



# A Variable Stiffness Skin for Morphing High-lift Devices

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# Outline

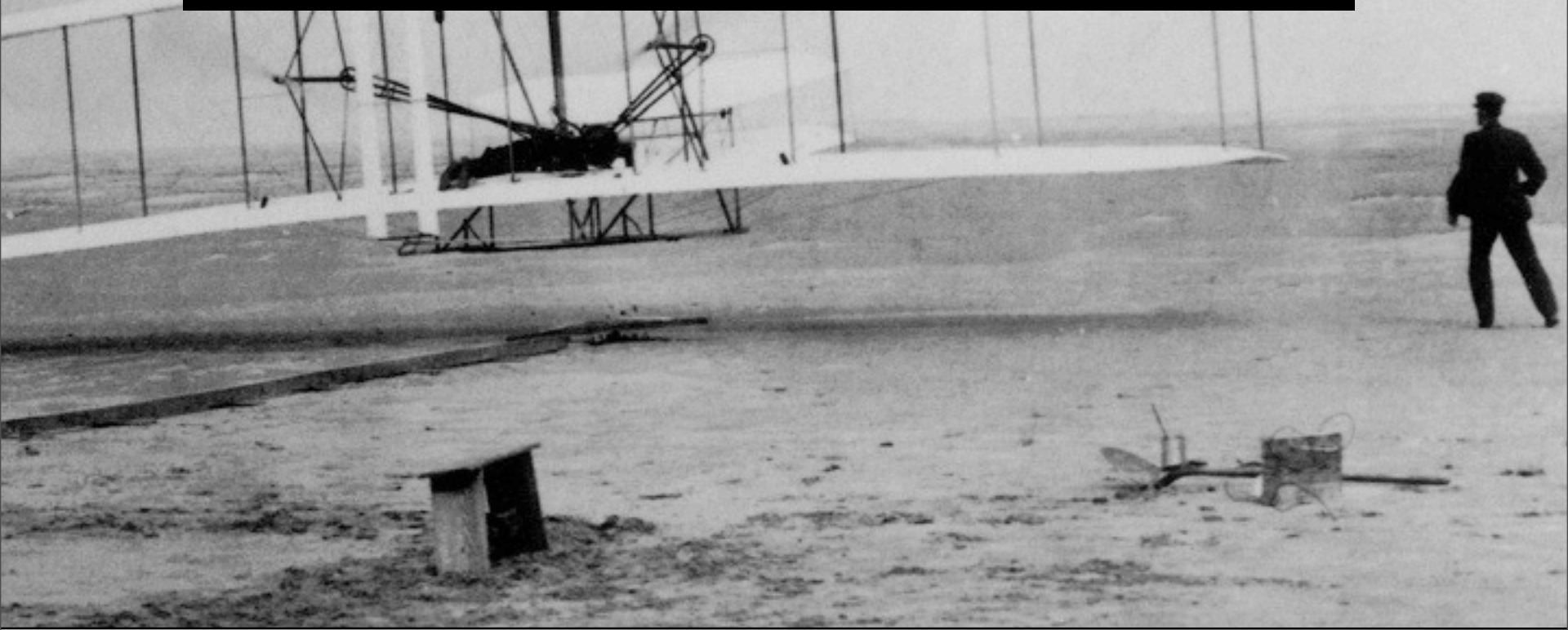
- Introduction: Skin Concept
- Aero-servo-elastic Framework
- Skin Stiffness Results
- Initial Actuation Topology Results
- Test Results
- Conclusions



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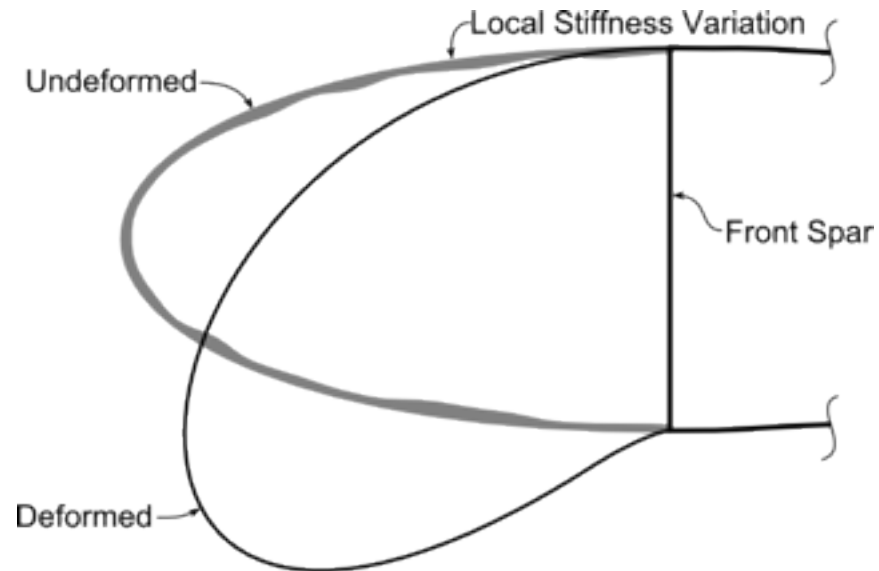
# Introduction: Skin Concept

