

Scalable Reduced-Order Optimization Frameworks for Composite Aerospace Structures

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PhD Aerospace Engineering UC3M

Doctoral Meetings 2026

2nd and 3rd June 2026

High-order model • Adjoint sensitivities • Gradient-based optimization • Scalable workflows

Design efficient aircraft

- 1 **Clean aviation targets**
lower emissions and fuel burn
- 2 **Lighter innovative structure**
mass reduction becomes a primary driver
- 3 **Composite materials**
anisotropy, stacking and coupling effects
- 4 **Larger design spaces**
more variables, constraints and load cases
- 5 **Repeated simulations**
DOE + sensitivities + optimization loops

Where the cost appears

Not in one accurate FEM analysis, but in the repeated calls inside DOE and optimization loops.

**Repeated FEM solves + constraints →
→ computational bottleneck**

Motivation of the PhD

Move from analysis-oriented structural models to **physics-based** tool that is cheap, differentiable, robust and scalable for **repeated design optimization**.

The challenge is finding the right **balance** between **accuracy** and **optimization-readiness**.

State of the Art, Current research directions

Representative path in preliminary composite aircraft design

1 Sizing & composite optimization

Wing-box / stiffened-panel sizing; stacking, stiffeners, manufacturability

Refs: Chintapalli; Irisarri;

2 High-fidelity

CFD/FEM, aeroelastic coupling & adjoint derivatives

Refs: Kenway, Kennedy & Martins; Bombardieri;

3 Low-/medium-fidelity

beam/wing-box tools for early design-space exploration

Refs: OpenAeroStruct; Chauhan & Martins;

4 Differentiable + surrogate methods

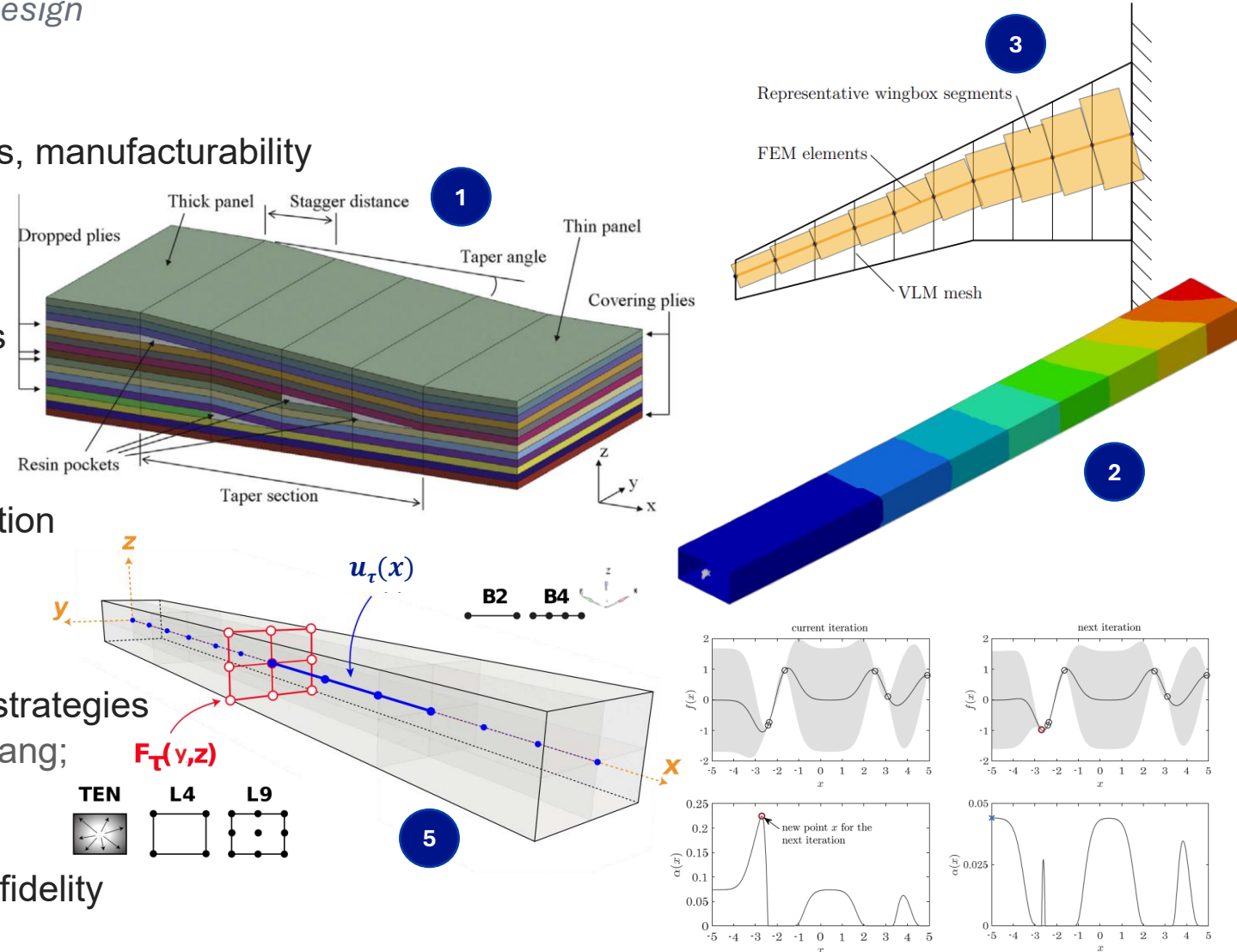
AD/adjoints, parallel FEM, GP, BO and multifidelity strategies

Refs: Kennedy & Martins; Scalia; Brevault; Do & Zhang;

5 High-order theories

Refined beam hierarchies for controllable structural fidelity

Refs: Carrera; Giunta;



State of the Art, limitations and PhD positioning

Powerful methods exist, but preliminary-design workflows remain fragmented.

Current research directions

- Sizing & composite optimization
- High-fidelity
- Low-/medium-fidelity
- Differentiable + surrogate methods
- High-order theories

Accuracy vs. cost

Gap: High-fidelity FEM is **accurate** but **expensive** for repeated early-stage loops.
Positioning: reduced structural block with **high-order beam model** fidelity.

Fast models vs. physics

Gap: Low-/medium-fidelity tools are **efficient** but can **oversimplify** composite sectional mechanics.
Positioning: **refined cross-sectional kinematics** for beam-like structures.

Large composite design spaces

Gap: **Many variables**, local constraints and load cases require scalable sensitivities.
Positioning: **AD** + **adjoint gradients** and KS **aggregation** for sizing.

Surrogate/MF/BO workflows

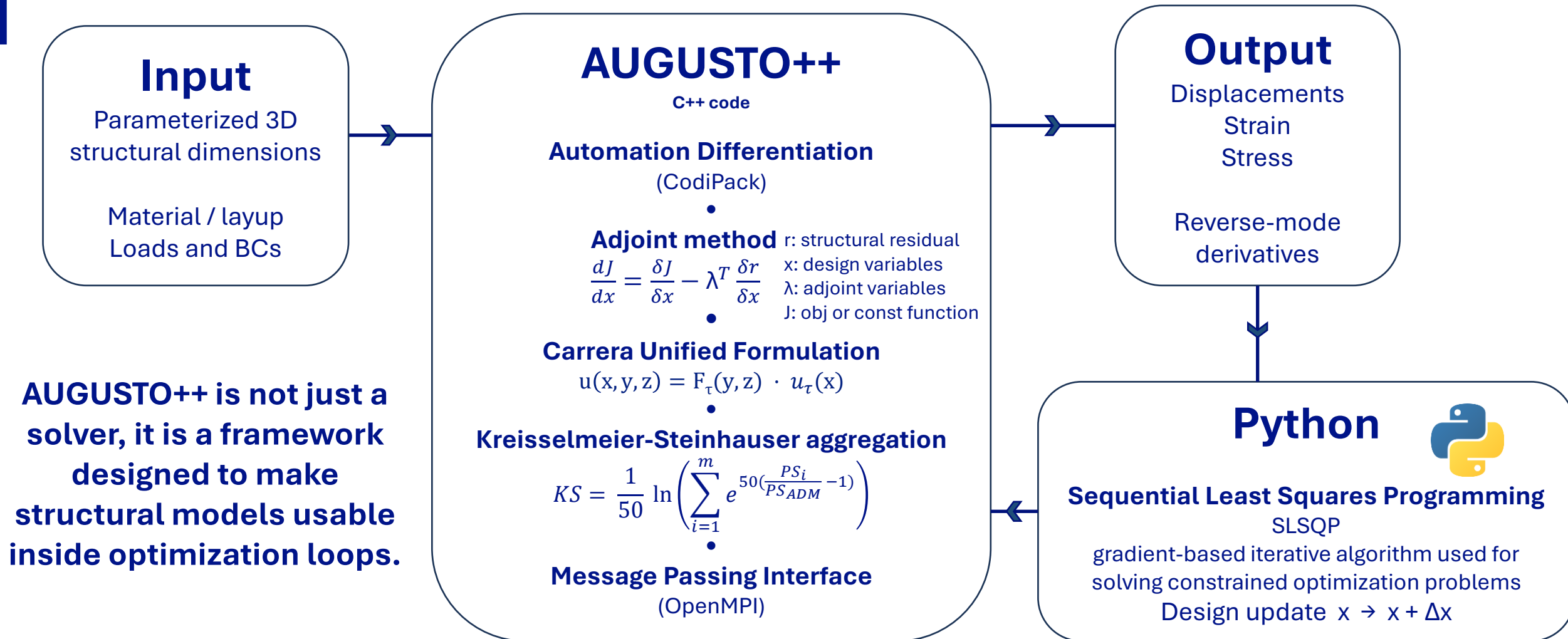
Gap: **Reliable fidelity** hierarchies and gradient information are needed.
Positioning: **High-order hierarchy** + code-**consistent sensitivities** for future GP/MF use.

Main gap:

Lack of an integrated structural block that is **simultaneously** high-order model, differentiable and optimization-ready.
AUGUSTO++ = structural reduced-order block for scalable preliminary composite design loops.

Methodology I: AUGUSTO++ Optimization Framework

Combines high-order structural modelling, exact sensitivities, optimization and scalability in one differentiable workflow.



Methodology II: CUF-based kinematics in FEM

CUF as a generator of beam structural theories via enhanced kinematics of the beam cross-sectional behavior

Model hierarchy

Cross-sectional richness is controlled by the choice expansion of $F_\tau(y, z)$.

1 Low-order theories

Euler–Bernoulli / Timoshenko-like behavior

2 Taylor Expansion models

TE1 (Timoshenko-like) → TE2 → TE3 → no limitation

3 Lagrange / layer-wise enrichment

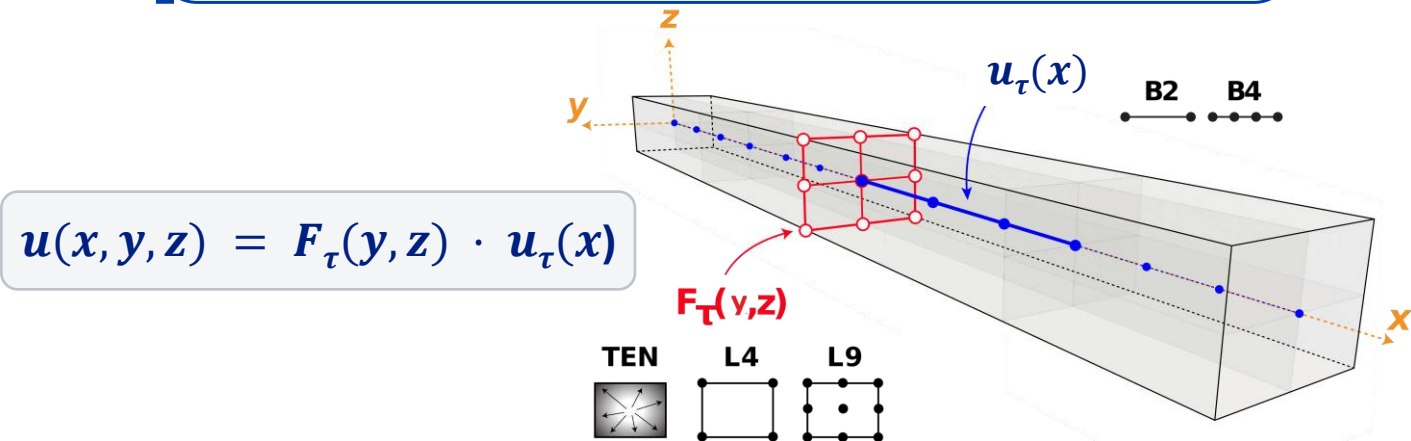
Localised effects, such as free edge effects, or a layer-wise description is aimed when dealing with composites

