



A Variable Stiffness Skin for Morphing High-lift Devices

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Outline

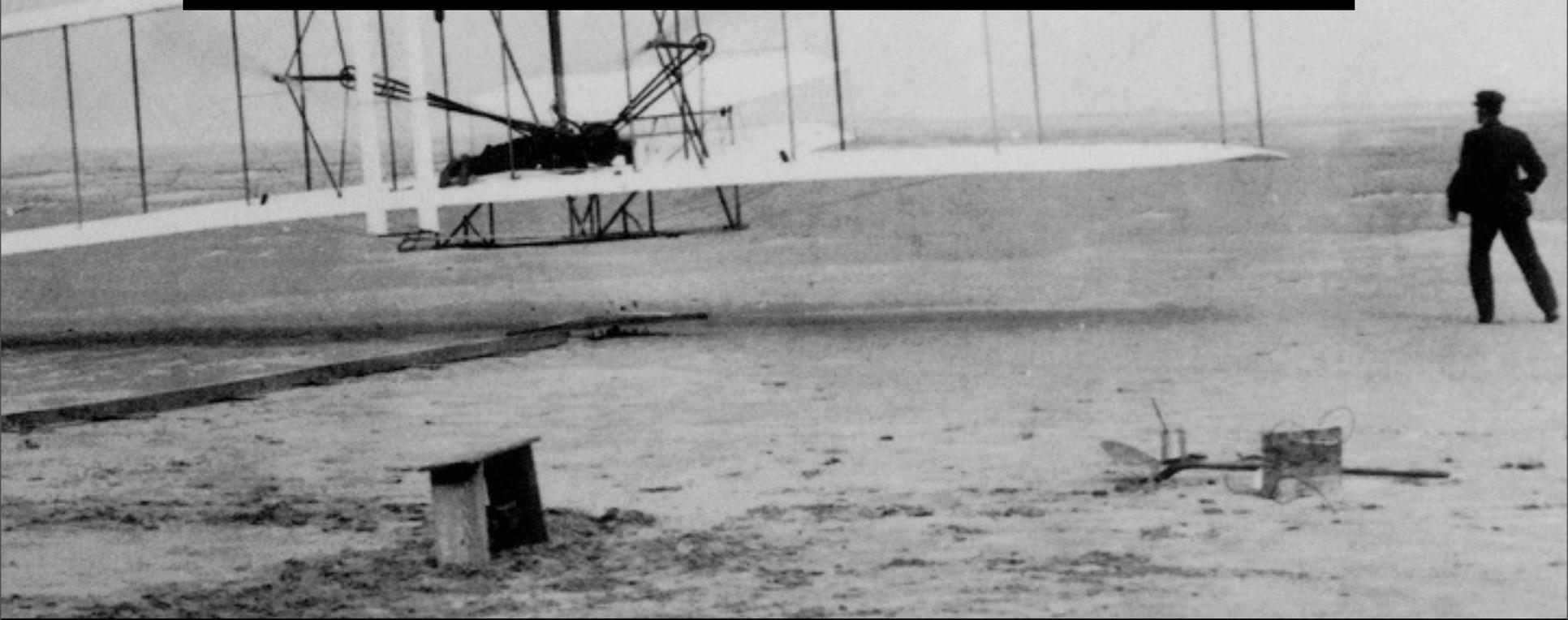
- Introduction: Skin Concept
- Aero-servo-elastic Framework
- Skin Stiffness Results
- Initial Actuation Topology Results
- Test Results
- Conclusions



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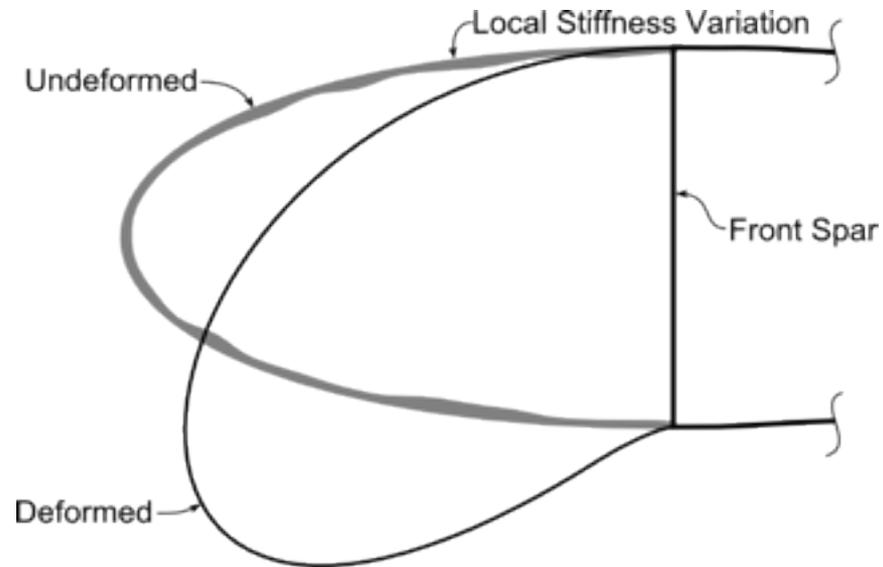
Introduction: Skin Concept

Variable Stiffness Composites



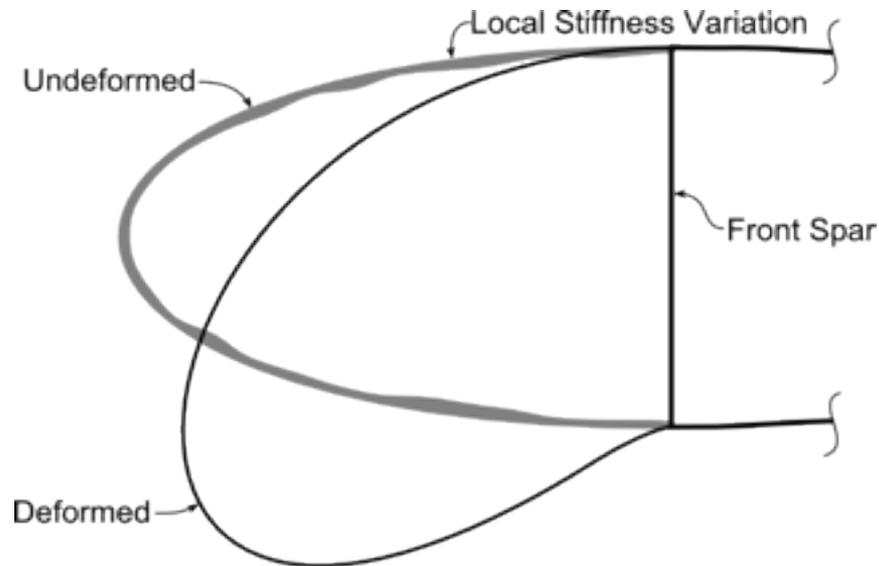
Goal

- Design a composite skin having a variable stiffness



Goal

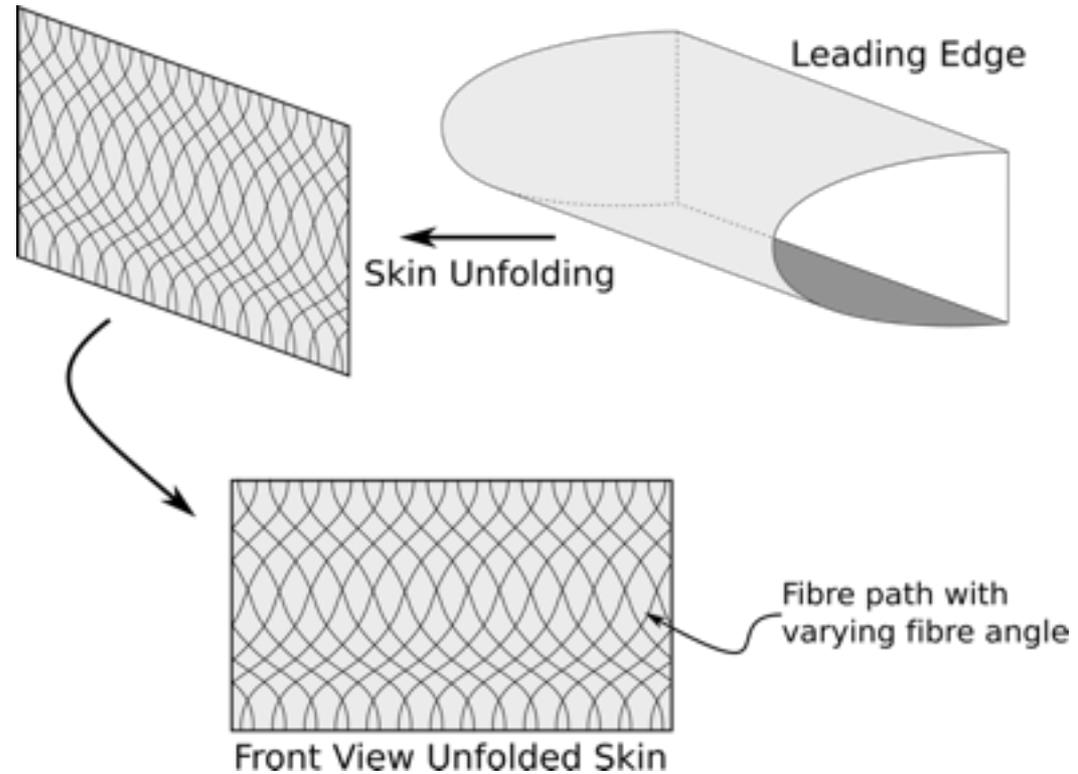
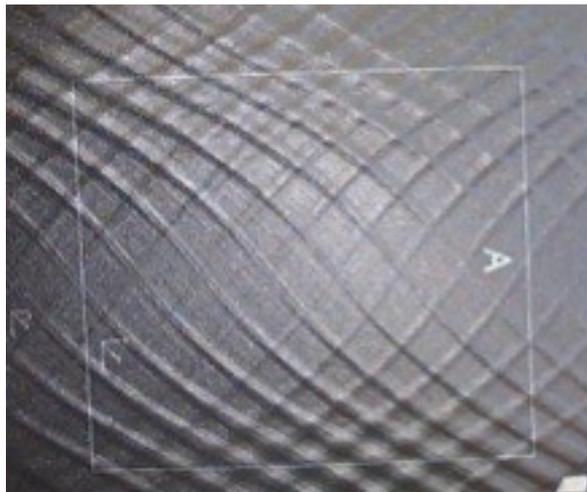
- Design a composite skin having a variable stiffness



⇒ Internal actuation provided by partner

Variable Stiffness Skin

- Variable stiffness can be achieved by:
 - fibre angle variation
 - thickness variation





Aero-Servo-Elastic Framework

Optimisation of High-lift Devices

Aero-servo-elastic framework

Non-linear Euler-
Bernoulli beam model
(2D)

Inviscid panel code
(2D)

Aero-servo-elastic framework

Aeroelastic Analysis (2D)

- Skin stiffness defined as:

$$EA = \beta E_1 h \qquad EI = \alpha \frac{E_1 h^3}{12}$$

Aero-servo-elastic framework

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Aero-servo-elastic framework

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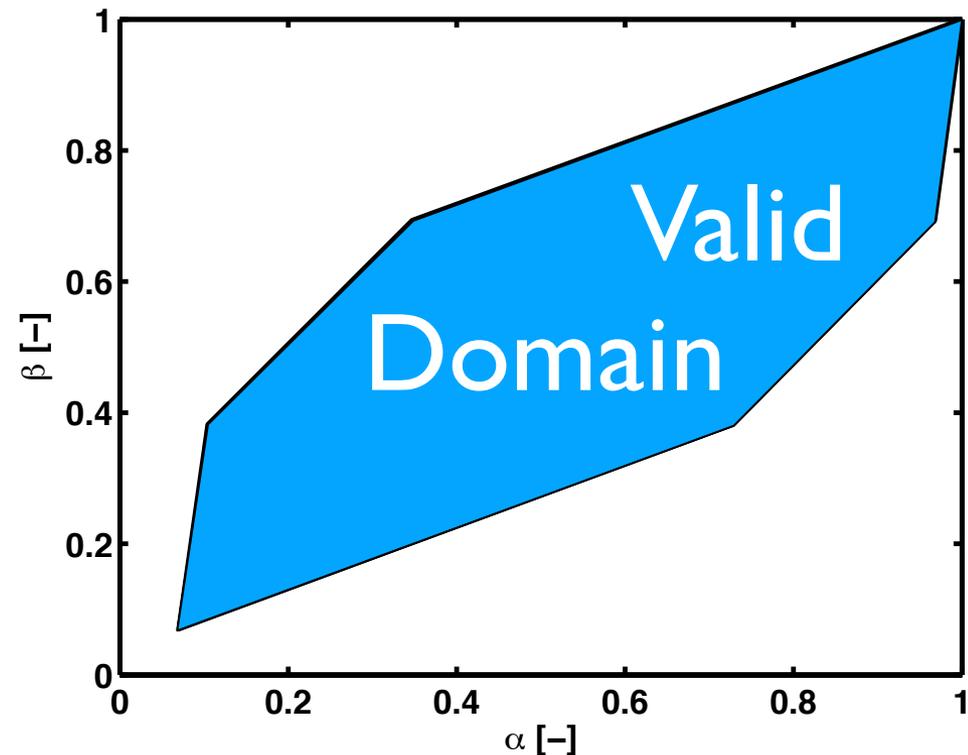
$$\mathbf{f}_{act} = \mathbf{f} \cdot \mathbf{c}$$

- Design variables become:

$$\mathbf{x} = \{\alpha, \beta, \mathbf{h}, \mathbf{c}\}$$

Feasible region

- Feasible skin design possible when α and β are within the feasible region
- Domain for balanced symmetric 12 layer laminate is conservative for thicker laminates
- Feasible domain ensures a valid relation between axial and bending stiffness

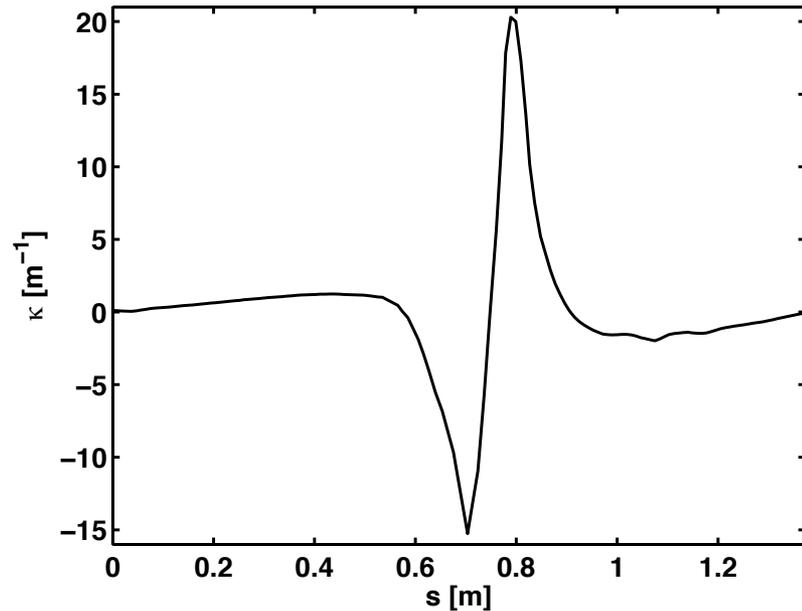
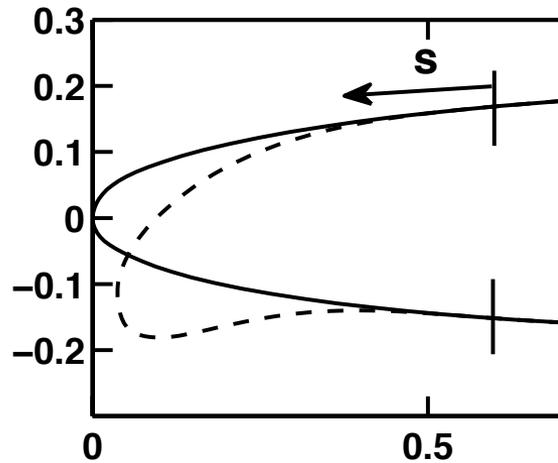


Optimisation Formulation

- Objective:
$$\min \mathbf{I} = \sum_{i=1}^N \left\{ \frac{L_i}{2} \int_{-1}^1 [\kappa_i(\eta) - \kappa_{t_i}(\eta)]^2 d\eta \right\}$$

Optimisation Formulation

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- Target curvature defined using SADE's target shape:



Optimisation Formulation

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$$\min \mathbf{I} = \sum_{i=1}^N \left\{ \frac{L_i}{2} \int_{-1}^1 [\kappa_i(\eta) - \kappa_{t_i}(\eta)]^2 d\eta \right\}$$
- subject to skin strain constraints:

$$\frac{\epsilon_i}{\epsilon_{max}} - 1 \leq 0$$

- Optimisation performed using **gradient** based optimiser GCMMA by Svanberg where sensitivities are provided by application of the adjoint method

Skin Stiffness Results

Using an existing actuation topology

```

161 -     Ka_s = zeros(Ndof,Ndof);
162 -     xp_a = zeros(Nae.all,1); yp_a = xp_a;
163 -     dx = eye(length(xp_a));
164 -     dy = eye(length(xp_a));
165 -     H = 0;
166 -     end
167 -     u_s = zeros(Ndof,1); % initial displacements
168 -     fs.act = u_s; % initial external actuation forces
169 -     fs.act(3*Nse.all+1:end) = f_act;
170
171 -     % Structural calculation (with aerodynamic updates within routine)
172 -     [u_s,dlambda,Kt,dKt,dqin,Ka_s,f_s,Cl,dCl,I,dI,du,e] = strucrunv6([xp_s,yp_s],[xp_a,yp_a],[Nse.all+N
173
174 -     if flag.grad
175 -     % Sensitivity calculation wrt local curvature constraints - skin element only!!!
176 -     dI.dx = zeros(Nse.all+Nse,3);
177 -     [sens.I] = adjoint(Kt,dKt,dqin,Ka_s,f_s,dof,fixdof,edof,Nse.all+Nse,dI);

```

x control_2D.m

x flexfoil_grad.m

x flexfoil_ini.m

x flexfoil_nograd.m

x flexfoil_opt.m

Command Window

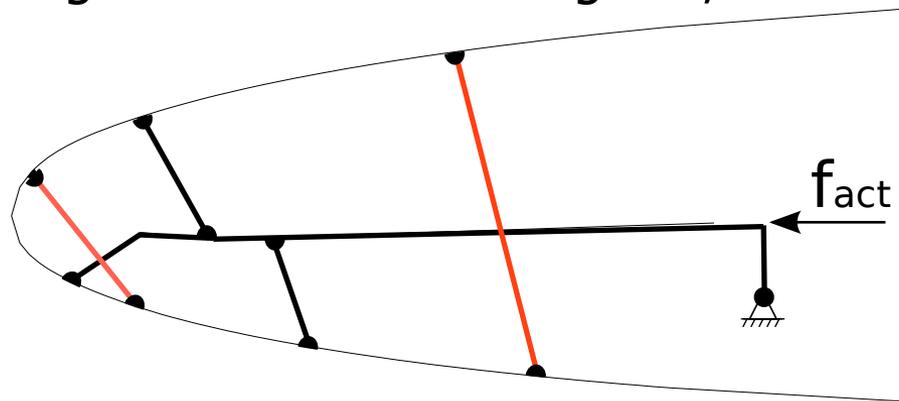
📌 New to MATLAB? Watch this [Video](#), see [Demos](#), or read [Getting Started](#).

>>

Study Cases

	Local variable	Global variable	Constant
Case 1	α, β, h	-	-
Case 2	α, β	h	-
Case 3	h	-	α, β

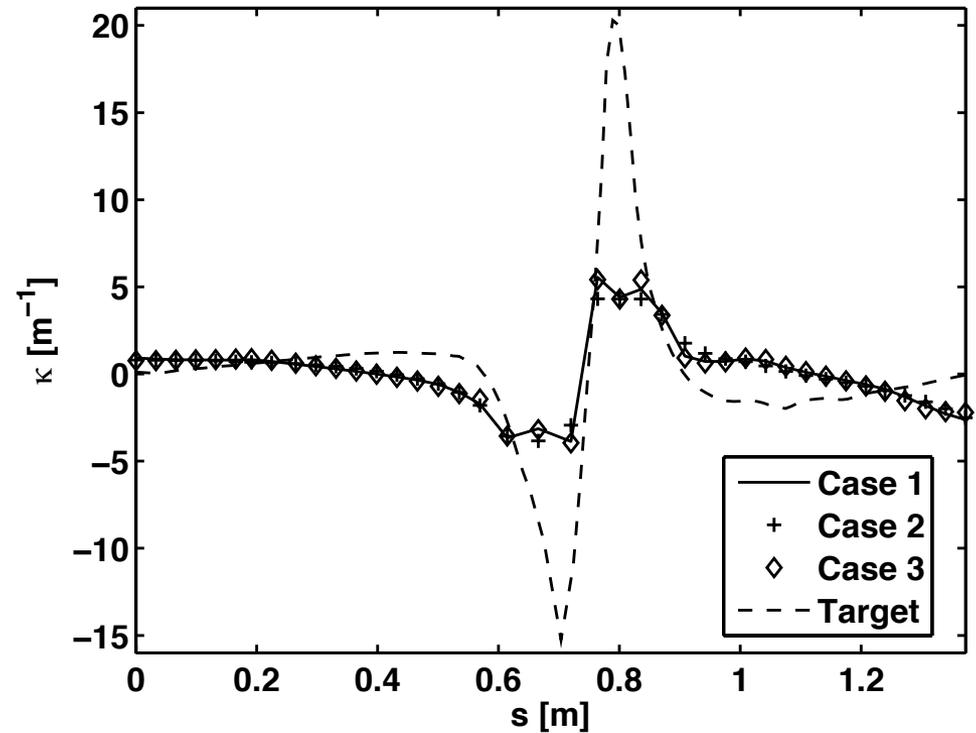
- Initial values: $\alpha = \beta = 0.9$ and $h = 12$ layers
- Wing at angle-of-attack of 10 degrees, and velocity of 50 m/s



by CIRA

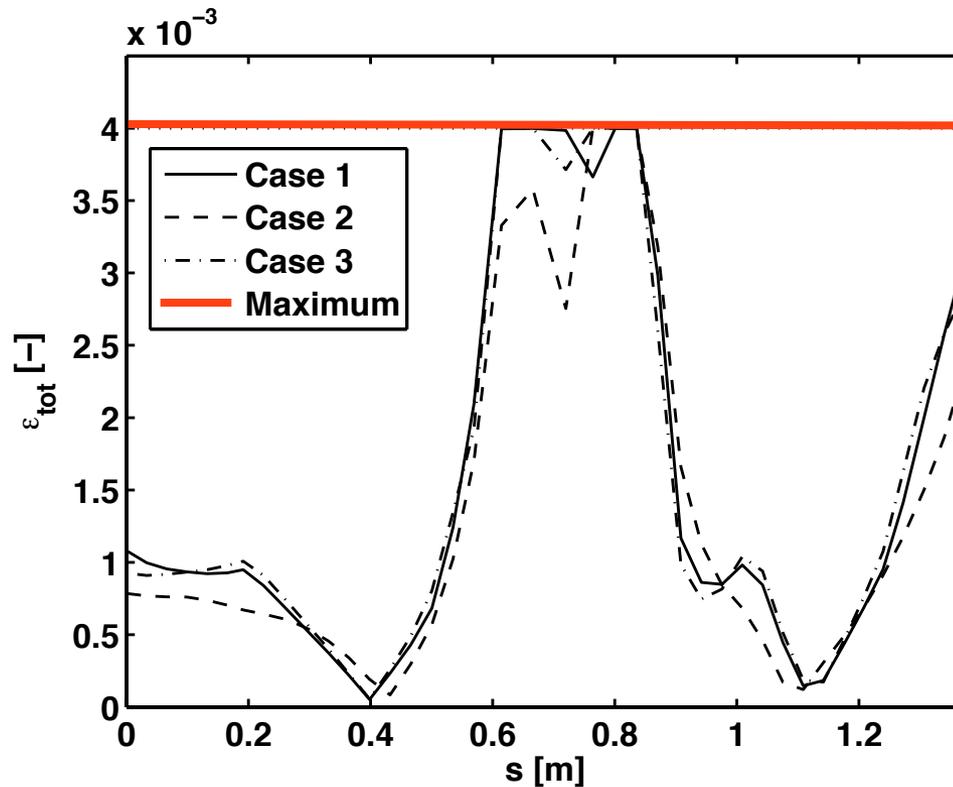
Curvature Objective

	Case 1	Case 2	Case 3
I	342	351	338

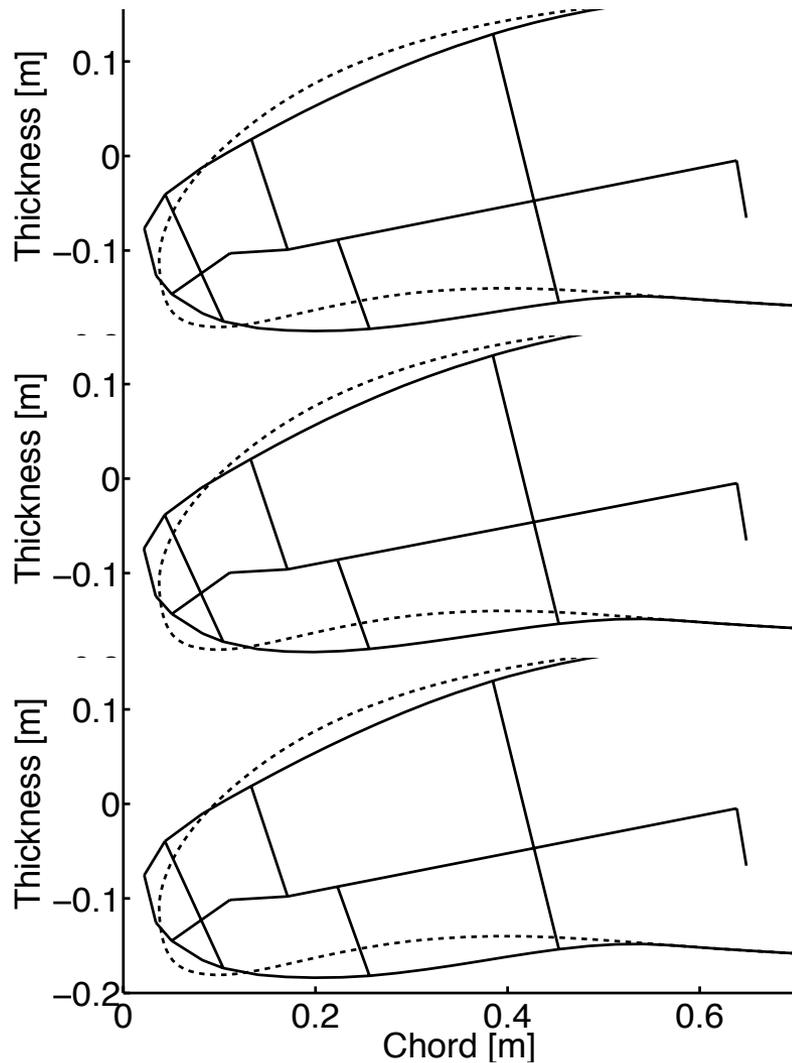


Applied Skin Strain

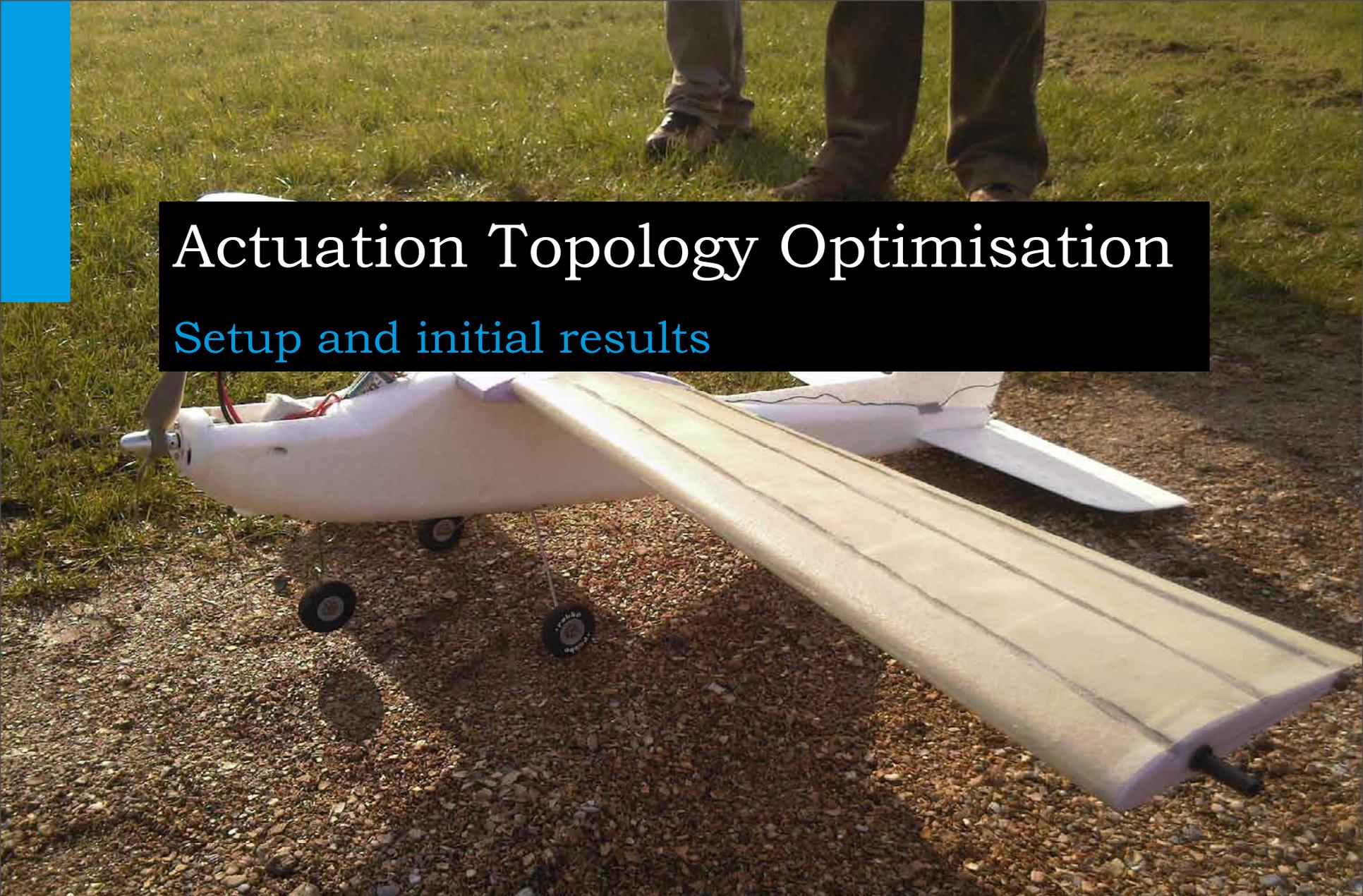
- Target curvature not achieved due to skin strain constraint



Final Deformed State



	Actuation force
Case 1	92 340 N
Case 2	78 570 N
Case 3	91 825 N

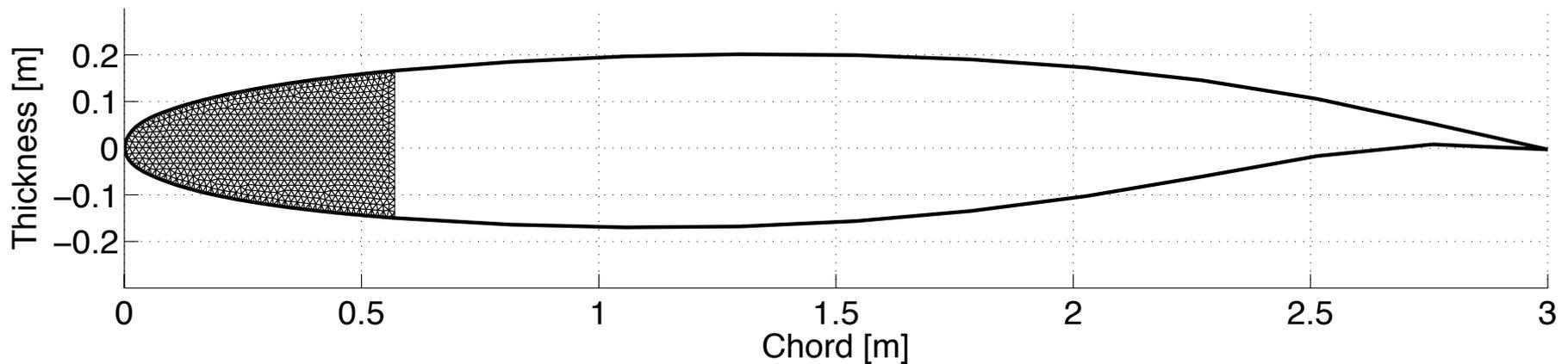
A photograph of a white morphing aircraft on a gravel surface. The aircraft has a long, slender wing with a variable stiffness skin. A person's legs are visible in the background, standing on grass. A black text box is overlaid on the image.

Actuation Topology Optimisation

Setup and initial results

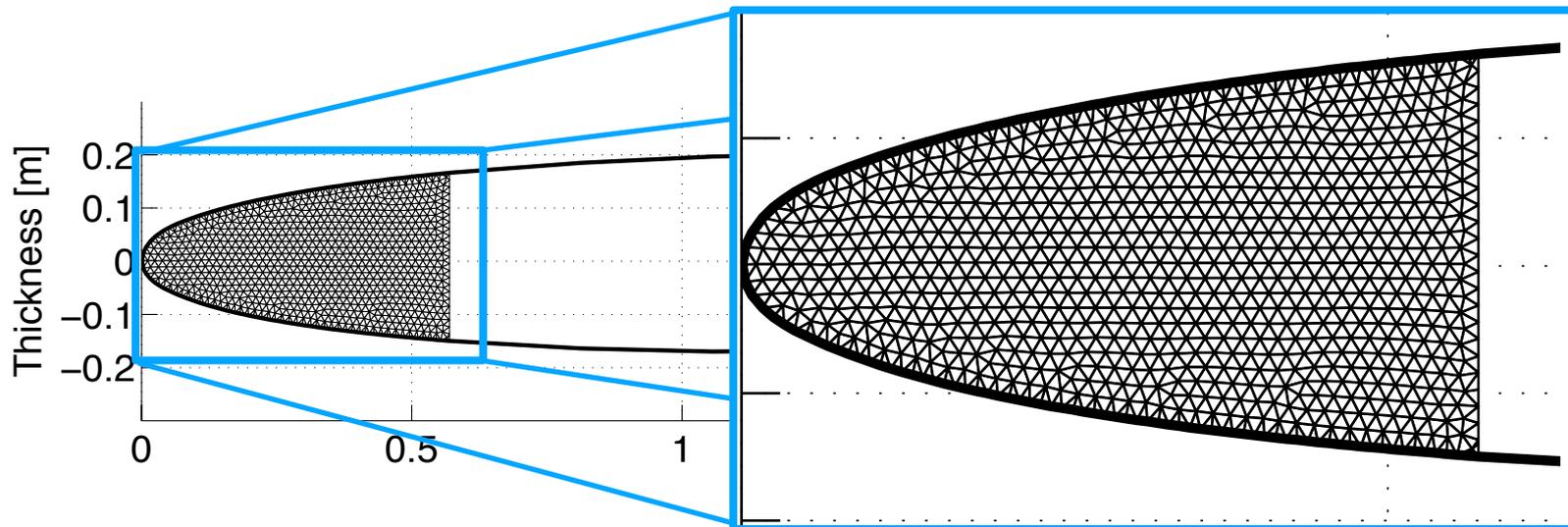
Actuation Topology Design

- Create internal unstructured mesh
- Apply Simple Isotropic Material with Penalisation (SIMP) approach
- Combined skin stiffness/actuation topology optimisation possible

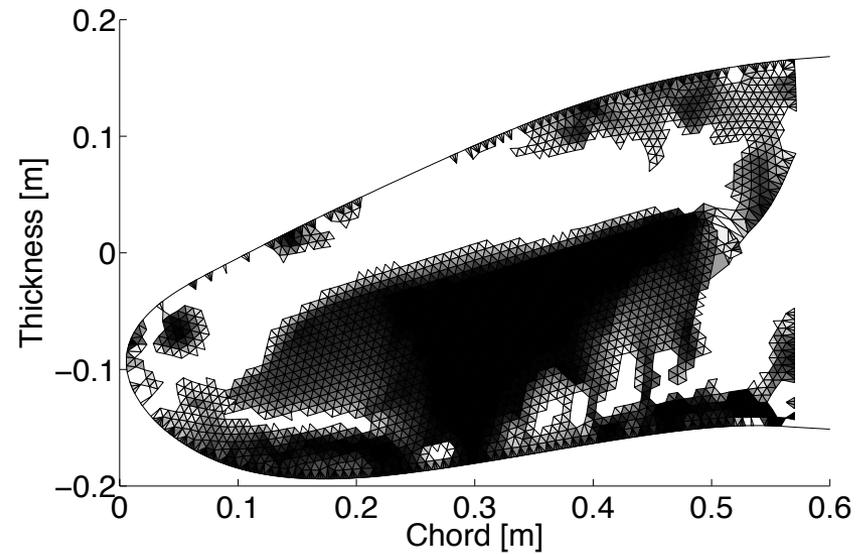
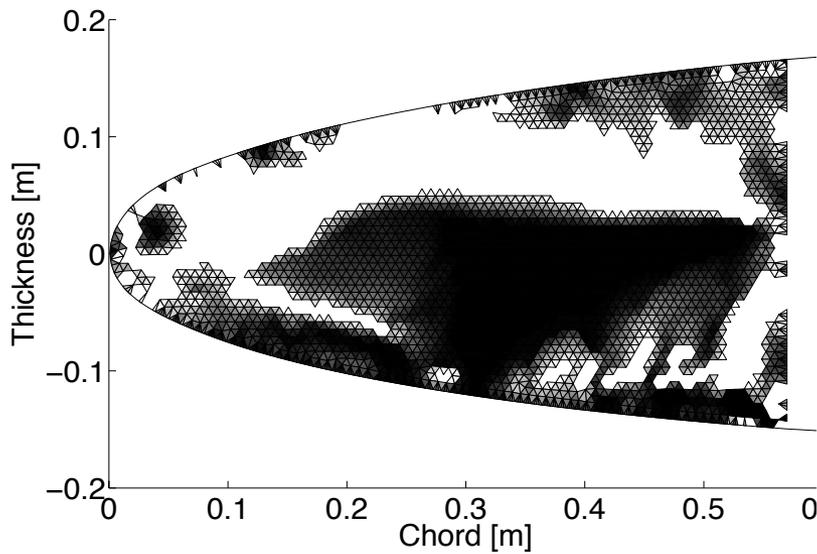
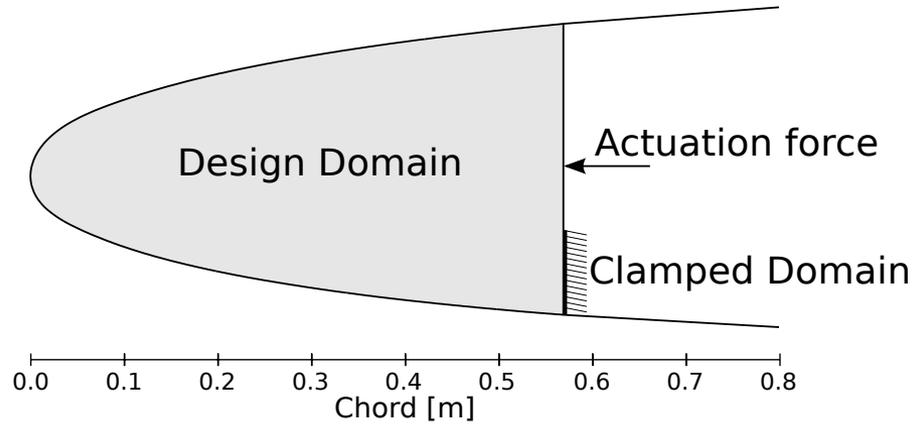


Actuation Topology Design

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Initial linear results



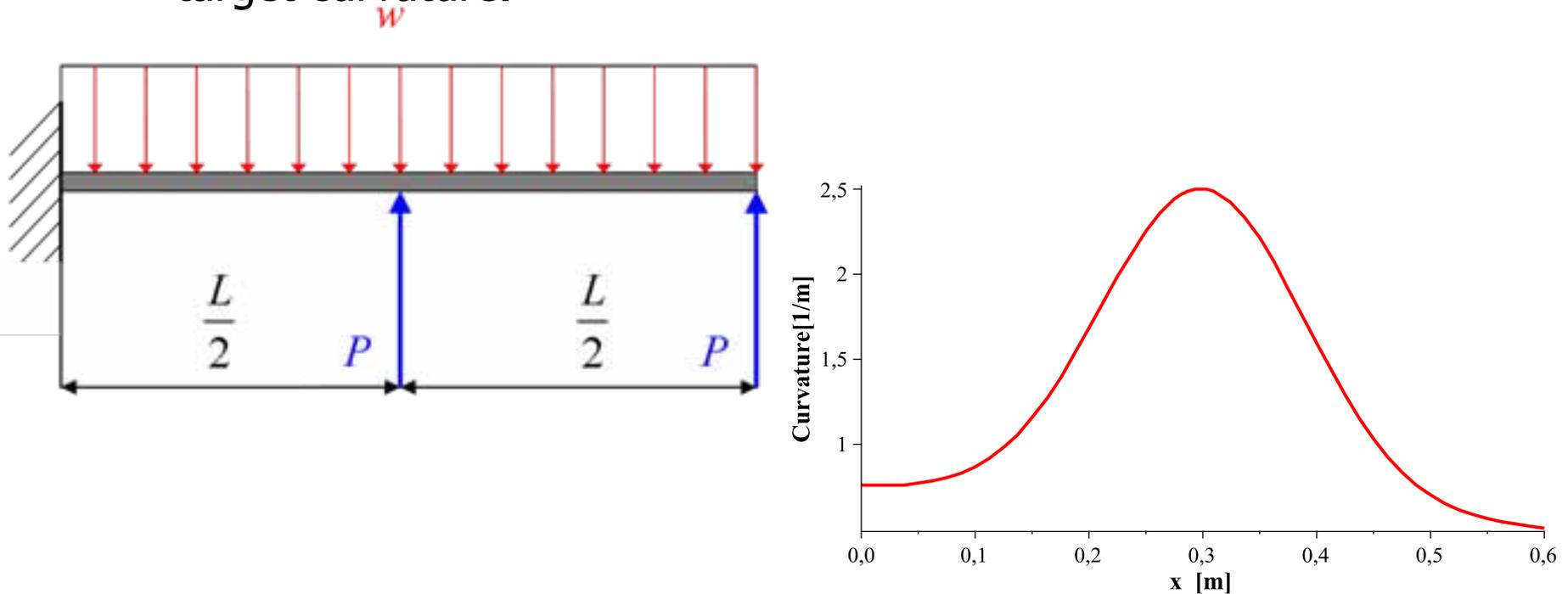
Test Results

Validating ‘Target Curvature Concept’

by Jaap Dekker MSc

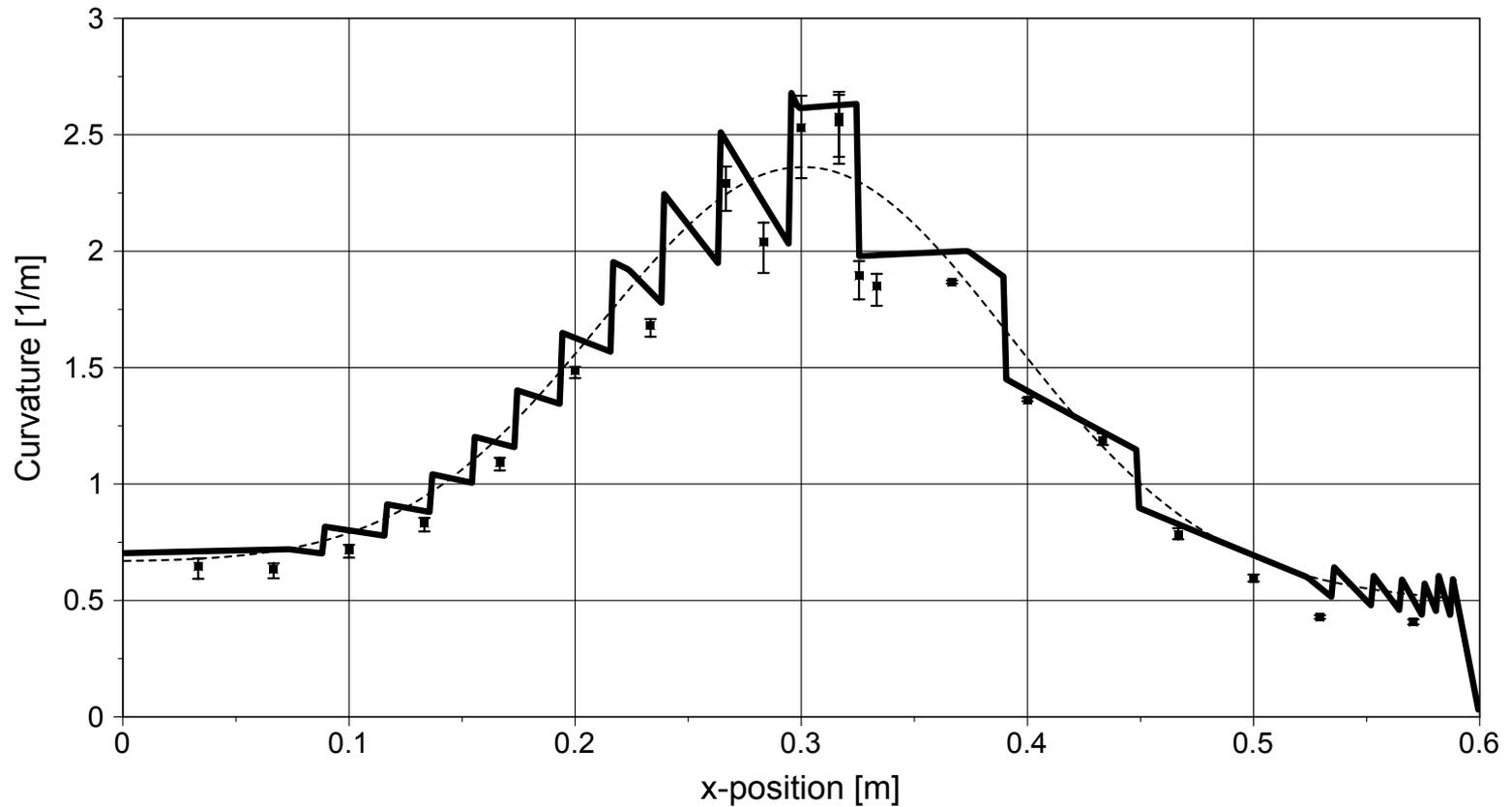
Design for Target Curvature Concept

- The stiffness distribution of the panel has to be designed such that the panel, in its deformed shape, matches the predefined target curvature.



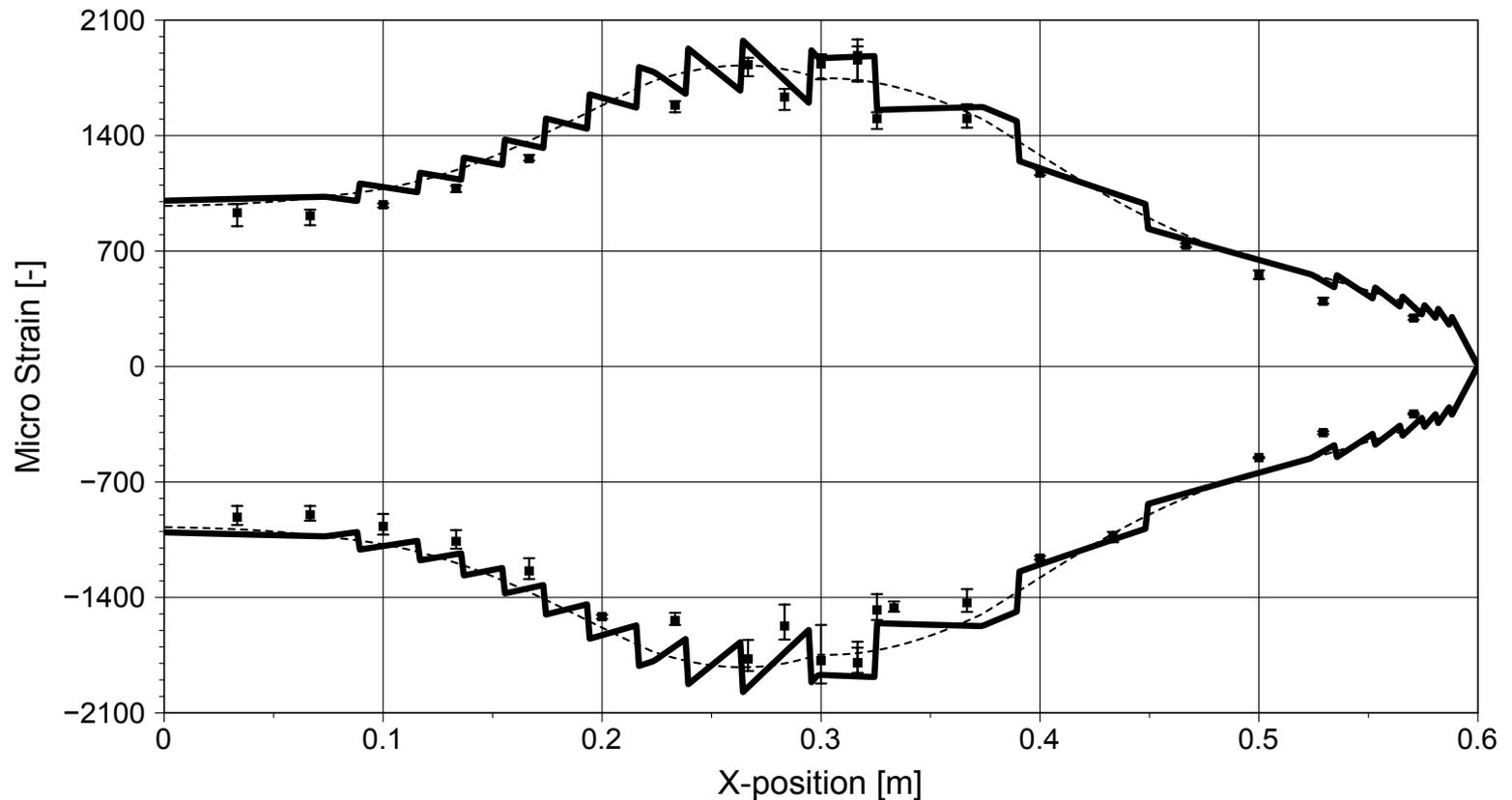
Curvature and Strain Measurements

- Measured (dots) versus expected (solid line) **curvature**



Curvature and Strain Measurements

- Measured (dots) versus expected (solid line) **strain**



Conclusions

summary

noun

a summary of the findings; SYNOPSIS, précis, résumé, abstract, digest, encapsulation, abbreviated version; outline, sketch, rundown
summing-up, overview, recapitulation, epitome; informal recap.

conclusion

noun

- 1 the conclusion
- 2 the conclusion
- 3 his conclusion

short, brief, pithy; formal
sudden; arbitrary, without

con·clu·sion |kən'kloo'ziən|
noun

- 1 the end or finish of an event or process : the conclusion of World War Two.
- the summing-up of an argument or text.
- the settling or arrangement of a treaty or agreement : the conclusion of a peace treaty.
- the settling or decision reached by reasoning : each research group came to its own conclusion.
- Logic a proposition that is reached from given premises.

PHRASES
in conclusion lastly; to sum up; in conclusion it is clear that the market is moving up.
jump (or leap) to conclusions make a hasty judgment before learning the facts.
ORIGIN late Middle English : from Latin conclusio(n)-, from the verb concludere 'to conclude', from con- 'with, together' + cludere 'to close, shut'.

sum·ma·ry |sə'məri|
noun (pl. -ries)

a brief statement or account of the main points of something : a summary of Chapter 7.

- adjective
- 1 dispensing with needless details or formalities; brief : summary financial statements.
 - 2 Law (of a judicial process) conducted without the customary legal formalities : summary arrest.
 - (of a conviction) made by a judge or magistrate without a jury.

PHRASES
in summary in short : in summary, there is no clear case for one tax system compared to another.

DERIVATIVES
sum·mar·i·ly |sə'me(ə)rəli; sə'mərəli| adverb
sum·mar·i·ness |sə'merənis| noun
English (as an adjective): from Latin summarius, from summa 'sum total' (see SUM).

Conclusions

- Variable stiffness skin has a broader design space compared to constant stiffness skin, local stiffness variation is beneficial
- Aerodynamic loads have a large influence on the final skin stiffness distribution and should thus be taken into account during the design process
- Initial actuation topology results show good potential, such a tool can be used to design a more coherent morphing high-lift system, i.e. combined skin stiffness/actuation topology design
- Test results validate the design for target curvature philosophy

Future work

- topology optimisation including aerodynamic loading
- application of topology optimisation to design an actuation system which facilitates the deformation defined in SADE
- improvement of the aerodynamic solver to include for example viscous effect and enable the definition of an objective function using aerodynamic performance, e.g. max lift, max L/D, min D

- Tests made possible thanks to:

