Embeddable Variable Stiffness Elements for Load Alleviation in Morphing Lift Generating Structures

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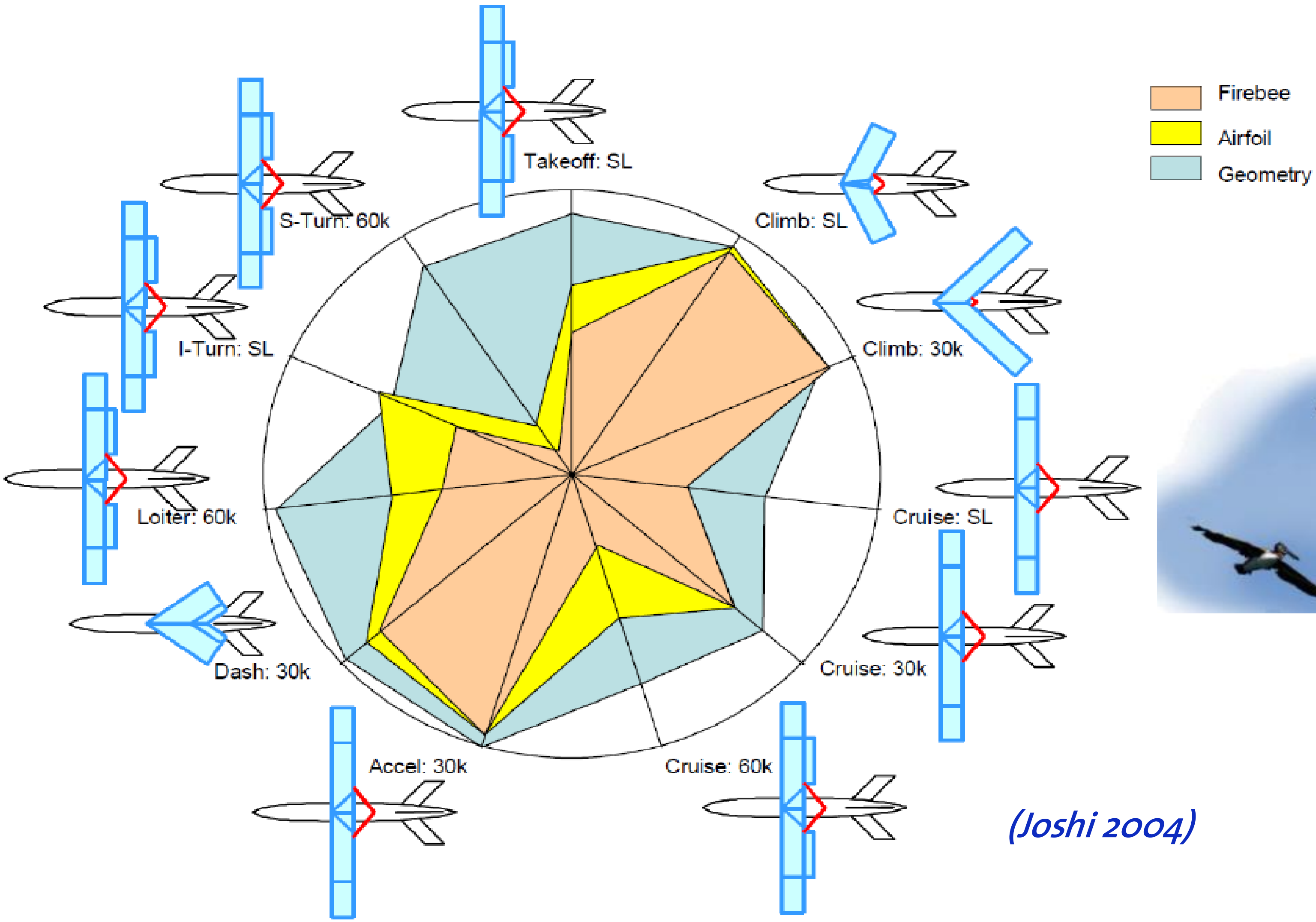
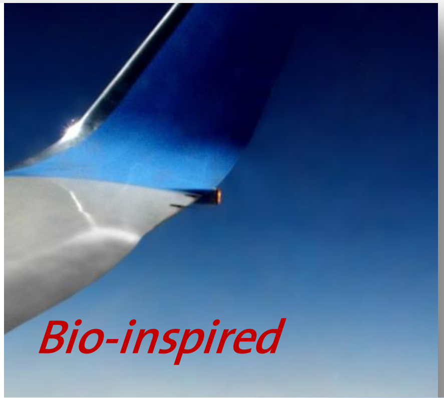
Introduction to morphing: shape adaptation