## Variable Stiffness Composites



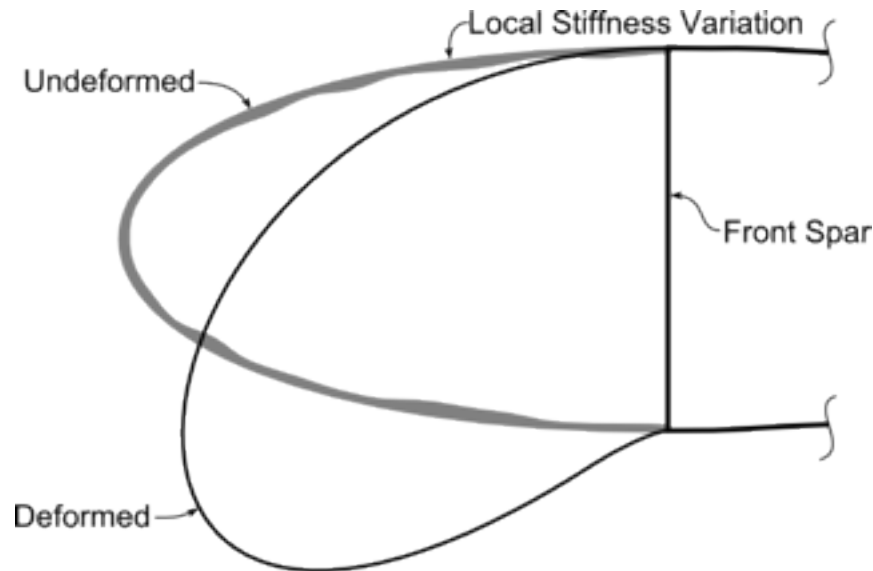
# Goal

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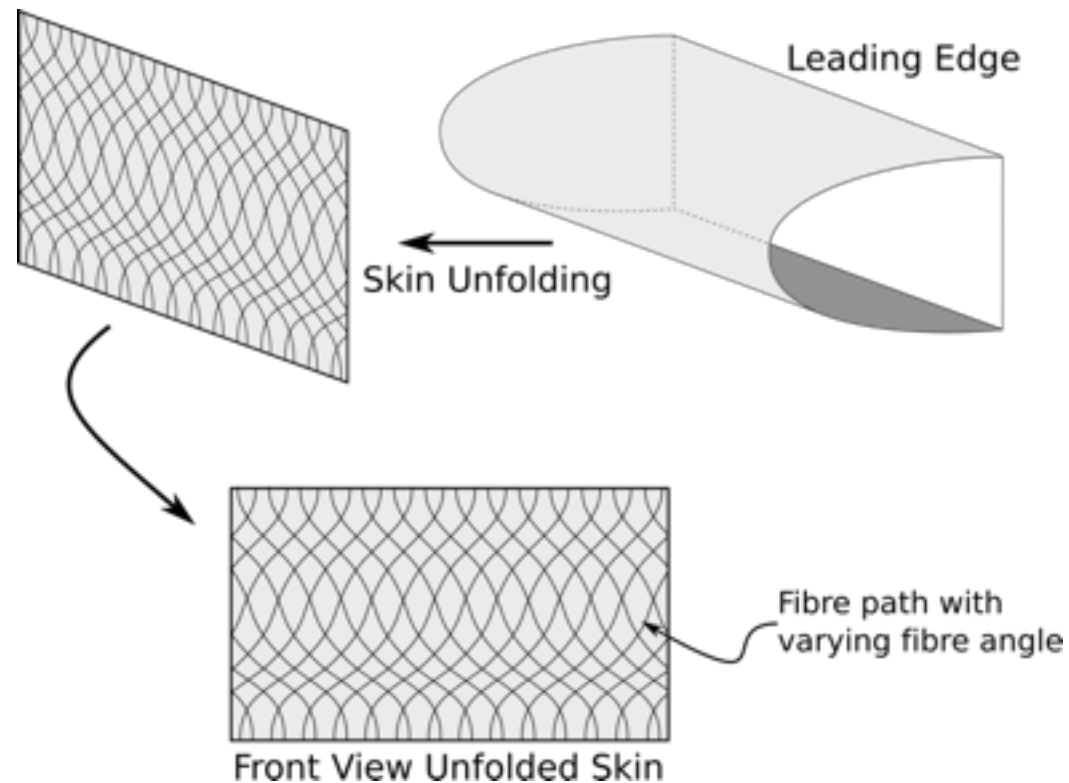
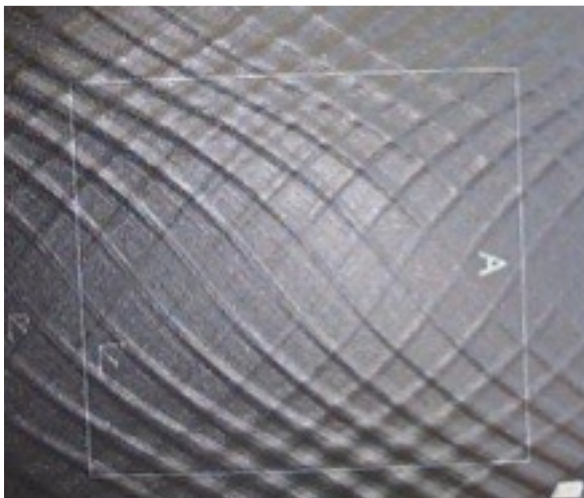


⇒ Internal actuation provided by partner



# 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:

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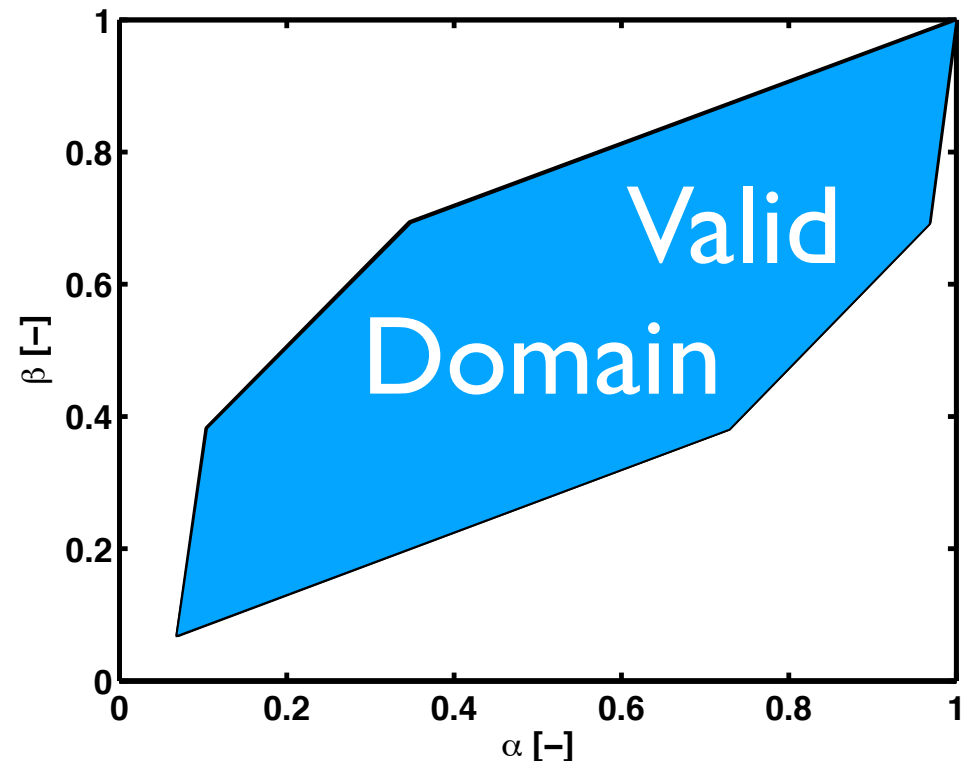
$$\mathbf{f}_{act} = \mathbf{f} \cdot \mathbf{c}$$

- Design variables become:

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

# Feasible region

- Feasible skin design possible when  $\alpha$  and  $\beta$  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



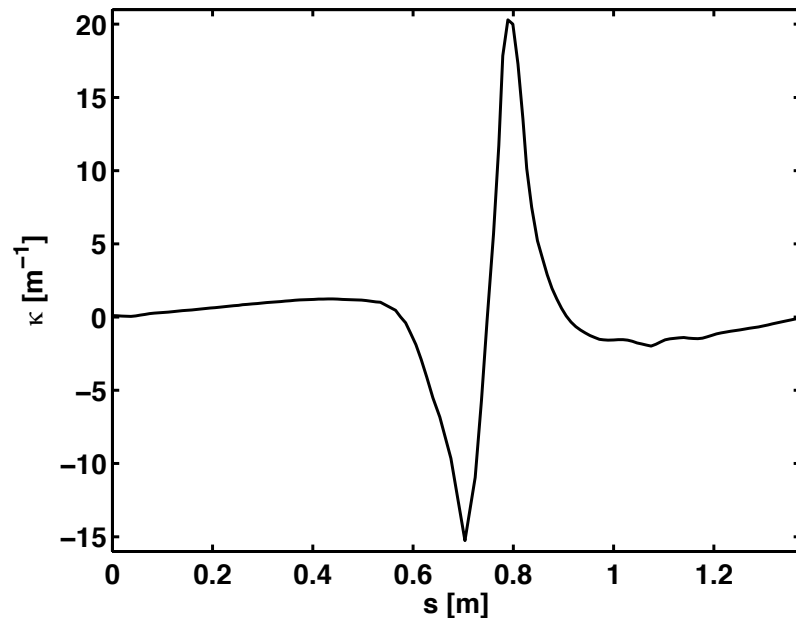
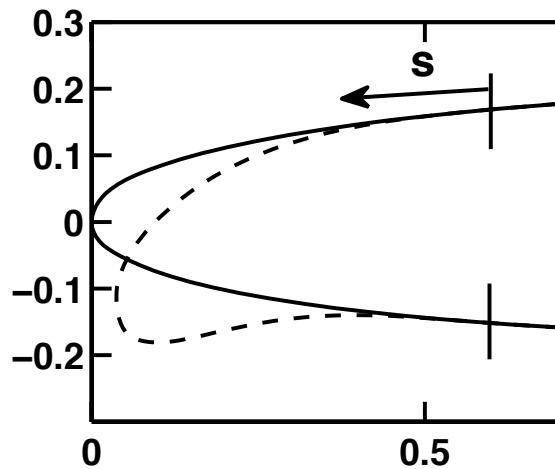


# Optimisation Formulation

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

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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,C1,dC1,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);

```

control\_2D.m

flexfoil\_grad.m

flexfoil\_ini.m

flexfoil\_nograd.m

flexfoil\_opt.m

Command Window

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

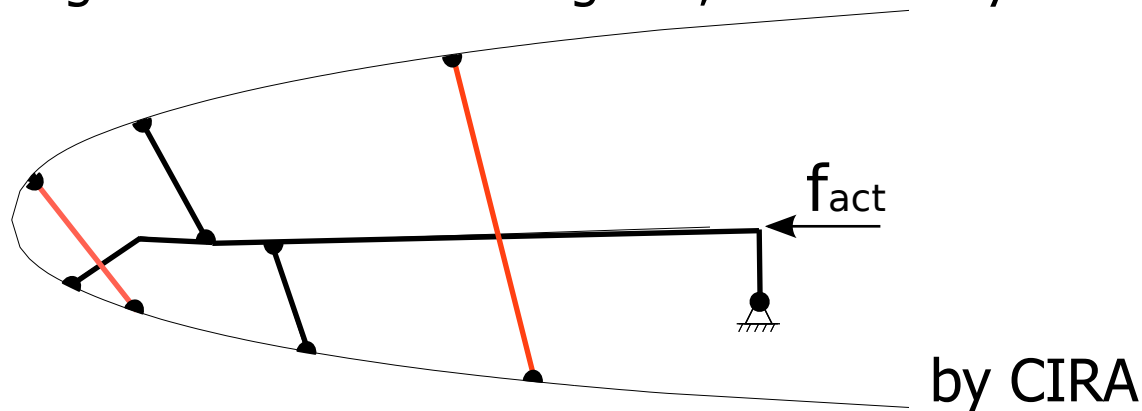
&gt;&gt;



# Study Cases

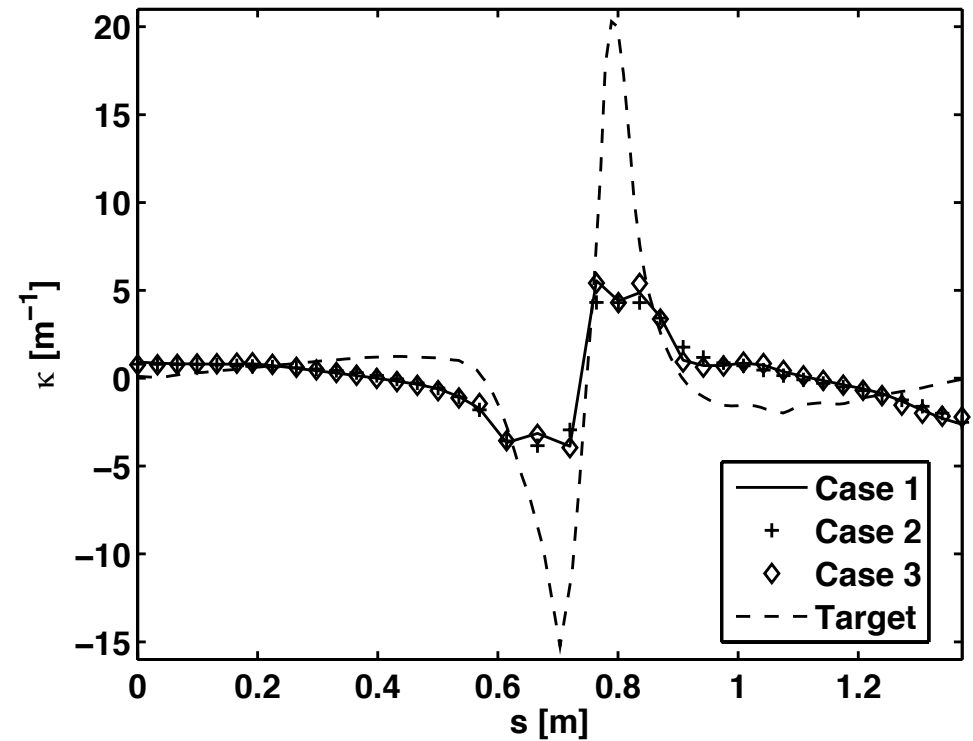
	Local variable	Global variable	Constant
Case 1	$\alpha, \beta, h$	-	-
Case 2	$\alpha, \beta$	$h$	-
Case 3	$h$	-	$\alpha, \beta$

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



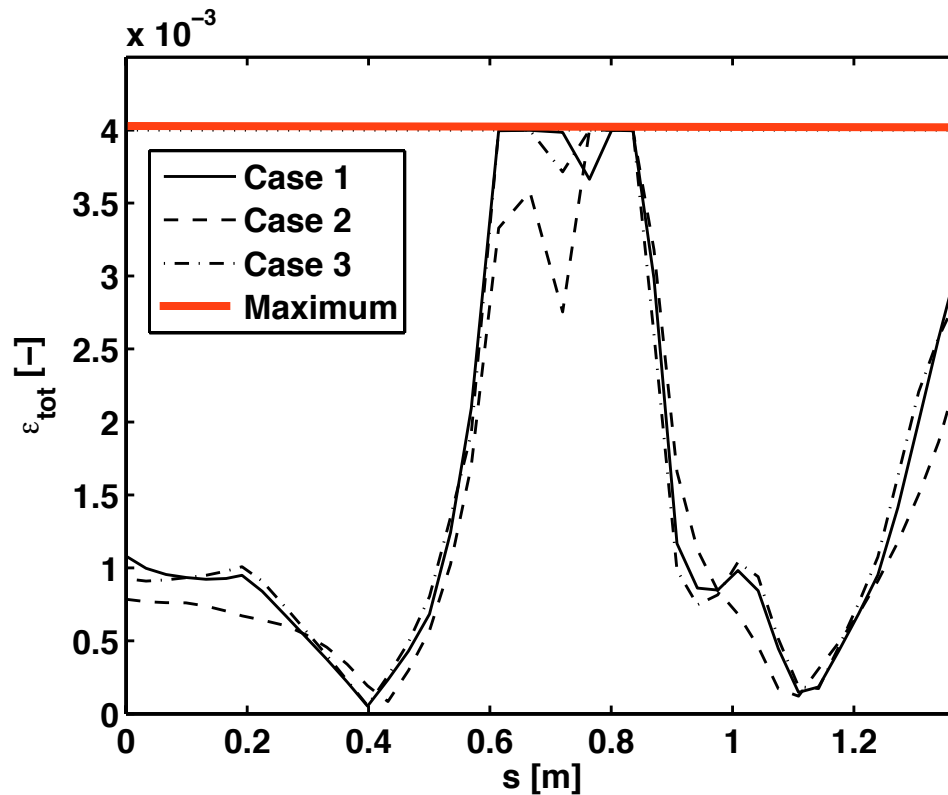
# Curvature Objective

	Case 1	Case 2	Case 3
I	342	351	338

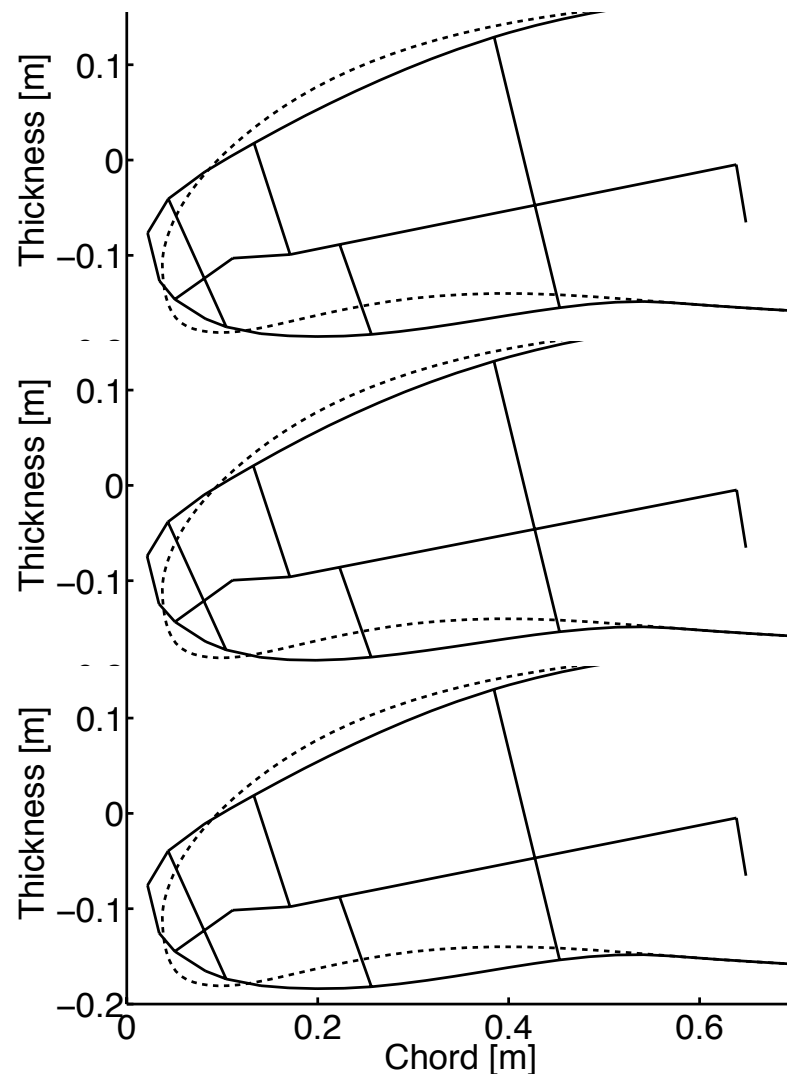


# Applied Skin Strain

- 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



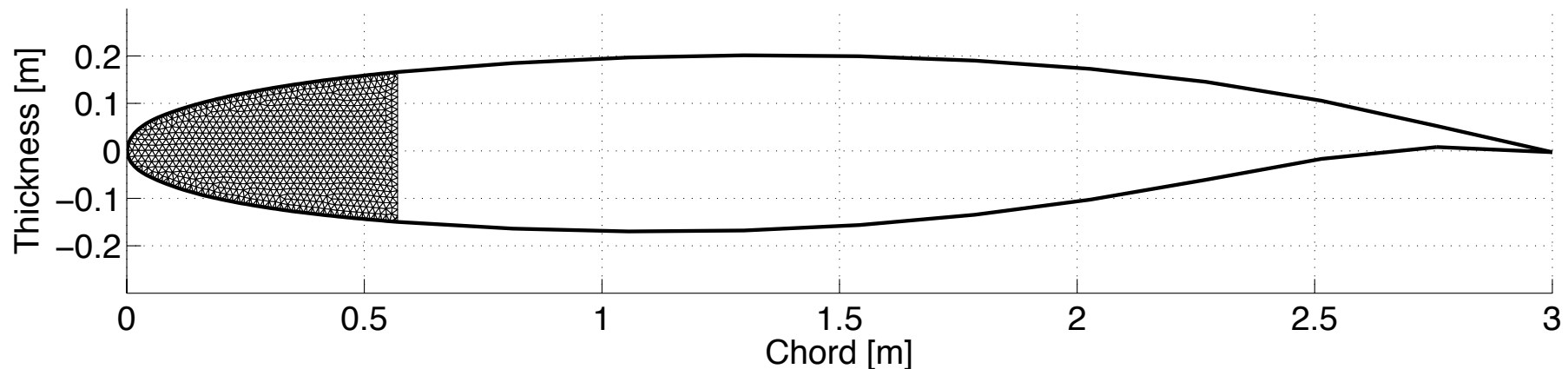
# Actuation Topology Optimisation

## Setup and initial results



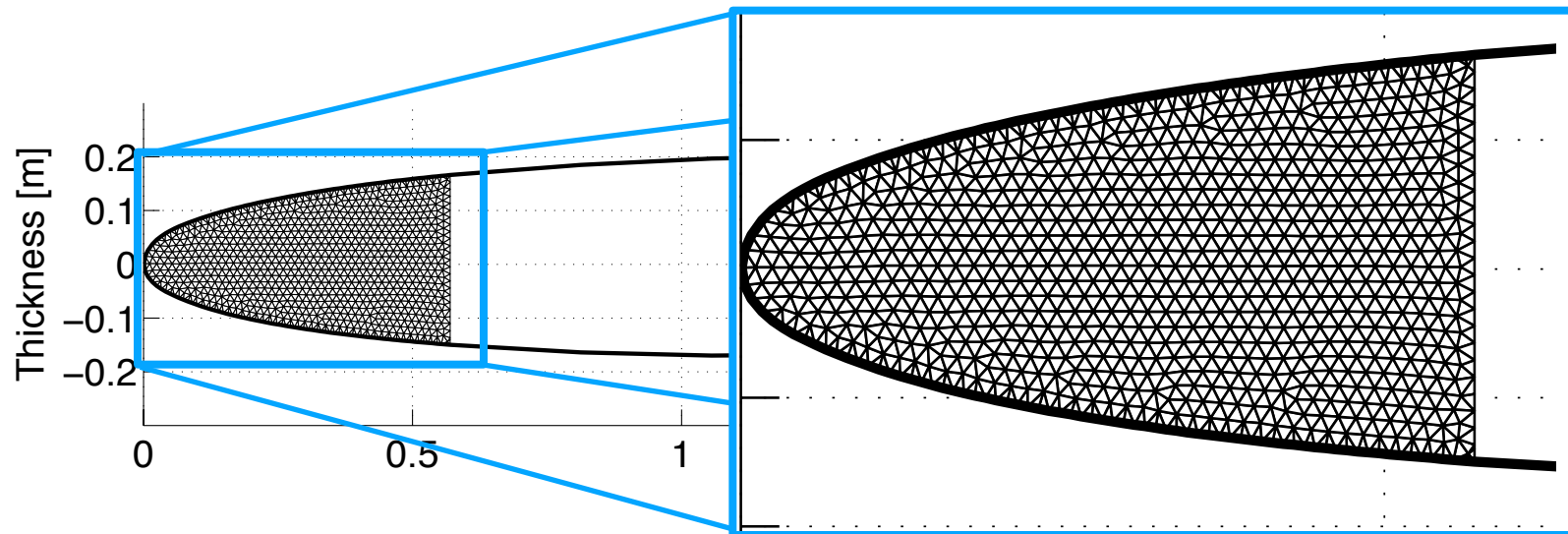
# Actuation Topology Design

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



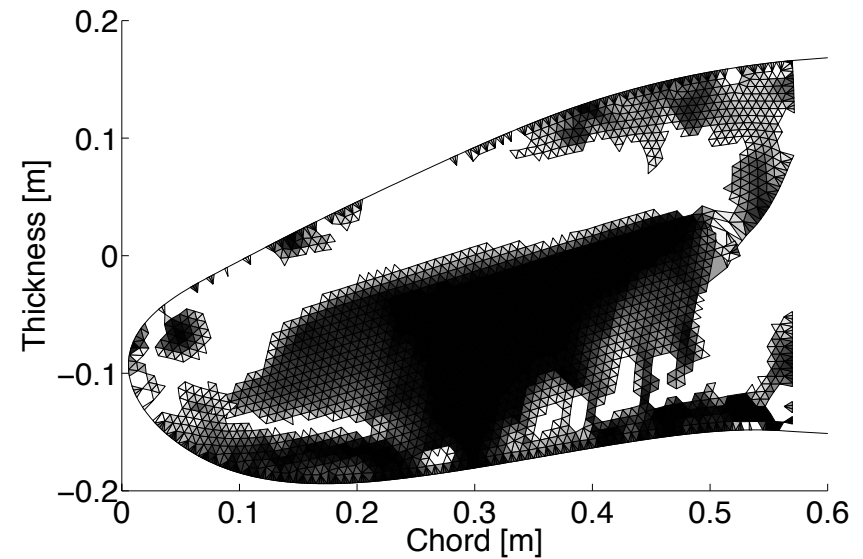
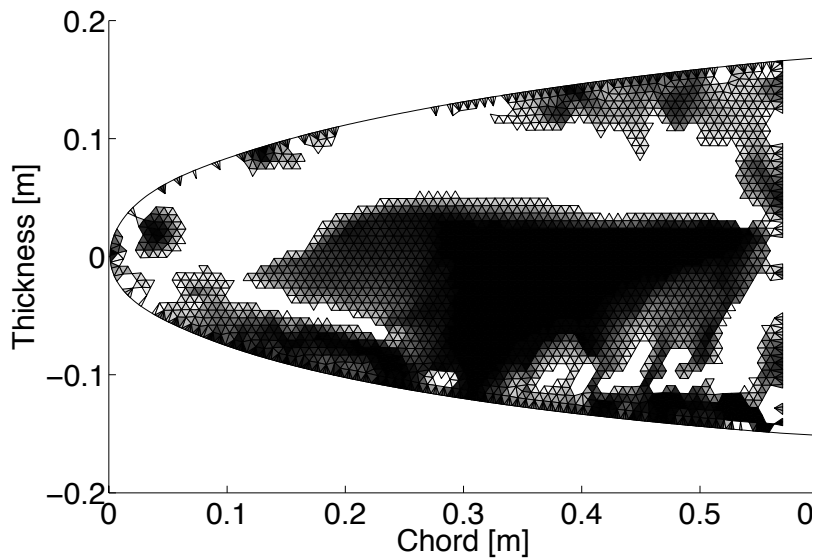
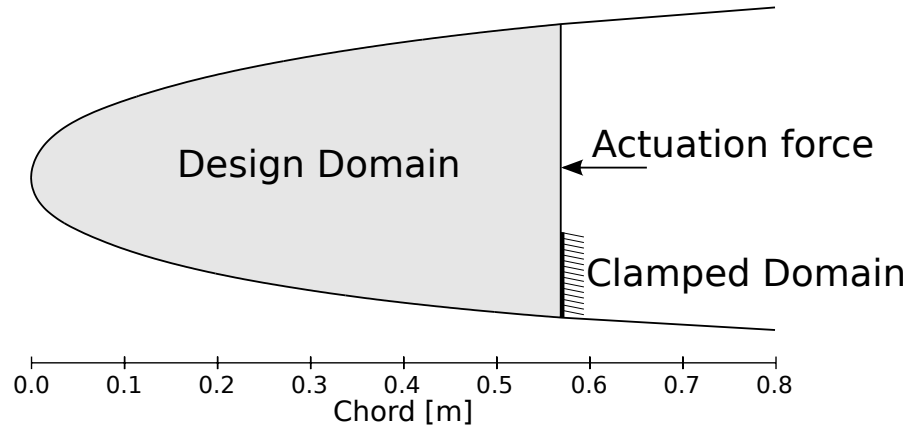
# Actuation Topology Design

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# Initial linear results





The background of the slide is a close-up photograph of a material with a distinct layered or laminated structure. The layers are horizontal and show varying shades of grey, white, and dark brown, suggesting a composite or biological material. A solid blue vertical bar is located on the far left edge of the slide.

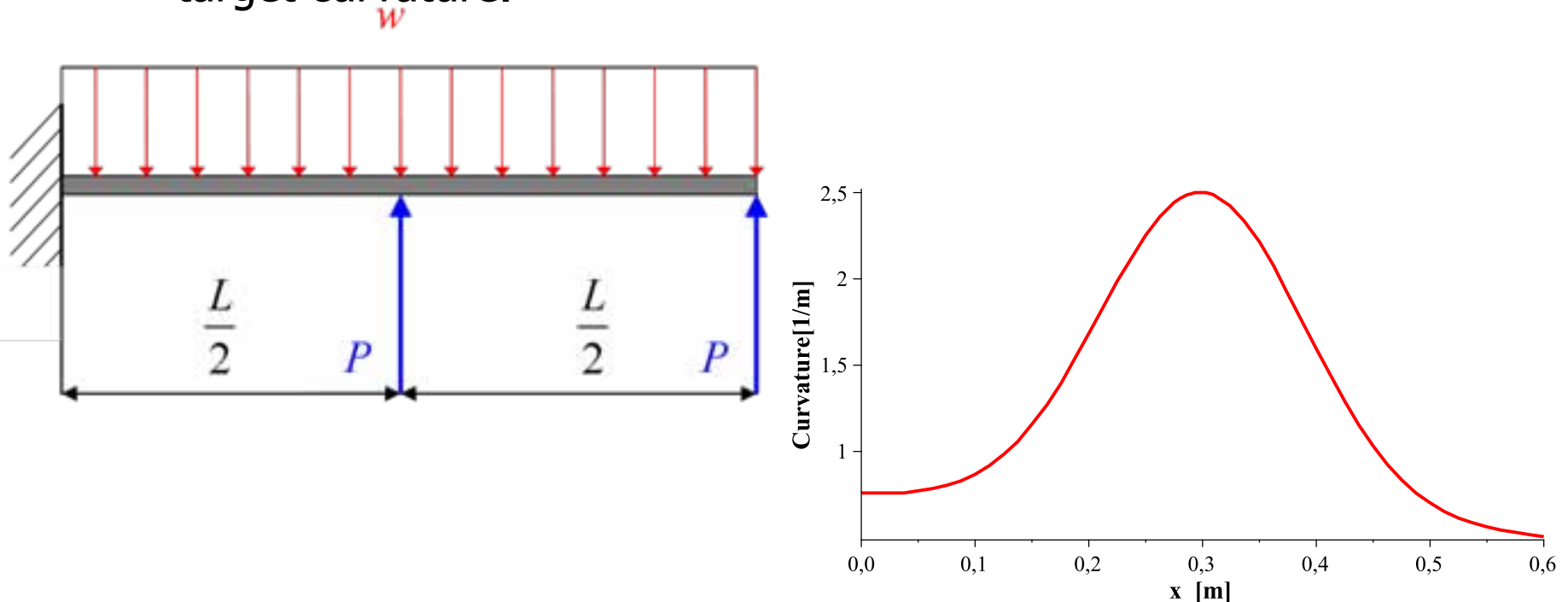
# Test Results

Validating ‘Target Curvature Concept’

by Jaap Dekker MSc

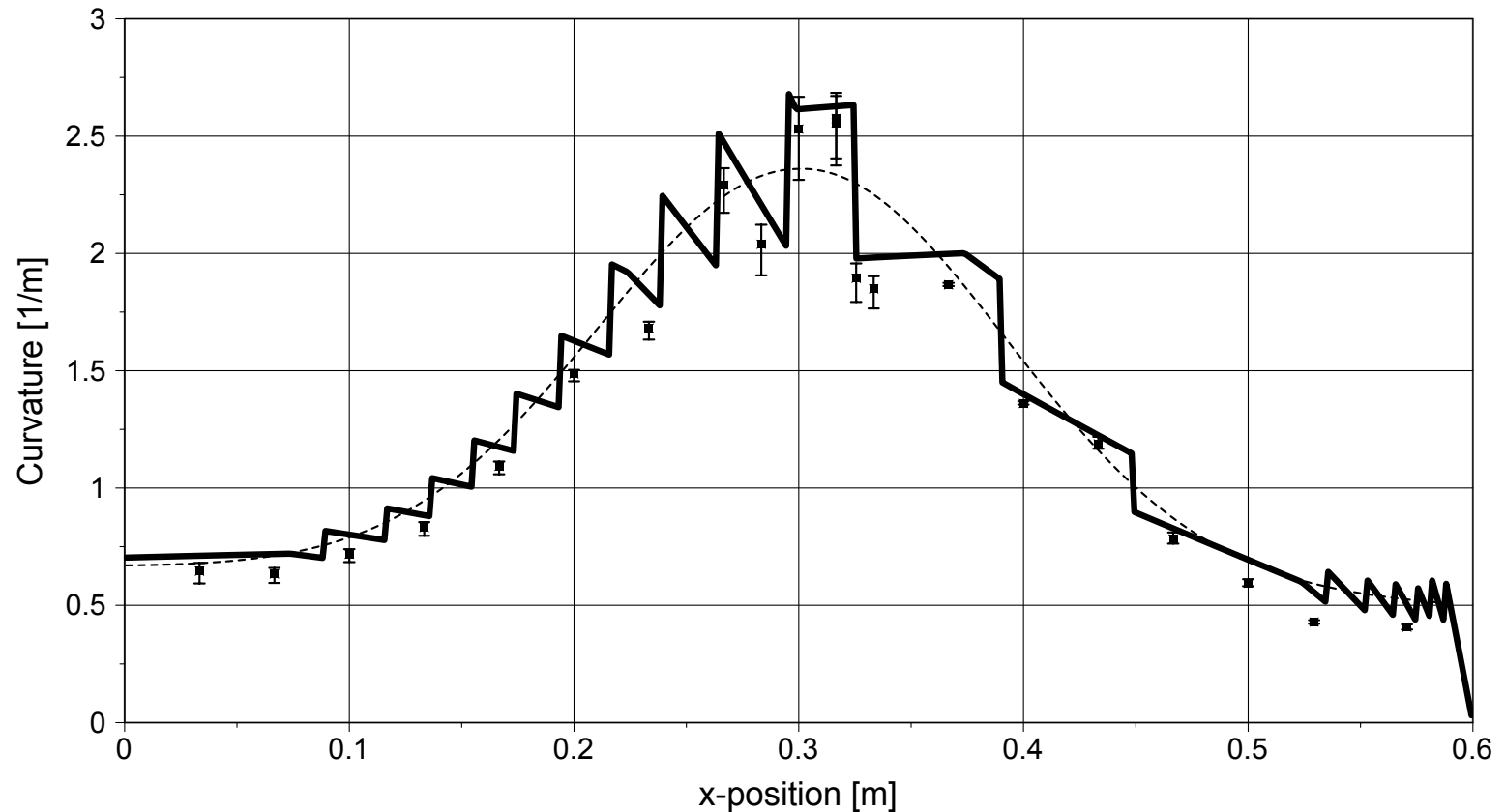
# Design for Target Curvature Concept

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



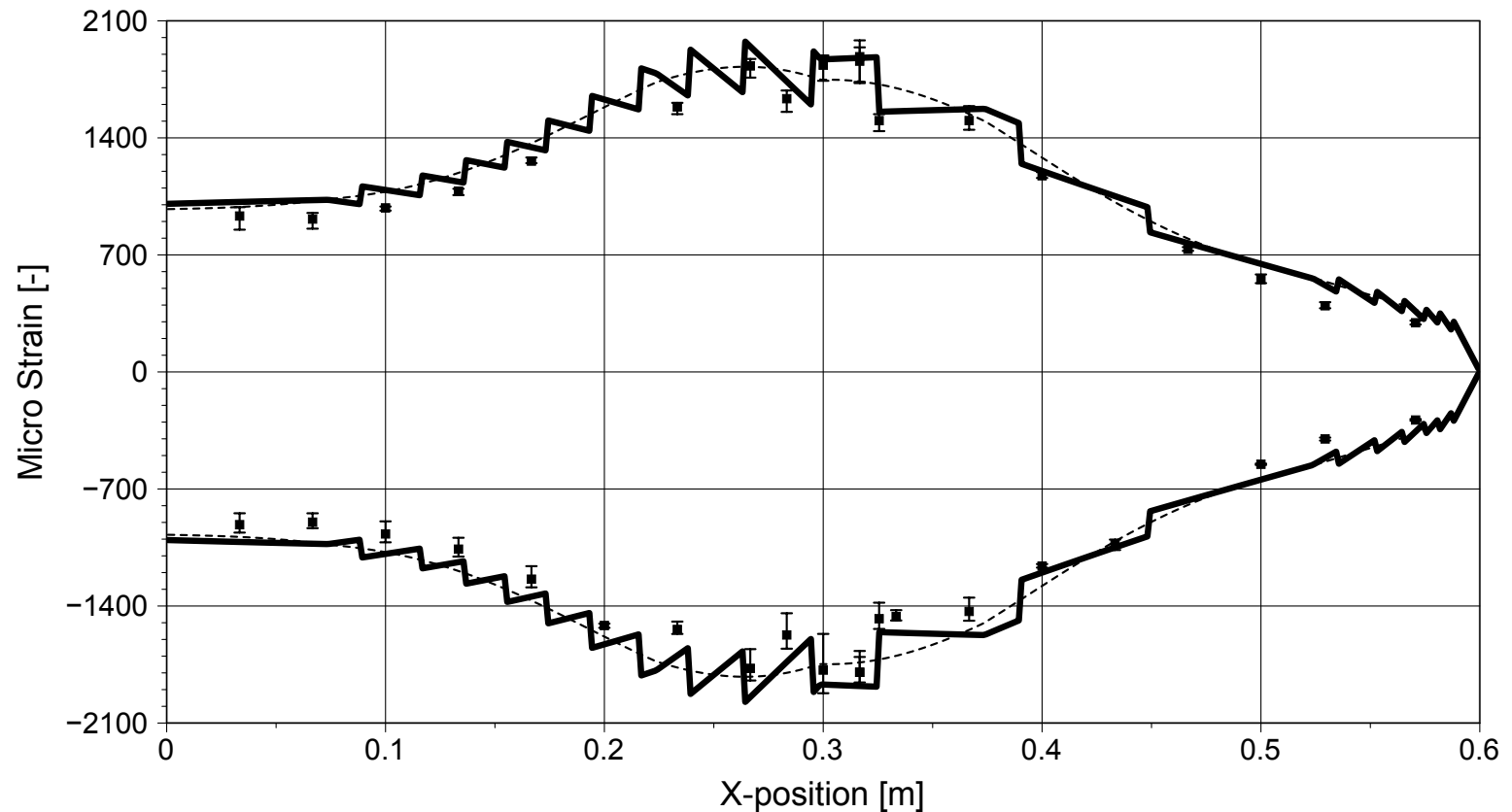
# Curvature and Strain Measurements

- 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 of an argument or process
- 2 the conclusion of a treaty or agreement
- 3 his conclusion was based on supposition

short, brief, pithy; formal

sudden; arbitrary, without warning

## con·clu·sion |kən'kloo' zən|

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.

2 a judgment or decision reached by reasoning; such research group came to a conclusion that the product was safe.

## PHRASES

in conclusion lastly; to sum up; in conclusion it is clear that the market is moving towards a more integrated approach.

jump (or leap) to conclusions make a hasty judgment before hearing all the facts.

ORIGIN late Middle English: from Latin conclusio(n)-, from the verb concludere 'to close, to conclude, last but not least'.

## sum·ma·ry |sə'məri|

noun (pl. -ries)

a brief statement or account of the main points of something: a summary of Chapter 10.

adjective

- 1 dispensing with needless details or formalities; brief: summary financial statement.
- 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·ma·ri·ly |sə'me(a)rə'le; 'sə'mərələ| adverb

sum·ma·ri·ness |sə'mərə'nɪs| 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:

