Multidisciplinary Design Optimization of a HALE drone regarding environmental impact

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ECO-HALE

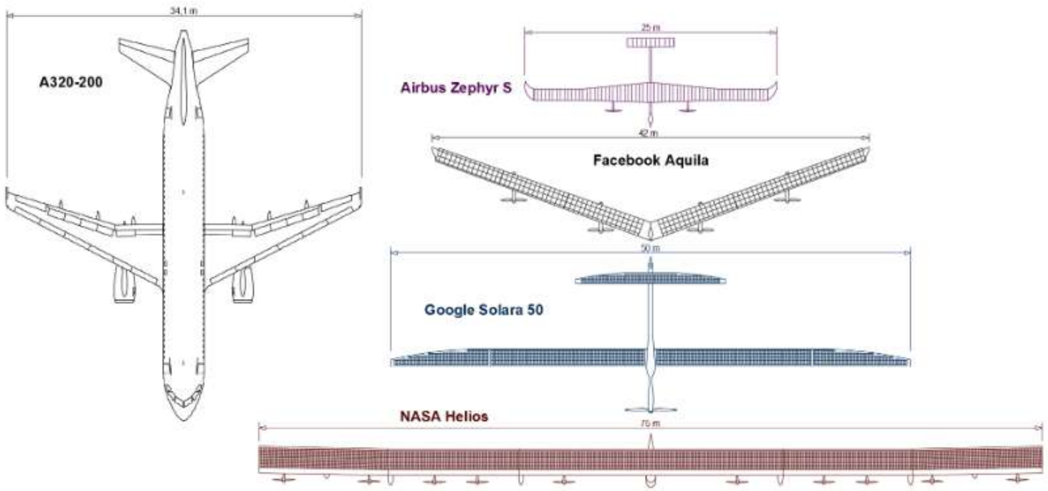
<u>Use : pseudo-satellite</u>
-Earth-observation
-Earth monitoring
-Communication
=> Long flight

<u>Principle</u>
-Solar powered
-Large-span
-Batteries

<u>Assets</u>
-Repairable
-Flexible
-Permanent coverage
-cheaper*
-Environmental friendly?

<u>Drawbacks</u>
-Technical complexity
-Smaller coverage

https://www.esa.int/Applications/Navigation/Crossing_drones_with_satellites_ESA_eyes_high-altitude_aerial_platforms



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*Gonzalo, J., López, D., Domínguez, D., García, A., Escapa, A., 2018. On the capabilities and limitations of high altitude pseudo-satellites. Progress in Aerospace Sciences 98, 37–56. https://doi.org/10.1016/j.paerosci.2018.03.006

I/Introduction

II/Background

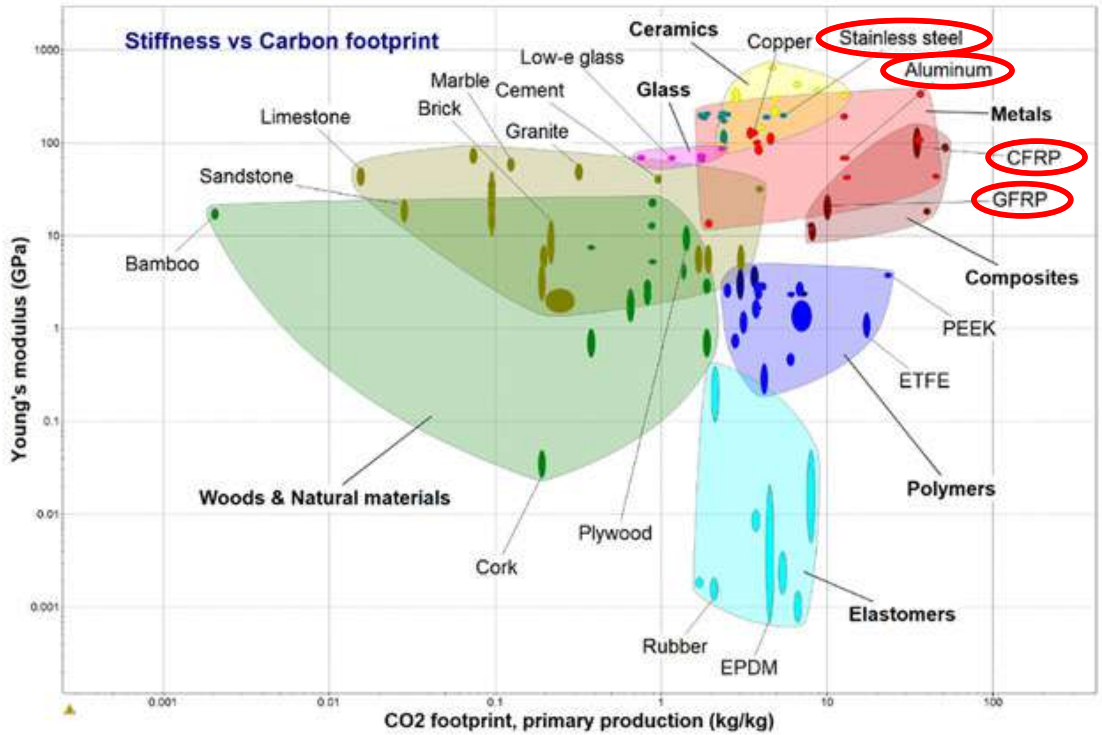
III/Model

IV/Results

V/Conclusion

Subject/aims

- Optimize the environmental impact of a HALE drone : eco-design
- Include material selection in MDO
- Select optimal material in a big database : CES Selector
- Significant computing time improvement compared to « brutal force »

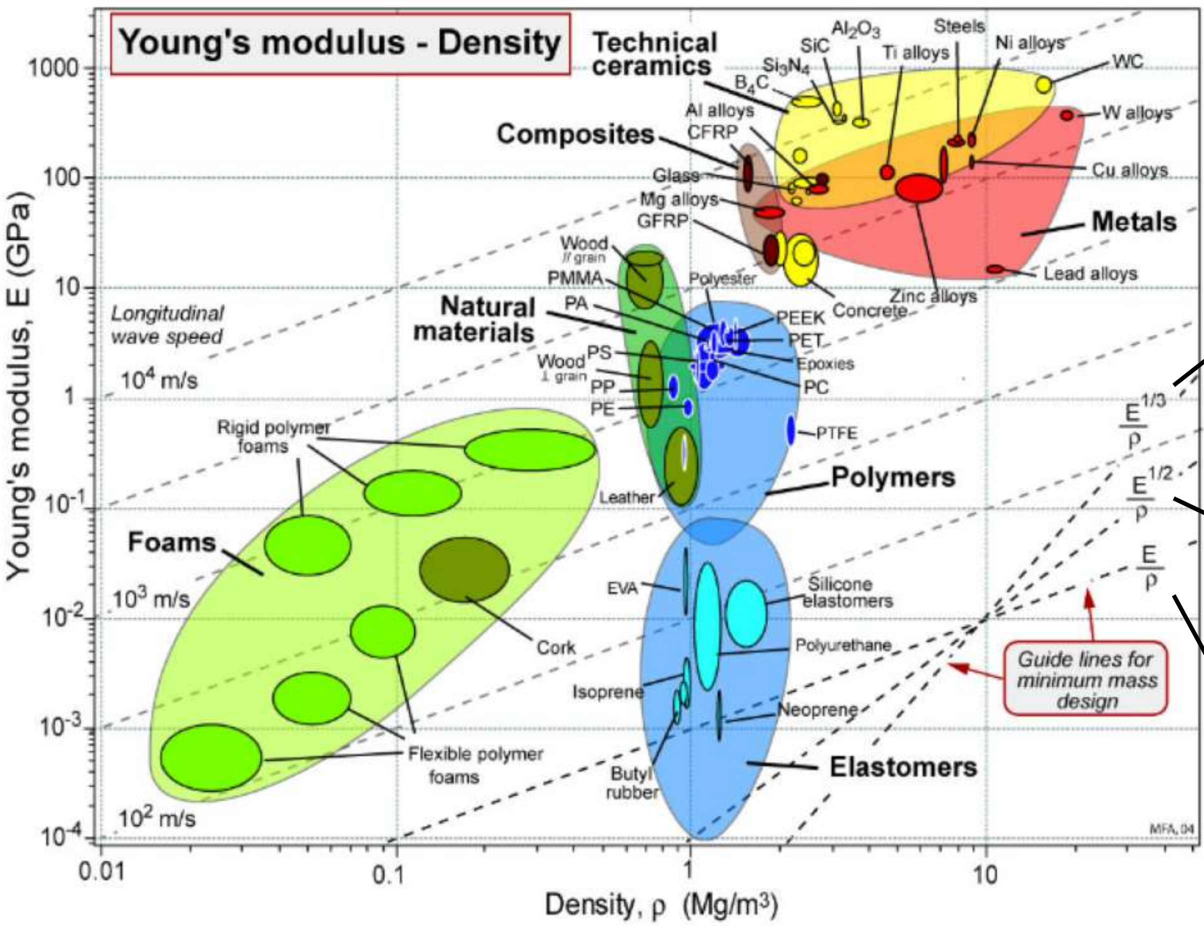


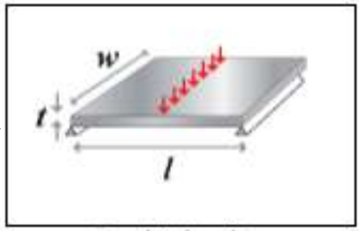
Material	E (GPA)	Density (kg/m3)	CO2 (kg/kg)
Stainless steel	200	7750	3.4
Aluminum	72.5	2800	8.2
GFRP	21.4	1860	6.2
CFRP	55	1565	48
Sandwich	42.5	500-560	40-45

Ashby, M.F., Miller, A., Rutter, F., Seymour, C., Wegst, U.G.K., n.d. The CES Eco Selector – Background Reading 24.

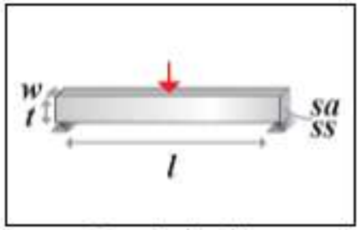
State of the art: Ashby's method

- One part at a time, one loading case at a time

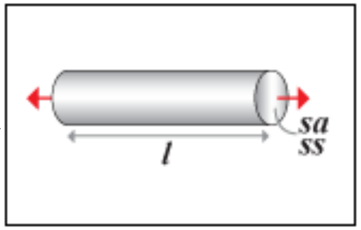




Panel in bending



Beam in bending



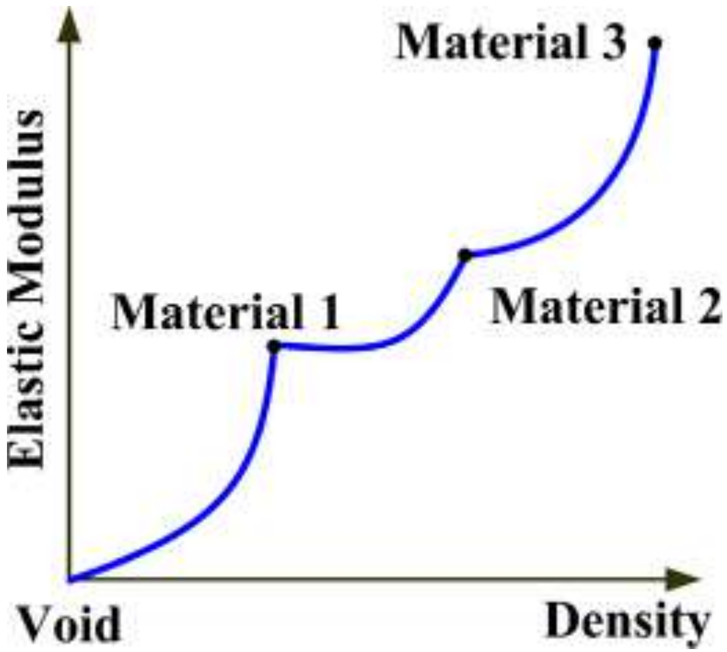
Tie in tension

Ashby, M. F. (2005). *Materials selection in mechanical design*. Amsterdam: Elsevier Butterworth-Heinemann.

State of the art : SIMP

- Solid Isotropic Material with Penalization (SIMP)
- $E_e(\rho_e) = A_E * \rho_e^p + B_E$,

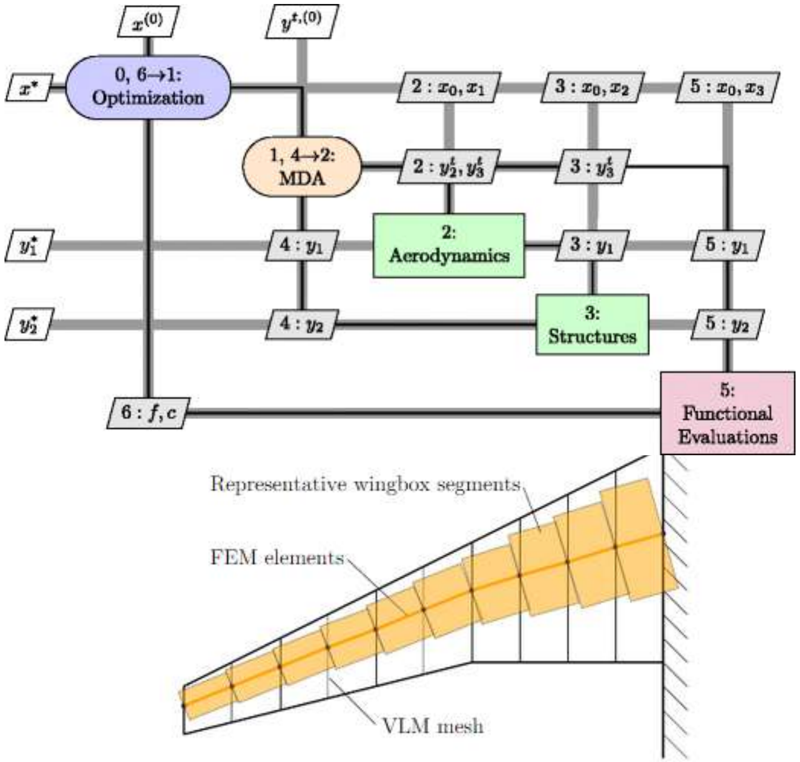
$\rho_e \in [\rho_i, \rho_{i+1}]$, $A_E = \frac{E_i - E_{i+1}}{\rho_i^p - \rho_{i+1}^p}$, $B_E = E_i - A_E * \rho_i^p$

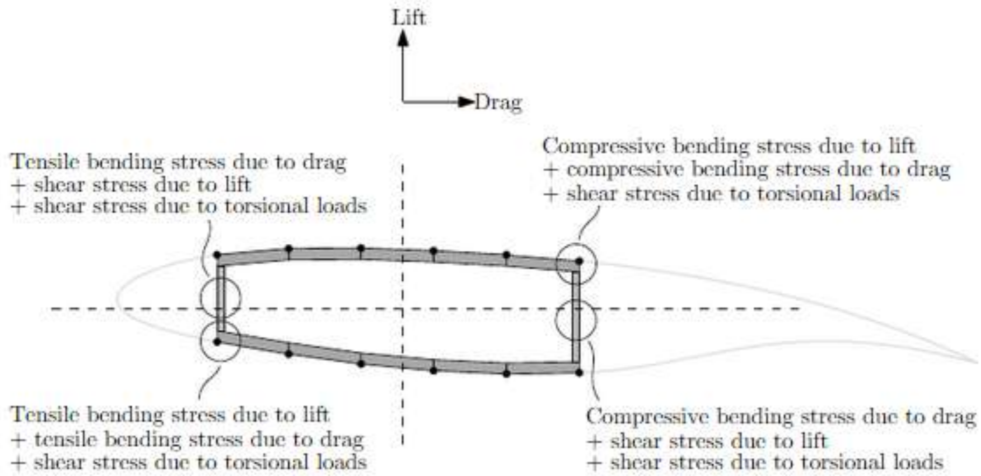


Zuo, W., & Saitou, K. (2016). Multi-material topology optimization using ordered SIMP interpolation. *Structural and Multidisciplinary Optimization, 55*(2), 477-491. doi:10.1007/s00158-016-1513-3

Technical context: OpenAeroStruct

- Low fidelity tool for aerostructural MDO, based on OpenMDAO framework (NASA). Optimizer used : SLSQP
- Derivatives by adjoint method with analytic gradients
- Aerodynamics : vortex lattice method (VLM)
- Structure: 1D finite element analysis with wingbox elements.





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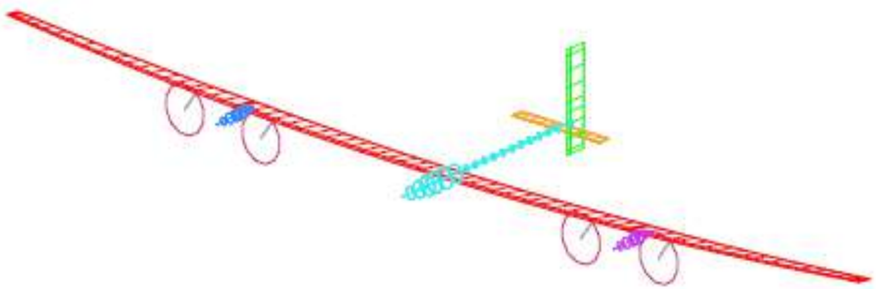
OpenAeroStruct new formulation

	Initial formulation	New formulation
Objective function	Fuel burn	CO2 impact of the drone
Constraints	• Mechanical failure • Range by Breguet equation • Flight (L=W)	• Enough power • Simple buckling constraint • Mechanical failure • Flight (L=W)
Design variables	• Thicknesses • Twist • Thickness to chord ratio	• Thicknesses • Twist • Thickness to chord ratio • Density

OpenAeroStruct new formulation

- Change commercial aircraft into HALE drone with same characteristics as FBHALE for comparison.
- Power balance depending on mass, payload and avionics -> constraint on wing surface
- Added mass of solar panels, batteries (worst case : 13h night), avionics, propulsion
- CO_2 impact of solar panels and batteries



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Material design variable

- OpenAeroStruct only accepts continuous design variables
  -> Material variable needed to be made continuous
- All material characteristics are introduced as a function of density, and linearly interpoled between two real materials.
  -> only one material design variable : density