4 Reference shell / solid FEM

validation target, not always the design model

CUF principle

Different expansion functions and orders generate different structural theories within the same formal framework.

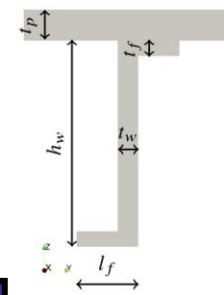
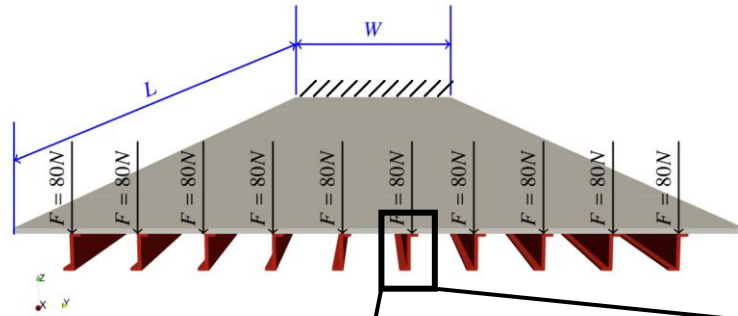


Optimization-oriented choice

Do not use the highest-order model everywhere. Select the lowest-order model that captures the design-driving response with sufficient accuracy.

Goal: tunable fidelity at reduced computational cost.

Results: validation and optimization composite structure



$L = 1620 \text{ mm}$

$W = 390 \text{ mm}$

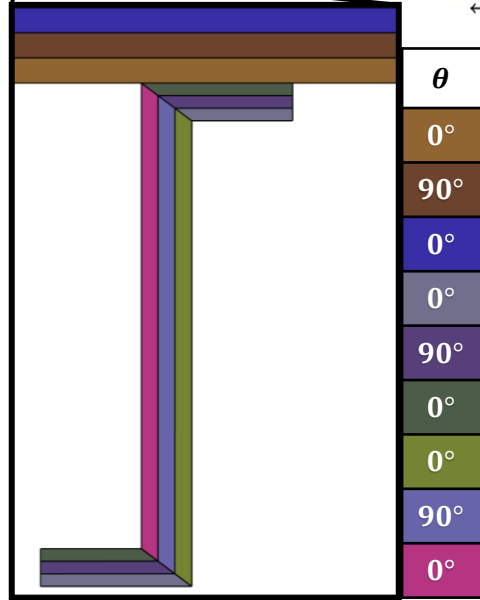
$t_p = 3 \text{ mm}$

$l_w = 6 \text{ mm}$

$h_w = 20 \text{ mm}$

$t_f = 1.5 \text{ mm}$

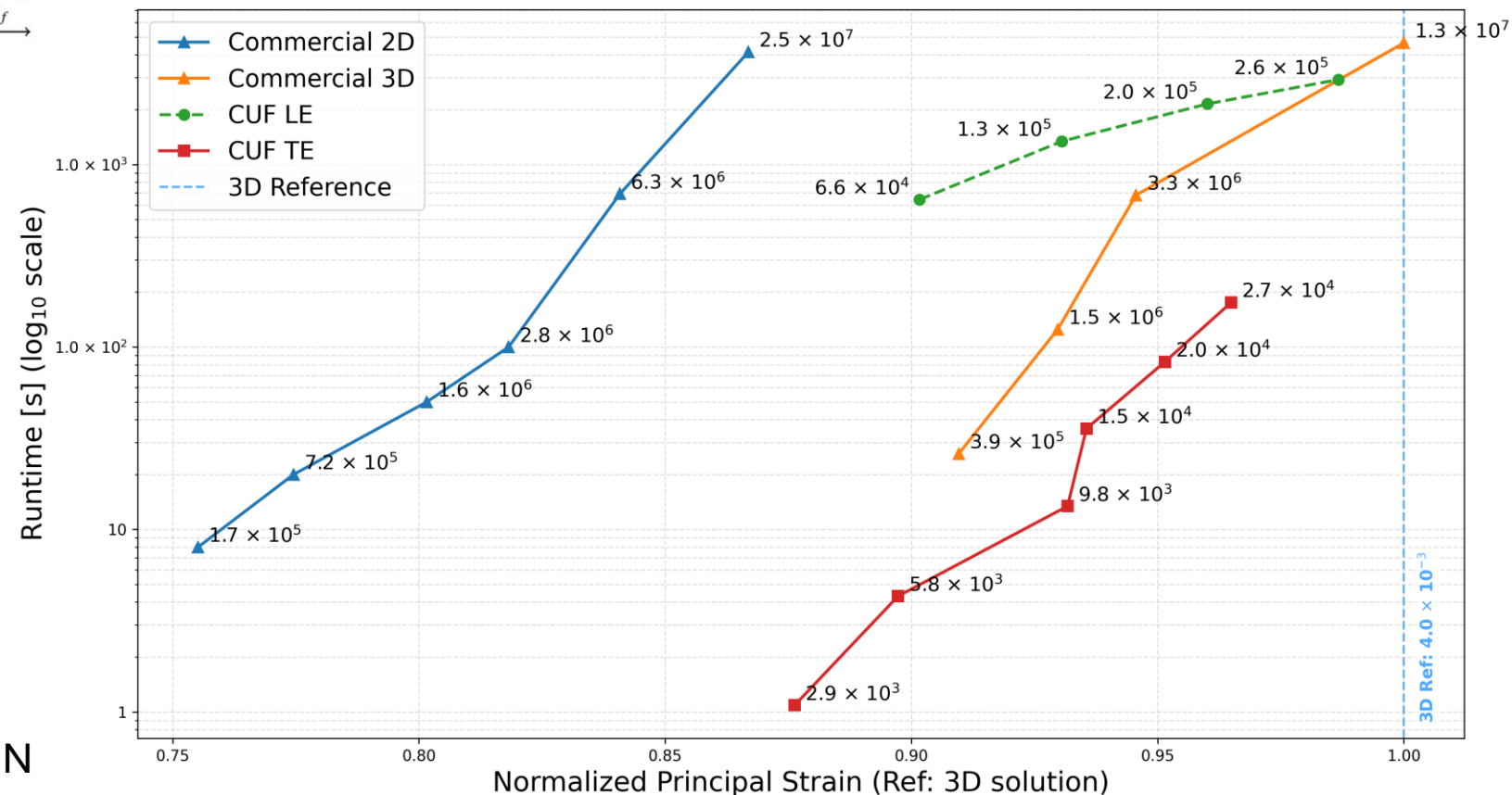
$t_w = 2 \text{ mm}$



Orthotropic
Material

E_1	$E_2 \text{ \& } E_3$	$\nu_{12} \text{ \& } \nu_{13} \text{ \& } \nu_{23}$	$G_{12} \text{ \& } G_{13} \text{ \& } G_{23}$	Density
130 GPa	10 GPa	0.25	5 GPa	1600 Kg/m ³

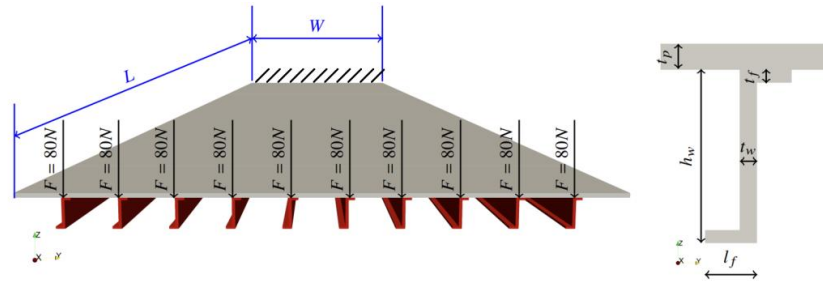
Runtime vs Normalized Principal Strain



Load & BCs:

- Clamped edge
- Free edge with 10 loads of 80 N

Results: validation and optimization composite structure



Static validation

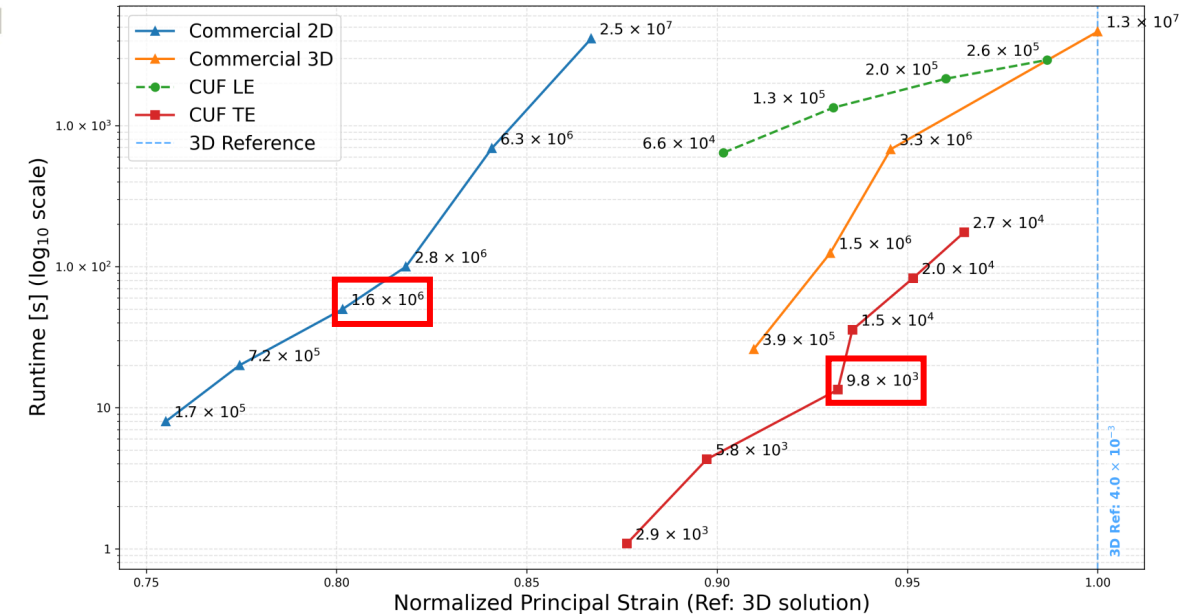
Model	Error vs 3D	DOFs	Time
3D solid	reference	1.3×10^7	4643 s
2D shell	strain $\approx -19.8\%$	1.6×10^6	50 s
CUF-TE3	strain $\approx -6.8\%$	9.8×10^3 (-99.4%)	13.4 s (x3.7)

Optimization

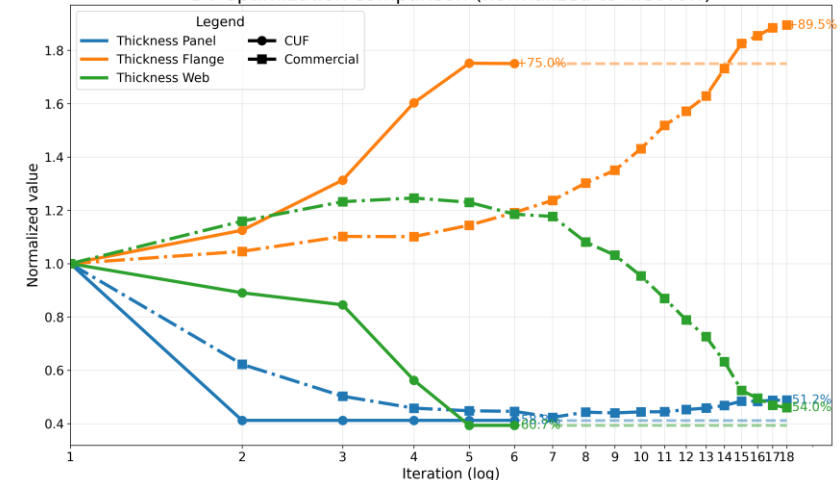
Model	Mass reduction	Iterations	Runtime
2D shell	-56.02%	18	2912 s
CUF-TE3	-64.27%	6	564 s

Proof of concept: a reduced structural model can be accurate enough and substantially cheaper inside optimization loops.

Runtime vs Normalized Principal Strain



DV optimization comparison (normalized to first row)



[12] Cardone, D., Cavallaro, R., & Cini, A. (2026). Gradient-Based Optimisation of Composite Aircraft Structures Using High-Order Beam Models. Engineering Proceedings, 133(1), 98.

1 Next conference

Composite structure:
Panel $\rightarrow$ box beam $\rightarrow$ stiffened box beam
High-order hierarchy for wing-like structures

2 Structural realism

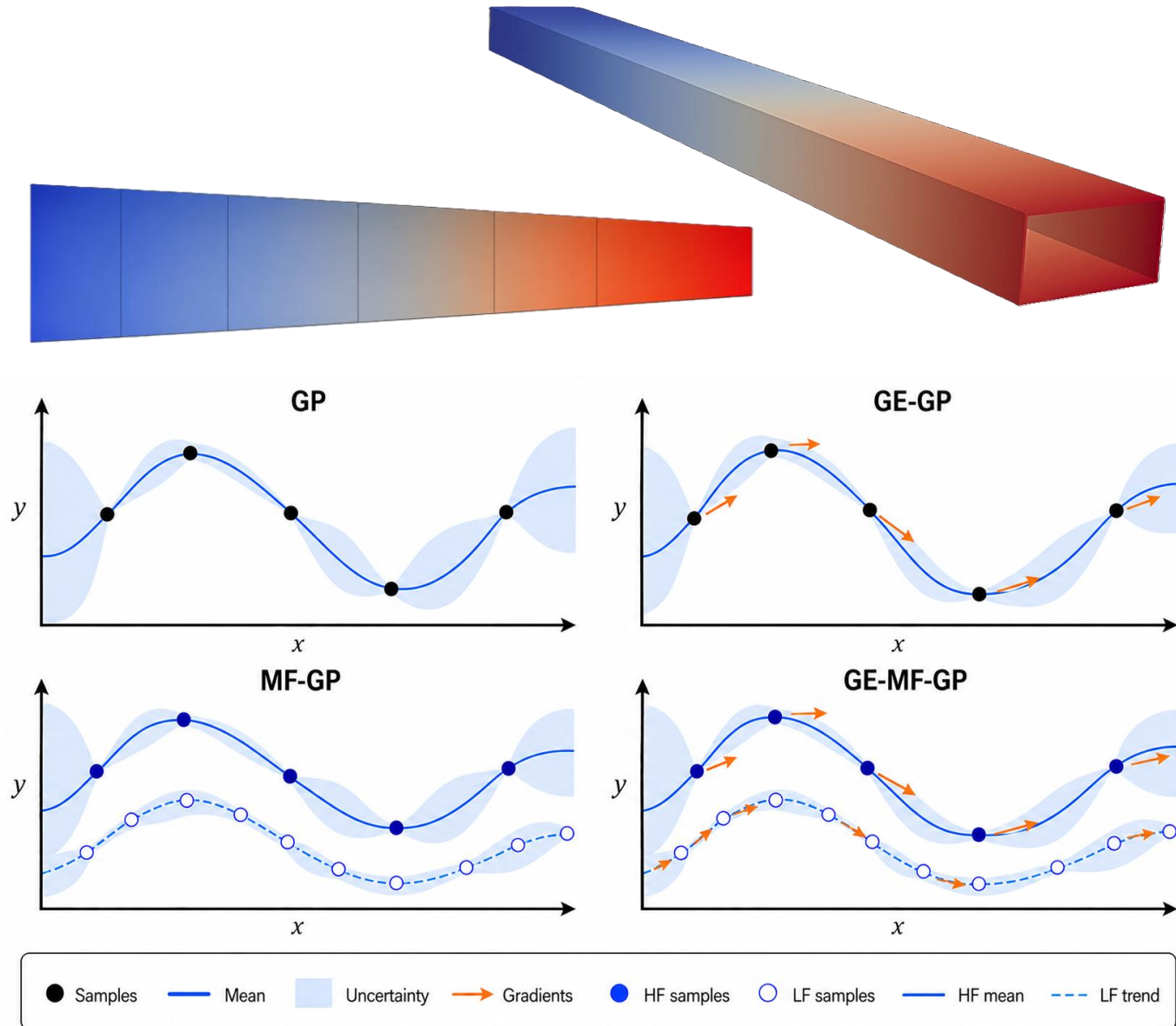
Non-prismatic / tapered composite wing-box
spanwise-varying section and stiffness

3 Surrogate-assisted design

GP, MF-GP, GE-GP and GE-MF-GP
Bayesian optimization and uncertainty

4 Long-term extension

Hybrid multi-fidelity optimization model
Static aeroelasticity FSI-oriented optimization



Scientific Dissemination

- ✓ AIAA SciTech 2025 – 08/01/2025
Application of CUF for the structural optimization of wings
DOI:10.2514/6.2025-1745
- ✓ EASN 2025 – 17/10/2025
Gradient-based optimisation of composite aircraft structures using high-order beam models
DOI:10.3390/engproc2026133098



Journal Publication

High-order + adjoint + AD framework on Lightworks Benchmark

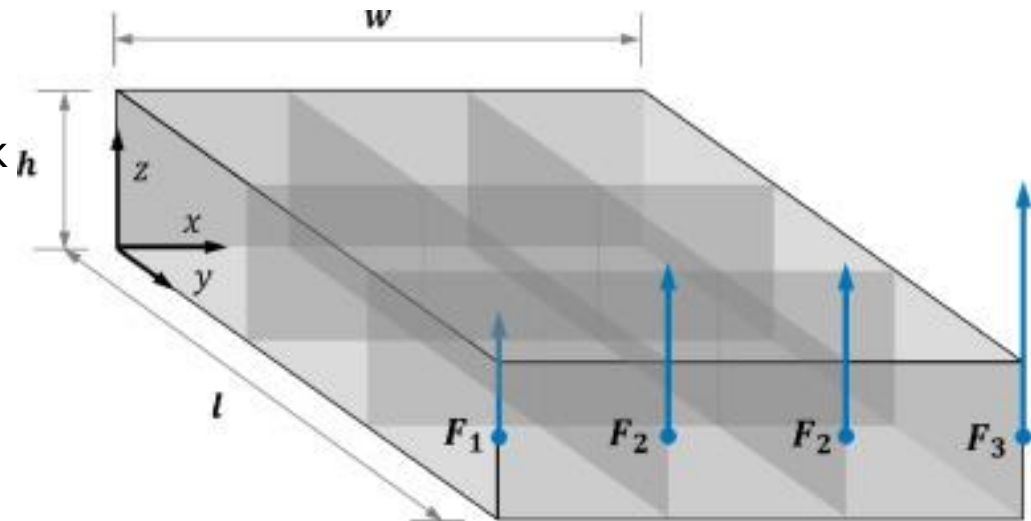
Target venues:

- Composite Structures
- Structural and Multidisciplinary Optimization
- Aerospace Science and Technology



Next Conference:

ECCOMAS: High-order hierarchy for wing-like composite structures



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Thanks!
Q&A

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