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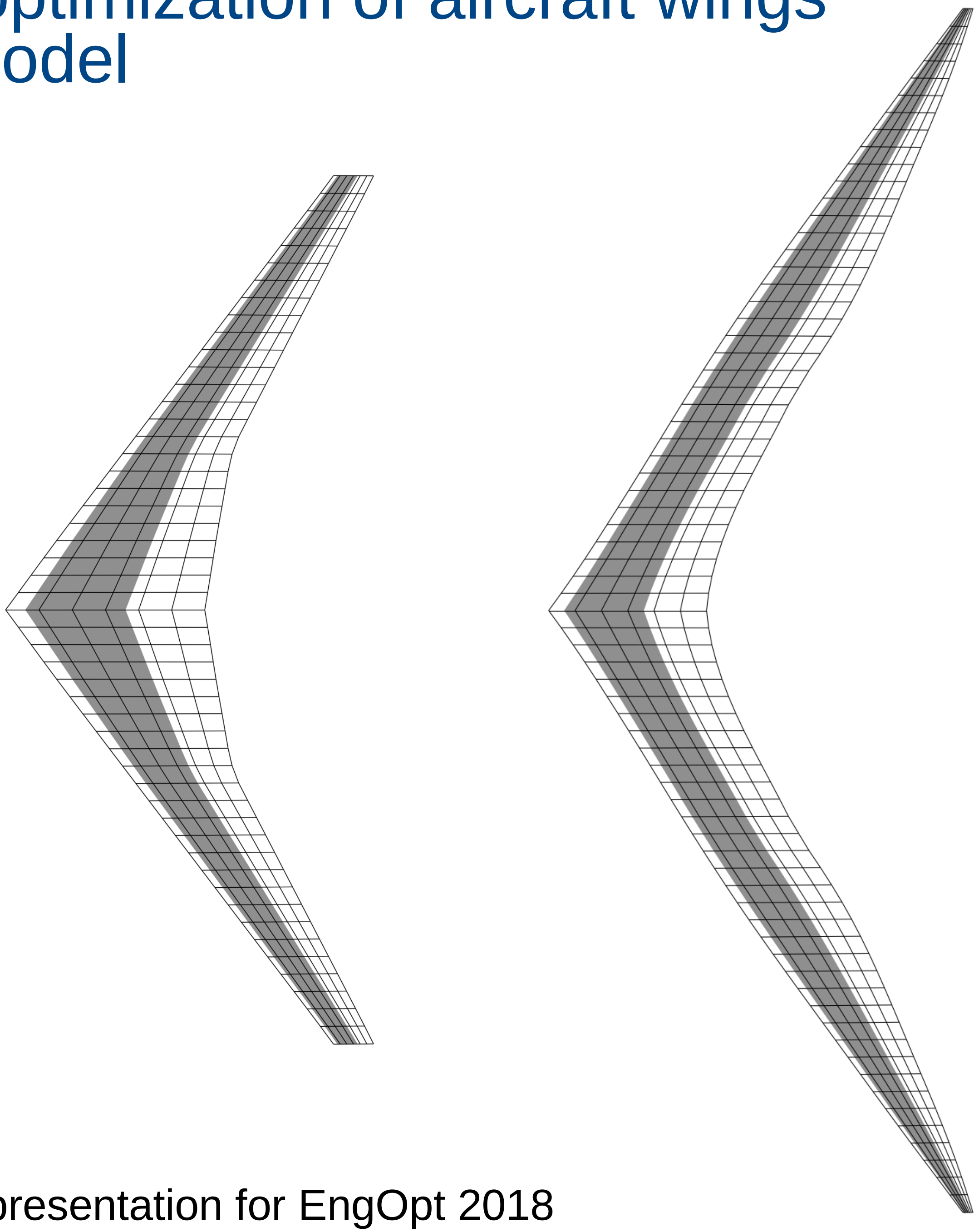
Low-fidelity aerostructural optimization of aircraft wings with a simplified wingbox model using OpenAeroStruct



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University of Michigan

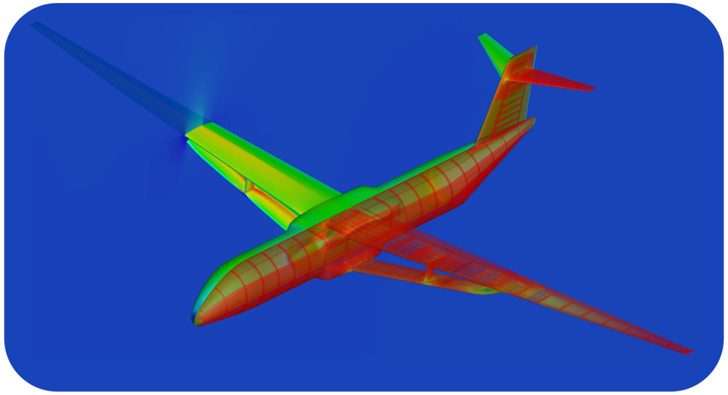
A presentation for EngOpt 2018
September 19, 2018, Técnico Lisboa, Lisbon, Portugal

Conference paper: https://doi.org/10.1007/978-3-319-97773-7_38

Background and motivation

Background: Wing design requires finding a balance between aerodynamics and structures

Span
Sweep
Taper
Airfoil shapes
Material thicknesses



Fuel burn

Cost

Structural stresses

Design changes

Motivation: Low-fidelity optimization remains popular

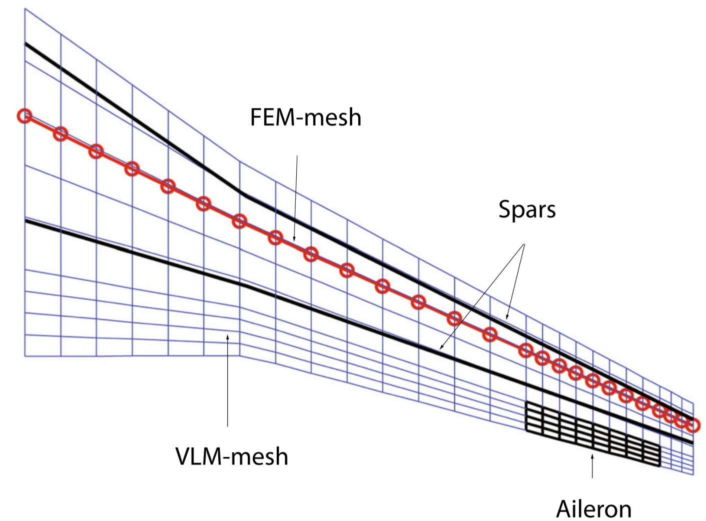
Despite the availability of high-fidelity tools, low-fidelity tools remain popular.

For example:

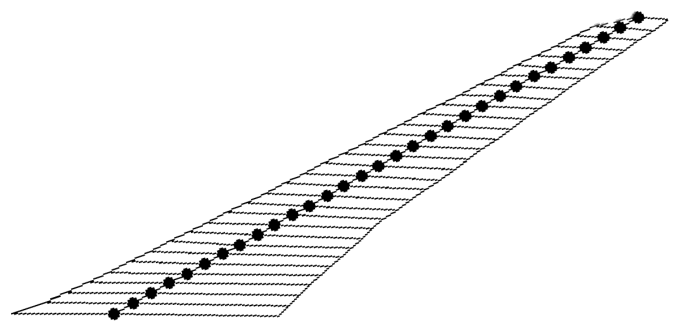
Vortex Lattice Method **(VLM)** codes

+

Simplified Finite Element Method **(FEM)** models



[Elham and van Tooren, **2016**]



[Fujiwara and Nguyen, **2017**]

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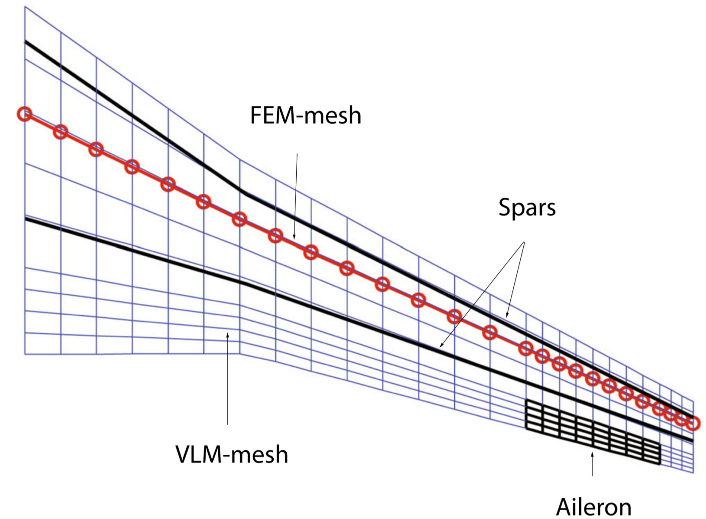
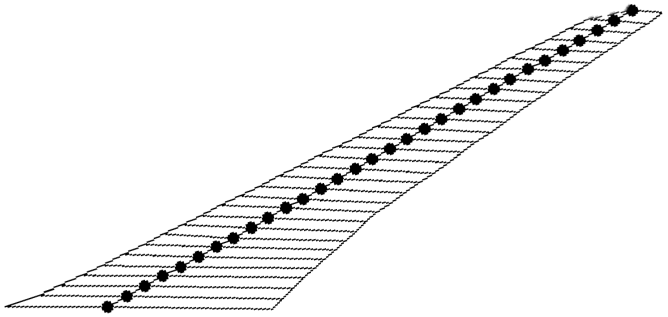


[Elham and van Tooren, **2016**]

Advantages:

- Low cost
- Captures major trends
- Reasonable results
- Useful for early design studies



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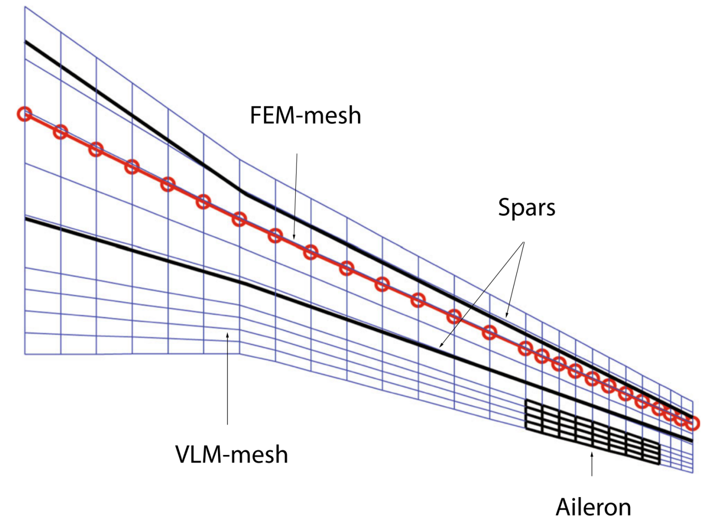

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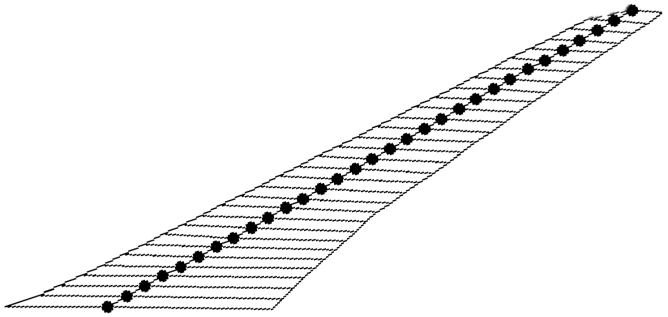


[Fujiwara and Nguyen, **2017**]

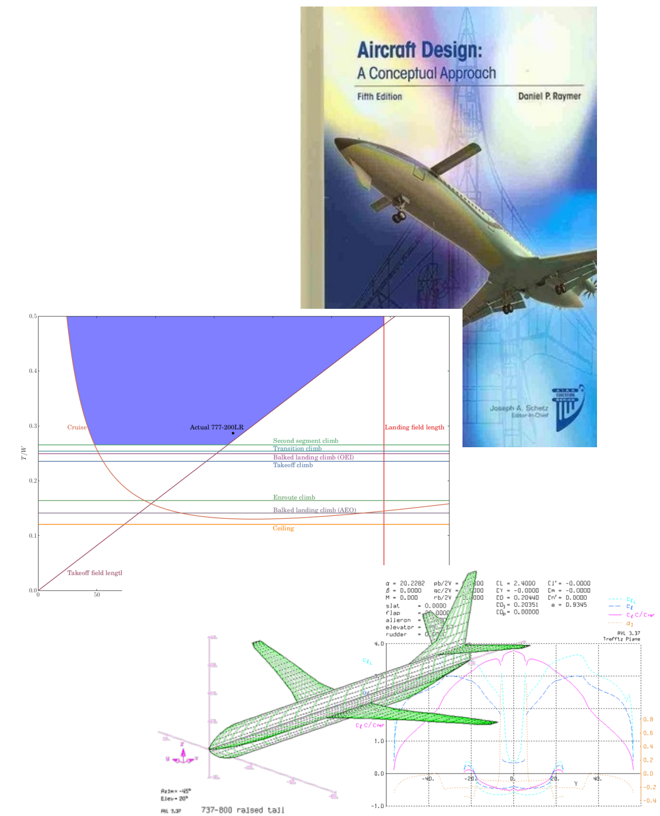
There is a lack of easily available and open-source tools!

Additional motivation: Education

Aircraft design courses usually fail to provide much insight on wing structures.

Limited insight on:

- Material thickness ranges and distributions
- Structural weight
- Advantages of inertial relief (how much of a difference does it make?)
- Certain trade-offs (e.g., thickness-to-chord ratio)
- Contribution of different types of stress (how does the bending stress compare to the torsional stress?)



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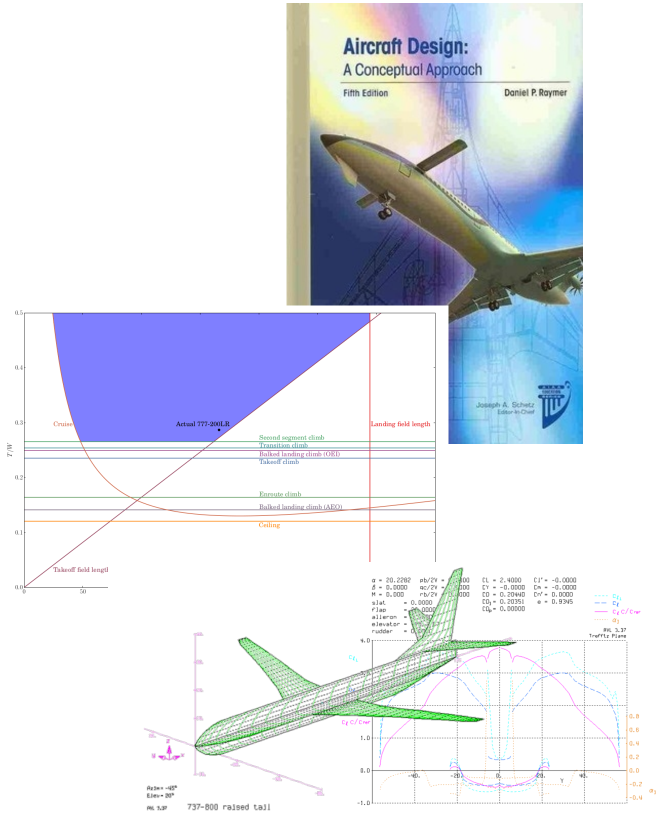
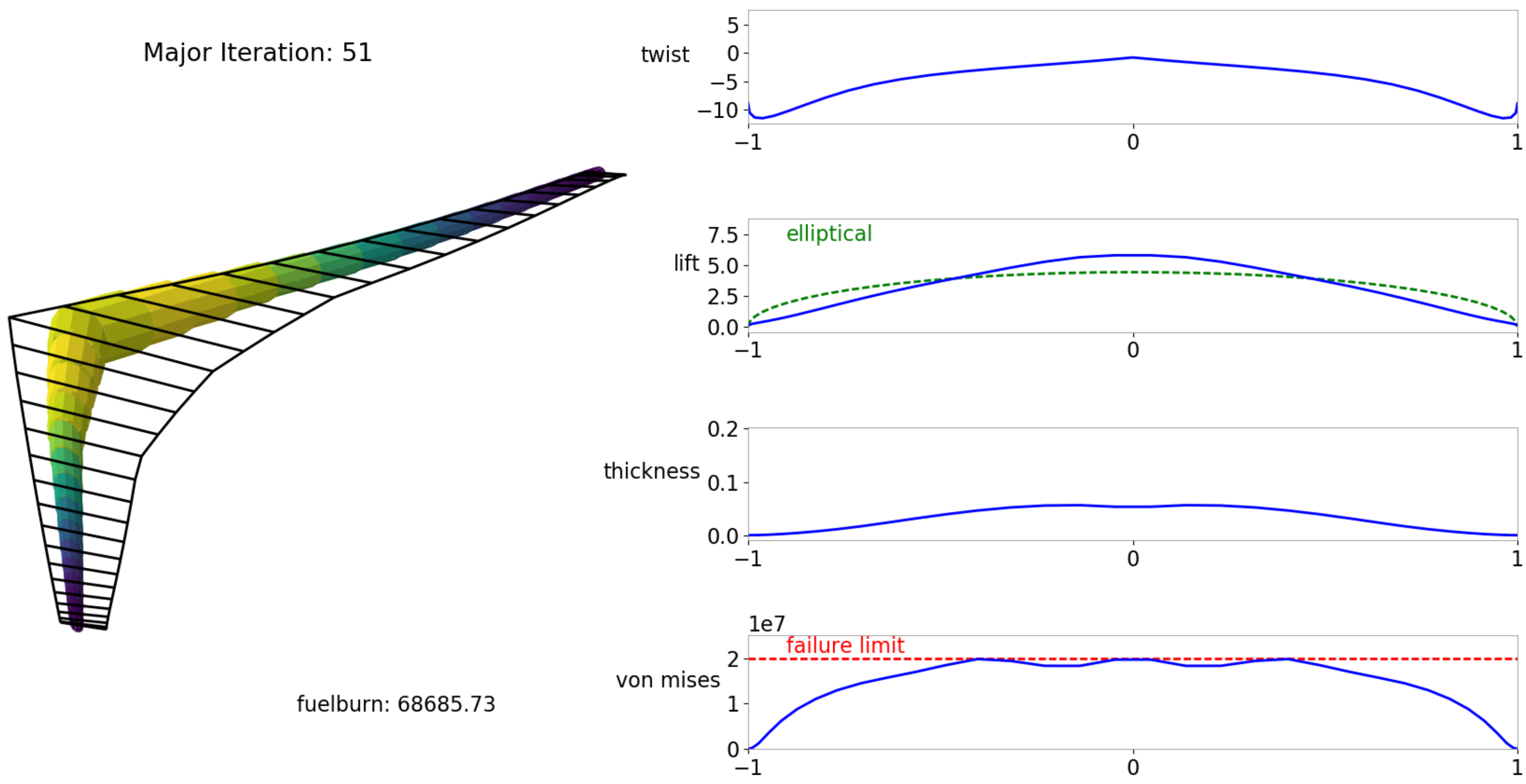


There is a lack of tools available to students that couple aero + structures, and can be used for optimization and experimentation.

OpenAeroStruct

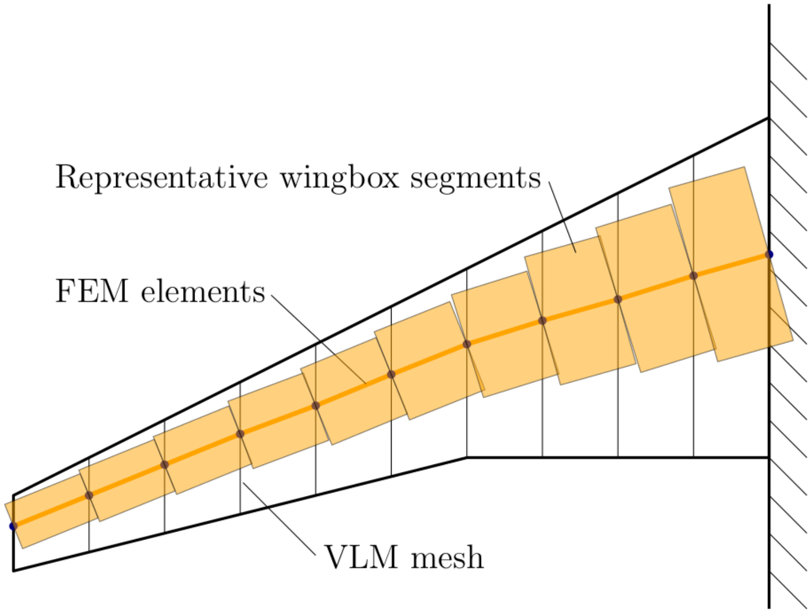
OpenAeroStruct



[Jasa et al., **2017**]

- An open-source tool for studying coupled aerostructural optimization trends
- Couples **VLM** + **FEM** using Python
- Analytical partial derivatives and gradients using the coupled-adjoint method
- Gradient-based optimization with the OpenMDAO framework

This work extends OpenAeroStruct with a wingbox model

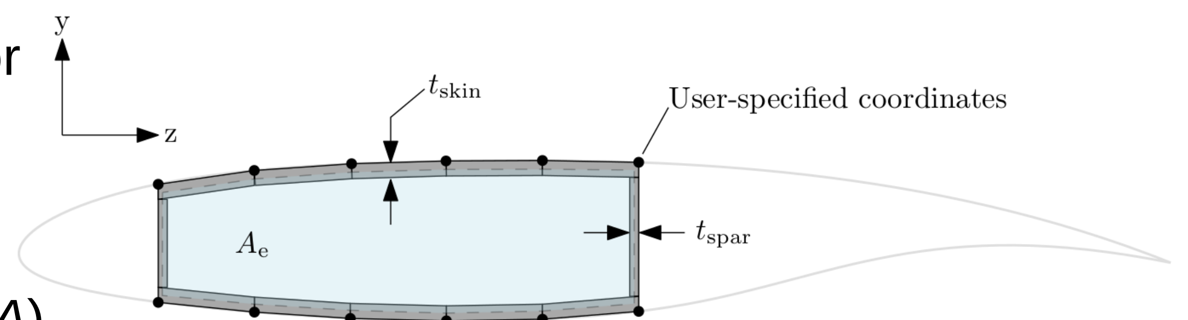


- We use 6-dof-per-node spatial beam elements to model a wingbox structure.

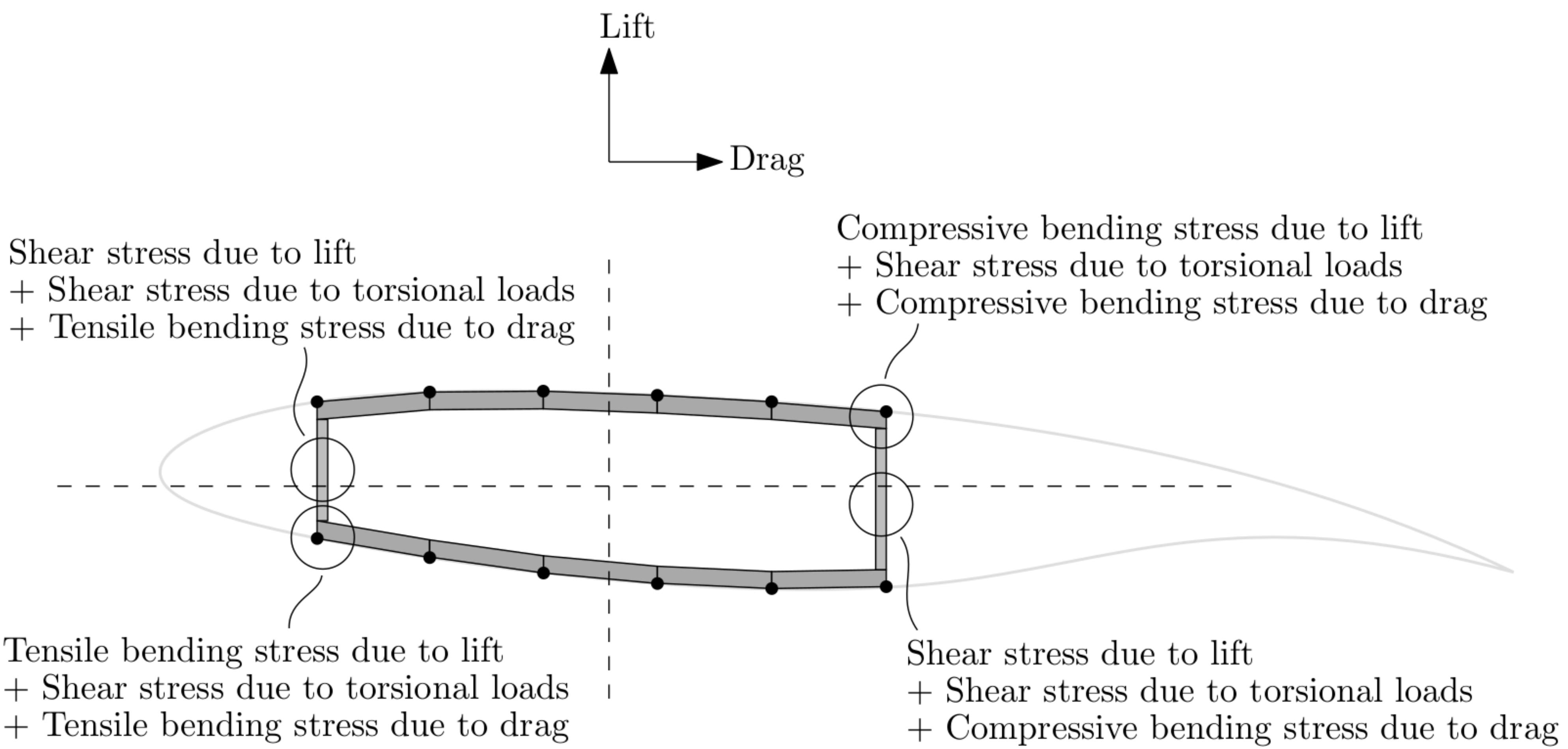
- Basically, these are superimposed beam, axial-spring, and torsional-spring elements.

- The user provides coordinates for the cross-section of the wingbox.

- Sectional properties (I_y, I_z, Q_z, J, A) are computed using these coordinates and thickness variables.



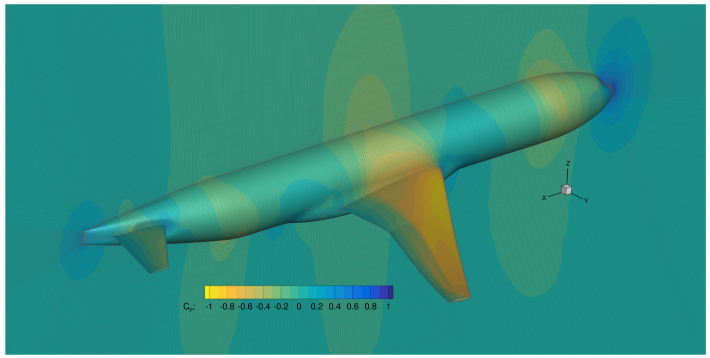
We consider multiple stress combinations for the analysis

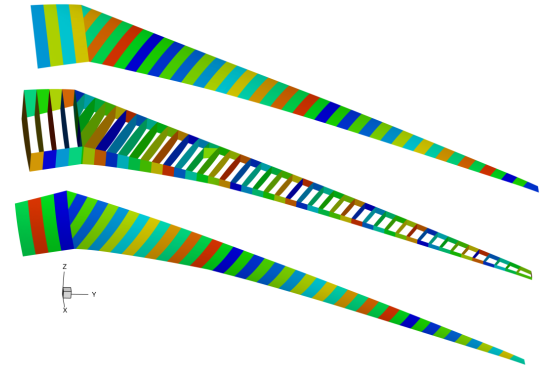


An example optimization problem

An example optimization problem to compare with hi-fidelity

- Optimization problem based on **Brooks et al.** (2017)
- They use: RANS CFD + FEM with shell elements

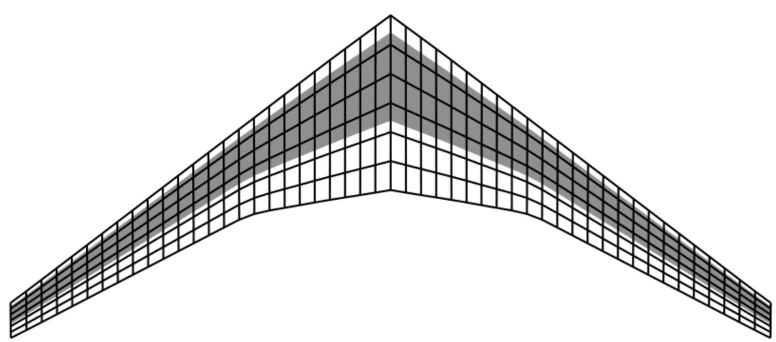




[Brooks et al., **2017**]

to optimize the undeflected Common Research Model wing (uCRM).

We replicate the problem with OpenAeroStruct



Example optimization problem formulation

Minimize:	Fuel burn	
With respect to:	Wing twist	(B-spline with 6 control pts.)
	Thickness-to-chord ratio	(B-spline with 6 control pts.)
	Spar thickness	(B-spline with 6 control pts.)
	Skin thickness	(B-spline with 6 control pts.)
	Angle of attack for the 2.5g case	
Subject to constraints:	$C_{L,cruise} = 0.5$	
	$\text{Lift}_{2.5g} = \text{Weight}_{2.5g}$	
	von Mises stresses ≤ 420/1.5 MPa	
	Fuel volume ≤ wingbox volume	

Example optimization problem formulation

Minimize: Fuel burn

With respect to:

Wing twist	(B-spline with 6 control pts.)
Thickness-to-chord ratio	(B-spline with 6 control pts.)
Spar thickness	(B-spline with 6 control pts.)
Skin thickness	(B-spline with 6 control pts.)
Angle of attack for the 2.5g case	

Subject to constraints:

$C_{L,cruise} = 0.5$

Cruise point at 37,000 ft and Mach 0.85 for computing the fuel burn

$Lift_{2.5g} = Weight_{2.5g}$

von Mises stresses ≤ 420/1.5 MPa

Fuel volume ≤ wingbox volume

Example optimization problem formulation

Minimize: Fuel burn

With respect to:

Wing twist	(B-spline with 6 control pts.)
Thickness-to-chord ratio	(B-spline with 6 control pts.)
Spar thickness	(B-spline with 6 control pts.)
Skin thickness	(B-spline with 6 control pts.)
Angle of attack for the 2.5g case	

Subject to constraints:

$C_{L,cruise} = 0.5$

$\text{Lift}_{2.5g} = \text{Weight}_{2.5g}$

von Mises stresses ≤ 420/1.5 MPa

Fuel volume ≤ wingbox volume

Cruise point at 37,000 ft and Mach 0.85 for computing the fuel burn

2.5g maneuver point at sea level and Mach 0.64 for the structural sizing

Example optimization problem formulation

Minimize:	Fuel burn	
With respect to:	Wing twist	(B-spline with 6 control pts.)
	Thickness-to-chord ratio	(B-spline with 6 control pts.)
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	von Mises stresses ≤ 420/1.5 MPa	
	Fuel volume ≤ wingbox volume	
Other considerations:	Loads from structural weight and fuel weight applied to the wing structure	

Example optimization problem formulation

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With respect to:	Wing twist	(B-spline with 6 control pts.)
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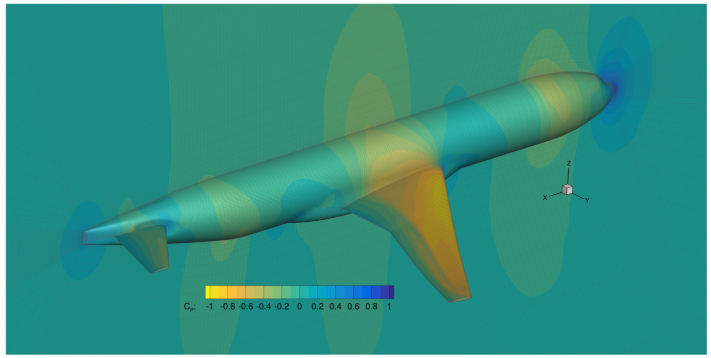
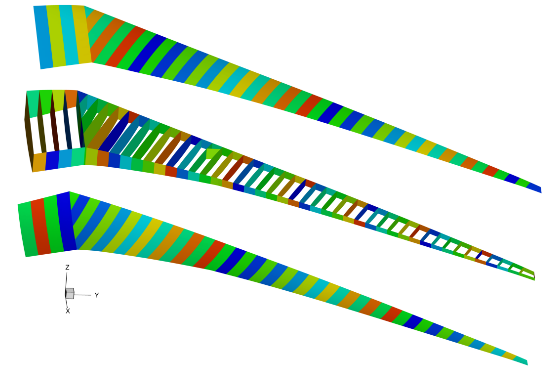
	$\text{Lift}_{2.5g} = \text{Weight}_{2.5g}$	
	von Mises stresses ≤ 420/1.5 MPa	
	Fuel volume ≤ wingbox volume	
Optimizer:	SNOPT ←	Gradient-based optimizer

Some differences between Brooks et al. and our simplified optimization problem

Brooks et al. (2017):

RANS CFD + FEM with shell elements

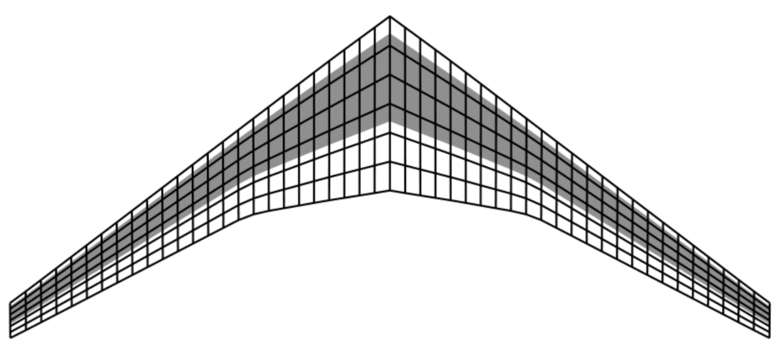




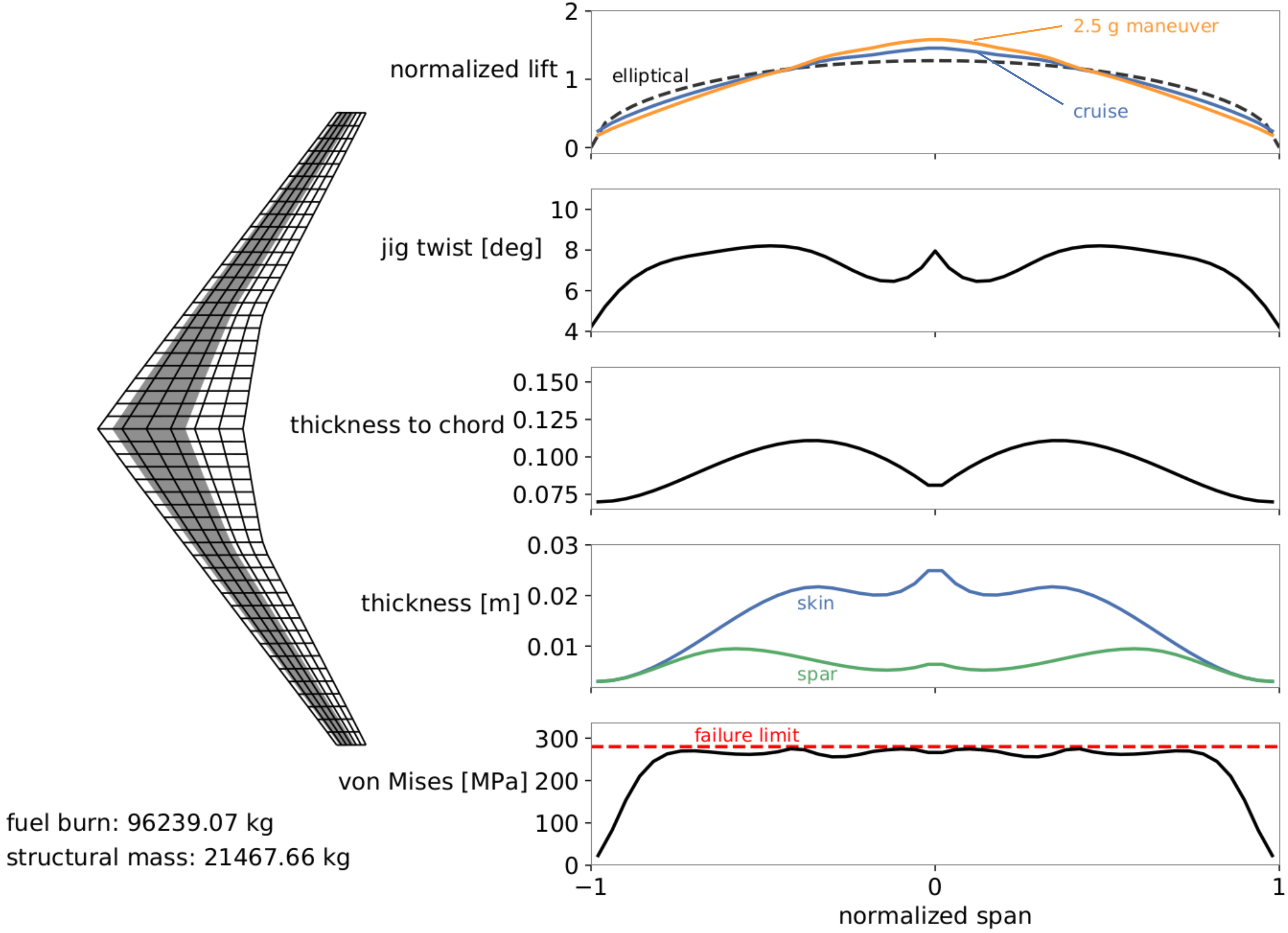
- A large difference in the number of design variables (1112 vs 25)
- We do not have any buffet constraints
- We do not model ribs and stiffeners, or have buckling constraints
- We do not use a gust case or -1g case for structural sizing
- Etc...

OpenAeroStruct:

VLM + FEM with spatial beam elements



Results

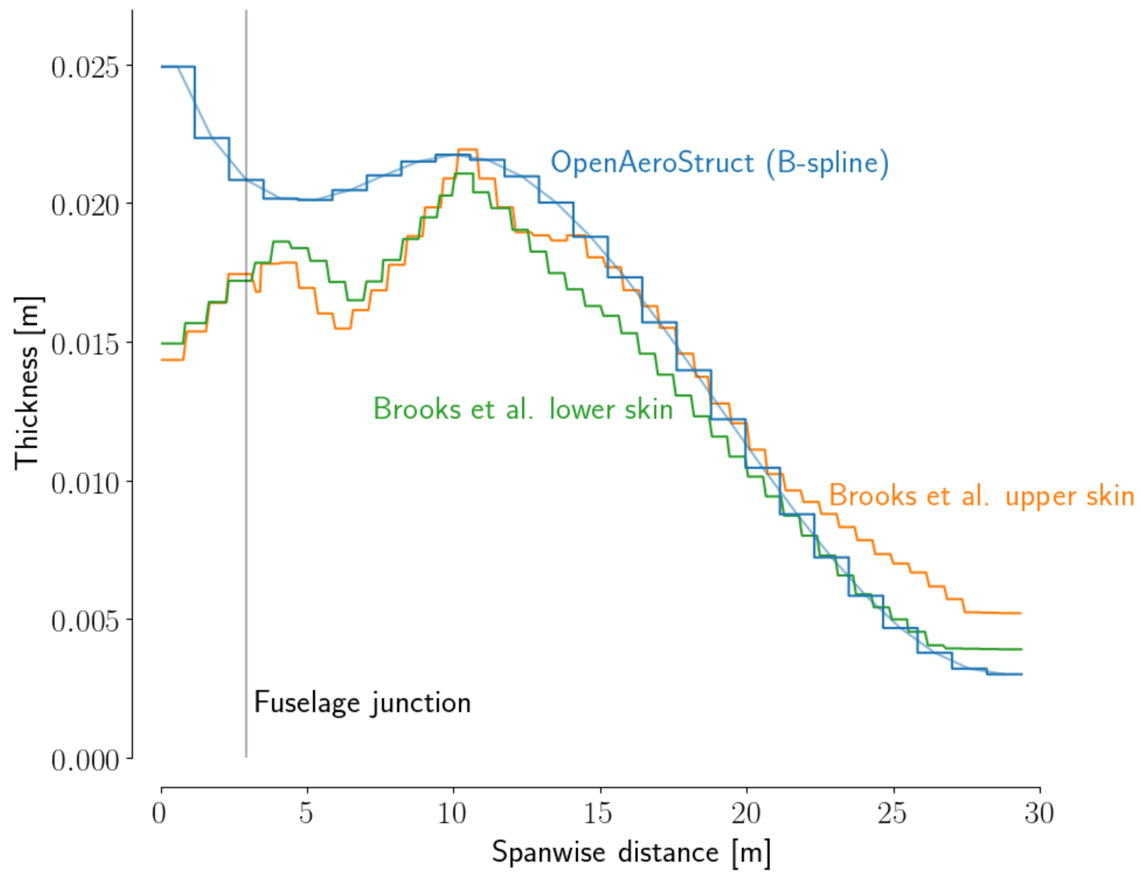


B-spline design variables

Comparison with the high-fidelity results of Brooks et al. shows reasonable agreement

	Wingbox mass	**Fuel Burn**
Brooks et al.	23,840 kg	94,037 kg
OpenAeroStruct	21,468 kg (**-10.0%**)	96,239 kg (**+2.3%**)

Wingbox skin thickness distribution



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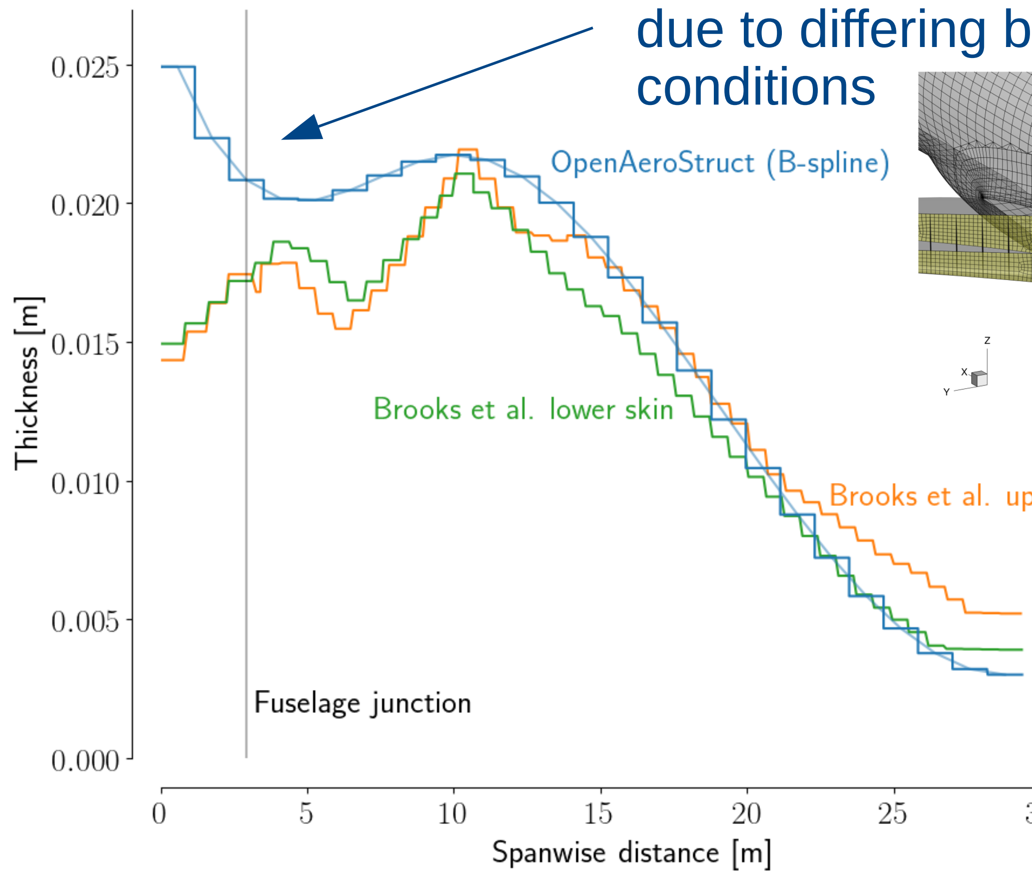
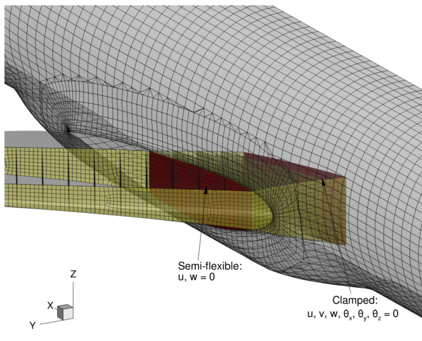
Wingbox skin thickness distribution

Differences at the root due to differing boundary conditions





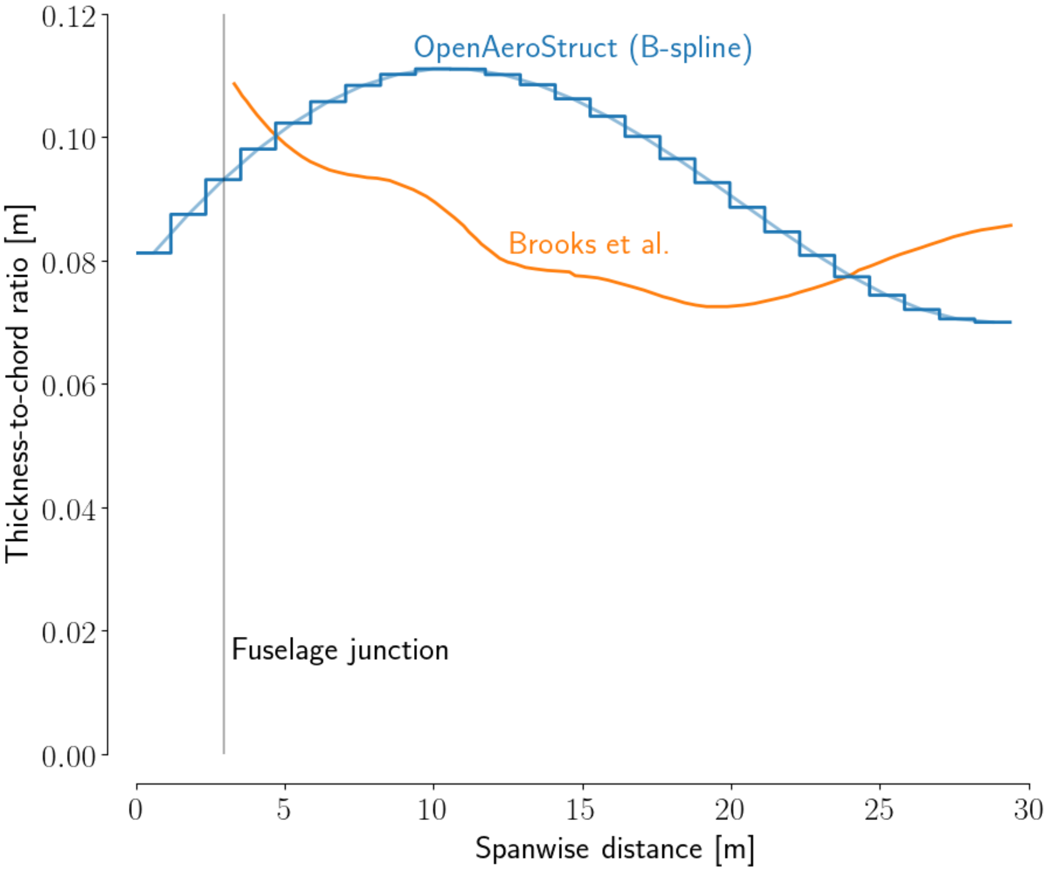
However, due to differences in fidelities, there are differences in some trends

- For example, the thickness-to-chord ratio (*t/c*) distributions have different trends.

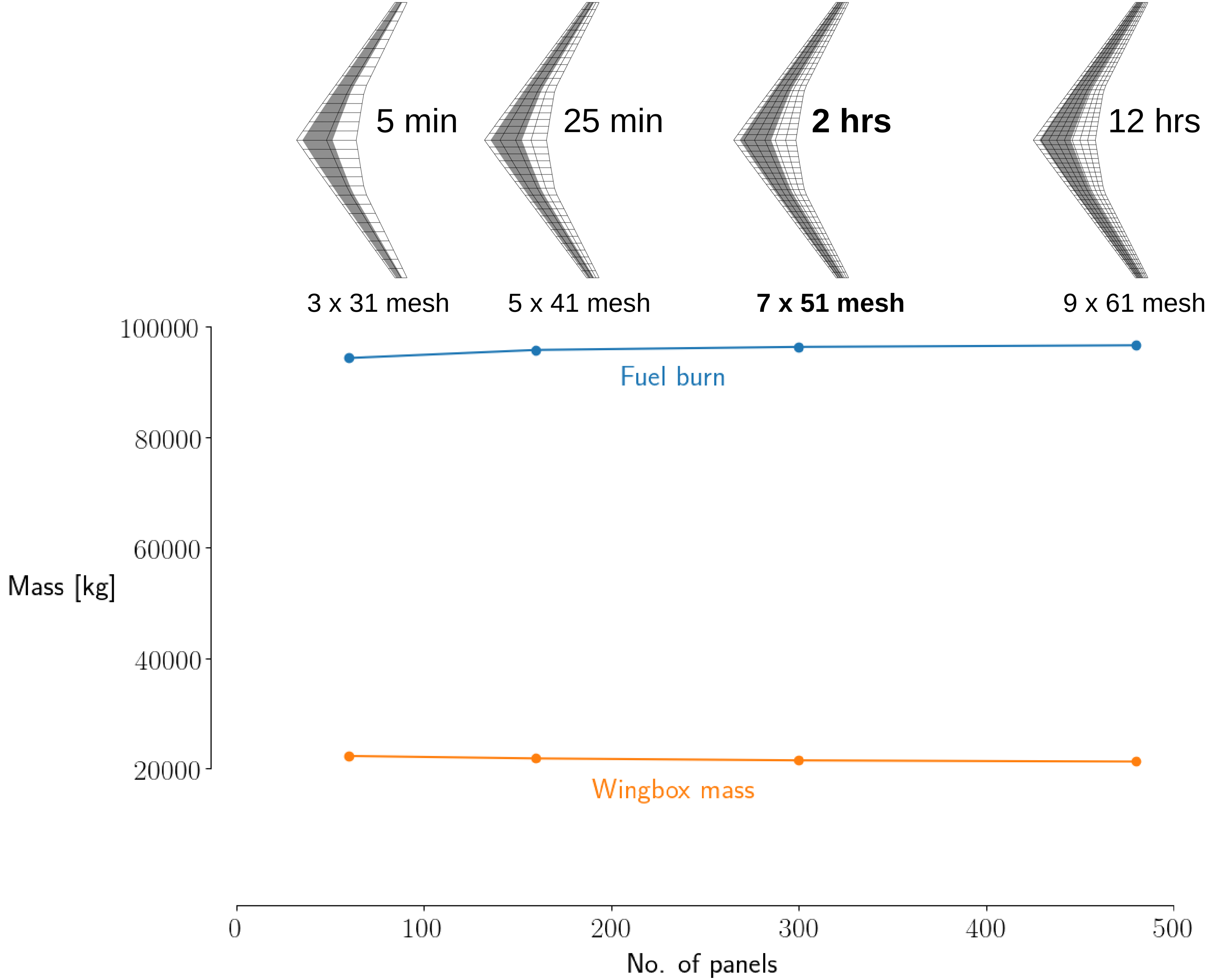
- We cannot capture the effects of *t/c* on wave drag and viscous drag as accurately as RANS CFD.

- We also do not have the same level of control on airfoil shapes.

Thickness-to-chord ratio distribution



How long does it take (on my laptop)?



2 hours on a laptop vs. 2 days on 1000 processors

	Wingbox mass	**Fuel Burn**
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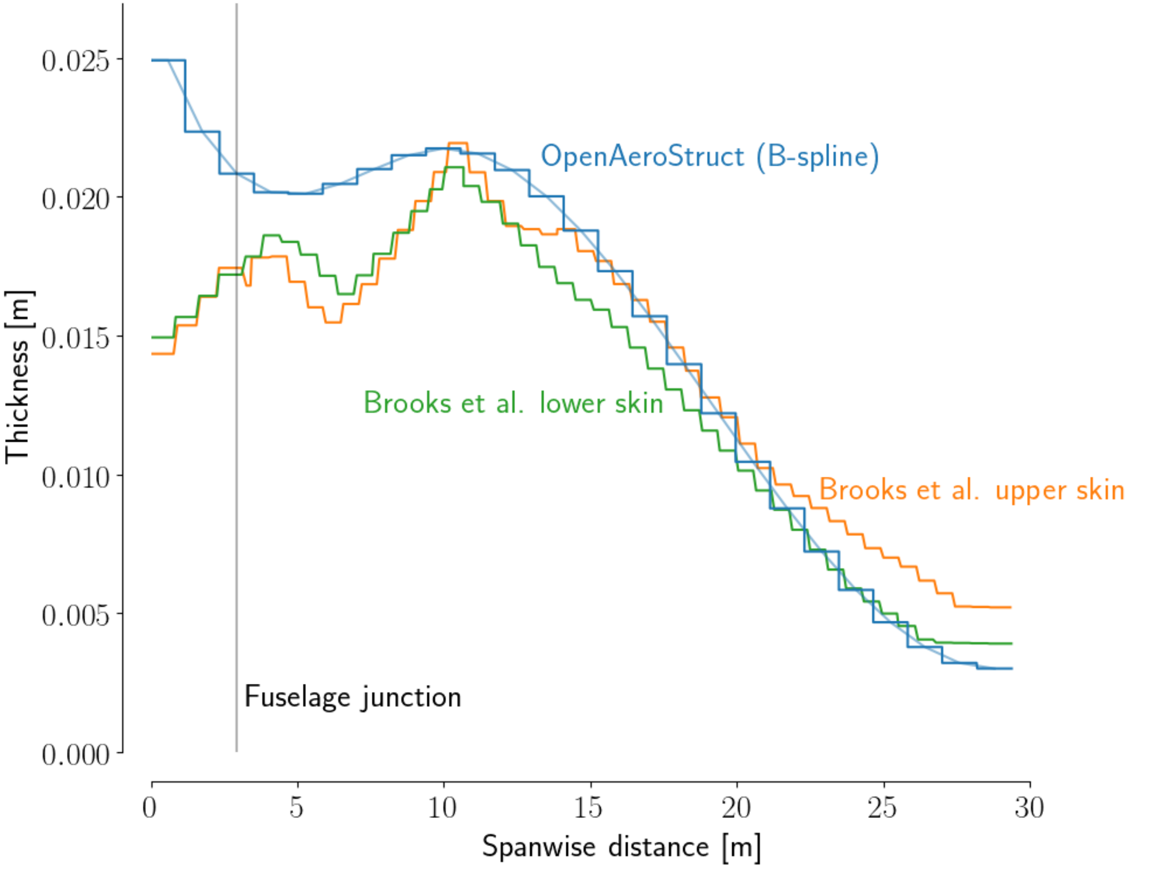
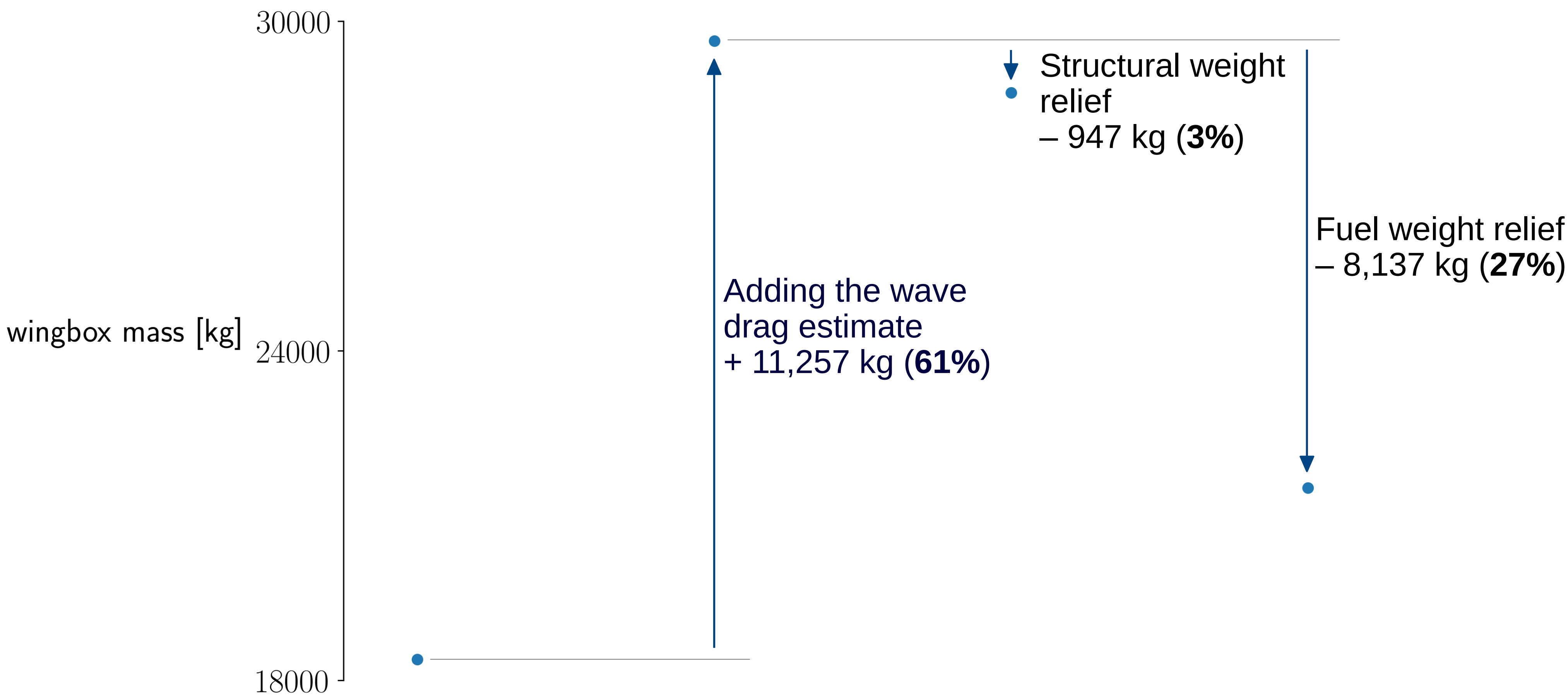
A reasonable starting point for more detailed optimization

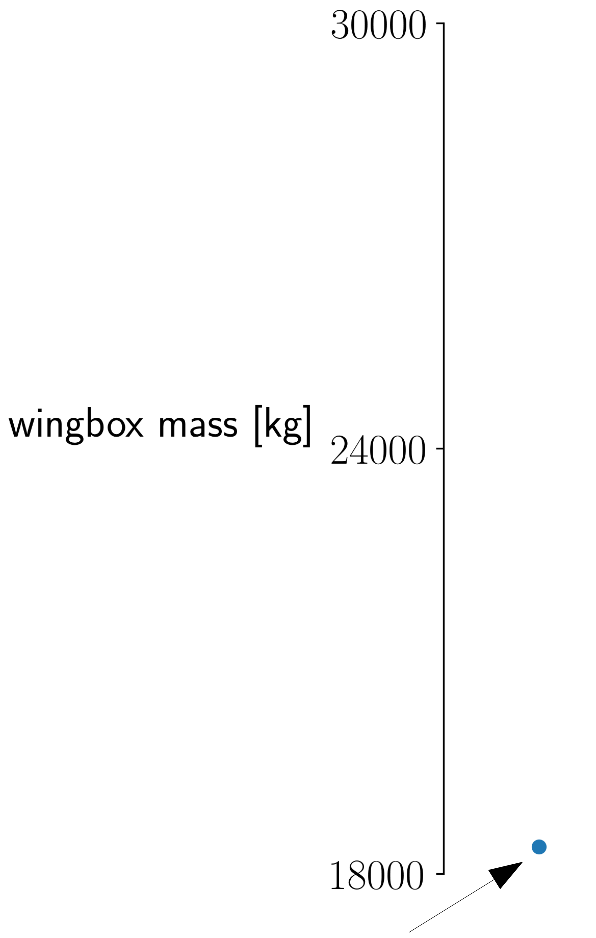


Some interesting studies to develop intuition

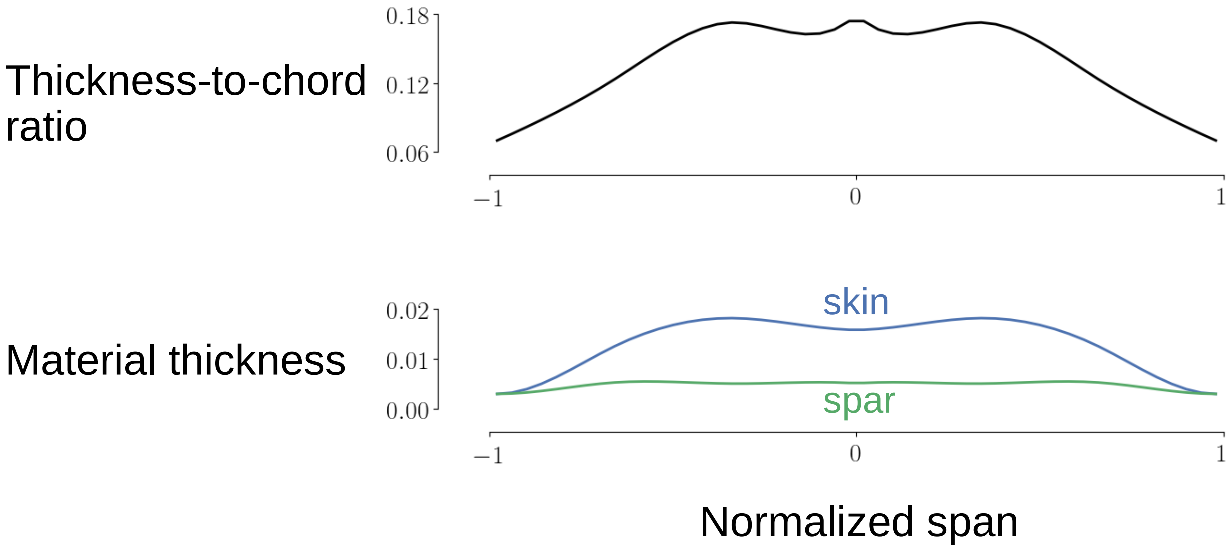
We can add new considerations one at a time to study how they impact the results



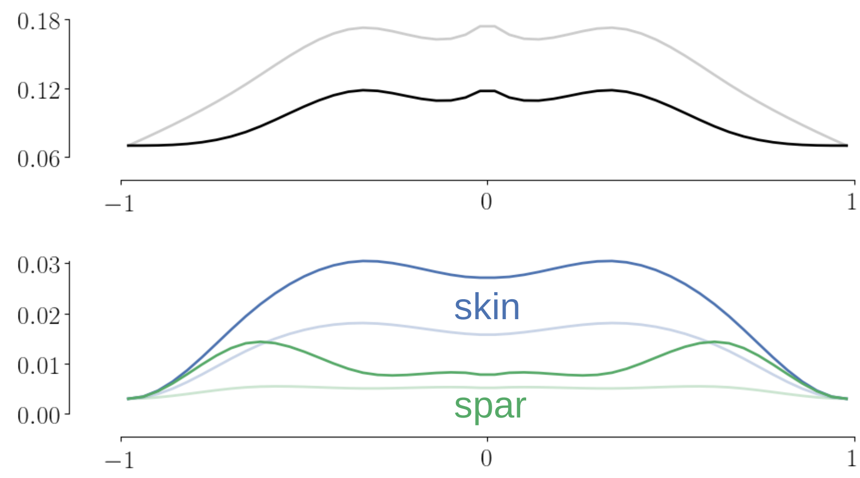
Start with no wave drag or load relief

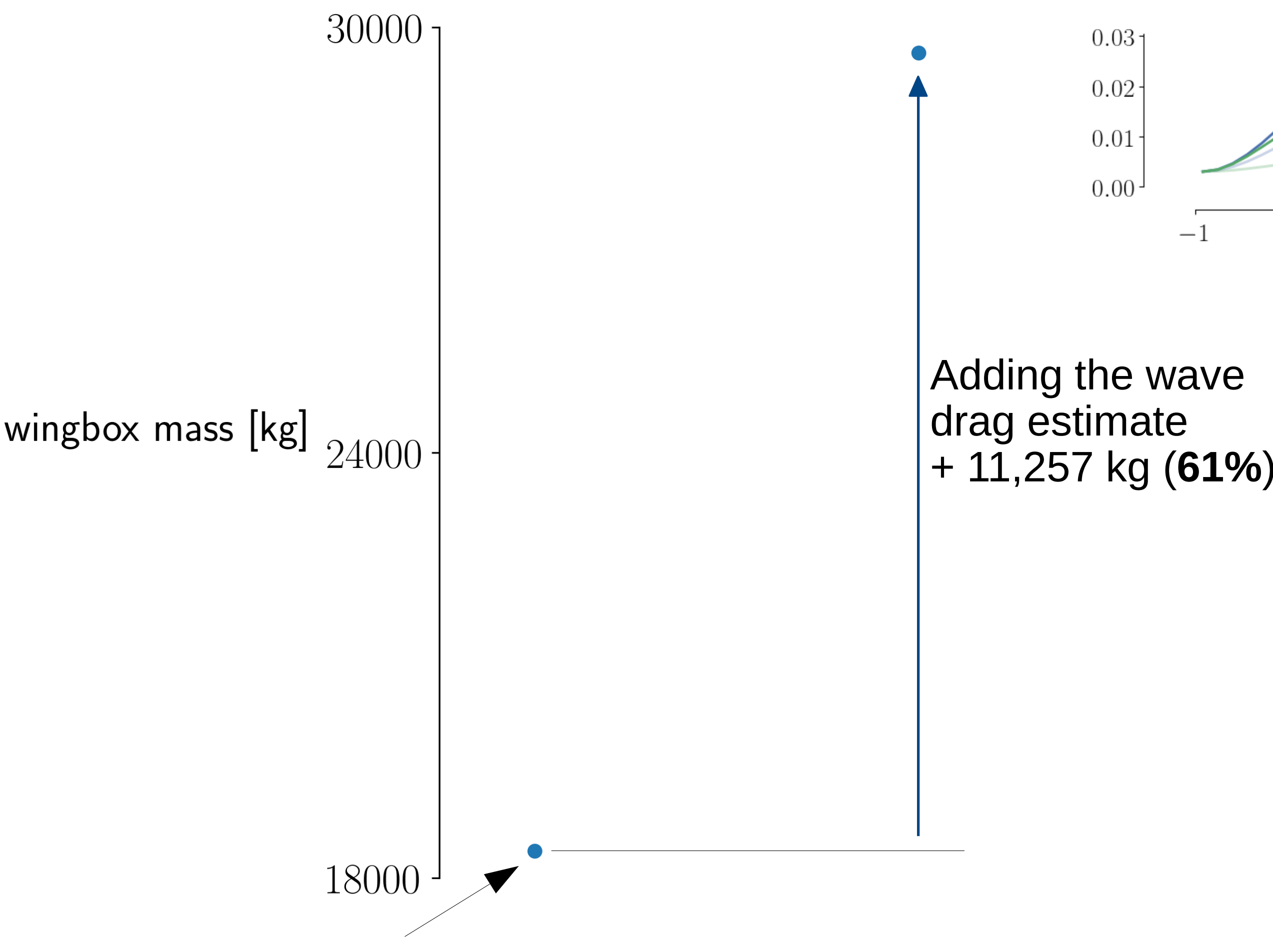


uCRM optimization with
- no wave drag computation
- no structural weight relief
- no fuel weight relief



Add wave drag based on the Korn equation





uCRM optimization with
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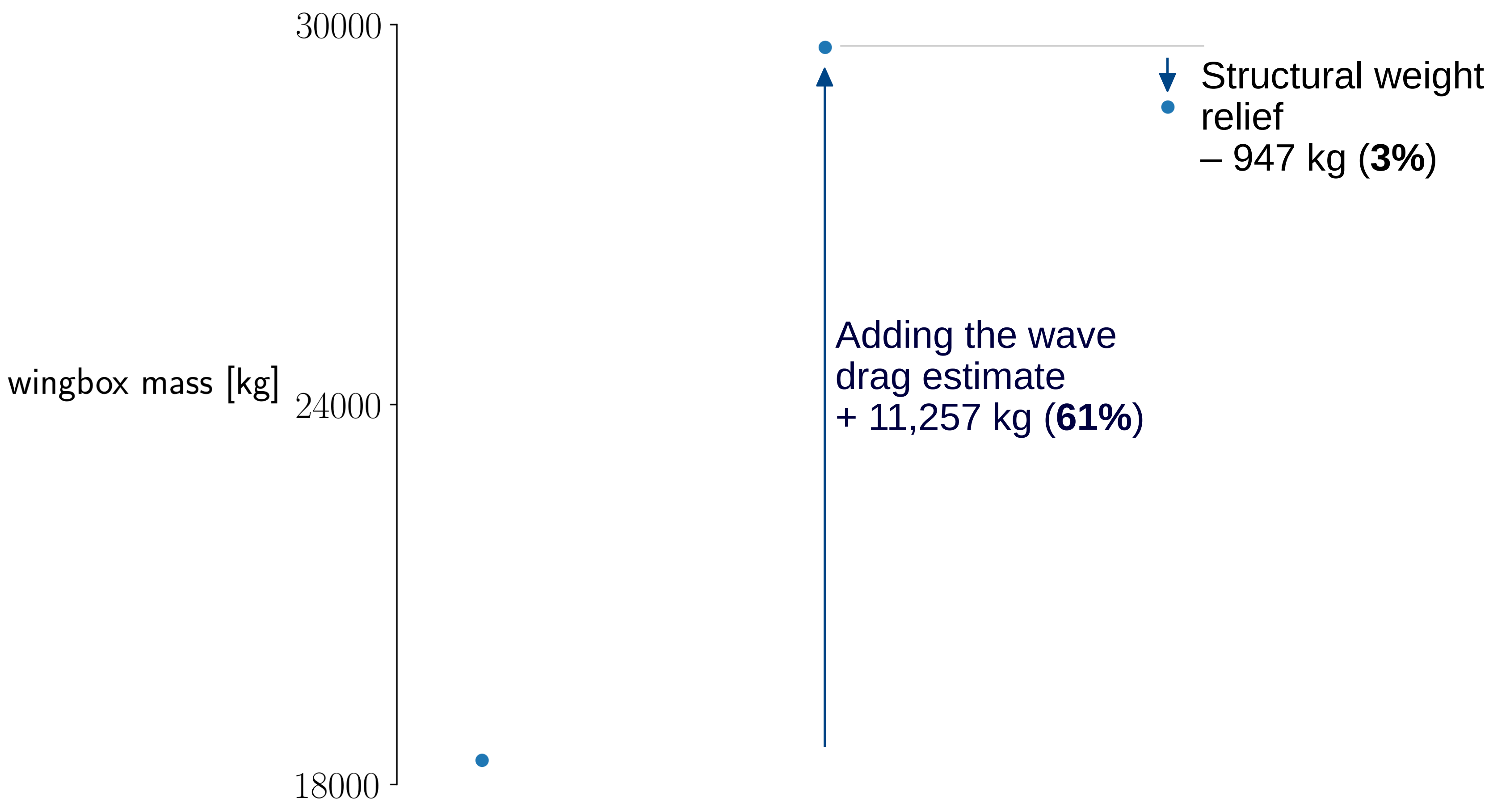
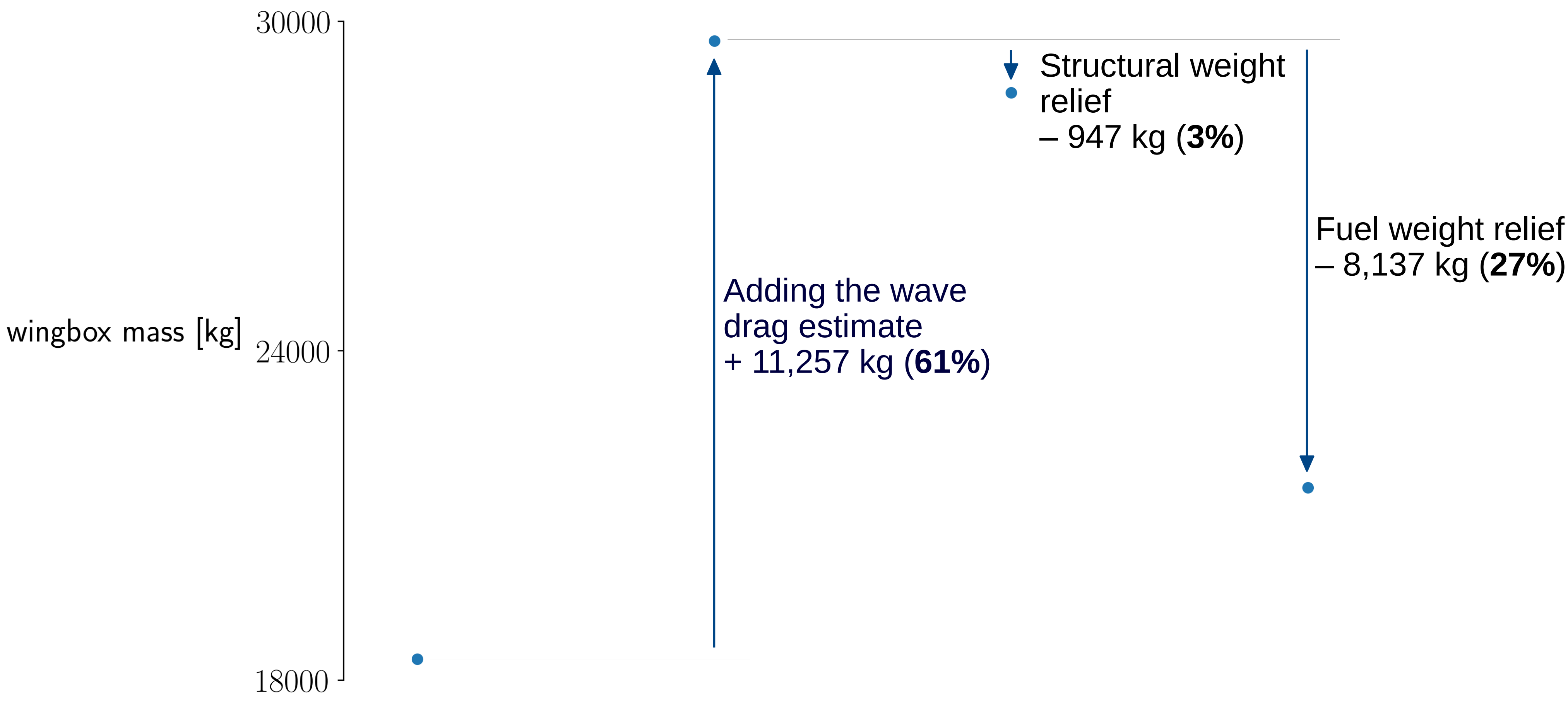
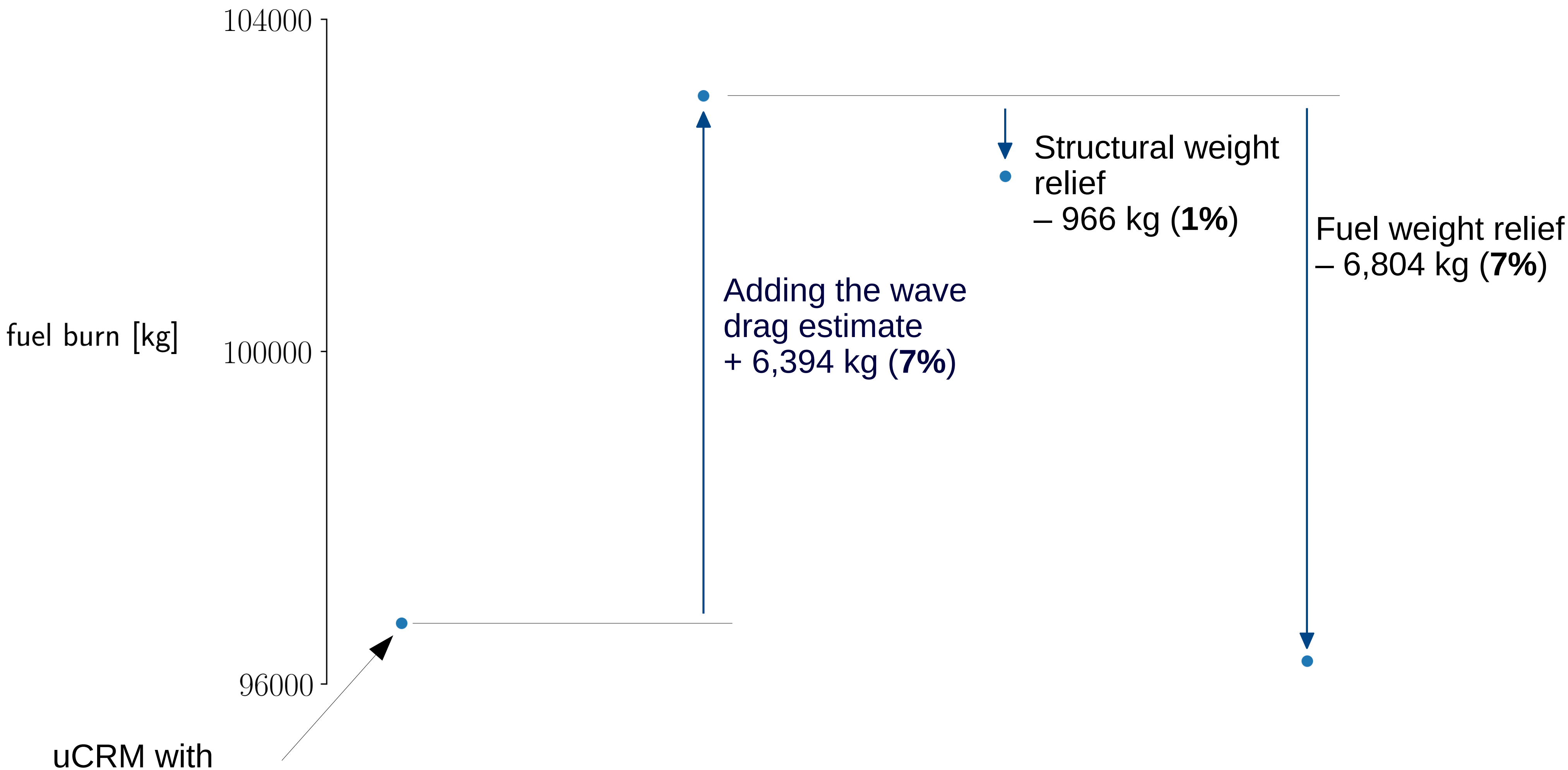
Adding loads from the weight of the wing structure



Adding loads from the weight of the fuel



Similarly for the fuel burn



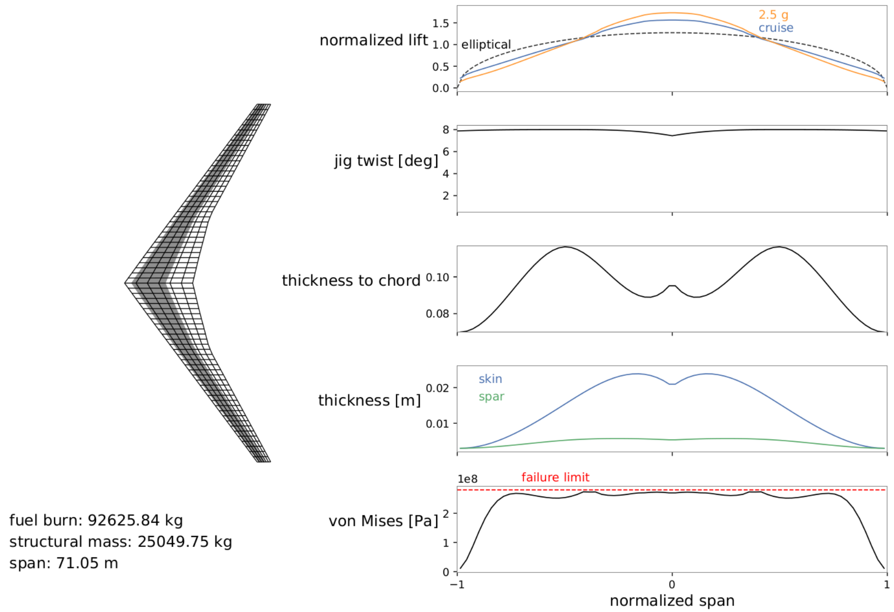
uCRM with
- no wave drag computation
- no structural weight relief
- no fuel weight relief

More design variables

Links to videos with more design variables:

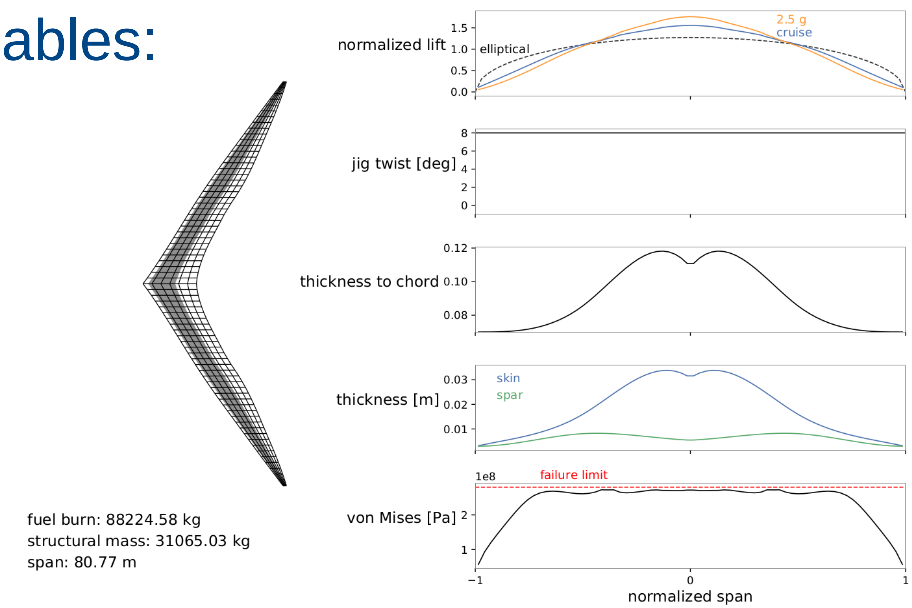
With span and sweep design variables:

https://youtu.be/c5qO-deZZgs



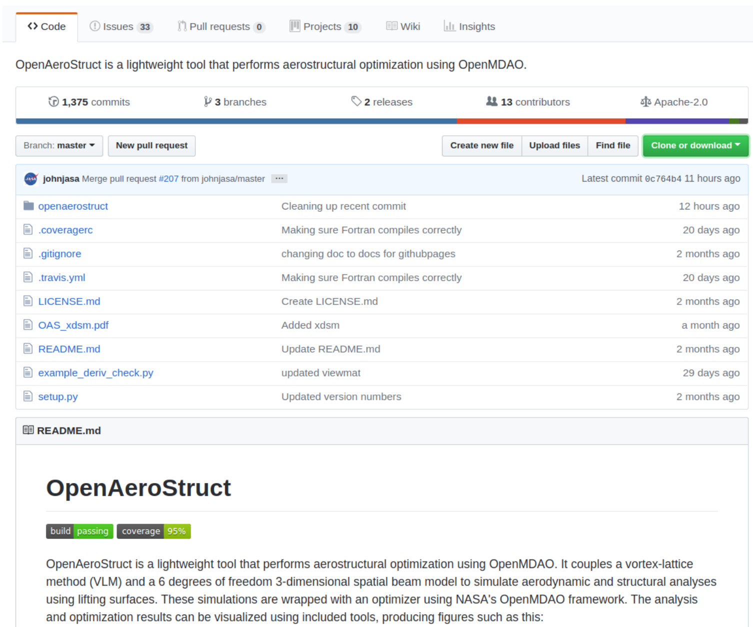
With span, sweep, and chord design variables:

https://youtu.be/Q36UYrk4H64



Questions?

Fork OpenAeroStruct on GitHub



github.com/mdolab/OpenAeroStruct

Visit mdolab.engin.umich.edu

for more from the MDOlab

Conference paper: https://doi.org/10.1007/978-3-319-97773-7_38

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