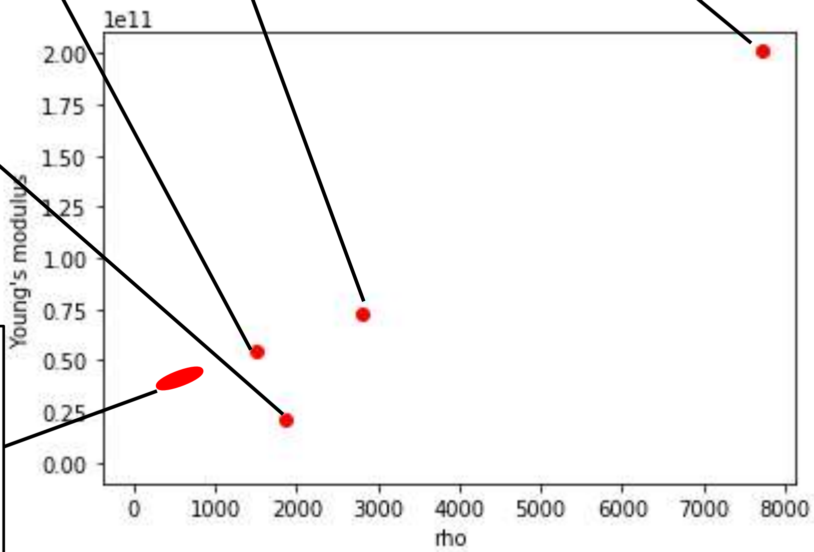
CFRP:
E=55MPa
ρ=1565kg/m3
CO_2=48kg/kg

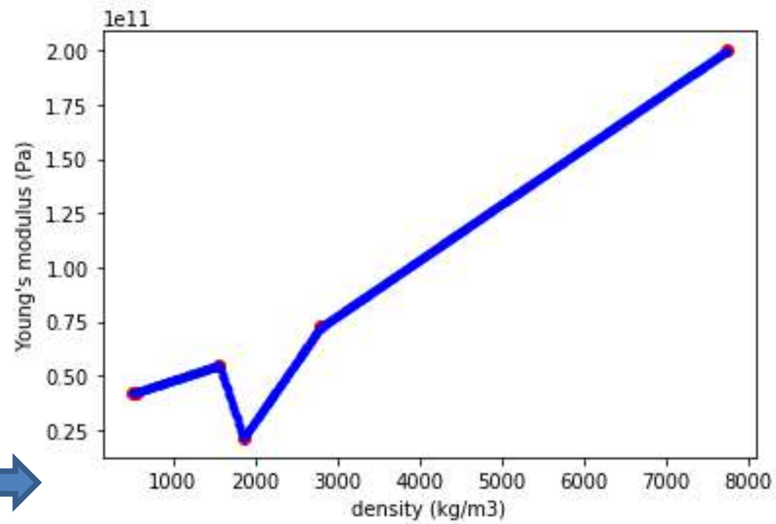
Aluminum:
E=72.5MPa
ρ=2800kg/m3
CO_2=8.2kg/kg

Steel:
E=200MPa
ρ=7750kg/m3
CO_2=3.4kg/kg

GFRP:
E=21.4MPa
ρ=1860kg/m3
CO_2=6.2kg/kg

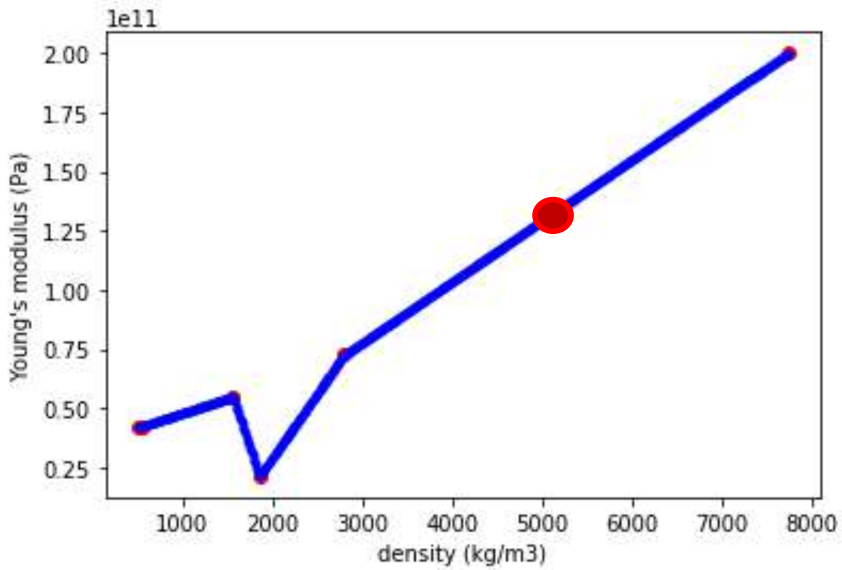
Sandwich:
E=42.5MPa
ρ=500-560kg/m3
CO_2=40-45kg/kg





Material design variable

- The optimum could be an unexisting material.
- A power term is added at the end of convergence in order to force it to a real material. (negative curvature for CO_2, as smaller CO_2 is advantageous)



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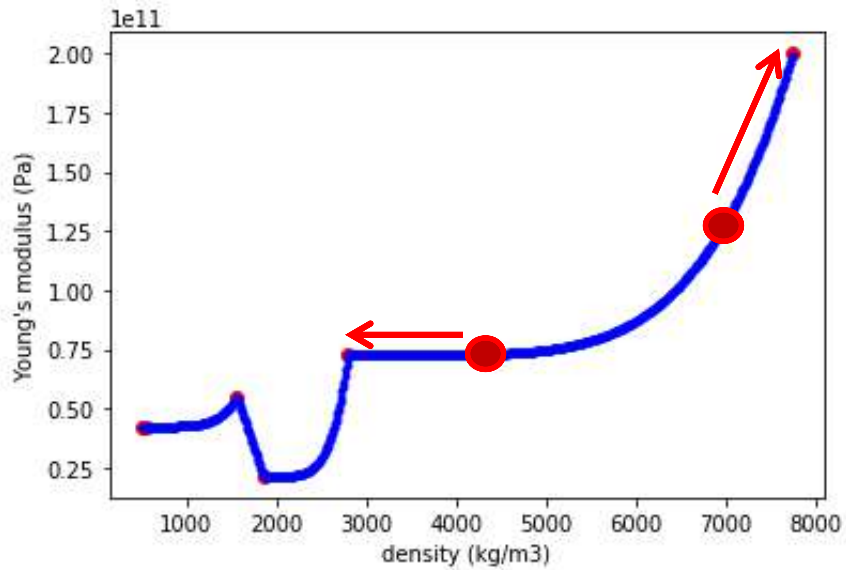


