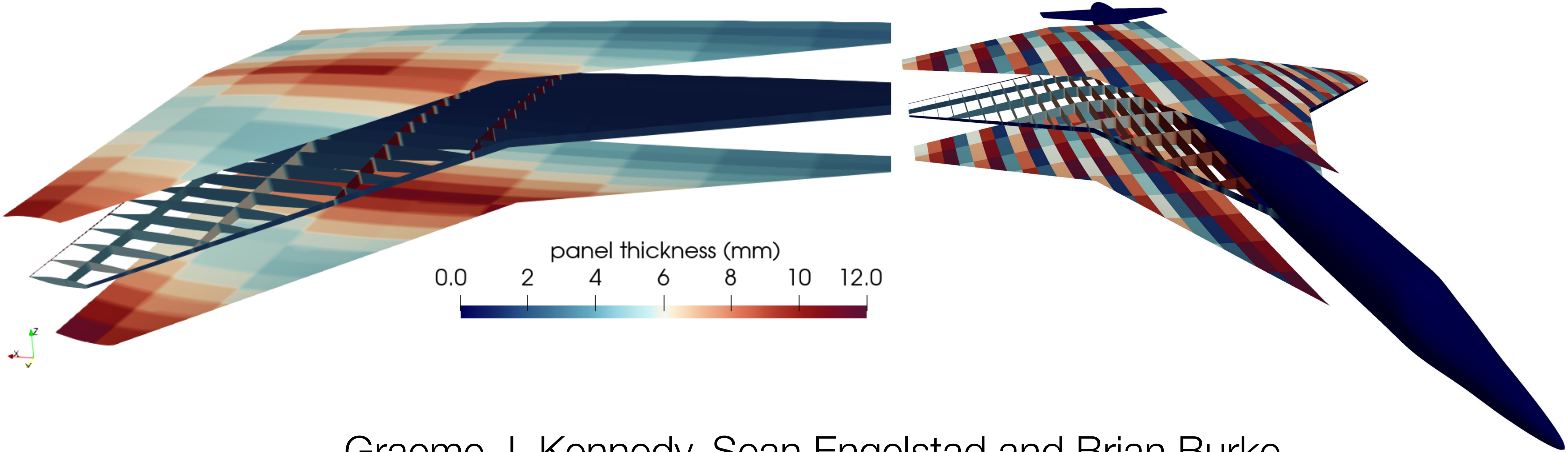
Aerothermoelastic Optimization using FUNtoFEM and ESP/CAPS



Graeme J. Kennedy, Sean Engelstad and Brian Burke

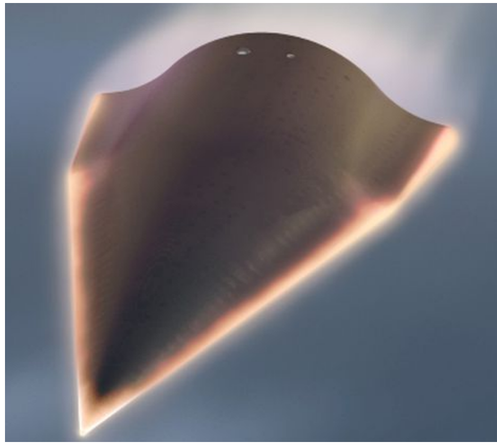
Structural and Multidisciplinary Optimization Group

Georgia Institute of Technology

Thermal design is critical for advanced vehicles

In this project:

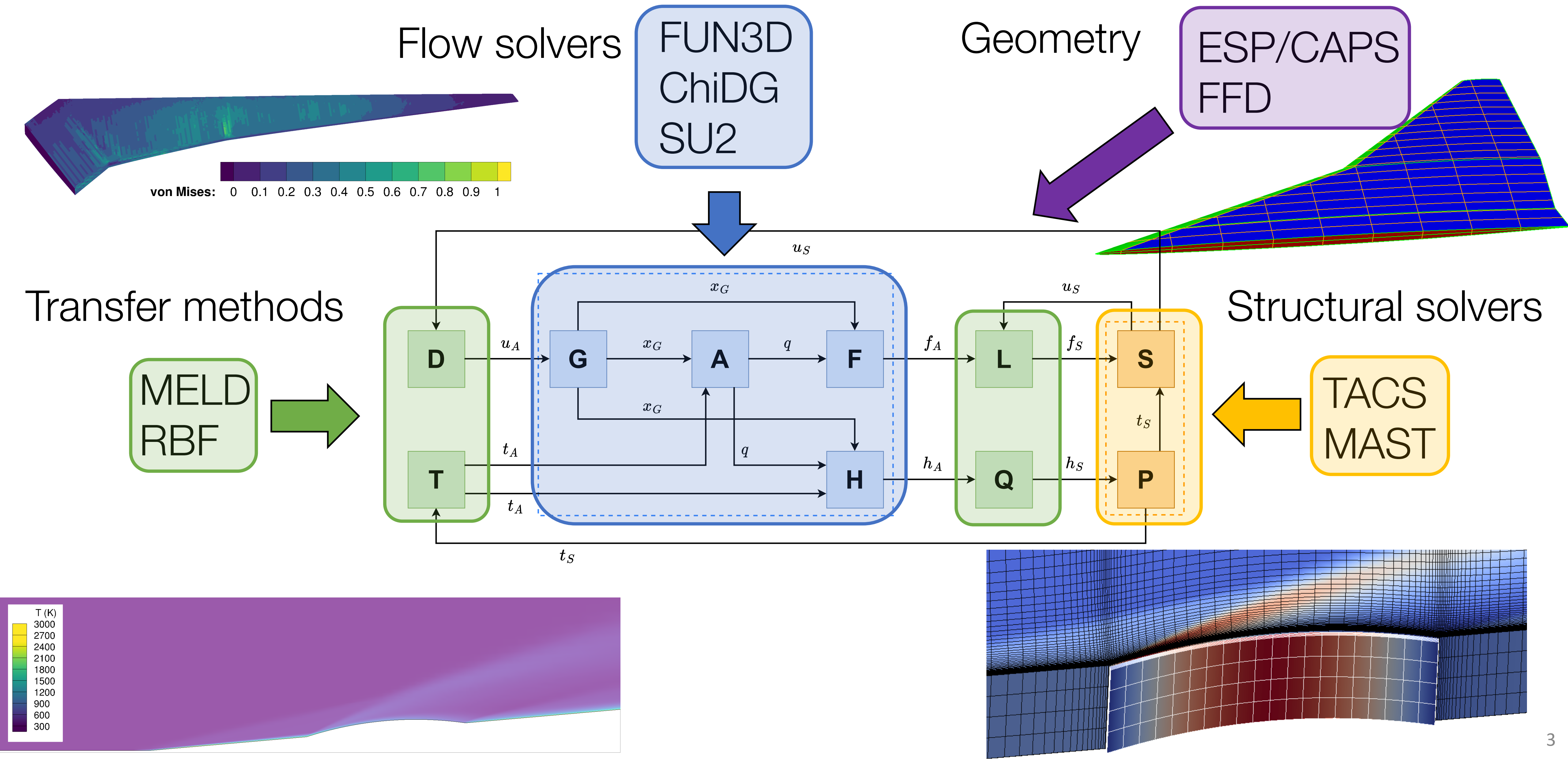
- Aerodynamic heating due to high-speed flow
- Hot exhaust-wash structures



Other heat sources/physics:

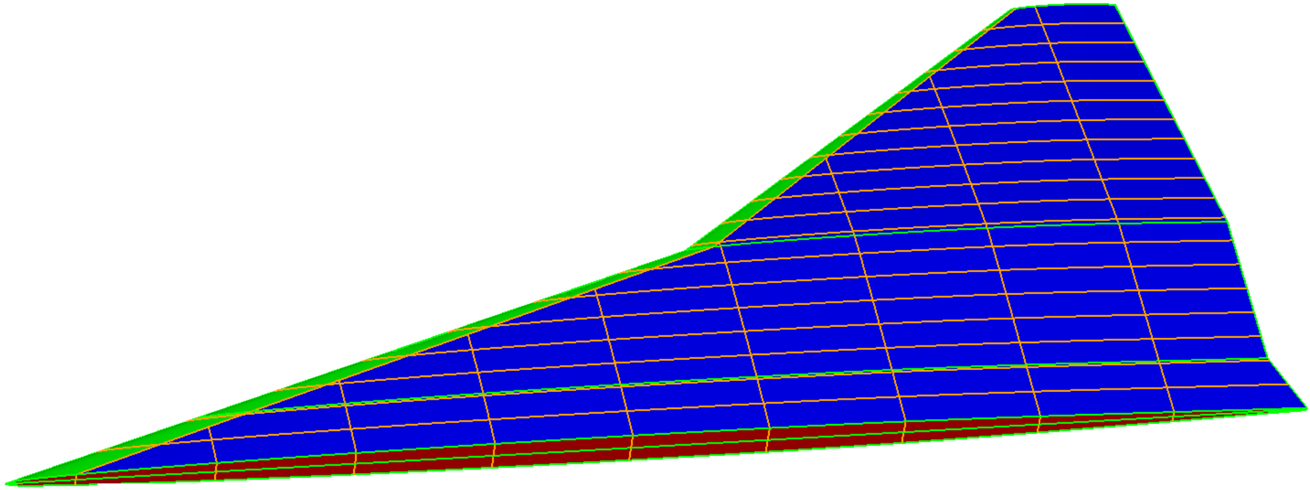
- Heat generated internally by subsystems
- Radiative heating

