioner for the CFD solver
- Validate the CFD, FEA, and coupled analysis
- Formulate a relevant design optimization problem
- Optimize composite layup for optimal aeroelastic tailoring
- Use of nonlinear frequency domain method for coupled unsteady analysis
- Add control for aeroservoelastic optimization



Thank you!



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