P=5

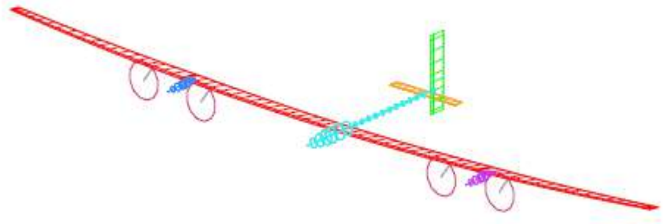
New formulation : design variables

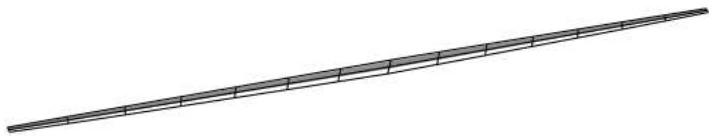
Variable	Bondaries	Lowest starting value	Highest starting value	Number of starting values	unit
Skin thickness	0,0001-0,1	0,001	0,0016	7	m
Spar thickness	0,0001-0,1	0,0001	0,0001	1	m
Wing span	1-1000	55	65	3	m
Wing chord	1,4-500	1,5	1,5	1	m
Wing taper	0,3-0,99	0,3	0,3	1	-
Wing thickness over chord ratio	0,01-0,4	0,11	0,17	3	-
Twist	-30 - +30	+15	+15	1	°
Density	400-8000	1250	2000	2	Kg/m3

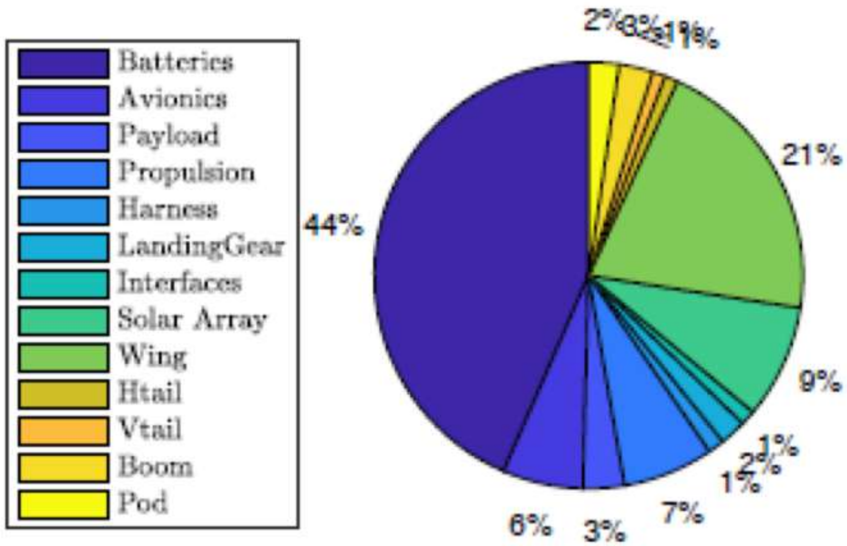
Validation : Comparison with FBHALE

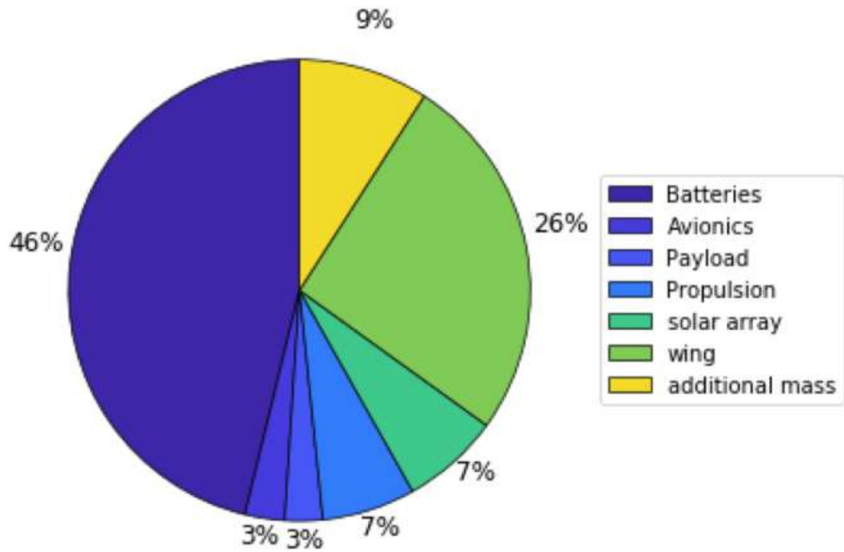
Fixed mass comparison with FBHALE:

Variable	Modified OpenAeroStruct	FBHALE
Total mass (kg)	378	320
Wing surface (m^2)	87	72
Aspect ratio	94	29
C_L	1.31	1.33



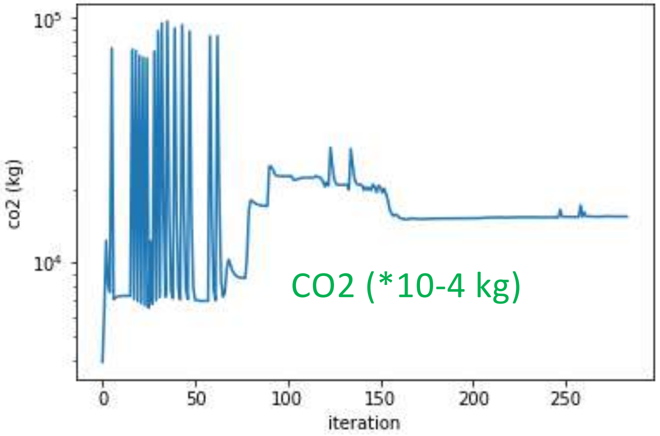


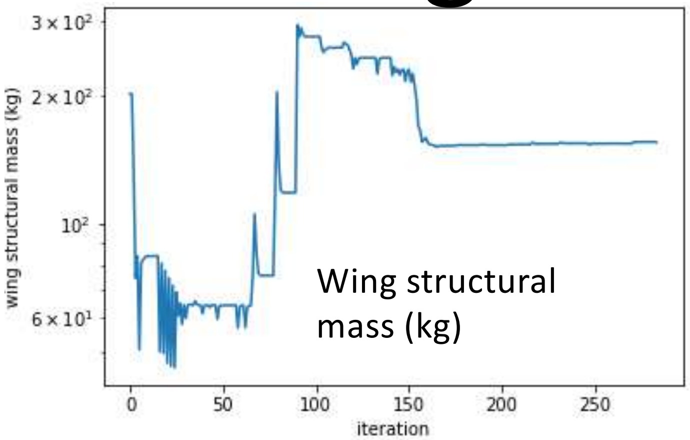


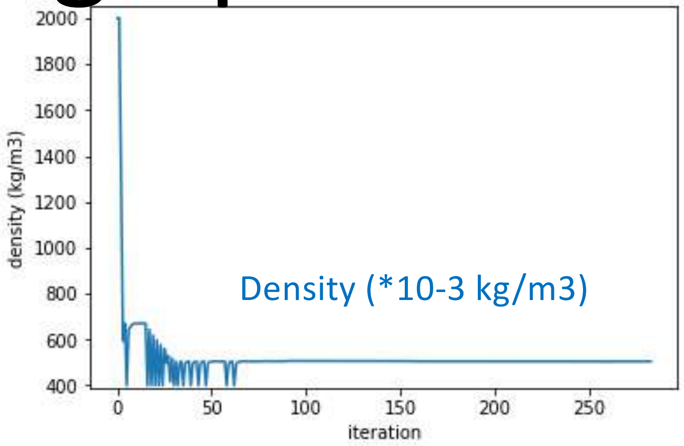


- Simple buckling, 1-cosine gust, flutter and snowball effect

Results : convergence graphs







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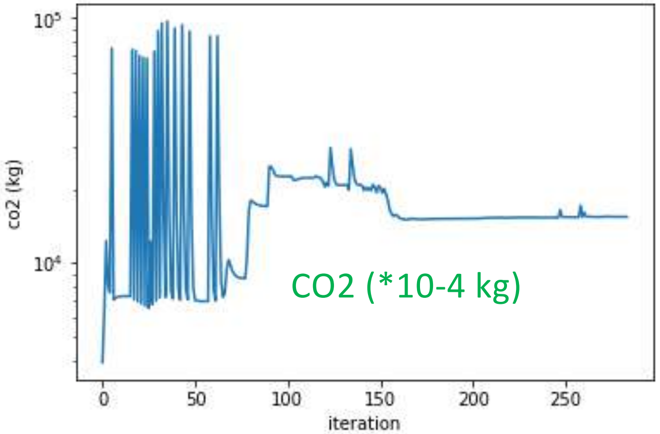
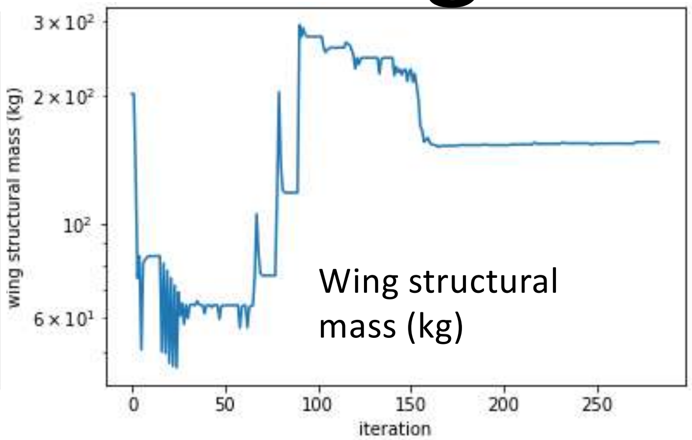
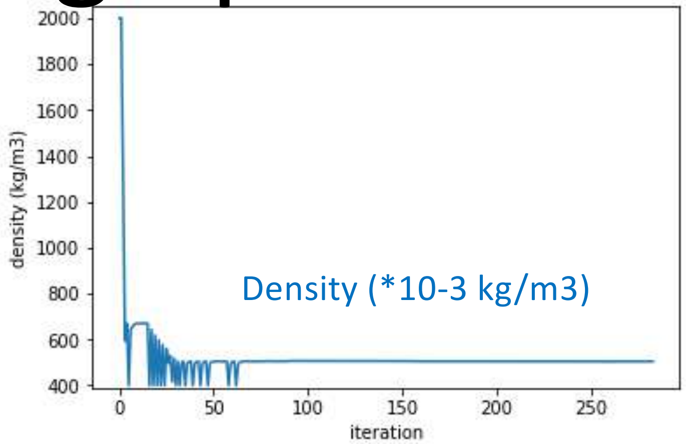
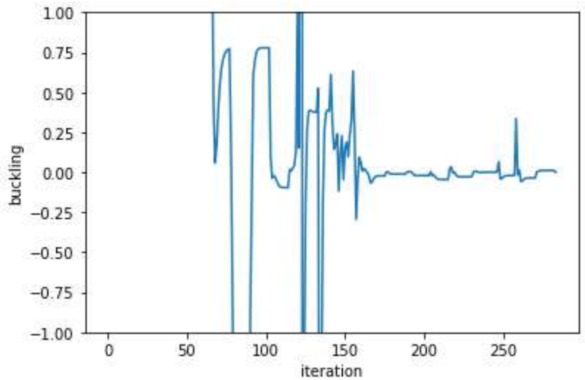
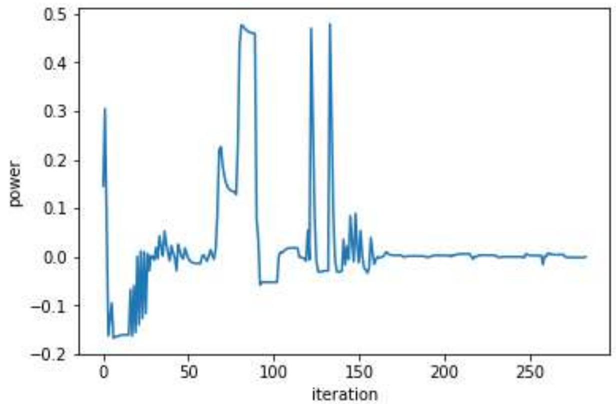




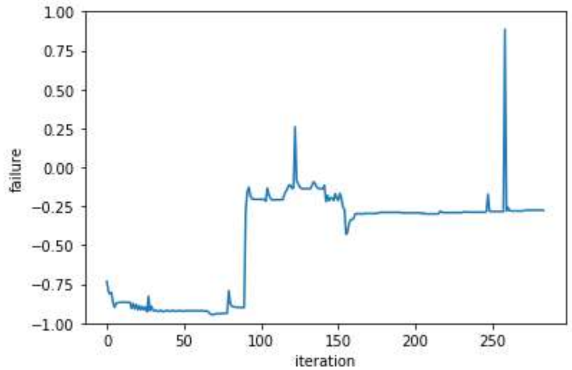




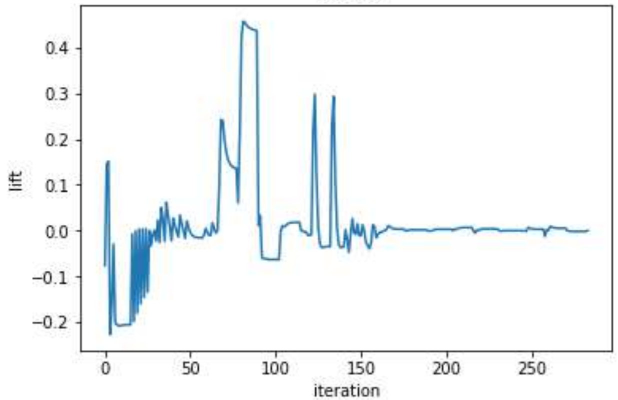
Buckling constraint:
Influence on skin thickness



Power constraint:
Influence on wing surface



Failure constraint:
Inactive because of buckling constraint



Lift=weight constraint:
Global influence

- Constraints normalized

Results : final design

Design variables	Final value
Span (m)	108
Chord (m)	1.4
Taper ratio	0.36
Density(kg/m3)	505
Skin thickness (mm)	1-6
Spar thickness(mm)	0.2
Wing twist(°)	12-30
T/C ratio	0.02-0.15

Constraints	Final value
Buckling	5.4 E-5
Failure	-0.28
Power	1.3 E-6
Lift	-7.3 E-7

Objective and other results	Final value
CO_2 emissions (kg)	15421
Total mass (kg)	473
Battery + PV mass (kg)	226
Payload + avionics mass (kg)	20.5
Wing Structure mass (kg)	155

The final material is a sandwich panel (UD CFRP – expanded PS foam – UD CFRP)
=> The same material as FBHALE

Results : density sensitivity

- Change in material CO2 => change in optimal material
- Big co2 change necessary for small rho change

Material data	CFRP - PS foam	CFRP - cork
Density	504.5	560.5
CO2/kg	44.9	44.9 / CO2ratio
Other material data	identical	

CO2 ratio	Optimal material
1	CFRP - PS foam
1.1	CFRP - PS foam
1.2	CFRP - PS foam
1.3	CFRP - cork
1.4	CFRP - cork
1.5	CFRP - cork
1.6	CFRP - cork

Results : comments

- Model very sensitive to the input data (snowball effect)

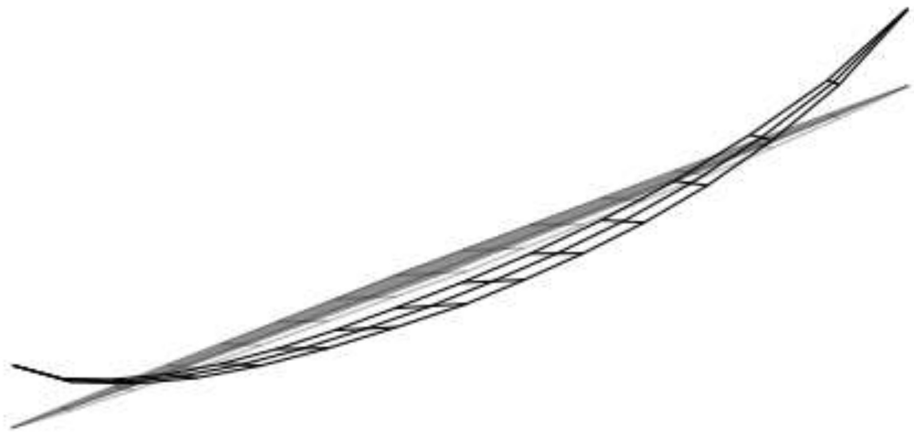
- Optimal material in terms of CO_2 very close to optimal material in terms of weight
  ->battery heaviest impact on CO_2

- CO_2 emitted by material must be significantly lower for an eco-material to be a good substitute.

Conclusion : Eco-design in the MDO loop

- OpenAeroStruct derived for HALE drones
- Material selection integrated to MDO as a continuous variable
- Method can be adapted to any aerostructure / MDO

- HALE drones could be a cleaner alternative to satellites (no launch) => important to make them as clean as possible.



Paper soon submitted to SMO!

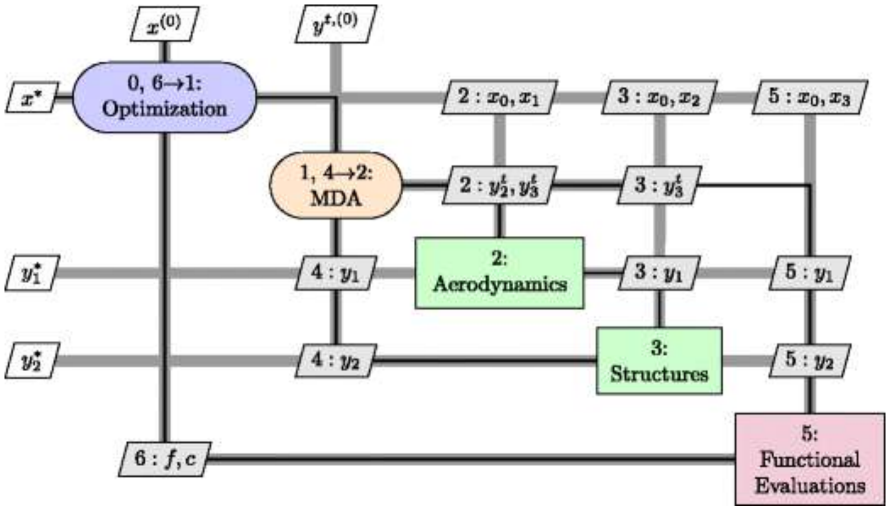
Conclusion : Next steps

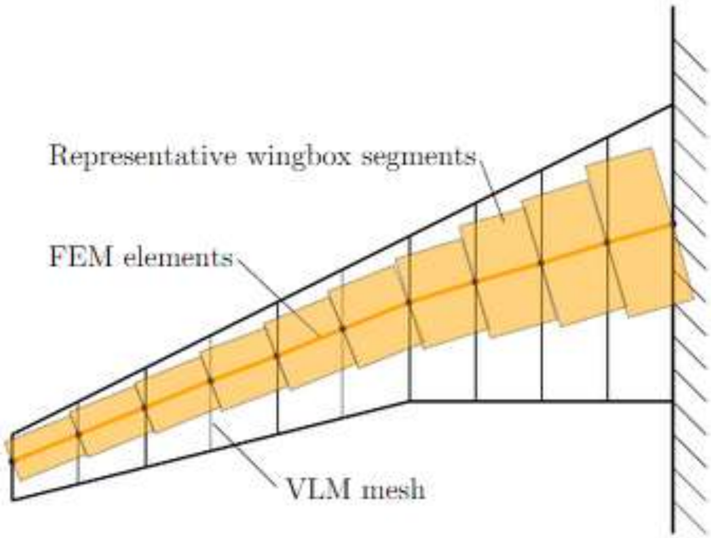
- Multi-material structure
- Improve model (gust, buckling)
- Adapt to bigger material database
- Speed up process (other material variable)

QUESTIONS ?

Technical context: OpenAeroStruct

- Low fidelity tool for aerostructural MDO, based on OpenMDAO framework (NASA). Solver used : NonLinearBlocksGaussSiedel
- Gradient optimization: derivatives obtained by couple adjoint method
- Aero : vortex lattice method (VLM)
- Structure (lifting surfaces): 1D finite element analysis with wingbox elements.
- Objective function : Fuel burn
- Design variables : thicknesses, twist, thickness to chord ratio





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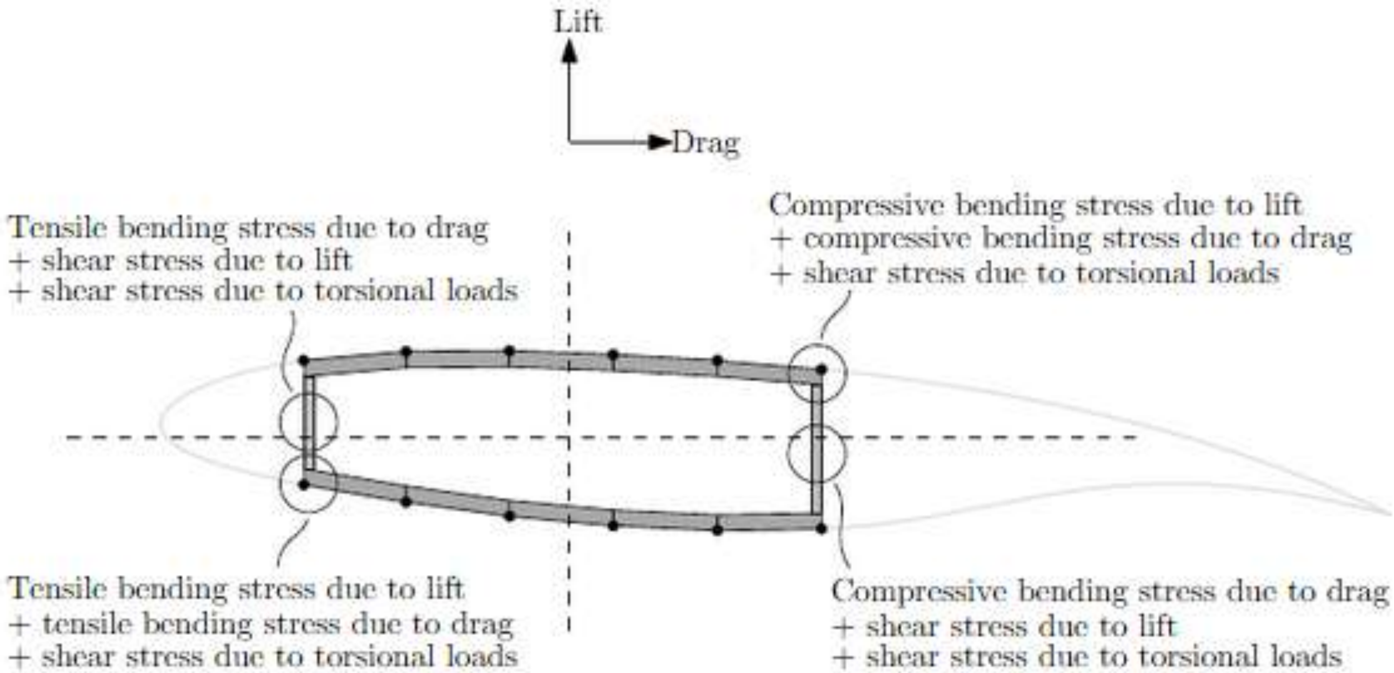
Technical context : OpenAeroStruct

- Constraints : - mechanical failure
  - range by Breguet equation
  - flight (L=W)
- Two test cases: - Cruise flight: Ma=0,85
  - Maneuver: Ma=0,64; 2,5g



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New formulation : Continuous material

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  -> Material variable needed to be made continuous
- All material characteristics are introduced as a function of density, and linearly interpoled between two real materials.