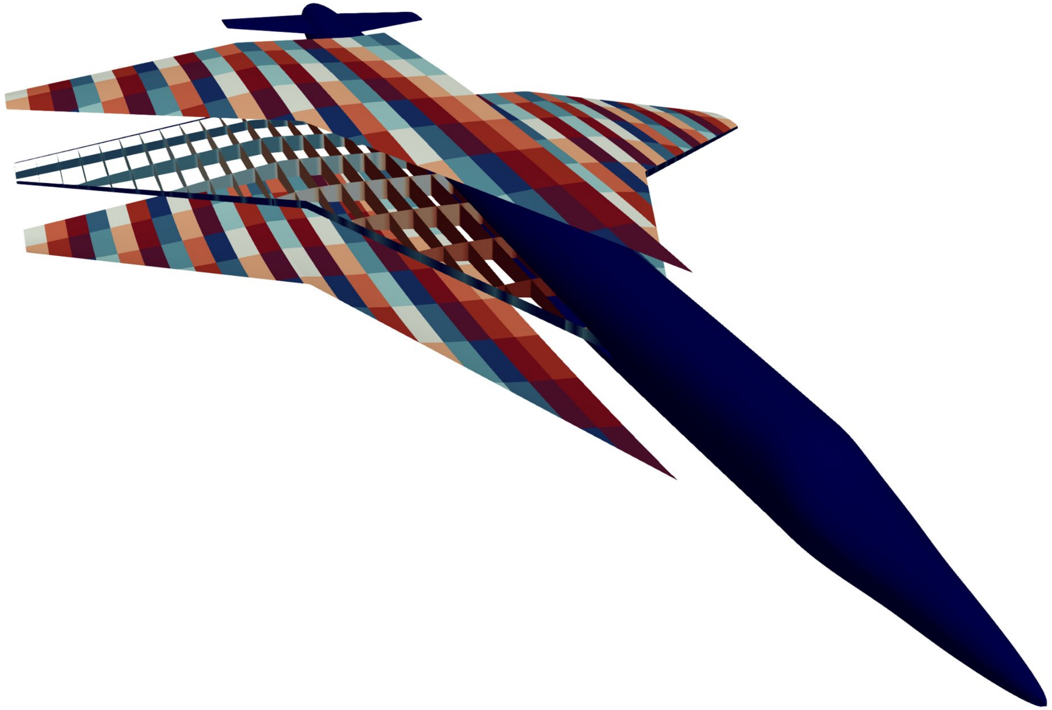
FUNtoFEM: High-fidelity analysis with derivatives



ESP/CAPS integration for geometry parametrization

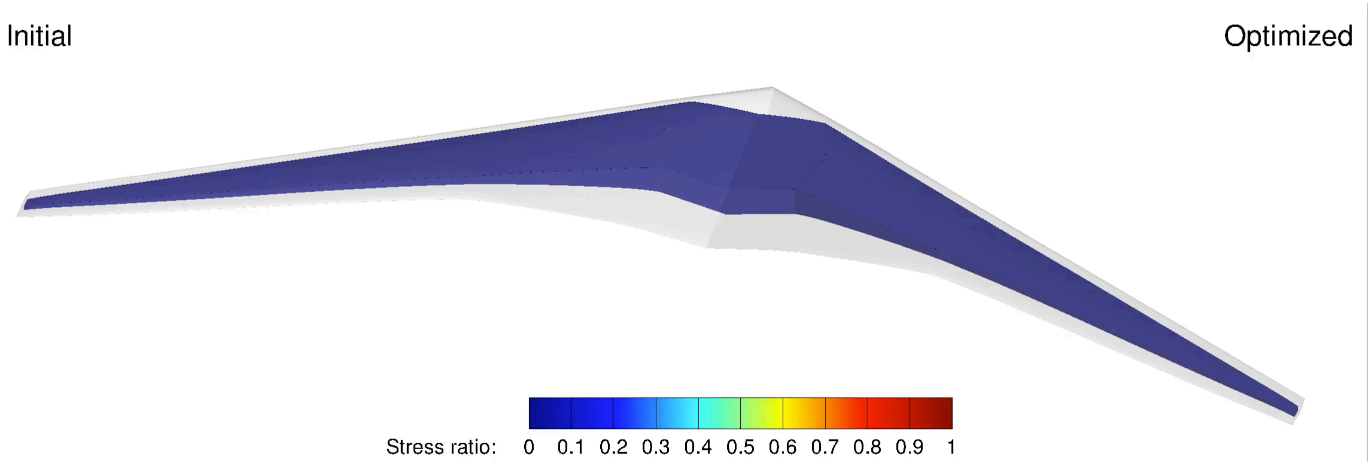
- Free-form deformation (FFD)
  - Not fully compatible with CAD
  - Less control over geometry
- ESP allows us to rapidly build parametrized geometries
- ESP/CAPS provides derivatives with respect to parametrized geometry
- GT tools that we've built to leverage ESP/CAPS: caps2tacs, caps2fun
  - Help facilitate setting up and solving design problems

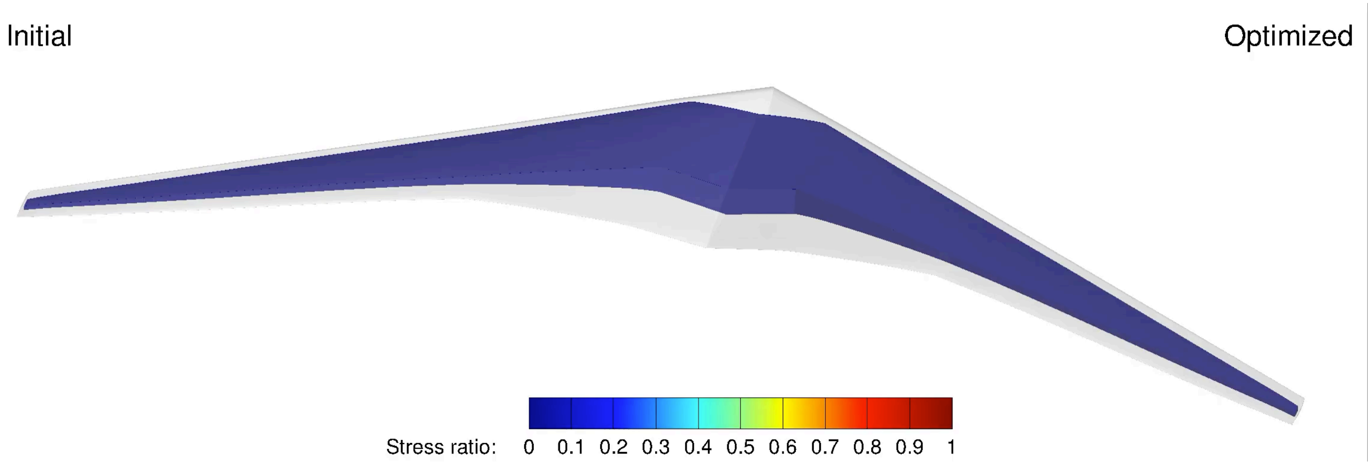


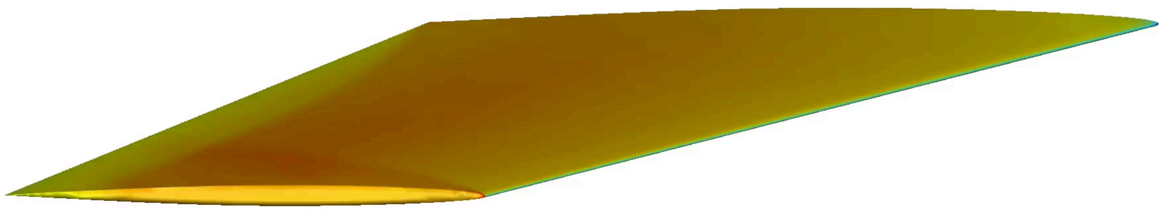


FUNtoFEM for time-dependent problems

- Some design problems require time-dependent physics
- Wing design subject to a gust encounter
- Flutter/LCO identification
- FUNtoFEM can compute the gradient with time-dependent analysis







FUNtoFEM: Adjoint and ESP/CAPS Integration

- Driver solves the adjoint equations

$$\begin{bmatrix} \frac{\partial \mathbf{G}}{\partial \mathbf{x}_G}^T & \frac{\partial \mathbf{A}}{\partial \mathbf{x}_G}^T & \frac{\partial \mathbf{F}}{\partial \mathbf{x}_G}^T & 0 & 0 & 0 \\ 0 & \frac{\partial \mathbf{A}}{\partial \mathbf{q}}^T & \frac{\partial \mathbf{F}}{\partial \mathbf{q}}^T & 0 & 0 & 0 \\ 0 & 0 & \frac{\partial \mathbf{F}}{\partial \mathbf{f}_A}^T & \frac{\partial \mathbf{L}}{\partial \mathbf{f}_A}^T & 0 & 0 \\ 0 & 0 & 0 & \frac{\partial \mathbf{L}}{\partial \mathbf{f}_S}^T & \frac{\partial \mathbf{S}}{\partial \mathbf{f}_S}^T & 0 \\ 0 & 0 & 0 & \frac{\partial \mathbf{L}}{\partial \mathbf{u}_S}^T & \frac{\partial \mathbf{S}}{\partial \mathbf{u}_S}^T & \frac{\partial \mathbf{D}}{\partial \mathbf{u}_S}^T \\ \frac{\partial \mathbf{G}}{\partial \mathbf{u}_A}^T & 0 & 0 & 0 & 0 & \frac{\partial \mathbf{D}}{\partial \mathbf{u}_A}^T \end{bmatrix} \begin{bmatrix} \psi_G \\ \psi_A \\ \psi_F \\ \psi_L \\ \psi_S \\ \psi_D \end{bmatrix} = - \begin{bmatrix} \frac{\partial f}{\partial \mathbf{x}_G}^T \\ \frac{\partial f}{\partial \mathbf{q}}^T \\ \frac{\partial f}{\partial \mathbf{f}_A}^T \\ \frac{\partial f}{\partial \mathbf{f}_S}^T \\ \frac{\partial f}{\partial \mathbf{u}_S}^T \\ \frac{\partial f}{\partial \mathbf{u}_A}^T \end{bmatrix}$$

- Driver computes the derivatives with respect to disciplinary coordinates

Structures

$$\frac{\mathrm{d}f}{\mathrm{d}\mathbf{x}_S} = \frac{\partial f}{\partial \mathbf{x}_S} + \psi_S^T \frac{\partial \mathbf{S}}{\partial \mathbf{x}_S} + \psi_L^T \frac{\partial \mathbf{L}}{\partial \mathbf{x}_S} + \psi_D^T \frac{\partial \mathbf{D}}{\partial \mathbf{x}_S}$$

Aerodynamics

$$\frac{\mathrm{d}f}{\mathrm{d}\mathbf{x}_{A0}} = \frac{\partial f}{\partial \mathbf{x}_{A0}} + \psi_G^T \mathbf{I}_{A0} + \psi_L^T \frac{\partial \mathbf{L}}{\partial \mathbf{x}_{A0}} + \psi_D^T \frac{\partial \mathbf{D}}{\partial \mathbf{x}_{A0}}$$

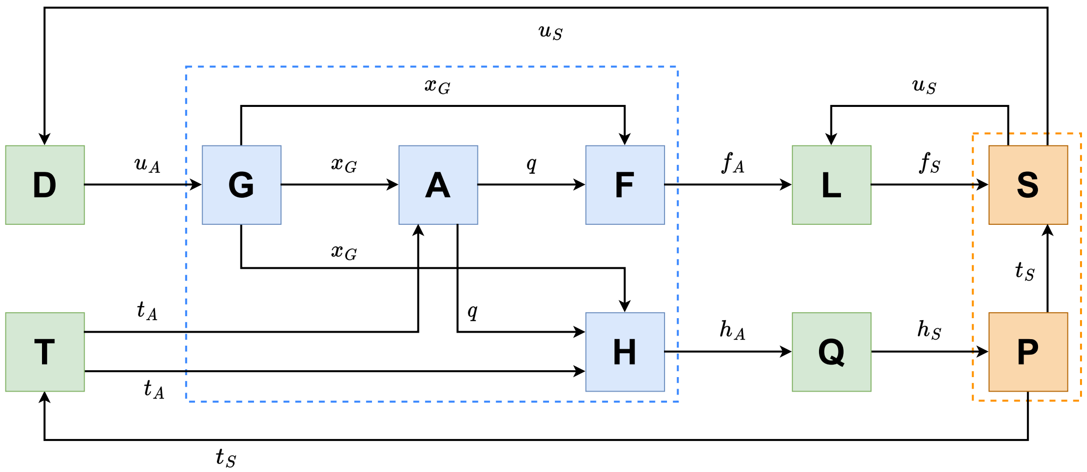
- ESP/CAPS computes the total derivatives using the coordinate derivatives

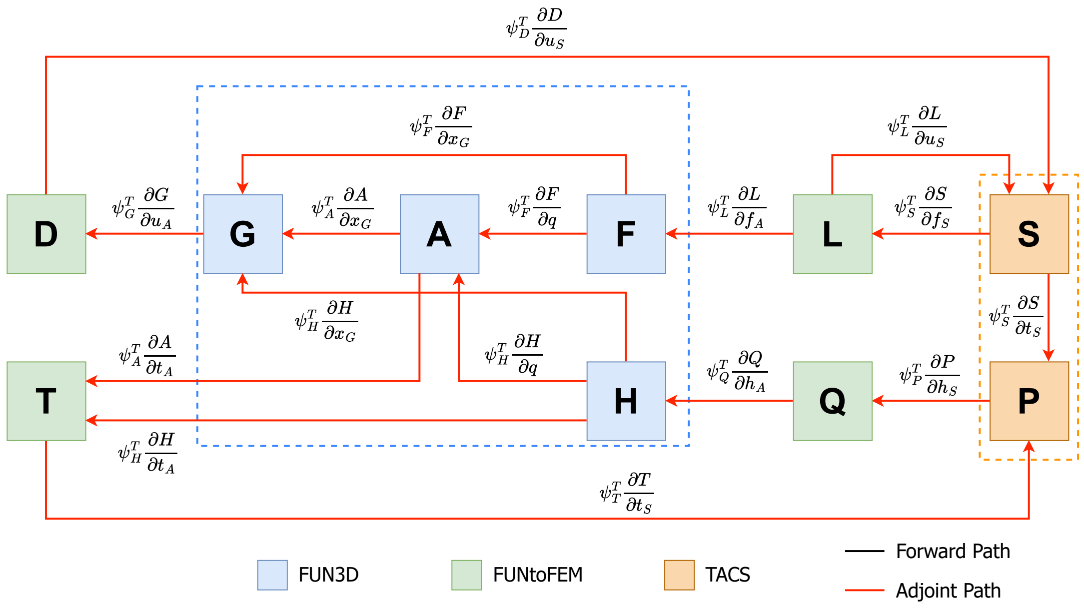
$$\nabla_x f = \frac{\mathrm{d}f}{\mathrm{d}\mathbf{x}_{A0}} \frac{\partial \mathbf{x}_{A0}}{\partial \mathbf{x}} + \frac{\mathrm{d}f}{\mathrm{d}\mathbf{x}_S} \frac{\partial \mathbf{x}_S}{\partial \mathbf{x}}$$

Reconfigurable framework for high-fidelity MDO

- FUNtoFEM runs steady-state or time-accurate aerothermal, aeroelastic and aerothermoelastic analysis
- Different CFD/FEM implementations
- Modular transfer operations
- Is the adjoint correct for all configurations?

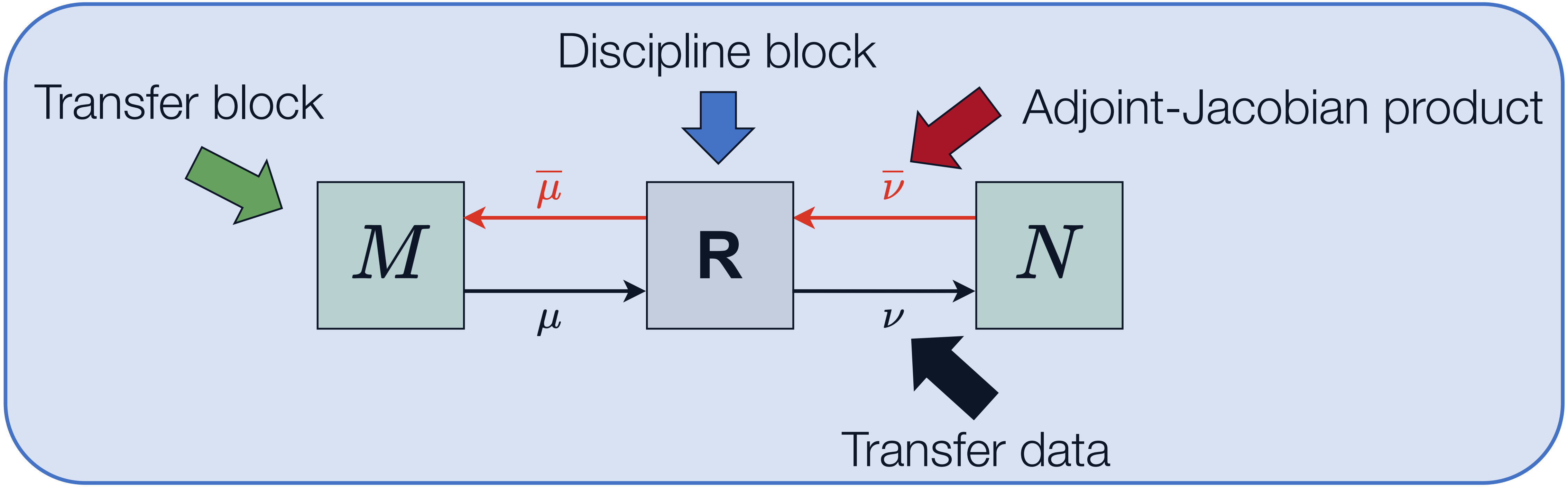
$$
\begin{bmatrix}
\frac{\partial \mathbf{A}}{\partial q}^T & \frac{\partial \mathbf{F}}{\partial q}^T & 0 & \frac{\partial \mathbf{H}}{\partial q}^T & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{\partial \mathbf{F}}{\partial f_A}^T & 0 & 0 & 0 & \frac{\partial \mathbf{L}}{\partial f_A}^T & 0 & 0 & 0 & 0 \\
\frac{\partial \mathbf{A}}{\partial x_G}^T & \frac{\partial \mathbf{F}}{\partial x_G}^T & \frac{\partial \mathbf{G}}{\partial x_G}^T & \frac{\partial \mathbf{H}}{\partial x_G}^T & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{\partial \mathbf{H}}{\partial h_A}^T & 0 & 0 & \frac{\partial \mathbf{Q}}{\partial h_A}^T & 0 & 0 & 0 \\
0 & 0 & \frac{\partial \mathbf{G}}{\partial u_A}^T & 0 & \frac{\partial \mathbf{D}}{\partial u_A}^T & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{\partial \mathbf{L}}{\partial f_S}^T & 0 & 0 & \frac{\partial \mathbf{S}}{\partial f_S}^T & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{\partial \mathbf{Q}}{\partial h_S}^T & 0 & 0 & \frac{\partial \mathbf{P}}{\partial h_S}^T \\
\frac{\partial \mathbf{A}}{\partial t_A}^T & 0 & 0 & \frac{\partial \mathbf{H}}{\partial t_A}^T & 0 & 0 & 0 & \frac{\partial \mathbf{T}}{\partial t_A}^T & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{\partial \mathbf{D}}{\partial u_S}^T & \frac{\partial \mathbf{L}}{\partial u_S}^T & 0 & 0 & \frac{\partial \mathbf{S}}{\partial u_S}^T & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{\partial \mathbf{T}}{\partial t_S}^T & \frac{\partial \mathbf{S}}{\partial t_S}^T & \frac{\partial \mathbf{P}}{\partial t_S}^T
\end{bmatrix}
\begin{bmatrix}
\psi_{\mathbf{A}} \\ \psi_{\mathbf{F}} \\ \psi_{\mathbf{G}} \\ \psi_{\mathbf{H}} \\ \psi_{\mathbf{D}} \\ \psi_{\mathbf{L}} \\ \psi_{\mathbf{Q}} \\ \psi_{\mathbf{T}} \\ \psi_{\mathbf{S}} \\ \psi_{\mathbf{P}}
\end{bmatrix}
= -
\begin{bmatrix}
\frac{\partial f}{\partial q}^T \\ \frac{\partial f}{\partial f_A}^T \\ \frac{\partial f}{\partial x_G}^T \\ \frac{\partial f}{\partial h_A}^T \\ \frac{\partial f}{\partial u_A}^T \\ \frac{\partial f}{\partial f_S}^T \\ \frac{\partial f}{\partial h_S}^T \\ \frac{\partial f}{\partial t_A}^T \\ \frac{\partial f}{\partial u_S}^T \\ \frac{\partial f}{\partial t_S}^T
\end{bmatrix}
$$





Modular discipline-level consistency checks

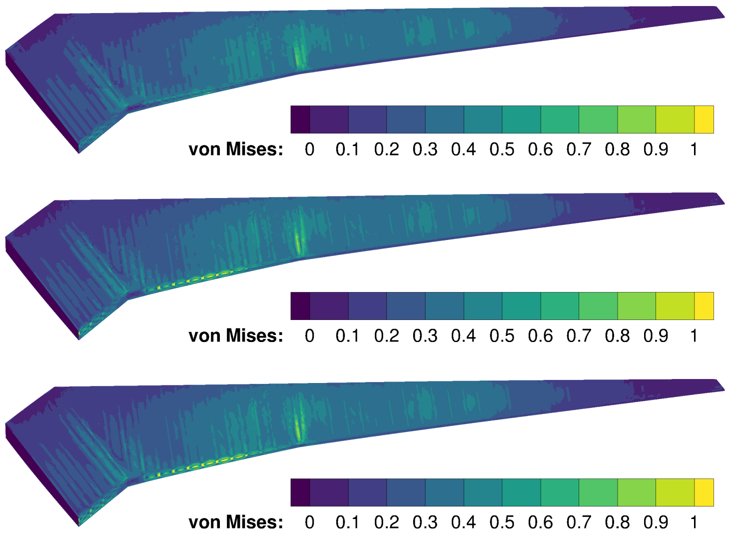
- Adjoint implementations are fragile to forward analysis changes
- Need effective tests to isolate errors within the coupled system
- FUNtoFEM uses a building block approach
  - API enables discipline-level verification of consistency between the forward and adjoint implementation



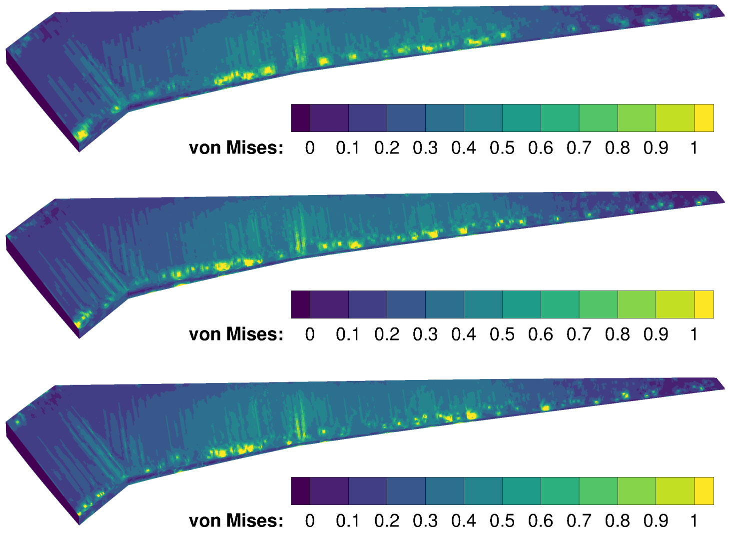
Modular transfer between disciplines

- FUNtoFEM defines interfaces for load/displacement and heat flux/temperature transfer
- Verification of derivatives for each transfer scheme to ensure consistency with the API

MELD transfer



Sub-sampled RBF



Integration test: gradient verification against complex-step

- Accuracy of derivatives with laminar and turbulent versions of FUN3D
- Gradient accuracy between 11 to 15 digits of accuracy compared to complex-step

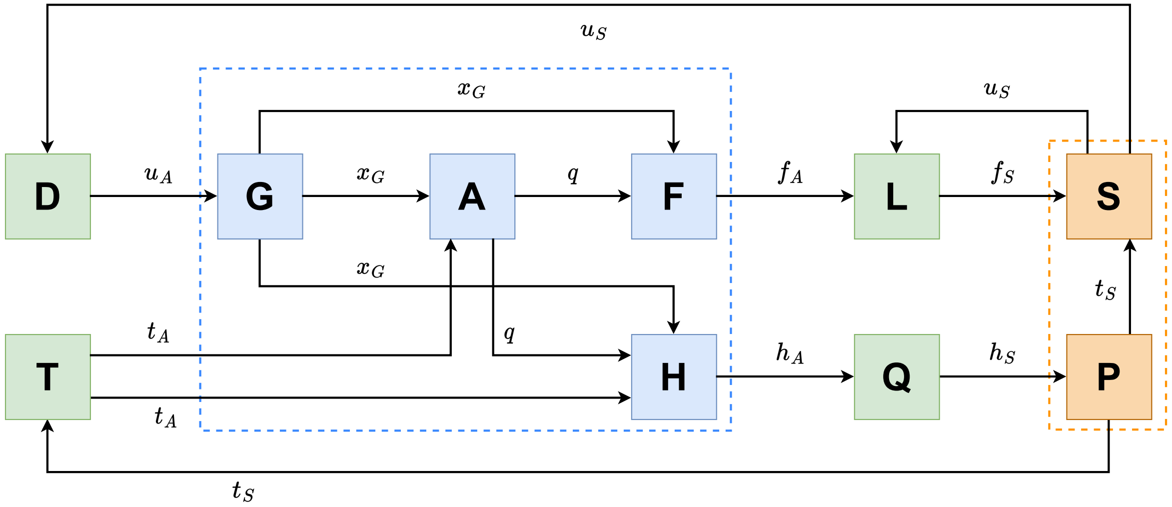


Table 3: Results from turbulent mini flat plate unit tests, with angle-of-attack design variable.

Aerothermoelastic (ATE)	Complex Step	Adjoint	Relative Error
$\partial c_{KS}/\partial\alpha$	0.000**120159932339**295229	0.000**120159932339**131483	-1.36**e-11**
$\partial C_L/\partial\alpha$	0.0**11922994232933**34	0.0**11922994232933**4032	5.81**e-14**
$\partial C_D/\partial\alpha$	0.00**620621438662**0087	0.00**620621438662**0354	4.29**e-14**
Aeroelastic (AE)	**Complex Step**	**Adjoint**	**Relative Error**
$\partial c_{KS}/\partial\alpha$	0.000**12943480095**484495	0.000**12943480095**31194	-1.33**e-11**
$\partial C_L/\partial\alpha$	0.0**1196592083591**8586	0.0**1196592083591**9373	6.58**e-14**
$\partial C_D/\partial\alpha$	0.00**7104645494166**799	0.00**7104645494167**113	4.42**e-14**
Aerothermal (AT)	**Complex Step**	**Adjoint**	**Relative Error**
$\partial c_{KS}/\partial\alpha$	**7.889391879260**282e-08	**7.889391879260**084e-08	-2.52**e-14**
$\partial C_L/\partial\alpha$	0.0**11947404608894**752	0.0**11947404608894**733	-1.60**e-15**
$\partial C_D/\partial\alpha$	0.00**6280552965314**82	0.00**6280552965314**813	-1.10**e-15**

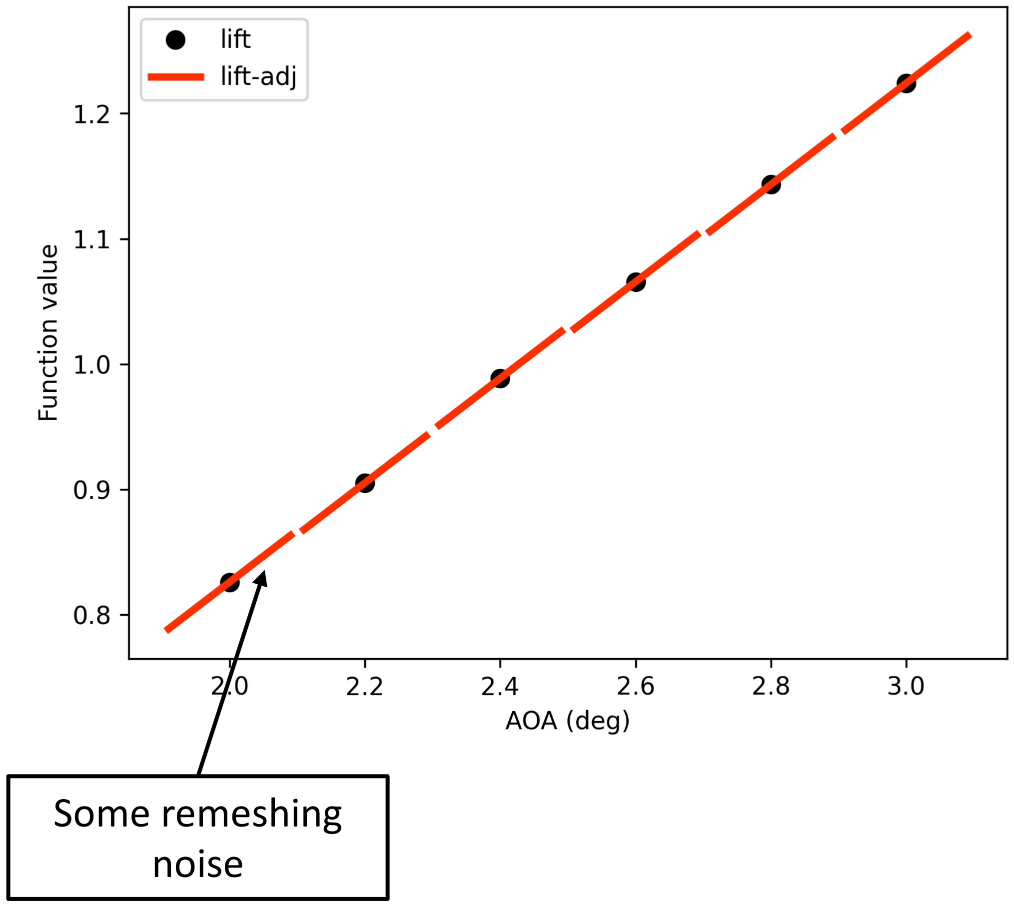
Table 4: Results from turbulent mini flat plate unit tests, with plate thickness design variable.

Aerothermoelastic (ATE)	Complex Step	Adjoint	Relative Error
$\partial c_{KS}/\partial\tau$	-0.0**81758171 2**6063319	-0.0**817581712**5879477	-2.25**e-11**
$\partial C_L/\partial\tau$	0.0**52759825737**342586	0.0**52759825736**49715	-1.60**e-11**
$\partial C_D/\partial\tau$	0.00**9327372488**400239	0.00**9327372488**205454	-2.09**e-11**
Aeroelastic (AE)	**Complex Step**	**Adjoint**	**Relative Error**
$\partial c_{KS}/\partial\tau$	-0.0**98349488**60025478	-0.0**98349488**59809094	-2.20**e-11**
$\partial C_L/\partial\tau$	0.0**6692342890**931798	0.0**6692342890**825743	-1.58**e-11**
$\partial C_D/\partial\tau$	0.0**1371727851 5**98814	0.0**13717278515**713624	-2.00**e-11**
Aerothermal (AT)	**Complex Step**	**Adjoint**	**Relative Error**
$\partial c_{KS}/\partial\tau$	**-2.96195257761 4**158e-05	**-2.961952577614**4264e-05	9.06**e-14**
$\partial C_L/\partial\tau$	0.000**387405259179888**38	0.000**387405259179888**06	-8.26**-15**
$\partial C_D/\partial\tau$	**3.389361572712 5**504e-05	**3.3893615727125**084e-05	-1.24**e-14**

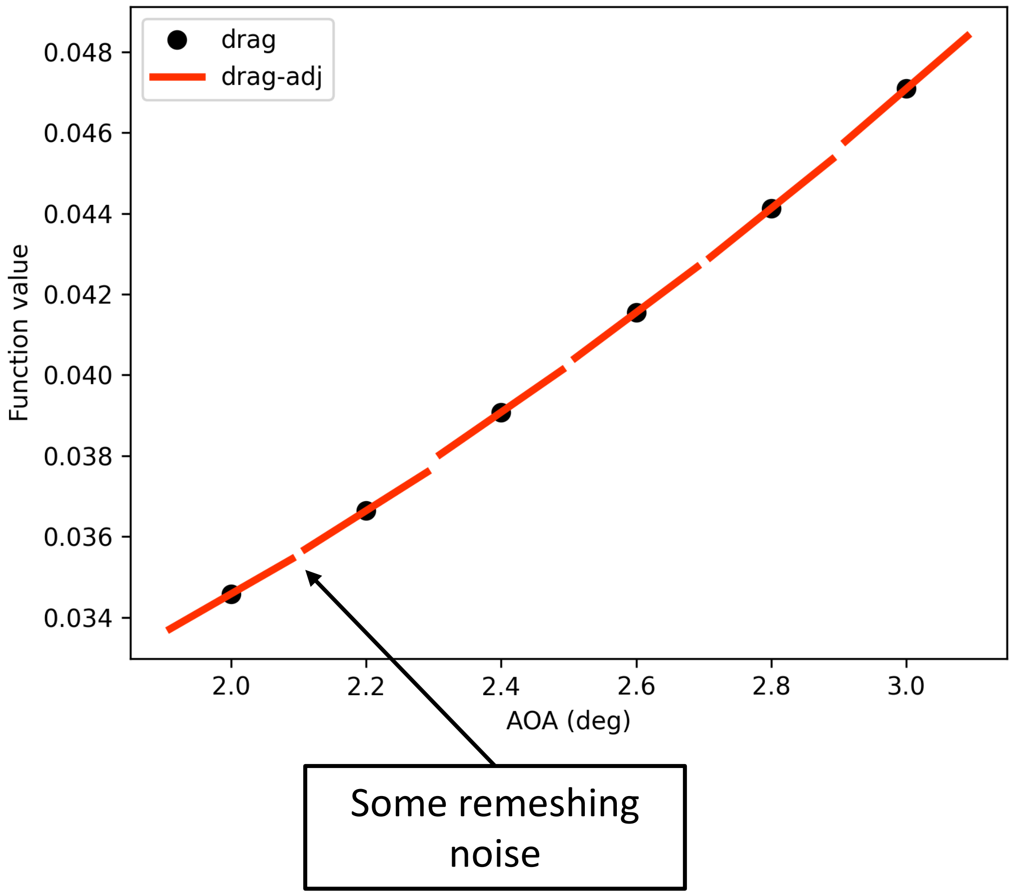
Remeshing vs mesh deformation derivatives

- ESP/CAPS offers capability to remesh at each design point – can this be used for optimization?

Lift derivative with remeshing

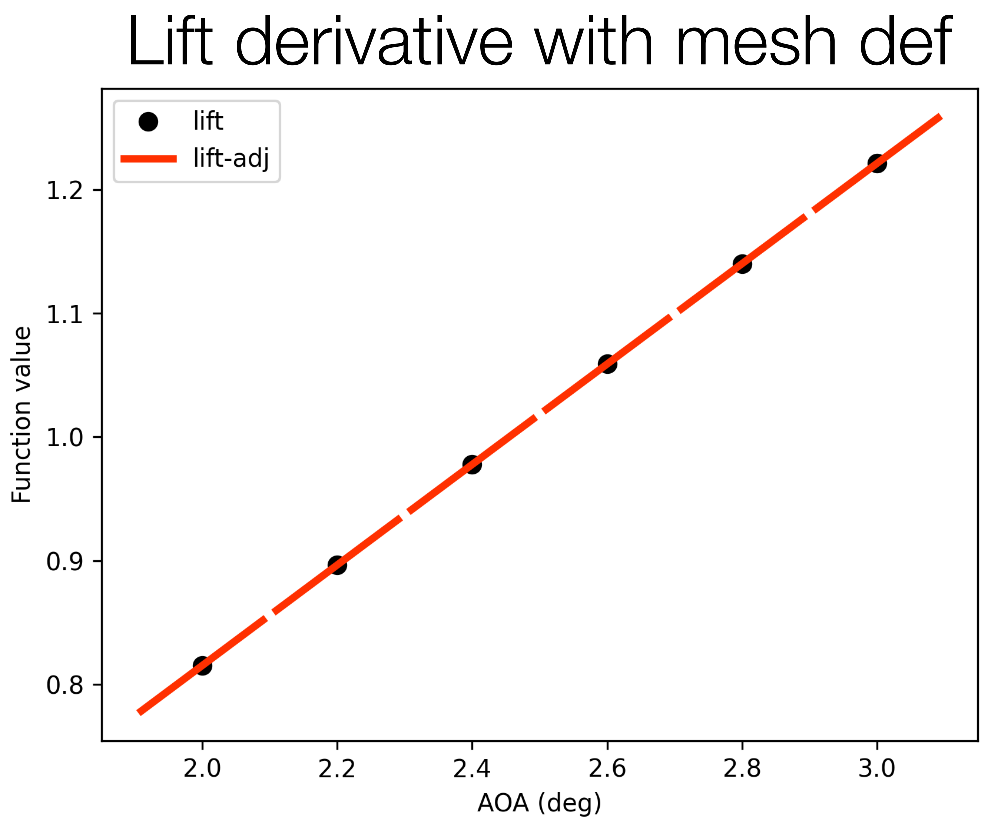


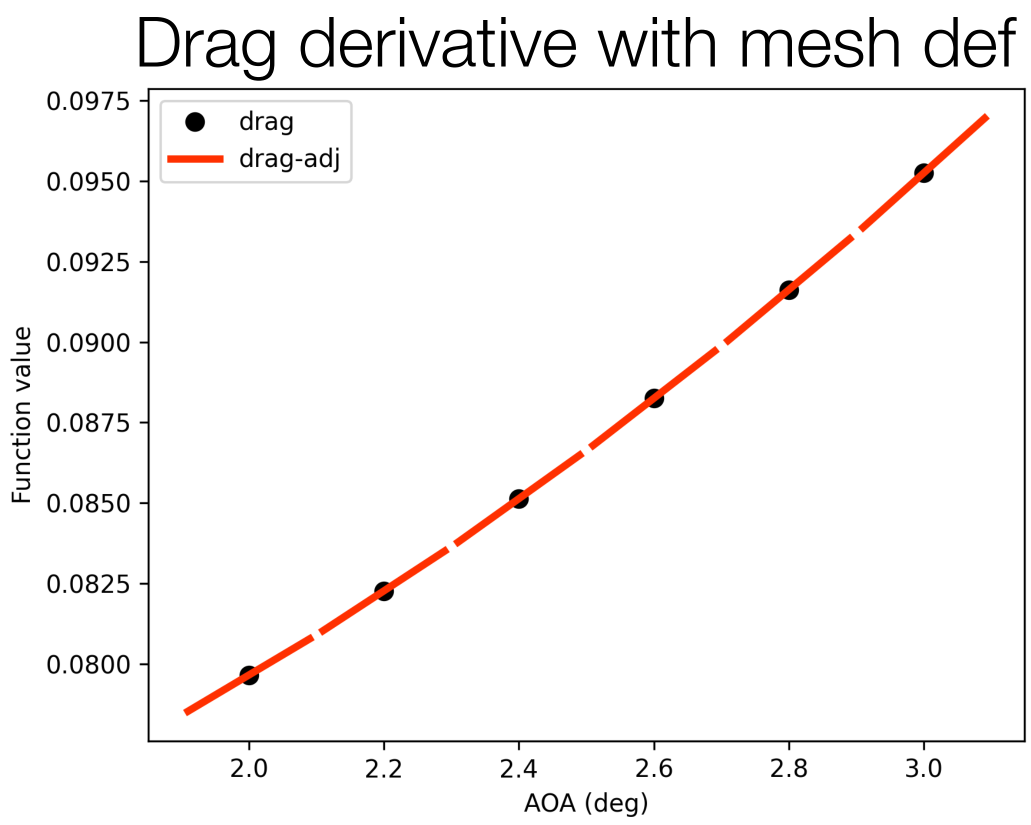
Drag derivative with remeshing



Remeshing vs mesh deformation derivatives

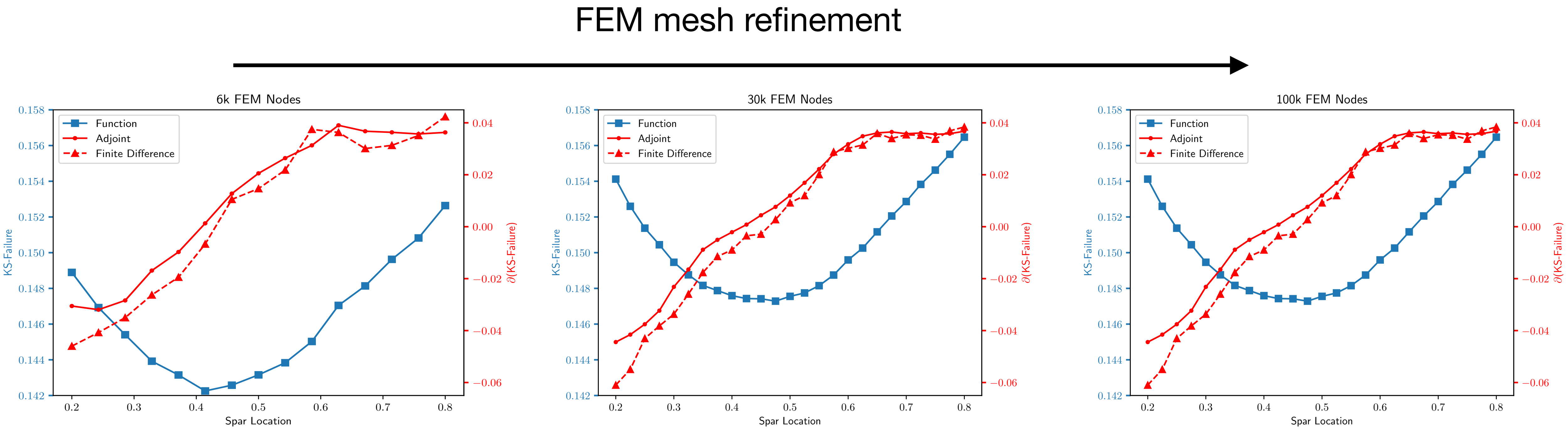
- With mesh deformation: no noise; consistent function and derivative
- However, mesh deformation method must be robust to design changes





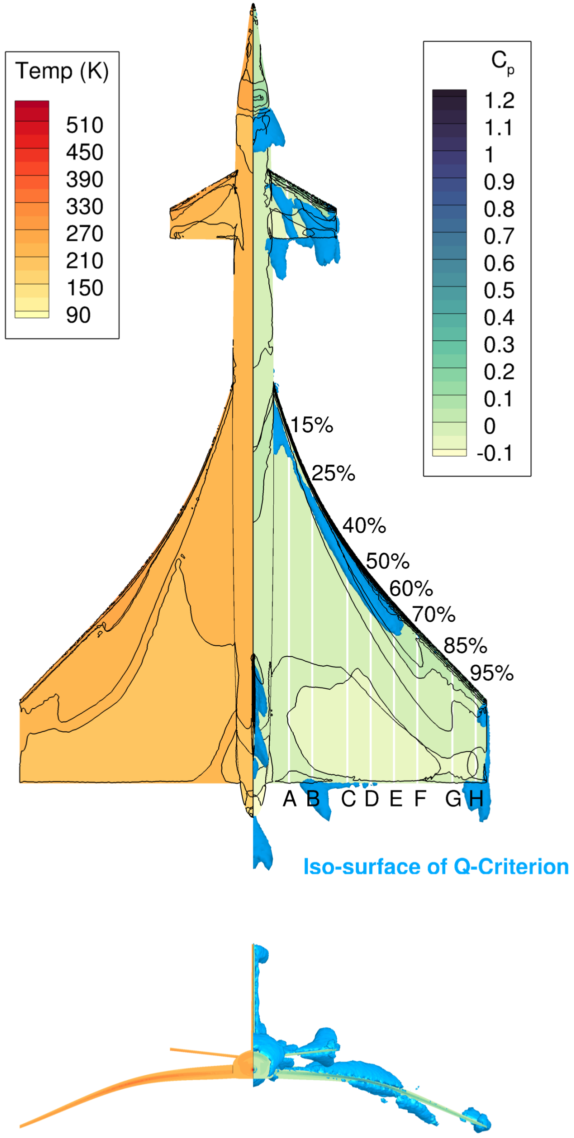
Global view of mesh def. vs remeshing

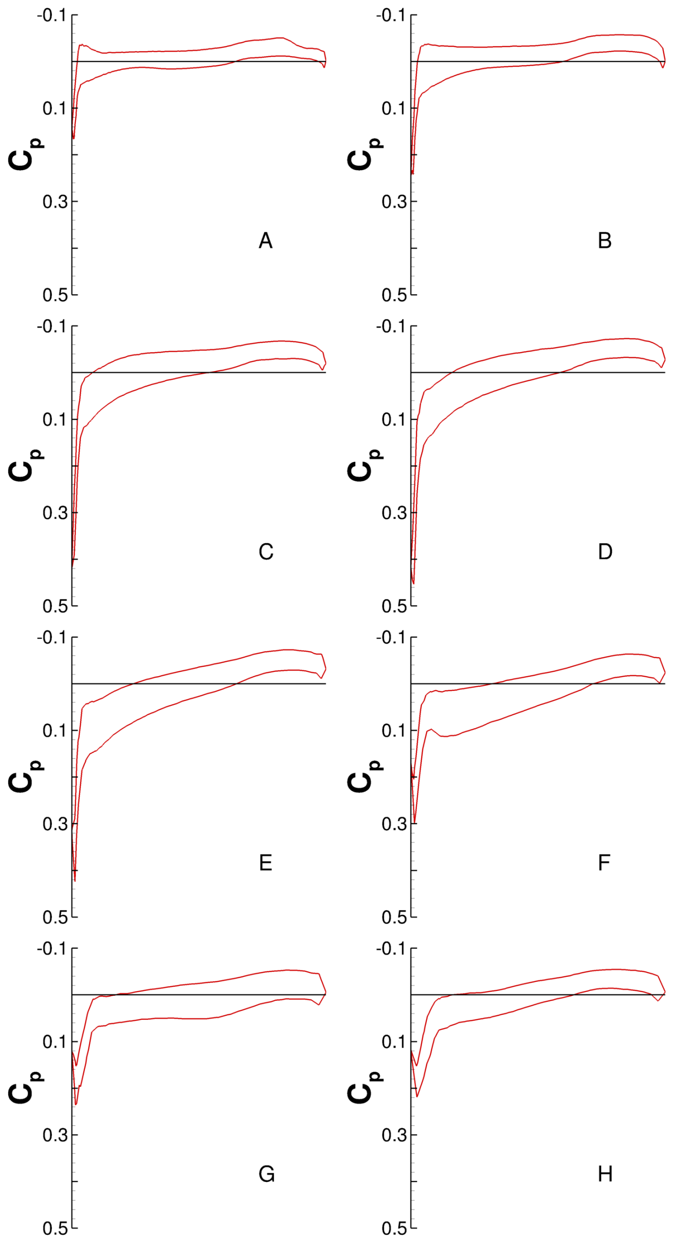
- KS failure function: Comparison between the adjoint-based derivative, finite-difference and function value for different sizes of structural mesh
- My opinion: Remesh-based optimization may be feasible if optimizer is noise-aware



Application: Rapid geometry creation and design assessment

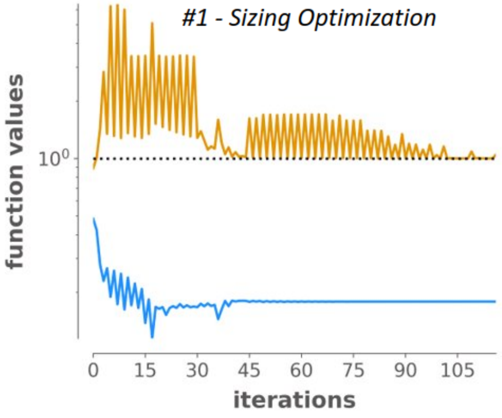
- FUNtoFEM with ESP/CAPS can be used to rapidly generate and assess a conceptual configuration with high-fidelity analysis
- Wave-rider supersonic transport concept



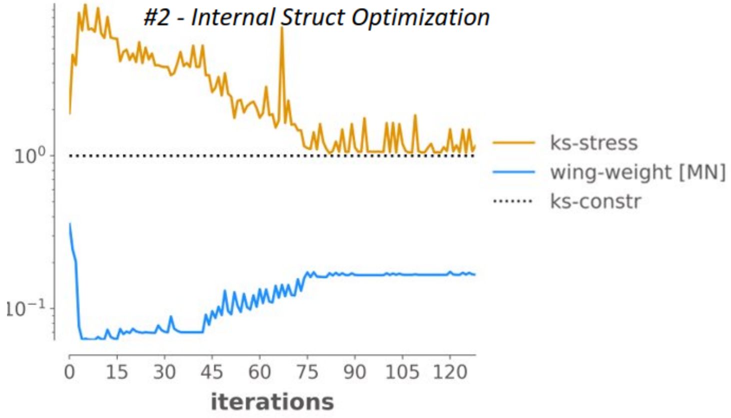


Applicaton: One-way design optimization

- Start multidisciplinary design optimization problems with sequential design process
- Use flexibility in ESP/CAPS to optimize internal structural layout
- Accurate derivatives obtained via FUNtoFEM



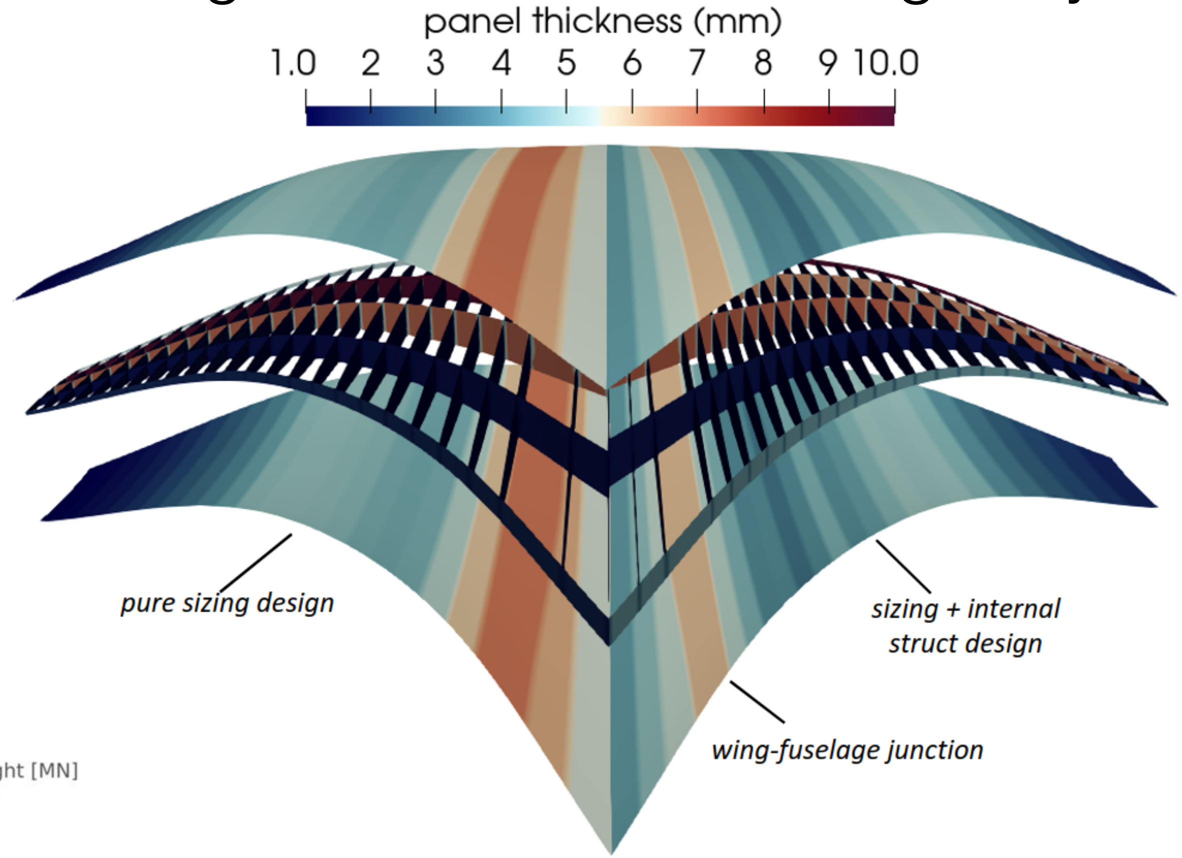
Initial sizing of panels



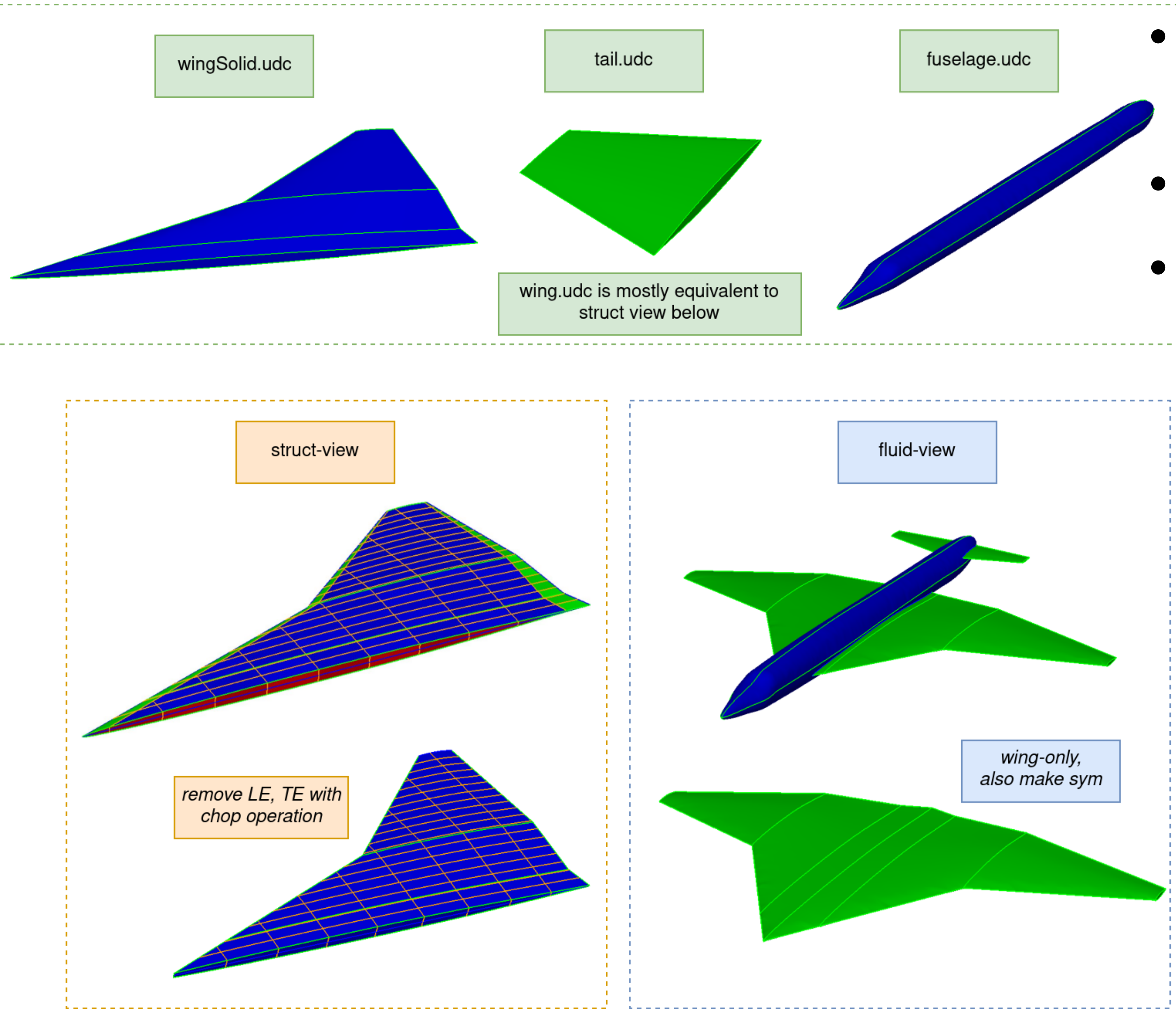
Optimize placement of ribs/spars

Sizing

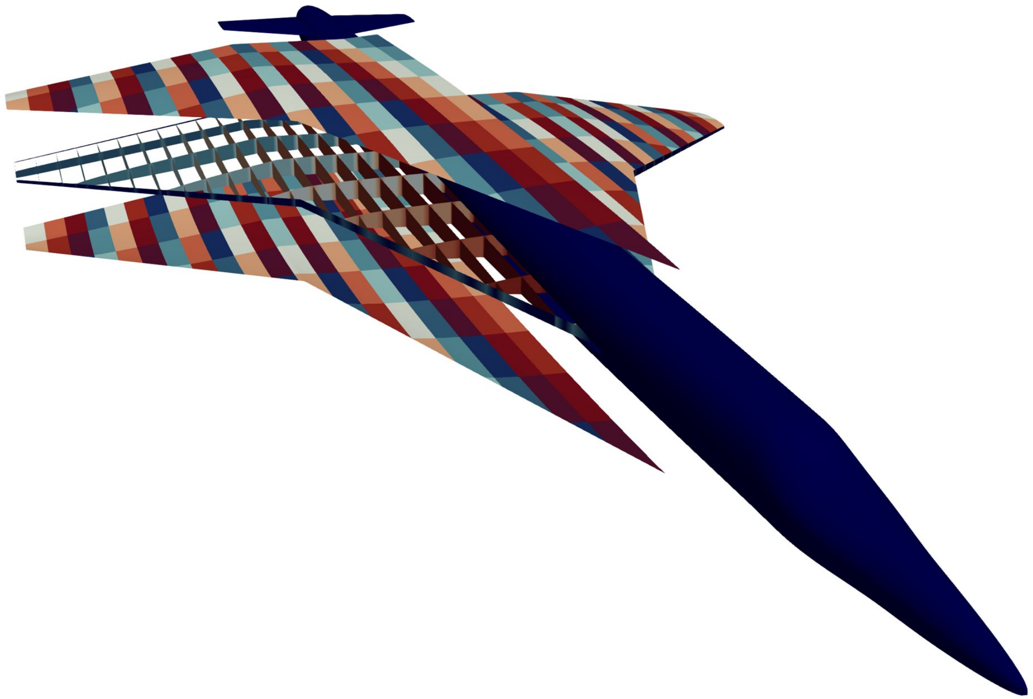
Sizing + layout



Using ESP/CAPS to generate an HSCT geometry

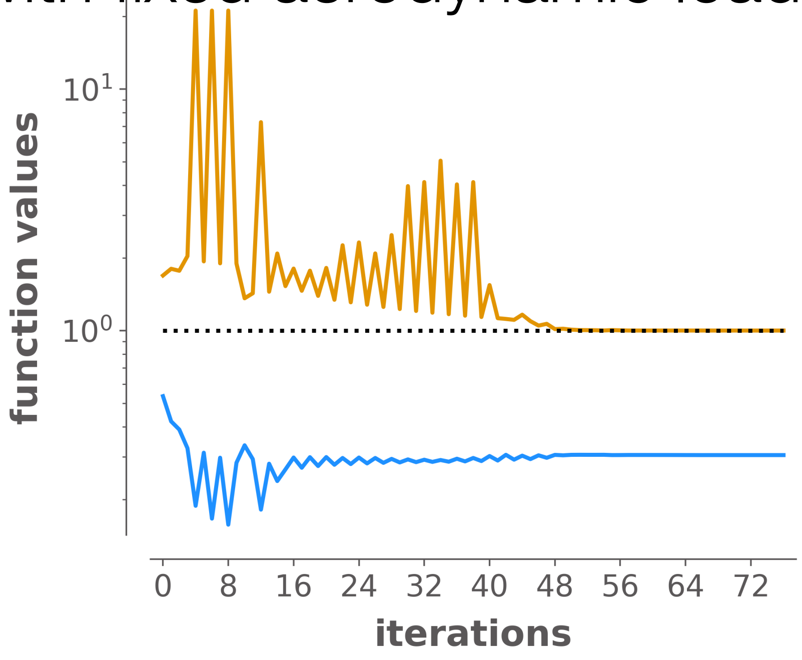


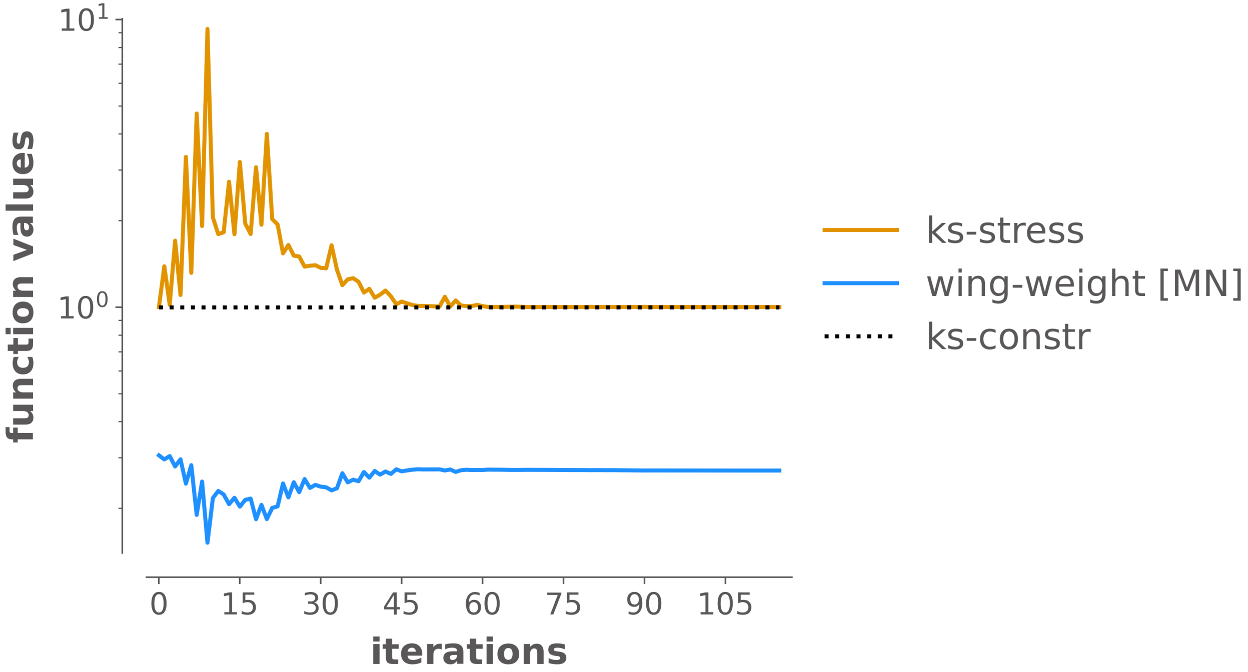
- Use ESP/CAPS to turn off/on parts of the geometry
- Full concept but wing-only opt
- Optimized wing can be integrated with the fuselage for next design step

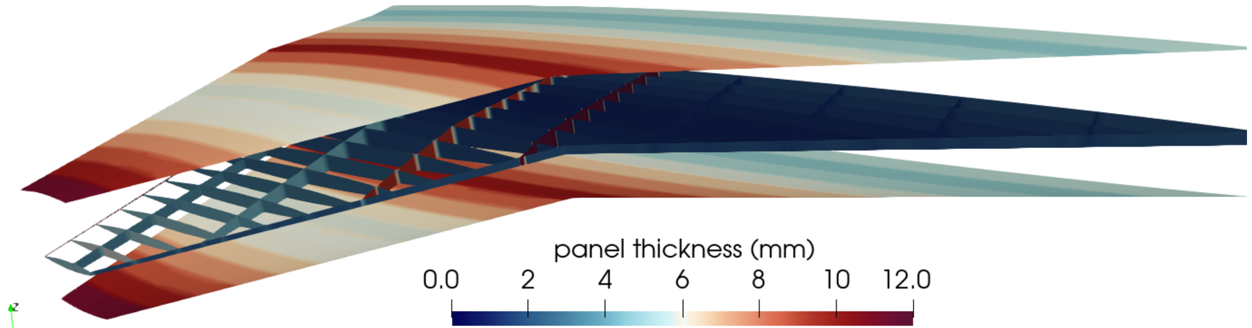


Aeroelastic sizing optimizations of an HSCT wing

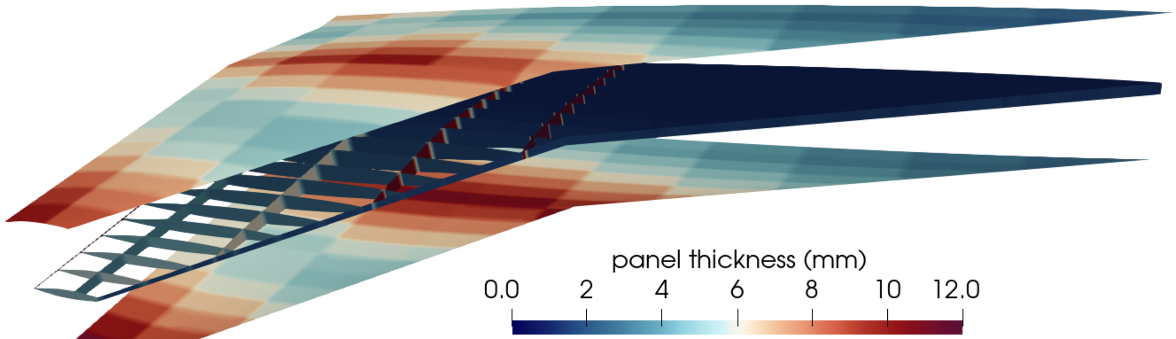
- Aeroelastic optimization with only structural design variables after initial sizing with fixed aerodynamic loads







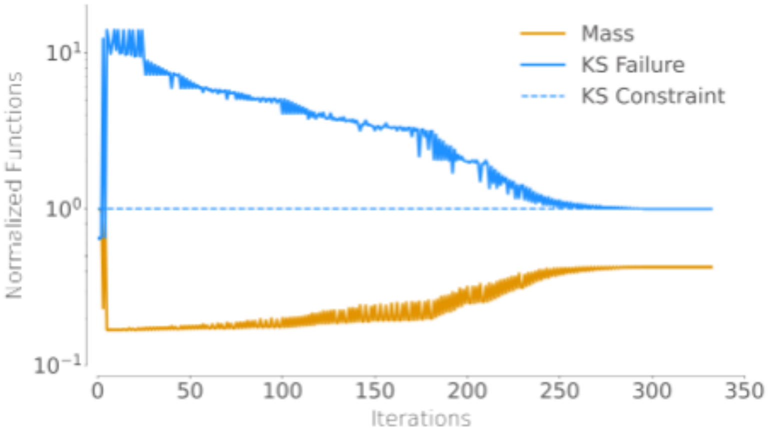
Panel thickness constant along the chord



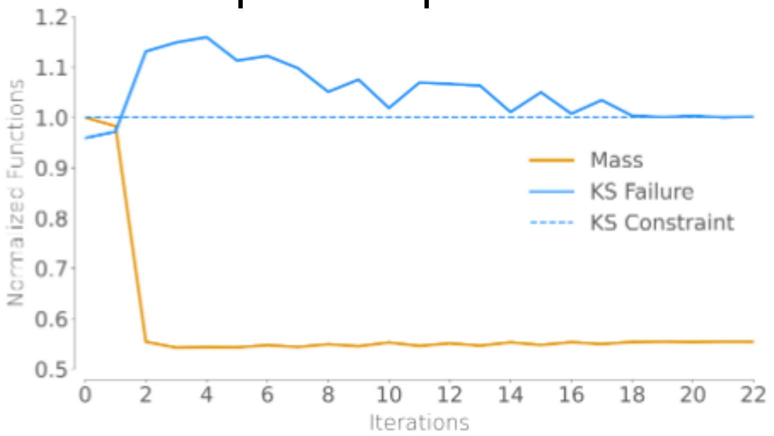
Panel thickness varying along the chord

Coupled aerothermoelastic optimization

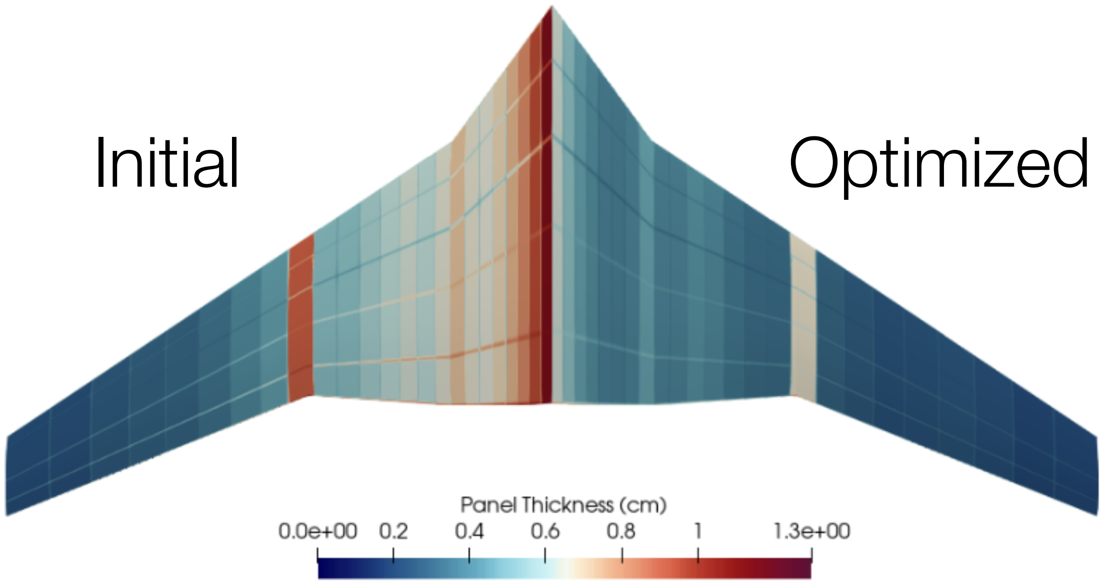
Initial one-way sizing

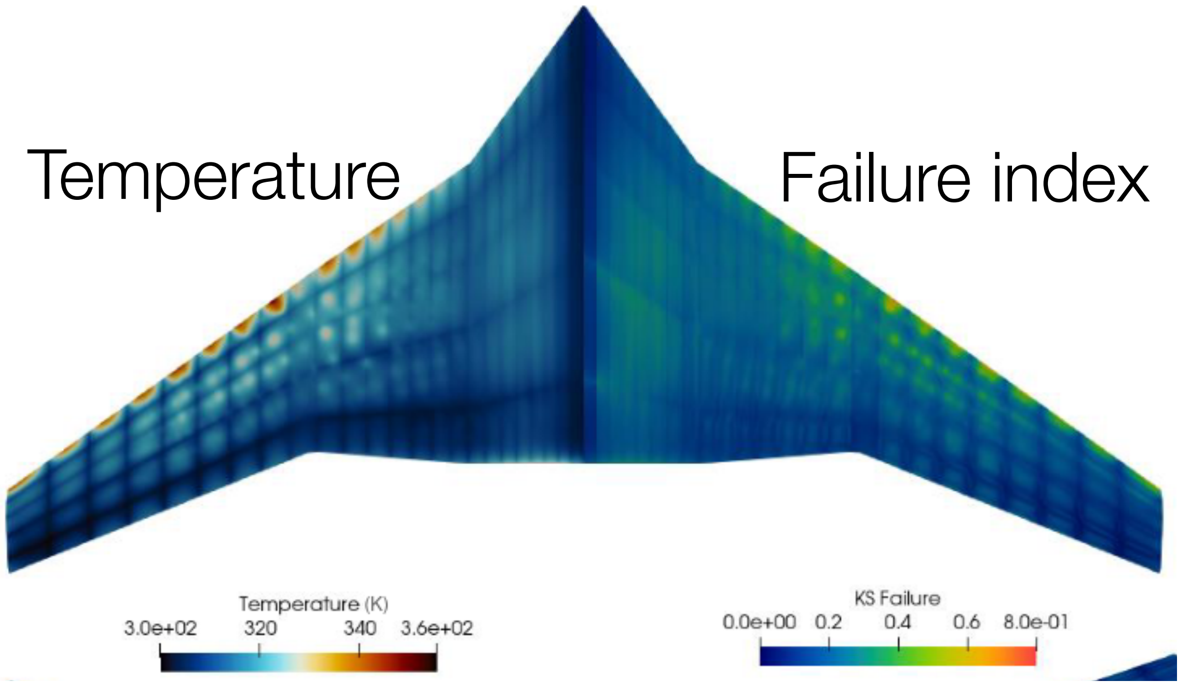


Coupled optimization



- Initial demo of a fully coupled aerothermoelastic optimization using FUNtoFEM





Conclusions

- FUNtoFEM is a flexible and modular framework that integrates ESP/CAPS for geometry parametrization
- Accurate derivatives are ensured through a series of tests for disciplinary-consistency
- Aerothermal, aeroelastic and aerothermoelastic design optimization problems can be solved using gradient-based optimization
- We’re working towards more complex design optimization problems

Questions

- Project funded by AFRL under contract FA8650-18-2-2227
- Thanks to Nathan Wukie, Marshall Galbraith, Neal Novotny and David Sandler