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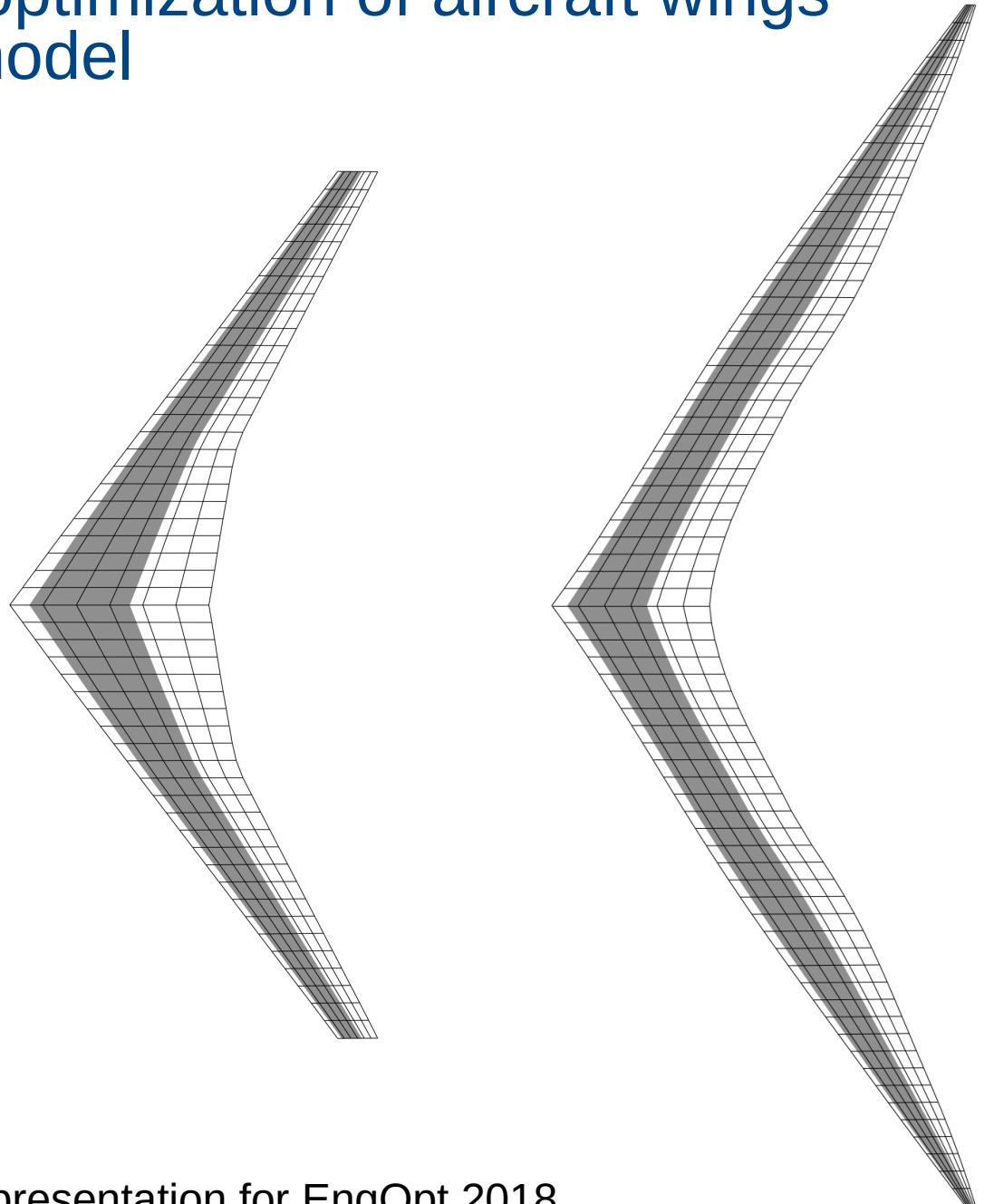


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Low-fidelity aerostructural optimization of aircraft wings with a simplified wingbox model using OpenAeroStruct

Shamsheer S. Chauhan

Joaquim R. R. A. Martins



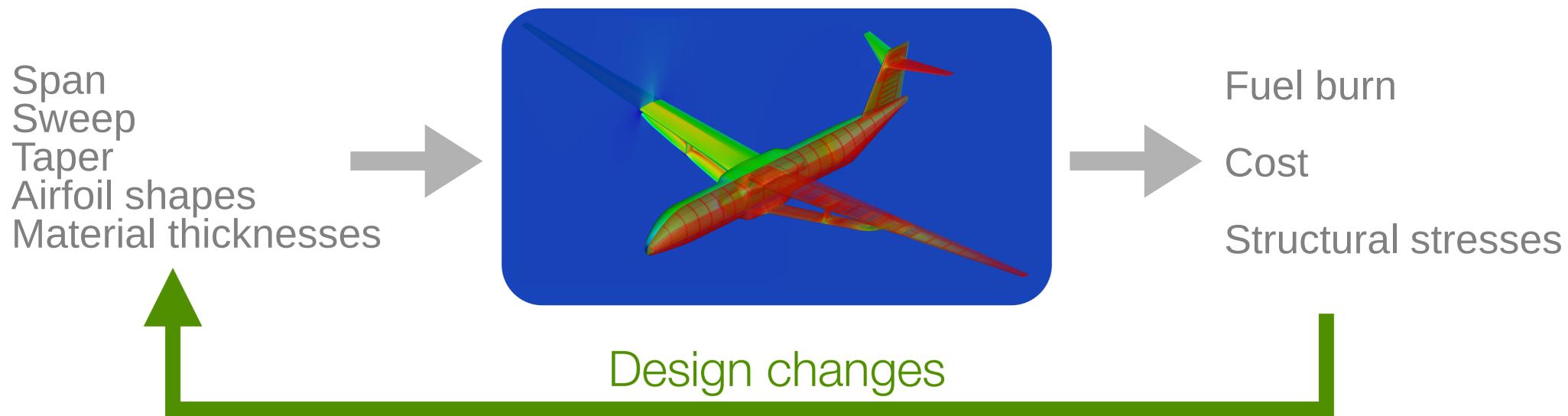
AEROSPACE
ENGINEERING

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



Motivation: Low-fidelity optimization remains popular

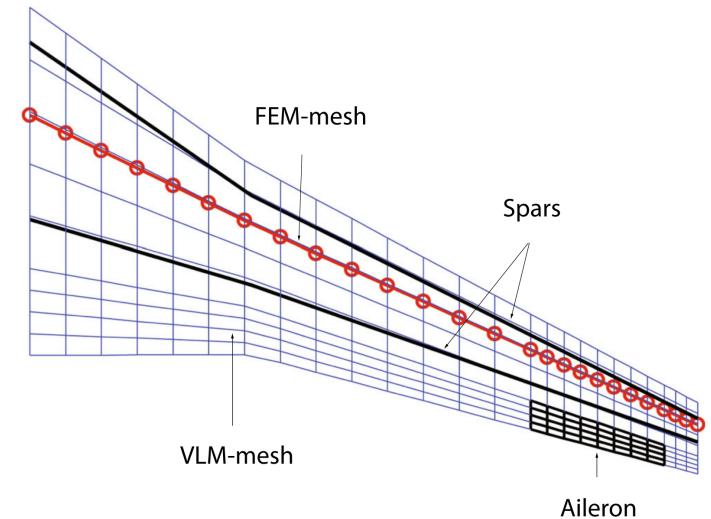
Despite the availability of high-fidelity tools, low-fidelity tools remain popular.

For example:

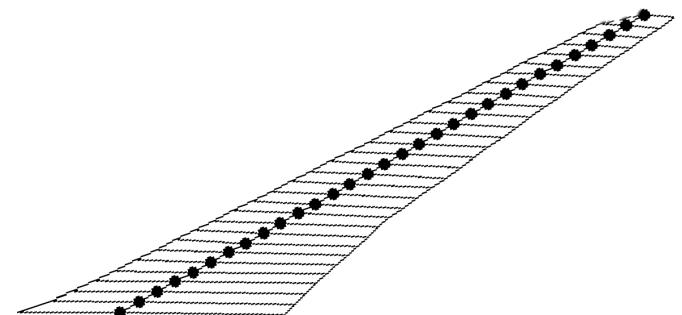
Vortex Lattice Method (**VLM**) codes

+

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



[Elham and van Tooren, 2016]



[Fujiwara and Nguyen, 2017]

Motivation: Low-fidelity optimization remains popular

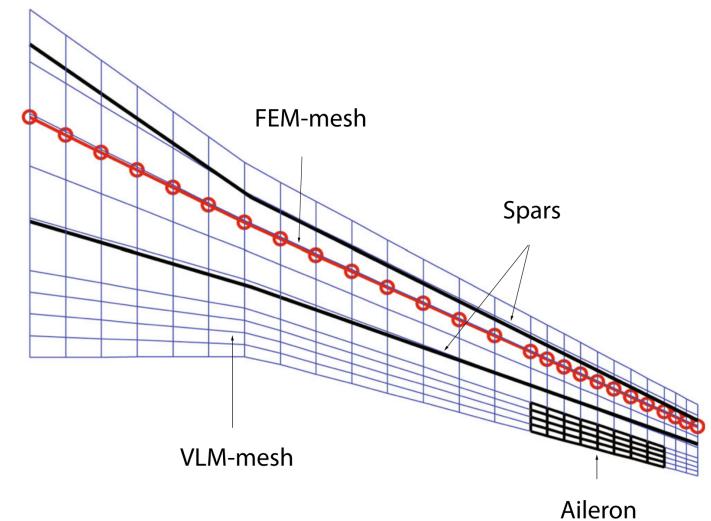
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+

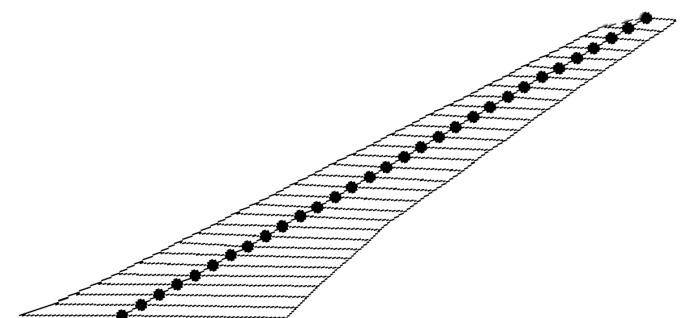
Simplified Finite Element Method (**FEM**) models



[Elham and van Tooren, 2016]

Advantages:

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



[Fujiwara and Nguyen, 2017]

Motivation: Low-fidelity optimization remains popular

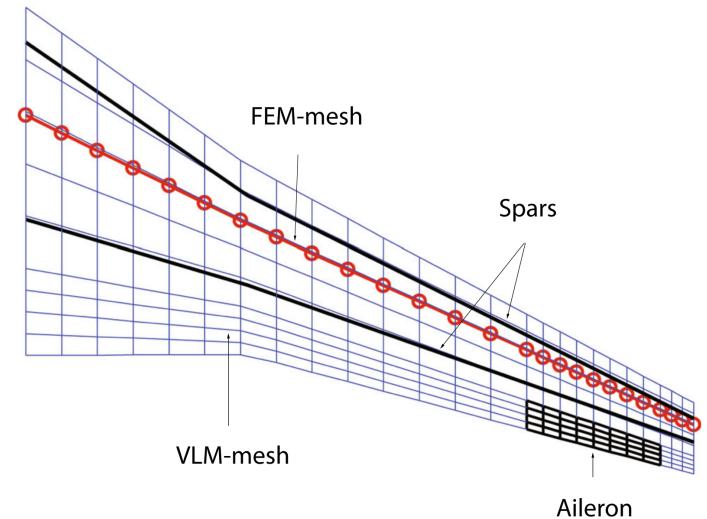
Despite the availability of high-fidelity tools, low-fidelity tools remain popular.

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Vortex Lattice Method (**VLM**) codes

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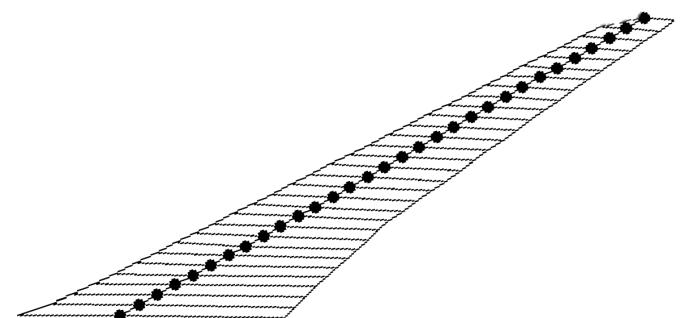
Simplified Finite Element Method (**FEM**) models



[Elham and van Tooren, 2016]

Advantages:

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



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

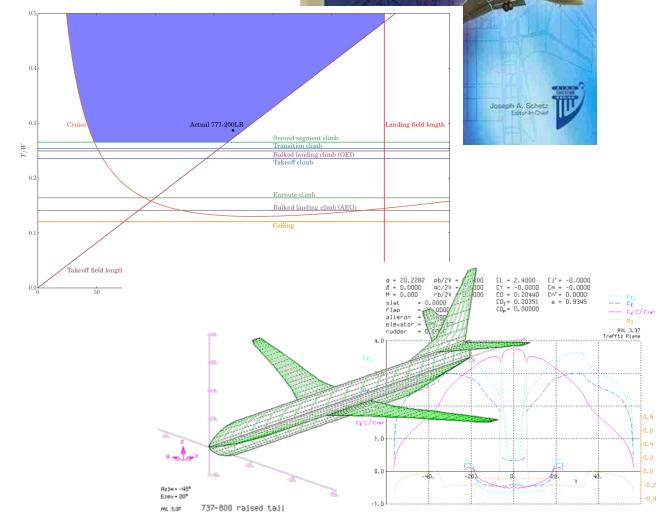
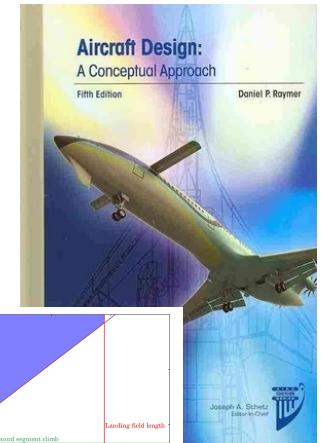
[Fujiwara and Nguyen, 2017]

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?)

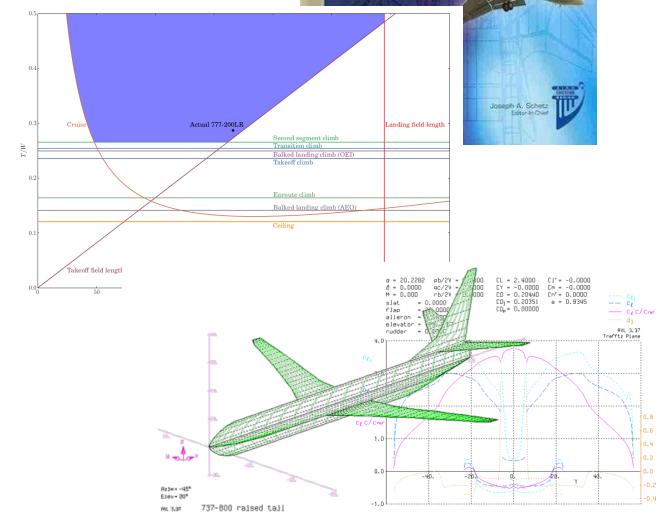
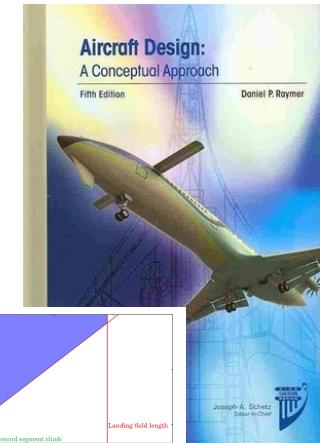


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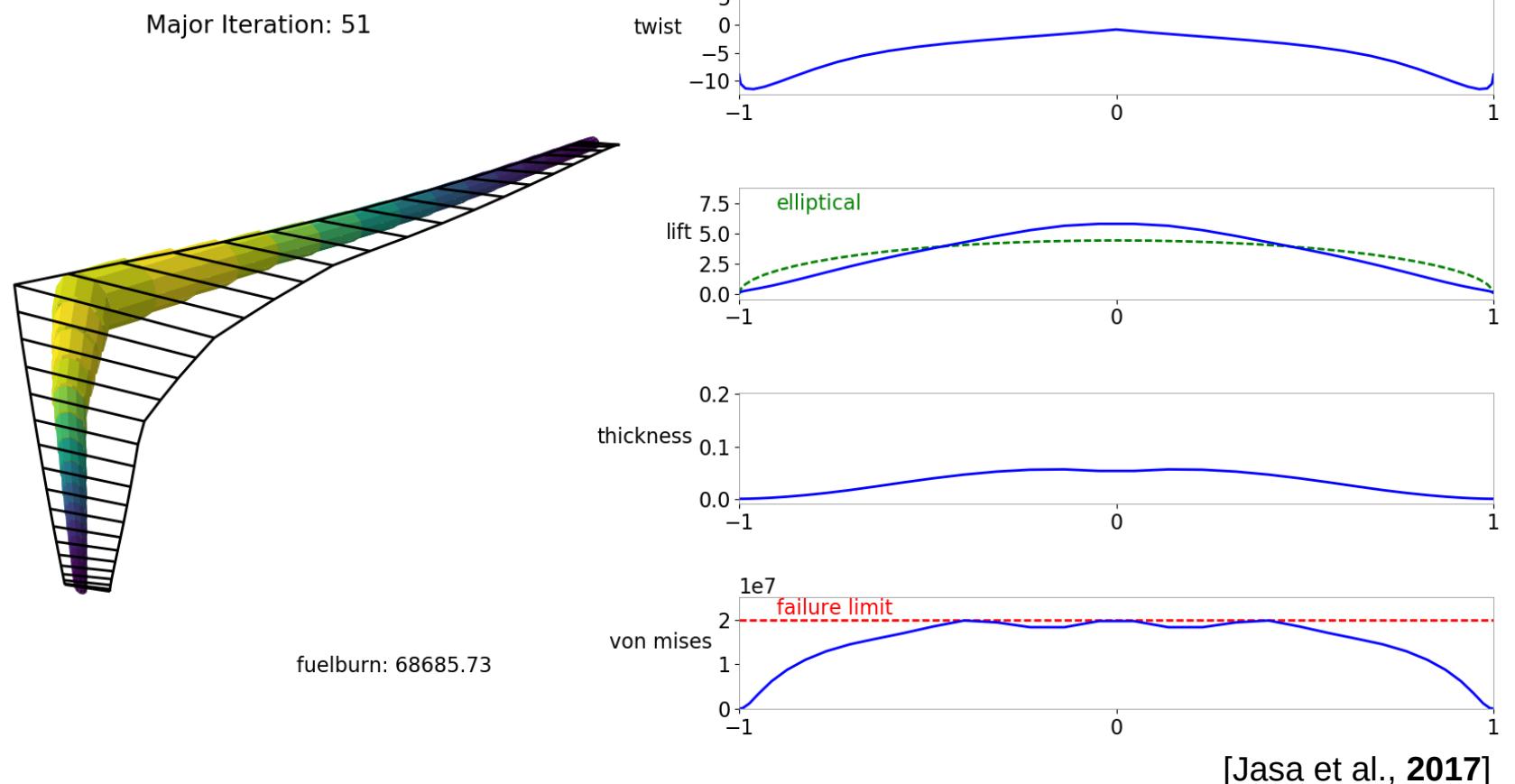
- Material thickness ranges and distributions
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- Advantages of inertial relief (how much of a difference does it make?)
- Certain trade-offs (e.g., thickness-to-chord ratio)
- Contribution of different types of stress (how does the bending stress compare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



There is a lack of tools available to students that couple aero + structures, and can be used for optimization and experimentation. 8

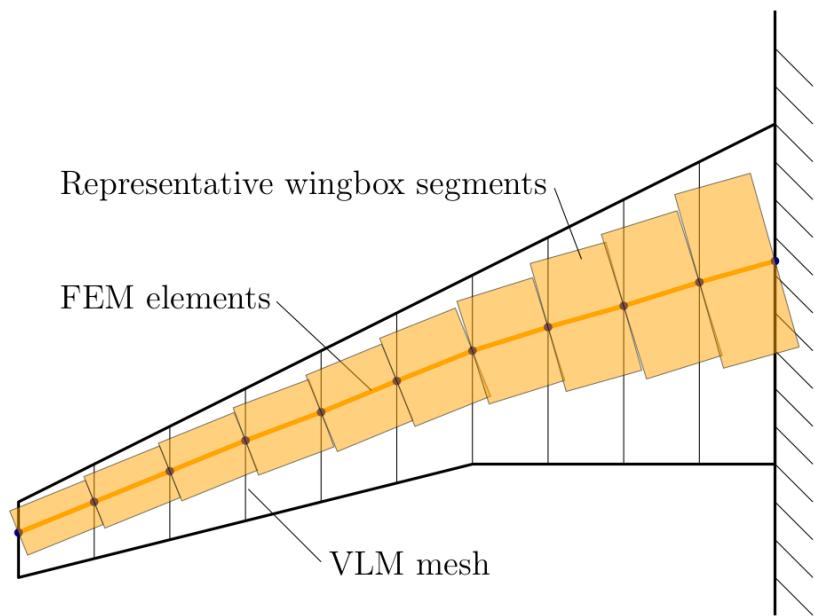
OpenAeroStruct

OpenAeroStruct



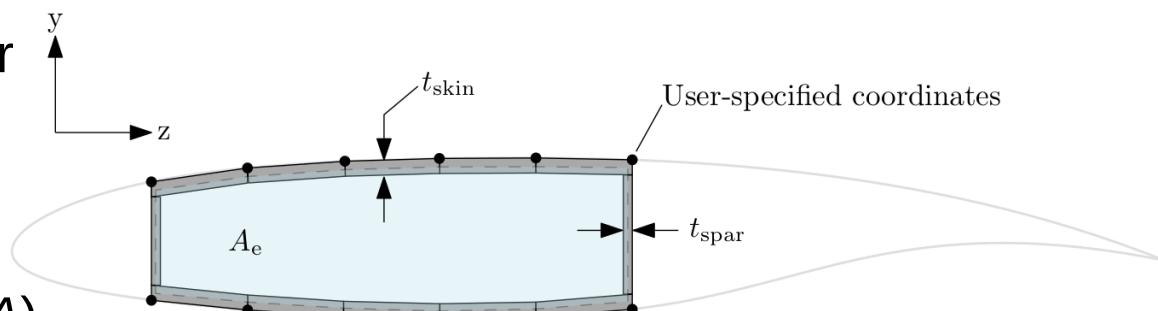
- An open-source tool for studying coupled aerostructural optimization trends
- Couples **VLM + FEM** using Python
- Analytical partial derivatives and gradients using the coupled-adjoint method
- Gradient-based optimization with the OpenMDAO framework

This work extends OpenAeroStruct with a wingbox model

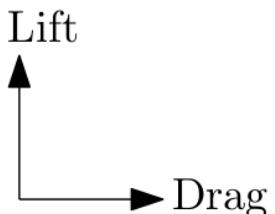


- We use 6-dof-per-node spatial beam elements to model a wingbox structure.
- Basically, these are superimposed beam, axial-spring, and torsional-spring elements.

- 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.

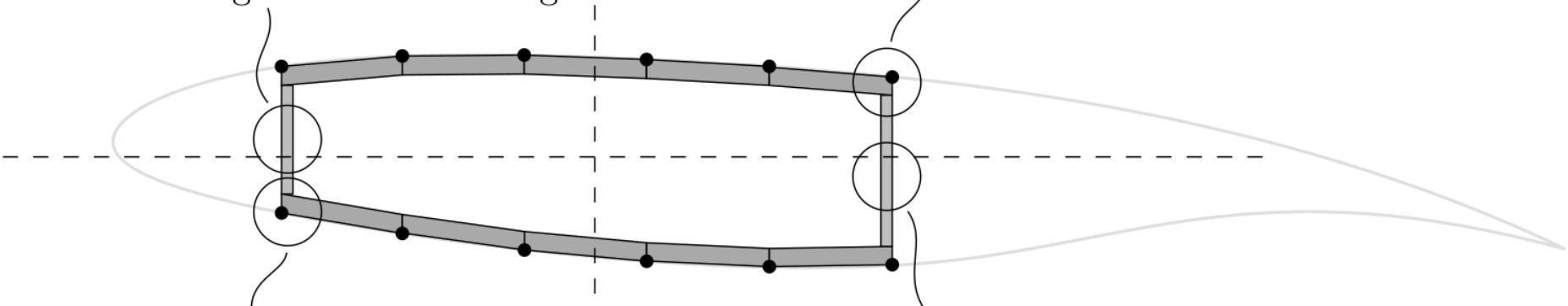


We consider multiple stress combinations for the analysis



Shear stress due to lift

- + Shear stress due to torsional loads
- + Tensile bending stress due to drag



Compressive bending stress due to lift

- + Shear stress due to torsional loads
- + Compressive bending stress due to drag

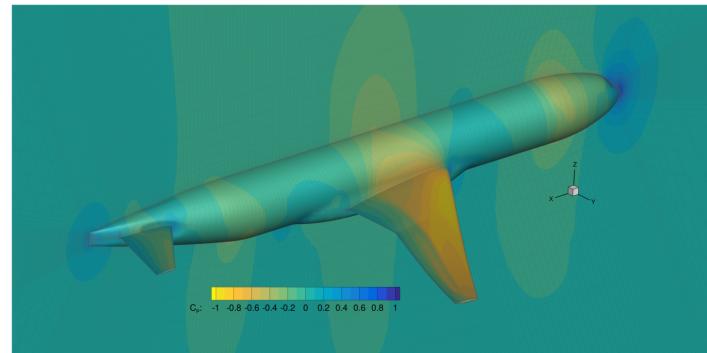
Shear stress due to lift

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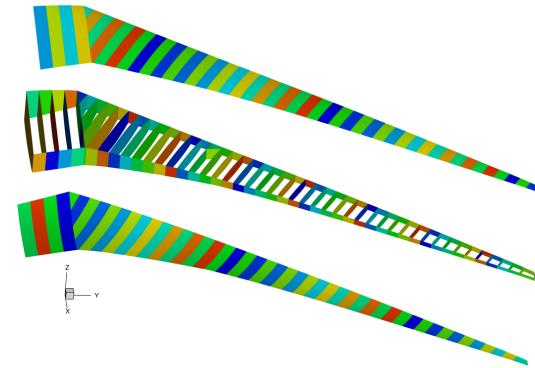
An example optimization problem

An example optimization problem to compare with hi-fidelity

- Optimization problem based on **Brooks et al.** (2017)
- They use:



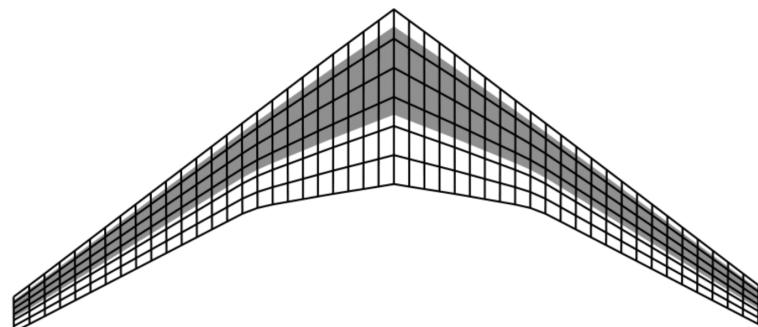
+ FEM with shell elements



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

Example optimization problem formulation

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Example optimization problem formulation

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Subject to constraints:	$C_{L,\text{cruise}} = 0.5$ $\text{Lift}_{2.5g} = \text{Weight}_{2.5g}$ von Mises stresses $\leq 420/1.5$ MPa Fuel volume \leq 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

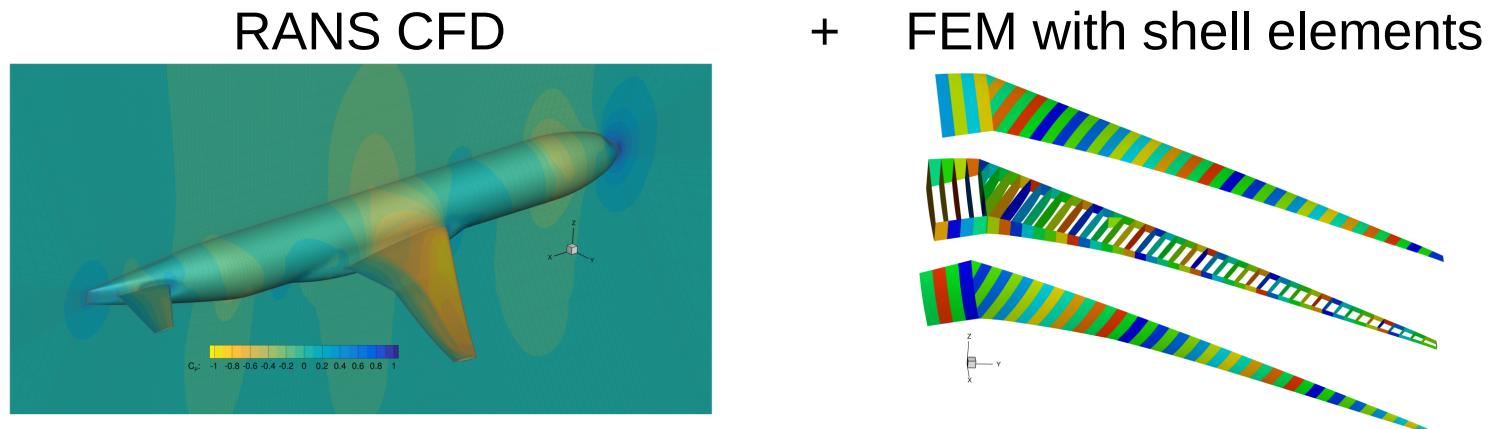
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Other considerations:	Loads from structural weight and fuel weight applied to the wing structure	

Example optimization problem formulation

Minimize:	Fuel burn	
With respect to:	Wing twist Thickness-to-chord ratio Spar thickness Skin thickness Angle of attack for the 2.5g case	(B-spline with 6 control pts.) (B-spline with 6 control pts.) (B-spline with 6 control pts.) (B-spline with 6 control pts.)
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Optimizer:	SNOPT	Gradient-based optimizer

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

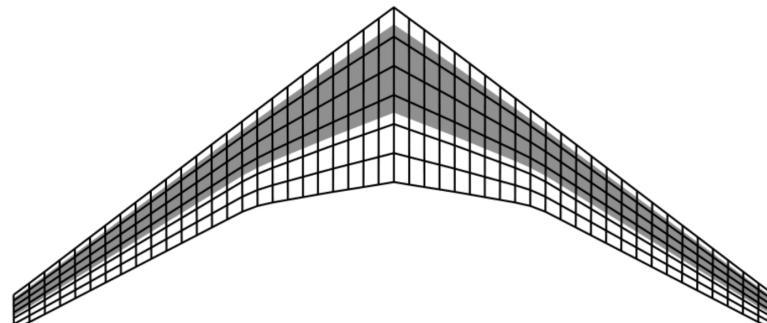
Brooks et al. (2017):



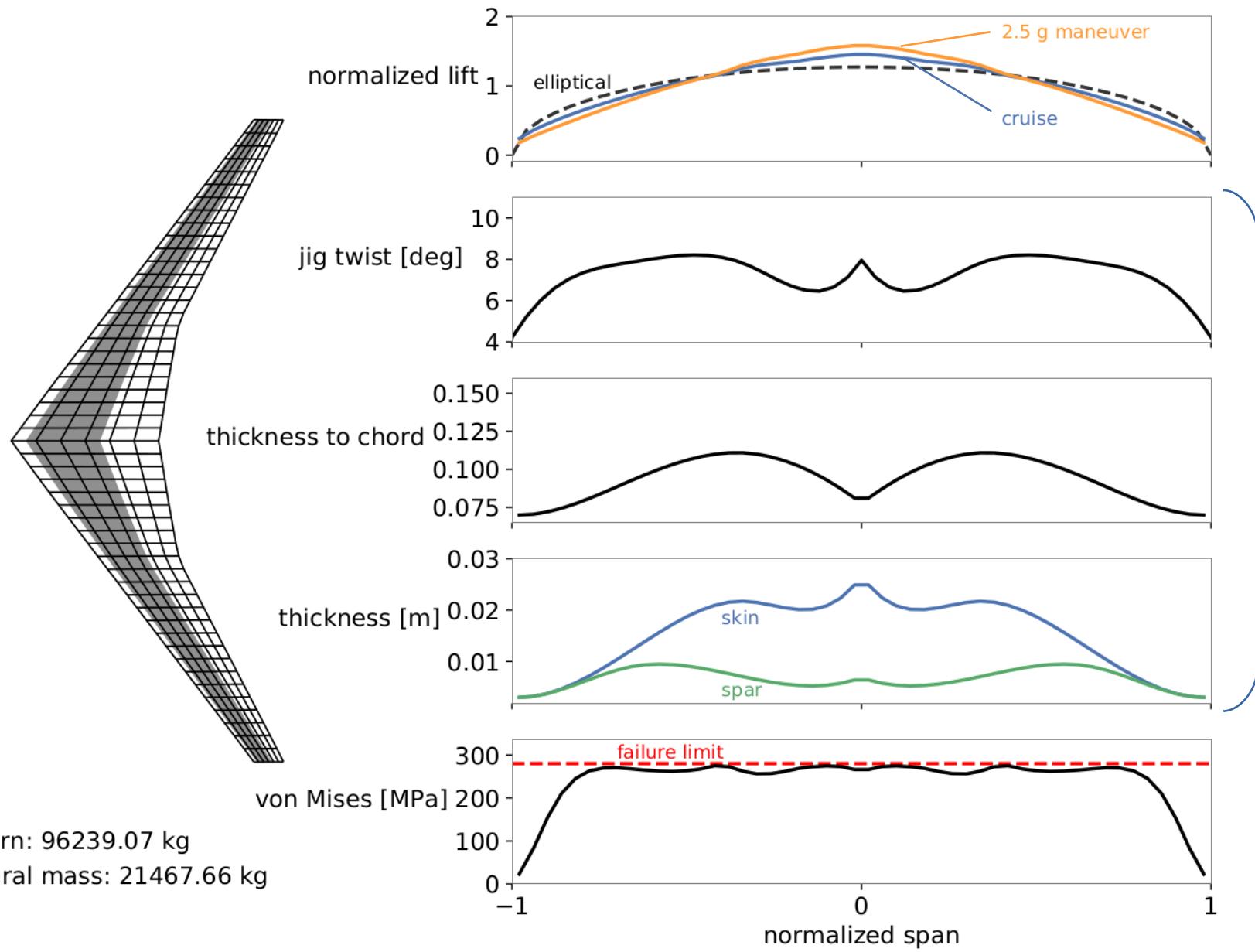
- A large difference in the number of design variables (1112 vs 25)
- We do not have any buffet constraints
- We do not model ribs and stiffeners, or have buckling constraints
- We do not use a gust case or -1g case for structural sizing
- Etc...

VLM + FEM with spatial beam elements

OpenAeroStruct:



Results

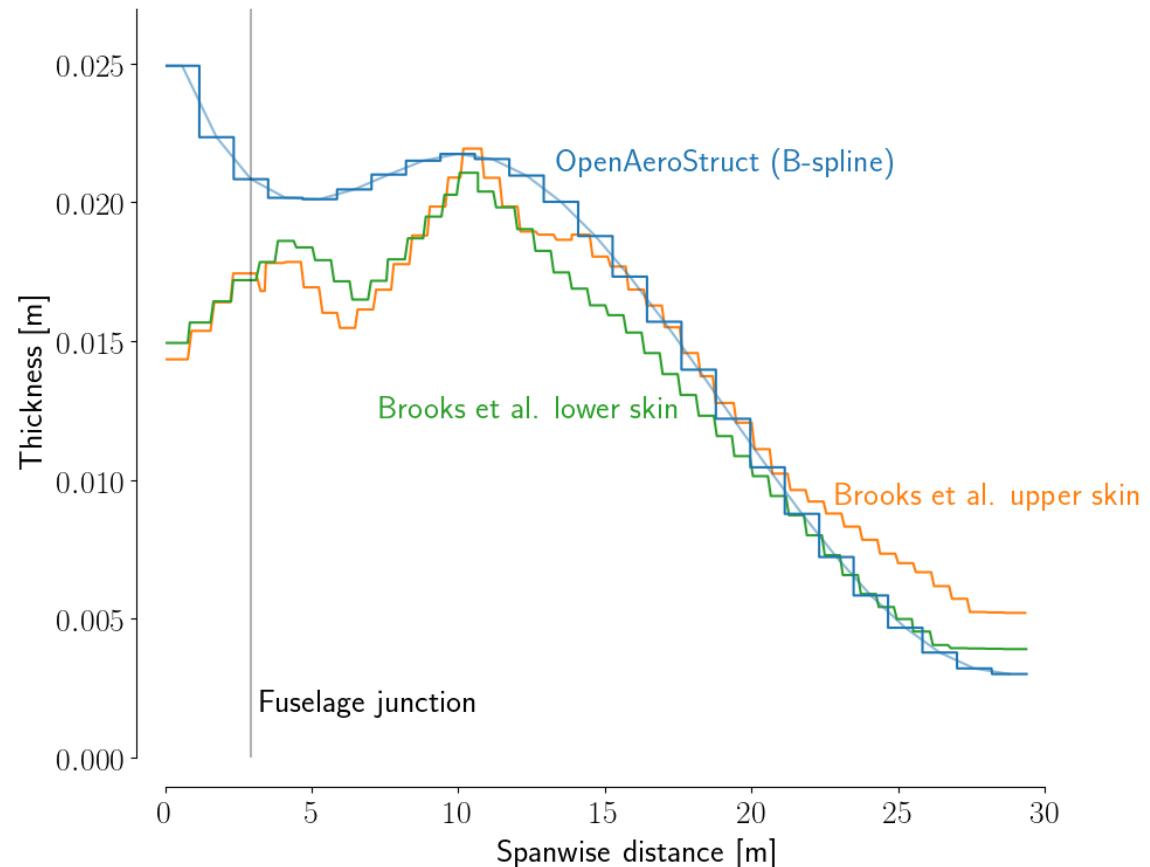


B-spline
design
variables

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%)

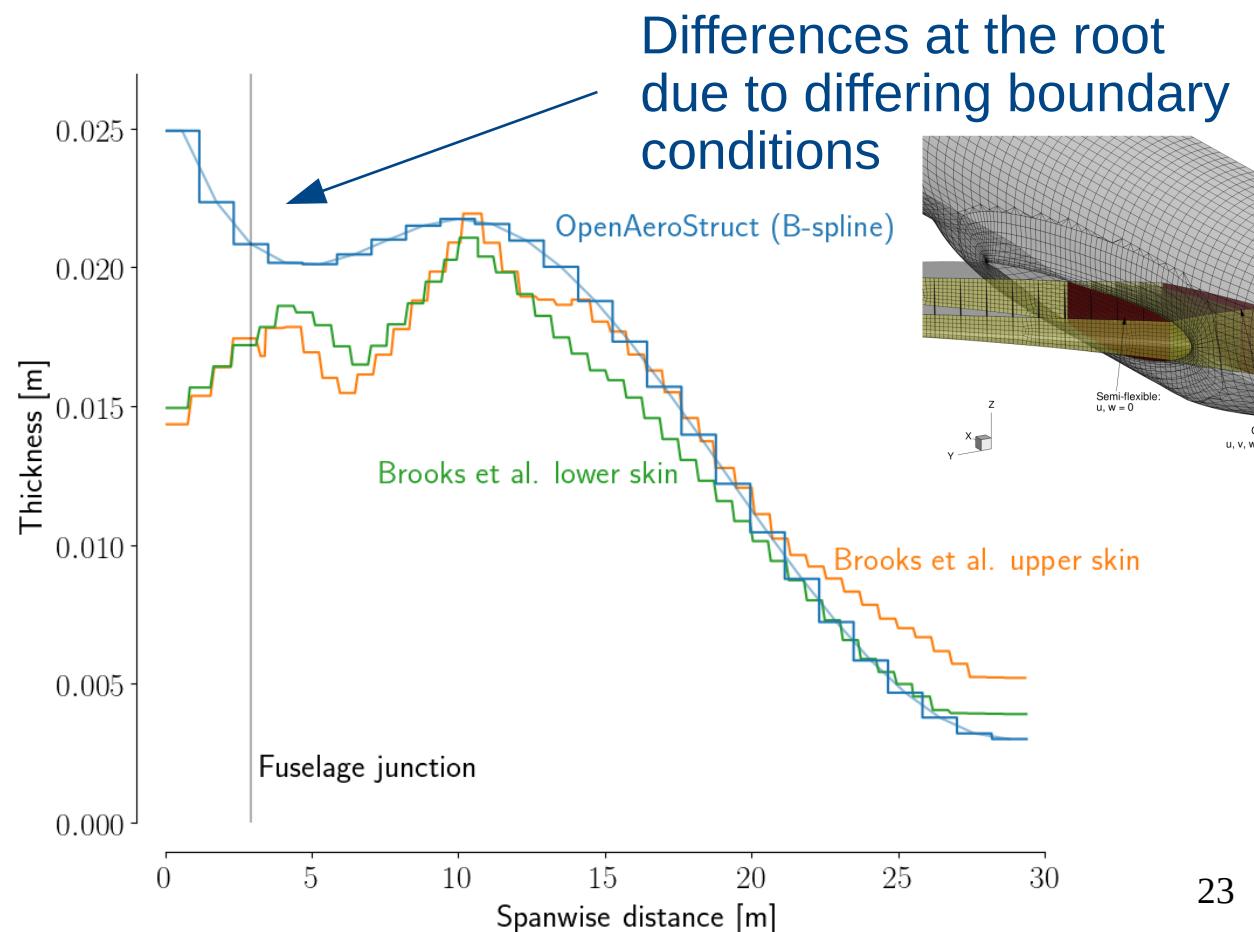
Wingbox skin thickness distribution



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

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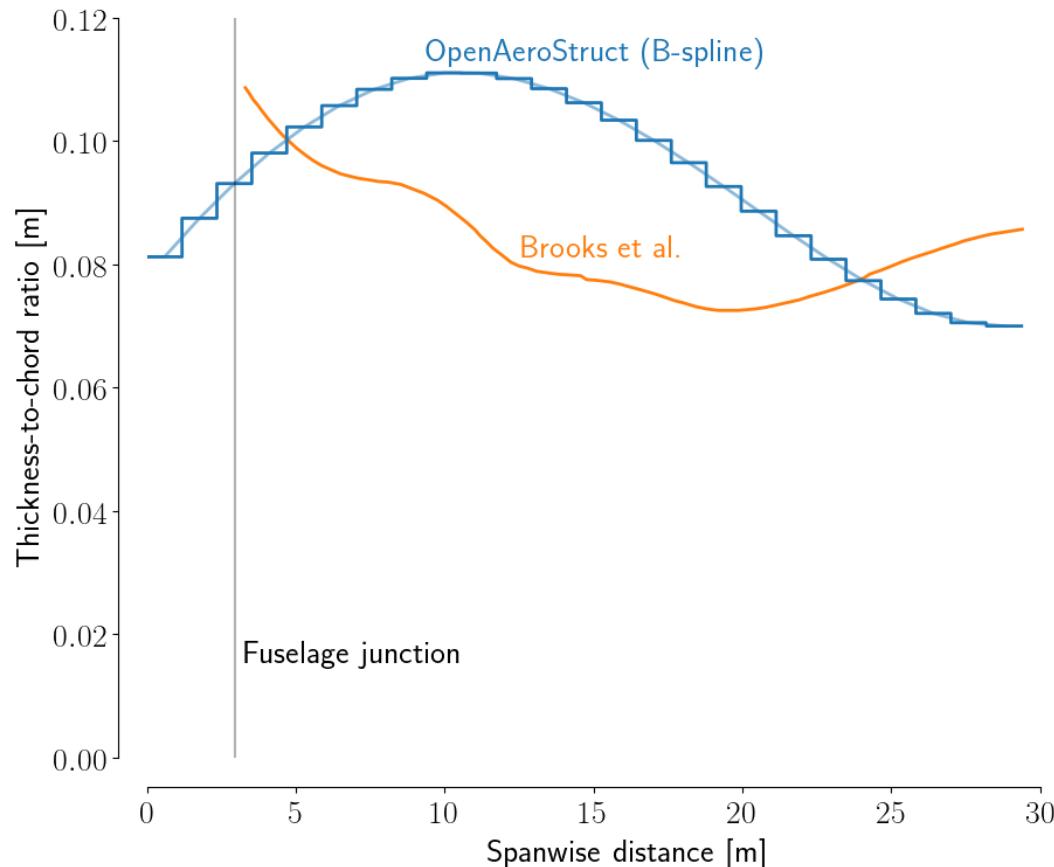
Wingbox skin thickness distribution



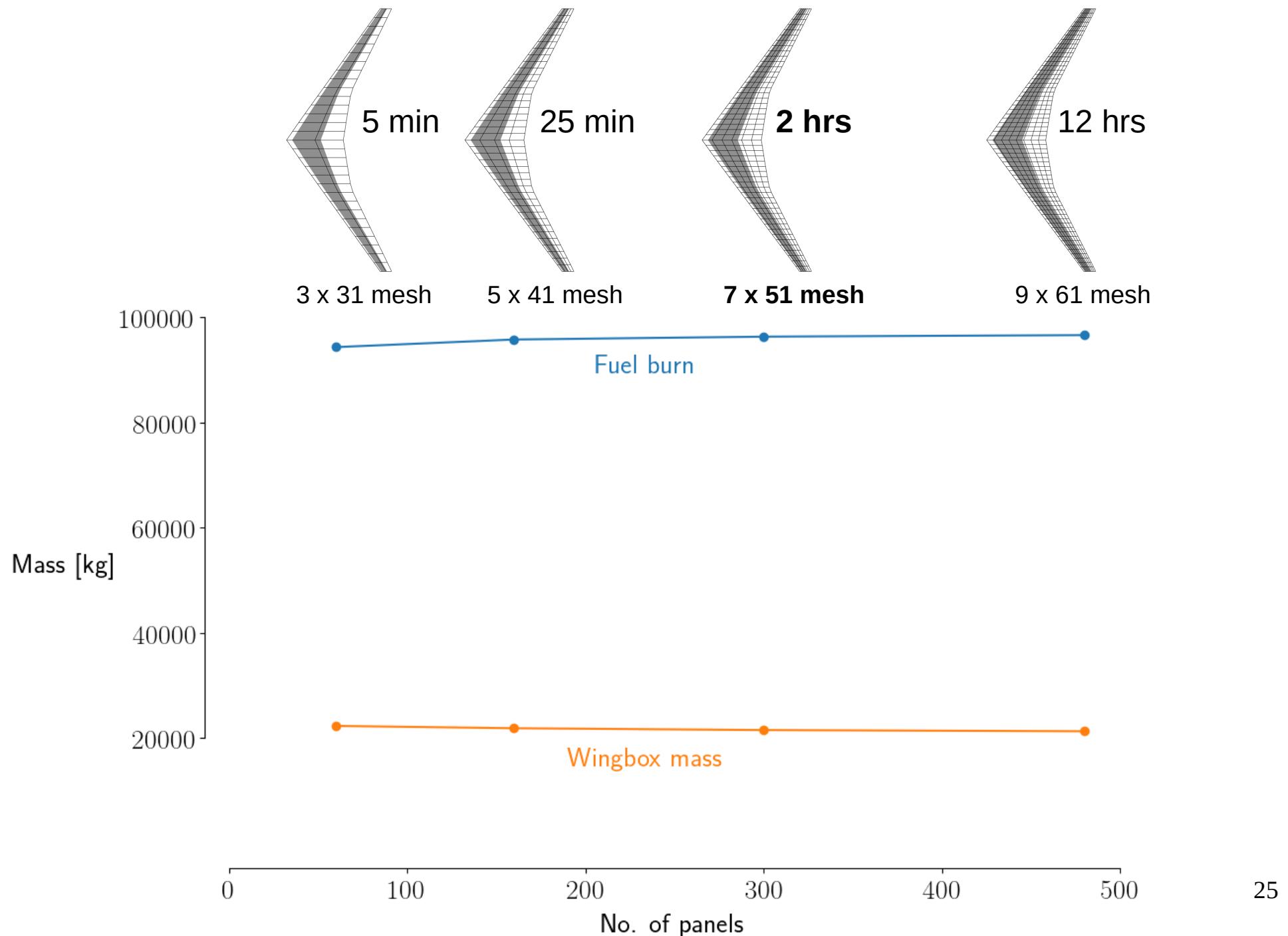
However, due to differences in fidelities, there are differences in some trends

- 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**



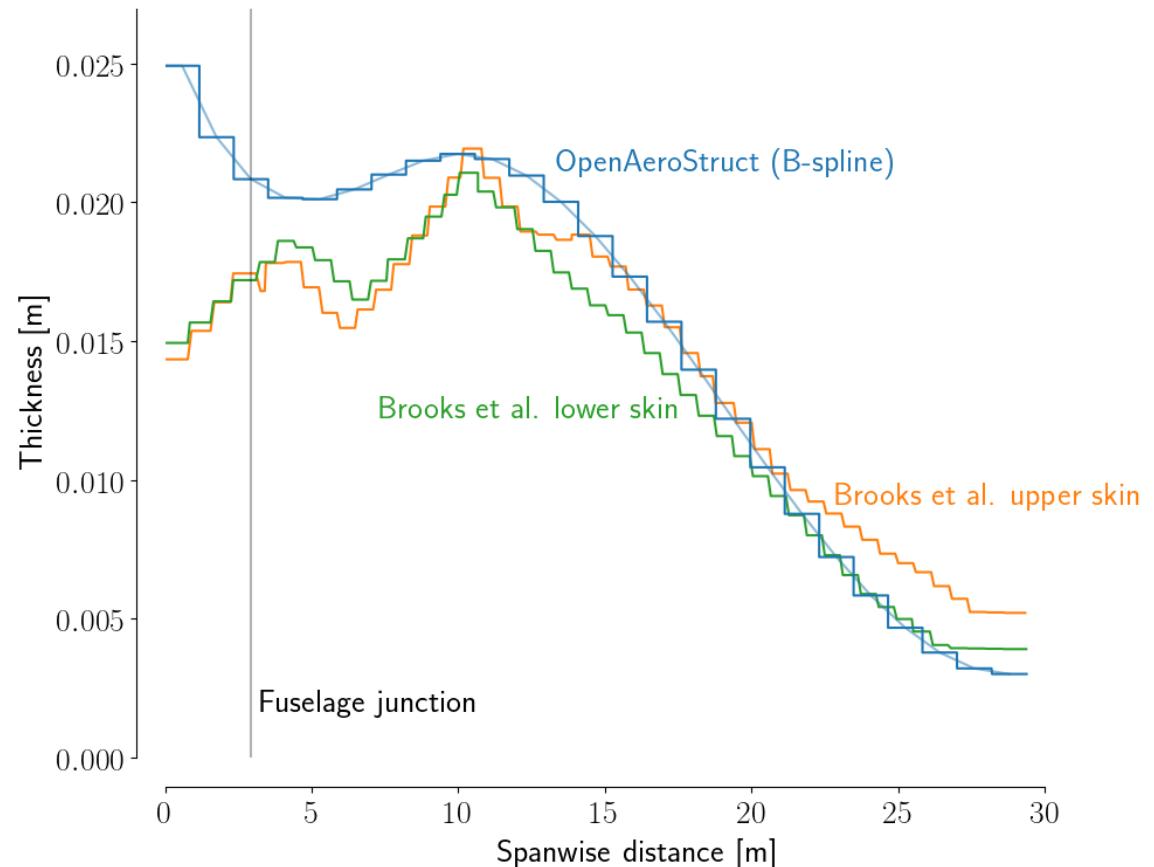
How long does it take (on my laptop)?



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

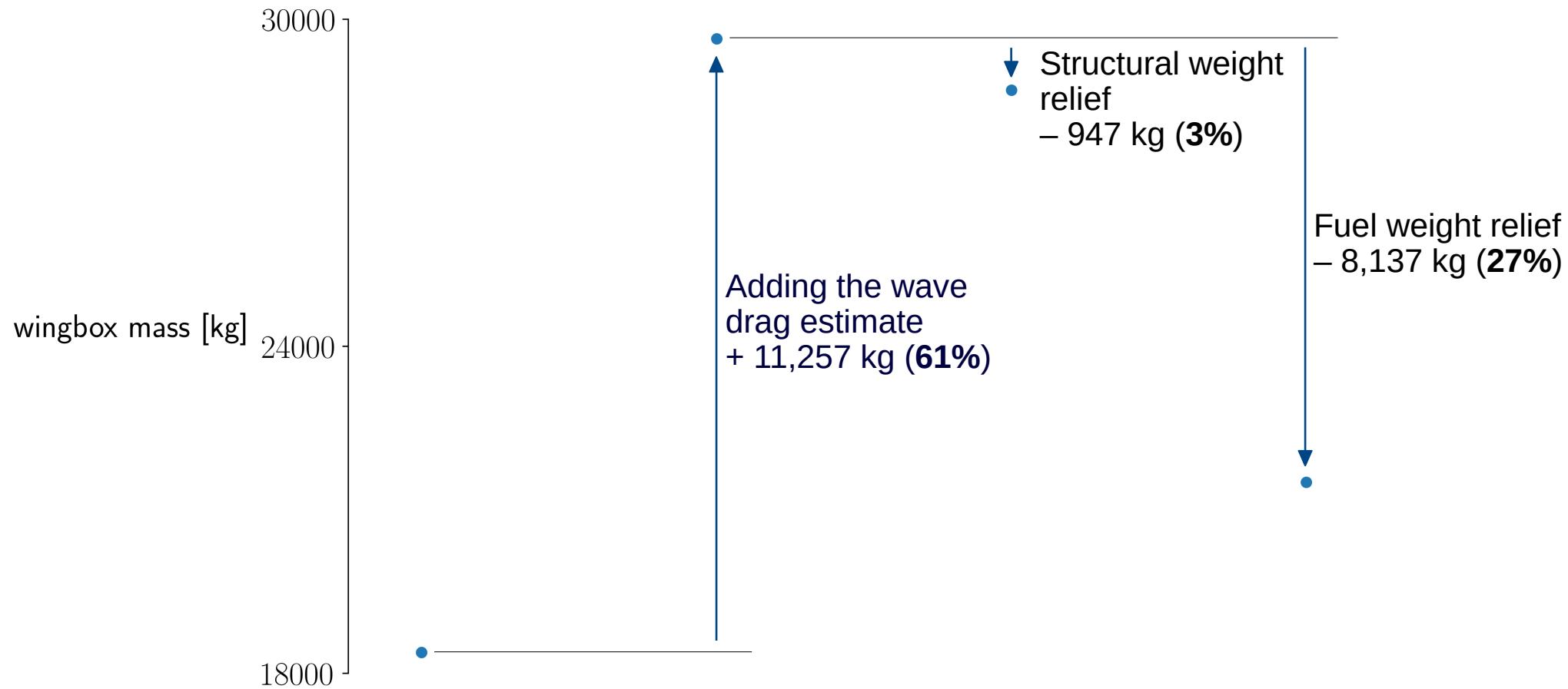
	Wingbox mass	Fuel Burn
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A reasonable starting point for more detailed optimization

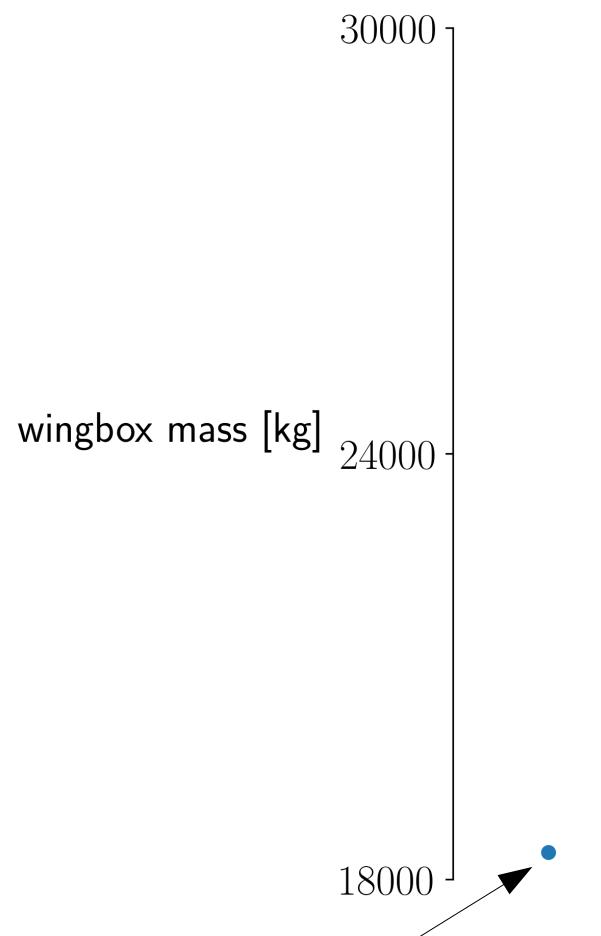


Some interesting studies to develop intuition

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



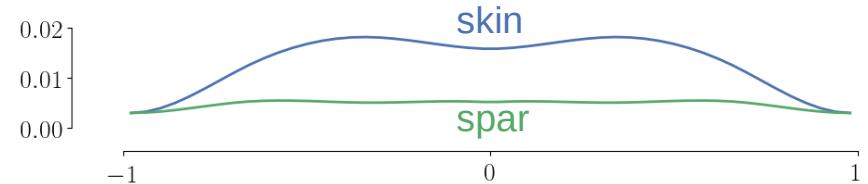
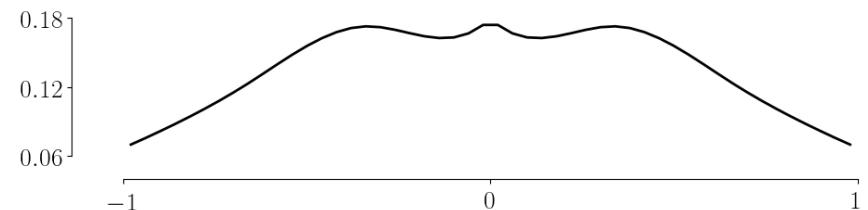
Start with no wave drag or load relief



Thickness-to-chord ratio

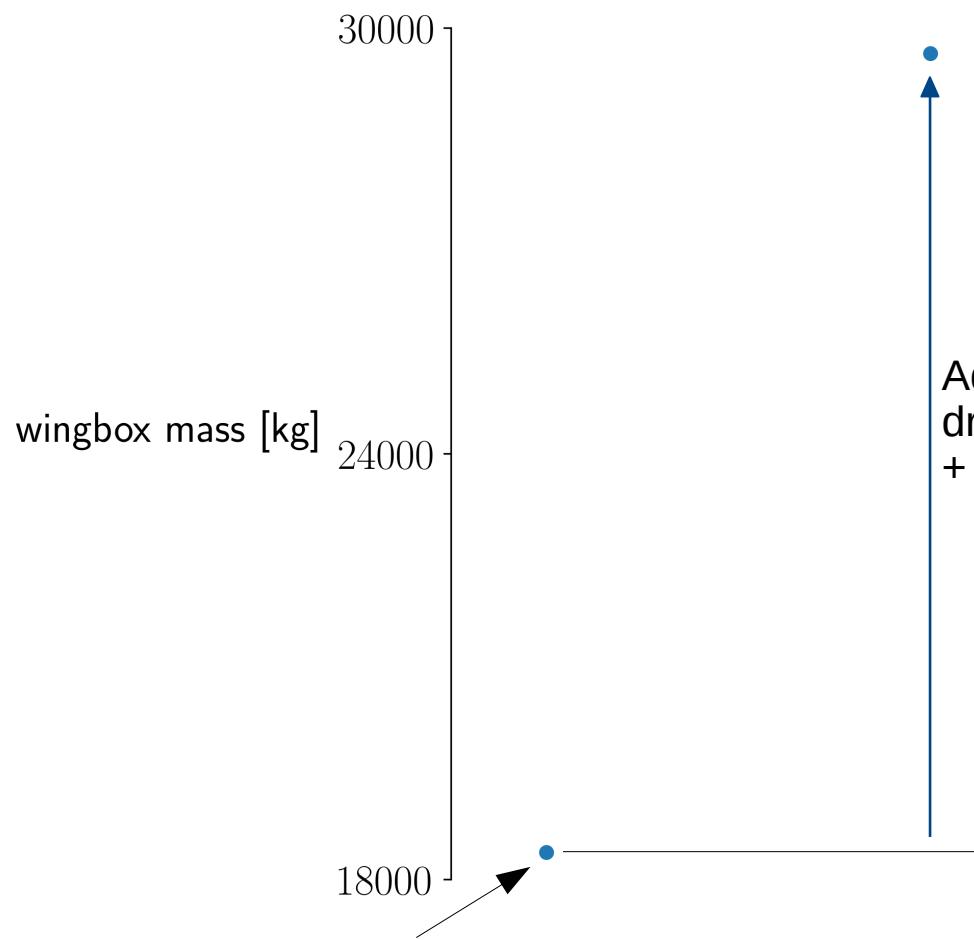
Material thickness

Normalized span



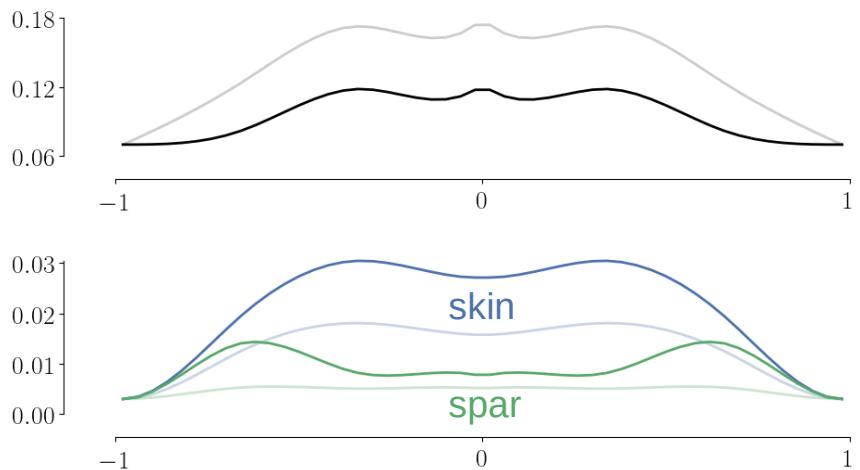
uCRM optimization with
- no wave drag computation
- no structural weight relief
- no fuel weight relief

Add wave drag based on the Korn equation

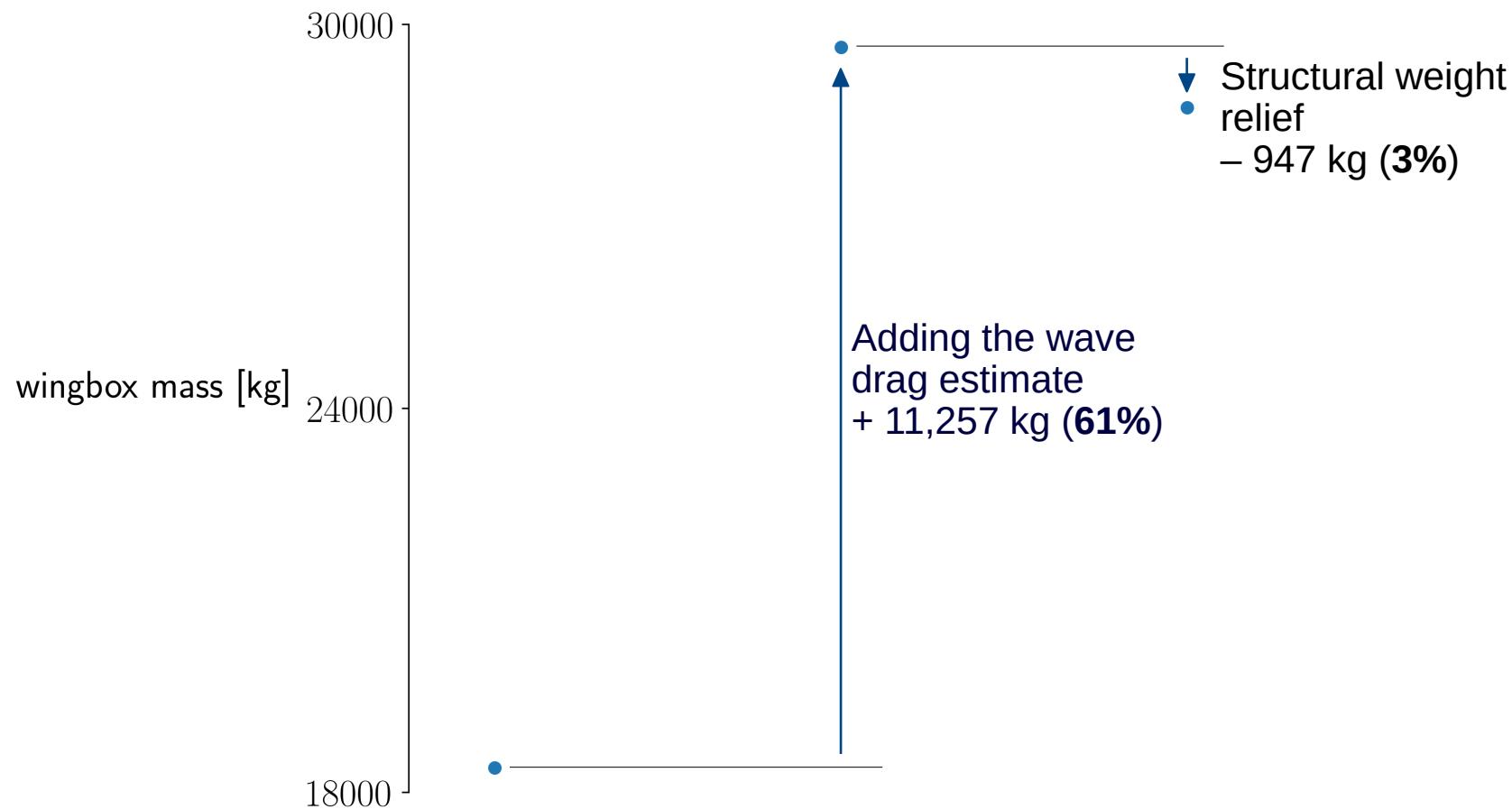


uCRM optimization with
- no wave drag computation
- no structural weight relief
- no fuel weight relief

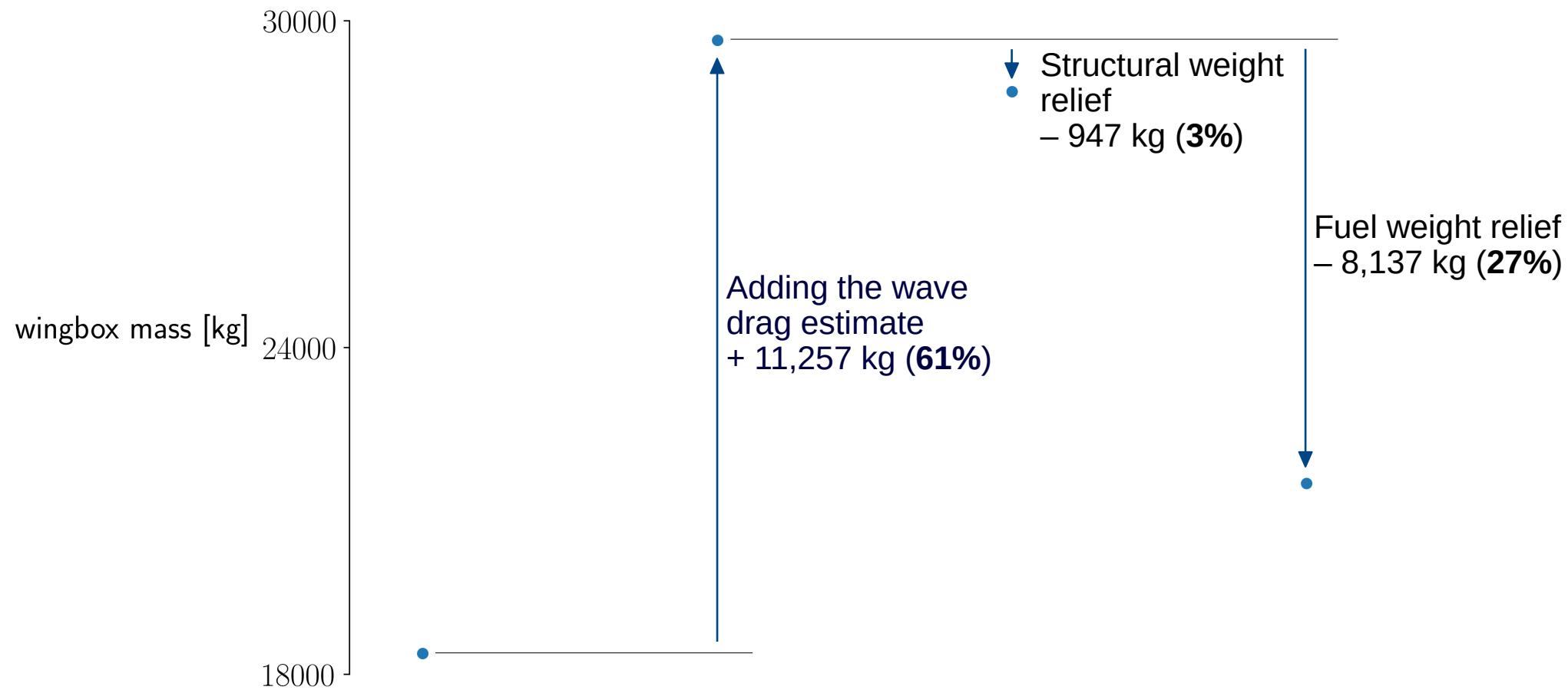
Adding the wave
drag estimate
+ 11,257 kg (**61%**)



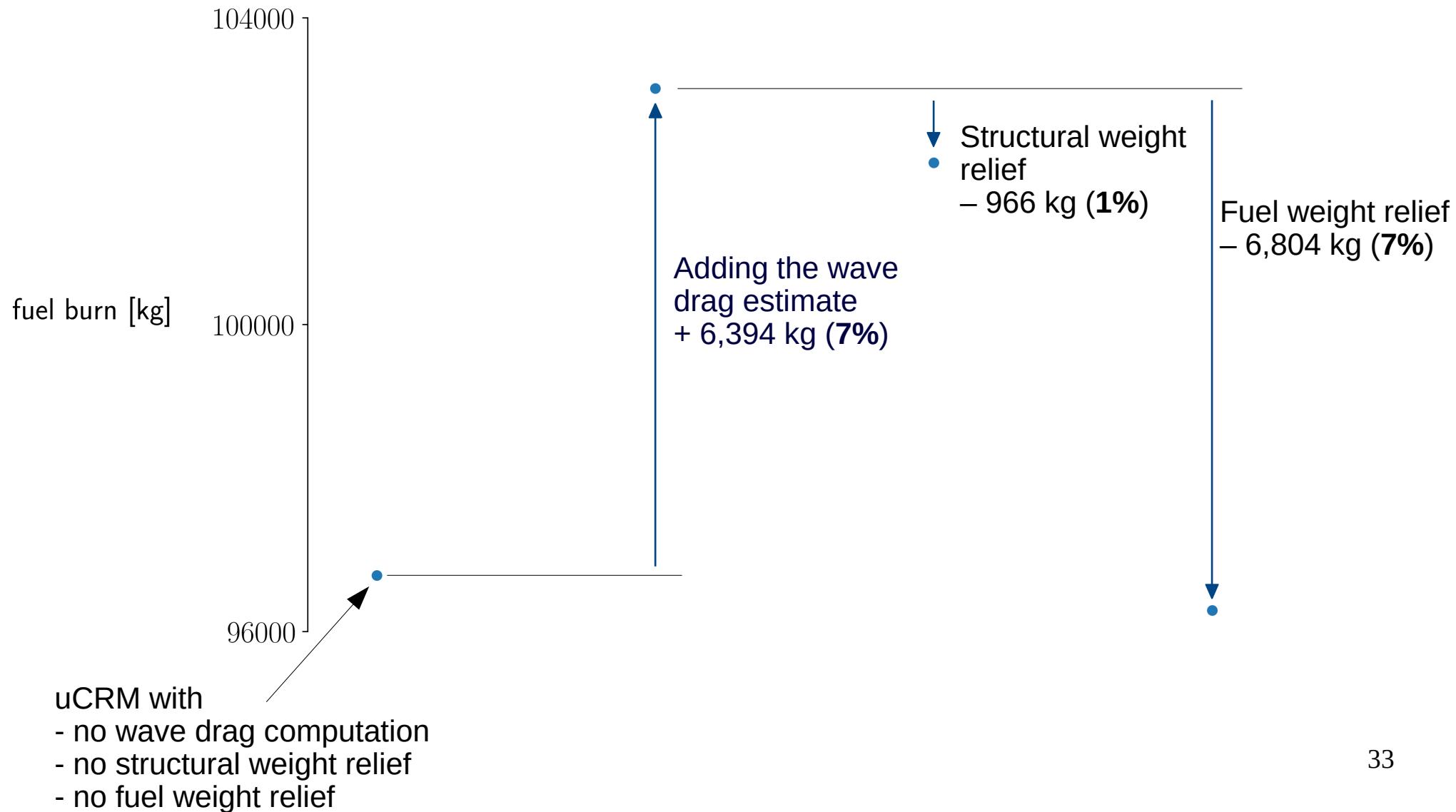
Adding loads from the weight of the wing structure



Adding loads from the weight of the fuel



Similarly for the fuel burn

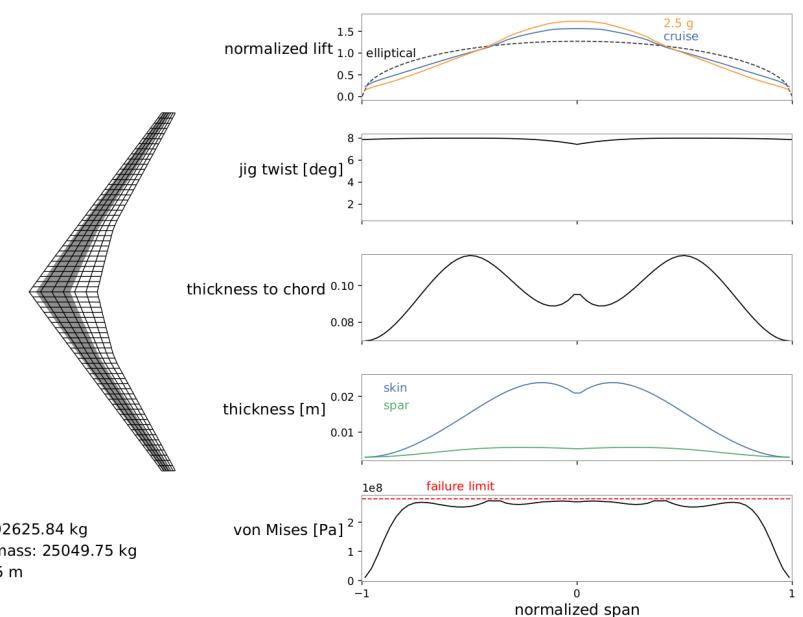


More design variables

Links to videos with more design variables:

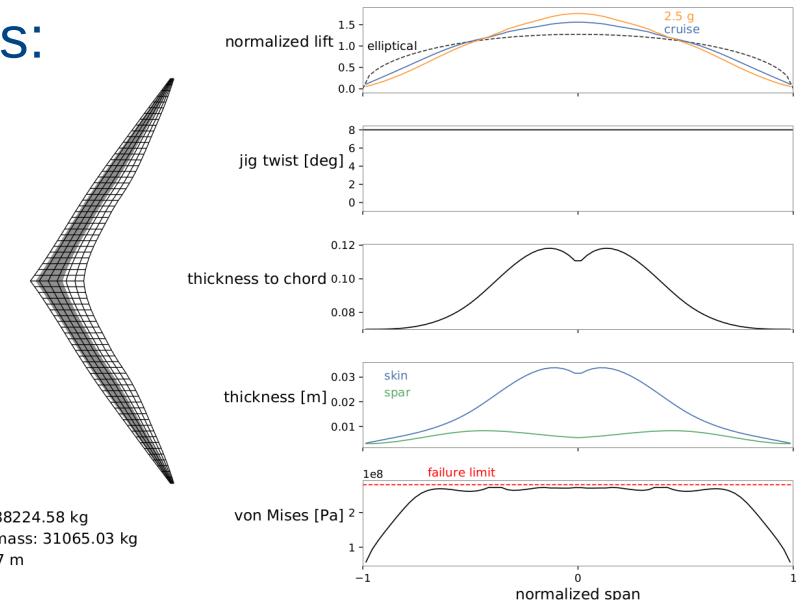
With span and sweep design variables:

<https://youtu.be/c5qO-deZZgs>



With span, sweep, and chord design variables:

<https://youtu.be/Q36UYrk4H64>



Questions?

Fork OpenAeroStruct on GitHub

OpenAeroStruct is a lightweight tool that performs aerostructural optimization using OpenMDAO.

1,375 commits 3 branches 2 releases 13 contributors Apache-2.0

Branch: master New pull request

johnjasa Merge pull request #207 from johnjasa/master 11 hours ago

openaerostruct Cleaning up recent commit 12 hours ago

.coverage Making sure Fortran compiles correctly 20 days ago

.gitignore changing doc to docs for githubpages 2 months ago

.travis.yml Making sure Fortran compiles correctly 20 days ago

LICENSE.md Create LICENSE.md 2 months ago

OAS_xdsm.pdf Added xdsm a month ago

README.md Update README.md 2 months ago

example_deriv_check.py updated viewmat 29 days ago

setup.py Updated version numbers 2 months ago

README.md

OpenAeroStruct

build passing coverage 95%

OpenAeroStruct is a lightweight tool that performs aerostructural optimization using OpenMDAO. It couples a vortex-lattice method (VLM) and a 6 degrees of freedom 3-dimensional spatial beam model to simulate aerodynamic and structural analyses using lifting surfaces. These simulations are wrapped with an optimizer using NASA's OpenMDAO framework. The analysis and optimization results can be visualized using included tools, producing figures such as this:

github.com/mdolab/OpenAeroStruct

Visit mdolab.engin.umich.edu

Multidisciplinary Design Optimization Laboratory

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Introduction

Many engineering systems involve multiple disciplines and require the coupled analysis of those systems to evaluate their overall performance. In addition, we must consider interdisciplinary trade-offs to design such systems. Multidisciplinary design optimization (MDO) aims to assist the design of coupled engineering systems through the use of numerical methods for the analysis and design optimization. For a review of MDO methods (called architectures), see this survey paper. An aircraft is a prime example of a multidisciplinary system, and it is no coincidence that aircraft design was one of the very first applications of MDO.

Prof. Martins founded the MDO Laboratory research group in 2002. The vision of our research group is that MDO will enable a relatively small team of engineers to explore possible designs quickly and early in the design process using powerful numerical tools. This story and this video introduction provide an overview of some of our research. See this page for the list of current and former members of the MDO Lab.

Research in the MDO Lab embraces both the theory and applications perspectives. On the theory side, we develop numerical methods that are applicable to a wide range of problems. Much of our work has focused on the accurate and efficient computation of derivatives to aid gradient-based optimization methods, but derivatives have many other applications. The complex-step method for computing derivatives, for example, has been applied to a wide range of disciplines, including geophysics, biotechnology and statistics. We have written a survey of MDO architectures, and we are constantly looking for opportunities to improve these architectures. We are currently collaborating with NASA in the development of OpenMDAO, a framework to facilitate the application of MDO to real world engineering design problems.

for more from the MDOlab

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