(Joshi 2004)



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less surface

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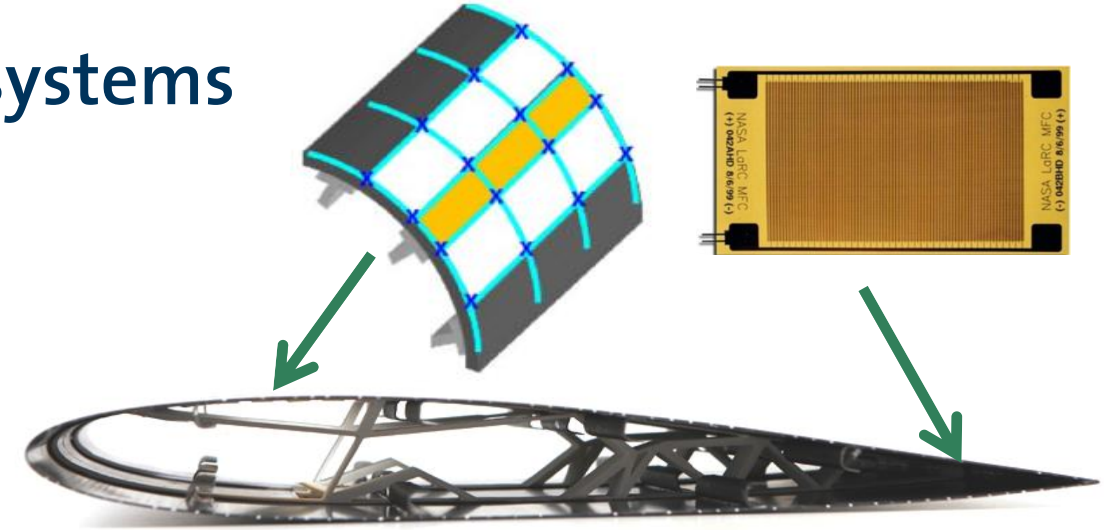
onditions

Morphing with complaint systems



Integration of different functions:

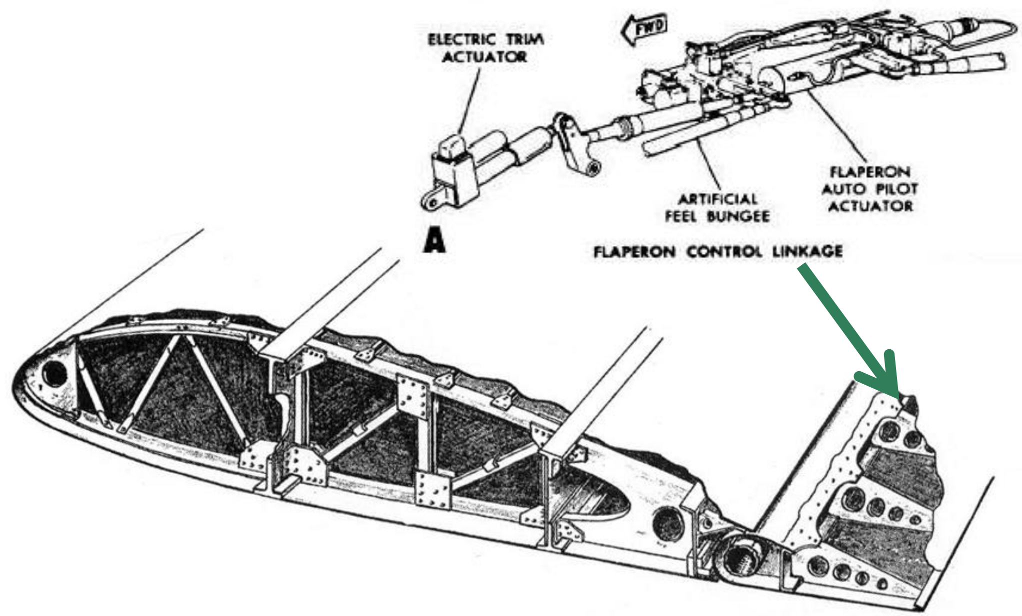
- Structural
- Actuation
- Sensing

} *Smart-adaptation*

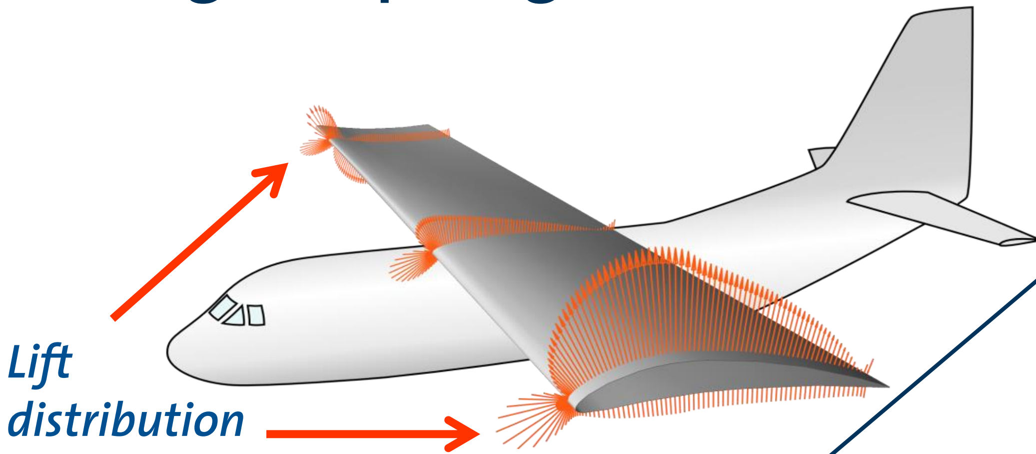
Reduced complexity:

- Joints
- Fixing elements
- No moving parts

} *Robustness*



Wing morphing for load alleviation



Spanwise morphing:

Optimal operation

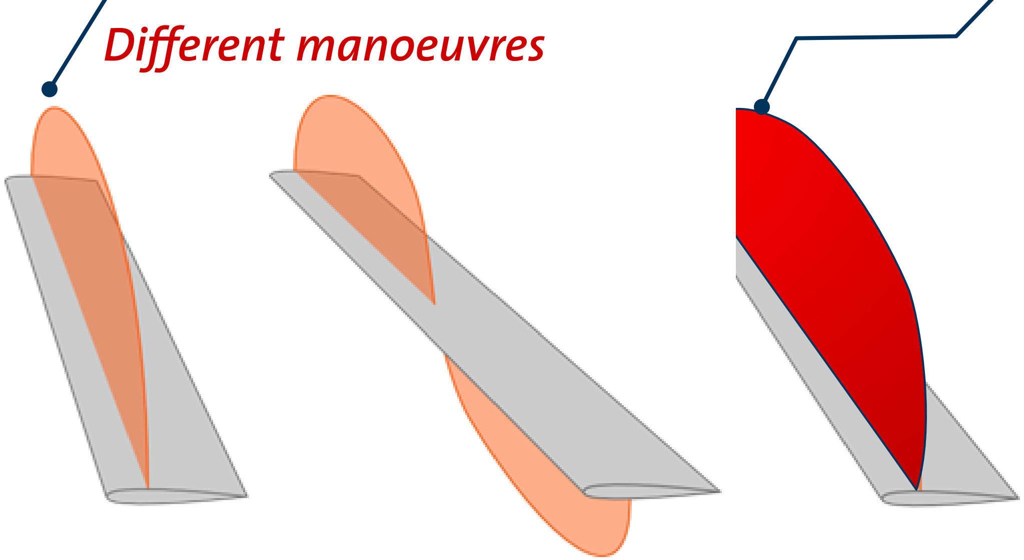
- Morphing wings can adapt to perform optimally at various flight states

Performance gains

- Control c_L can be achieved along the entire wingspan

→ **Load alleviation:**

- Higher structural efficiency
- Less fuel, materials required



Variable stiffness components for morphing

- **Morphing challenge: conflicting stiffness Vs. compliance trade off**

Summary of stiffness variability data of selected material engineering concepts.

Reference	Material	Stiffness variability	Conditions
Shape memory alloys			
[50]	55-NiTiNOL	$E_{hot}/E_{cold} \approx 4$	82–38 °C
Shape memory polymers			
[51]	Polyurethane of polyester polyole series	$E_{cold}/E_{hot} \approx 100$	Below and above $T_g = 55$ °C
[52]	Polystyrene-based	$G_{cold}/G_{hot} \approx 326–517$	at T_{room} and $T = 95$ °C
[53,54]	CTD-DP-5.1 bulk thermoset resin	$E_{cold}/E_{hot} \approx 100$	20–80 °C
Elastic memory composites			
[55]	Reinforcement: carbon-fibre (T300) Resin: styrene-based Veriflex® S, VF 62	$E_{cold}/E_{hot} \approx 79$	23–90 °C
Shape memory composite topology concepts			
[56–58]	Constant-variable stiffness layer laminate Reinforcement: 1095-steel hexagonal elements Resin: polyurethane-based Diaplex 5510	$E_{cold}/E_{hot} \approx 15–77$	35–75 °C
Fluidic flexible matrix composites			
[59]	Tube: $\pm 35°$ carbon fibre, silicone matrix Working fluid: water	$E_{closed}/E_{open} \approx 25.1$	Discrete: closed/open-valve
[59]	F^2MC sheet Four $\pm 35°$ carbon fibre/silicone matrix tubes Sheet resin: silicone	$E_{closed}/E_{open} \approx 21.6$	Discrete: closed/open-valve

Kuder et al. Variable stiffness material and structural concepts for morphing applications, Progress in Aerospace Sciences, 2013

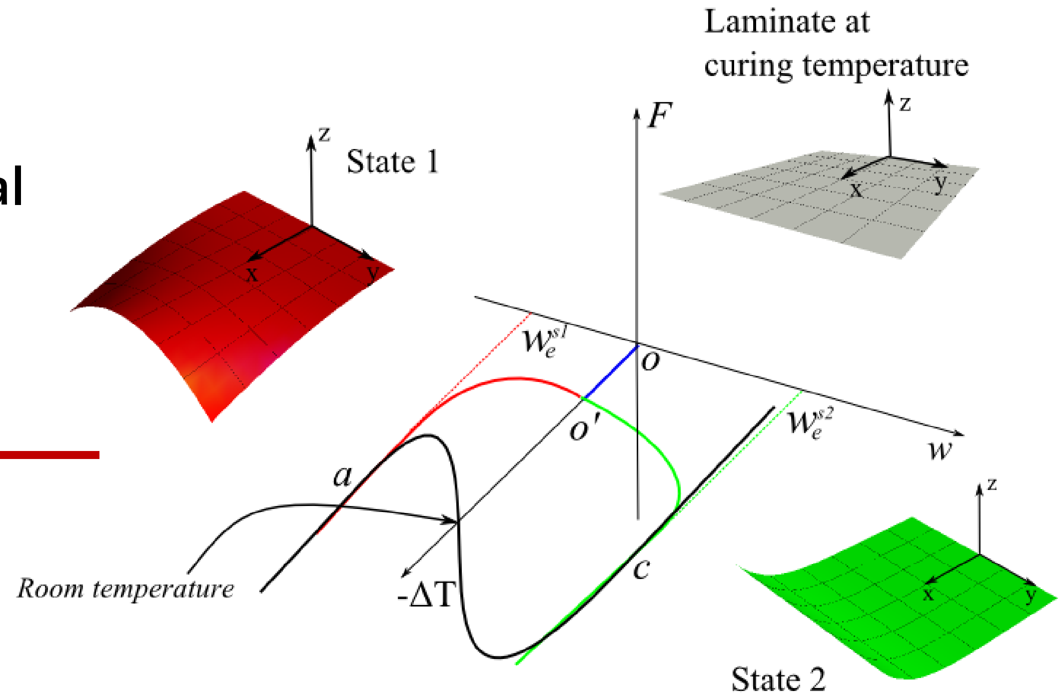
Presentation outline

- Multi-stable composites
- Embeddable multi-stable composites: novel lay-out
- Stable configurations
- Parameter study
- Variable stiffness of multi-stable: longitudinal stiffness
- Integration into a wider structure
- Conclusion and discussion

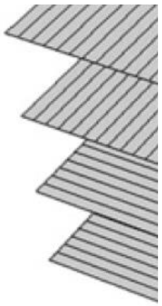
Multi-stable composites

- **Multi-stability arises due to a residual stress field in the laminates**
  - **Pre-stress**
  - **Unsymmetrical lamination** ←
  - **Complex lay-out**

- **For unsymmetric laminated composites residual stresses caused by a mismatch of CTE**



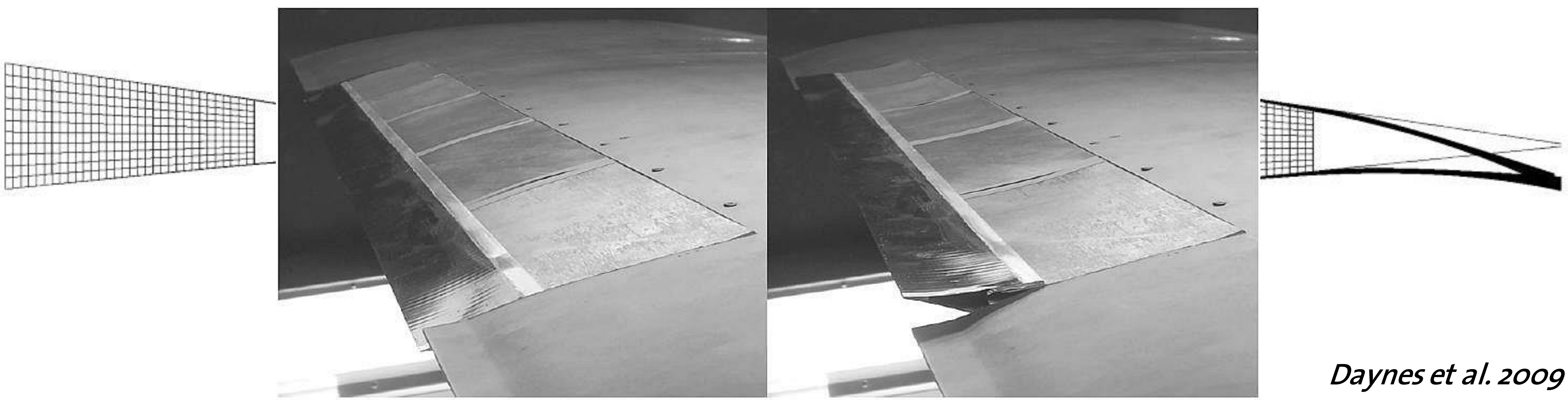
[0,0,90,90]



Multi-stable components in morphing

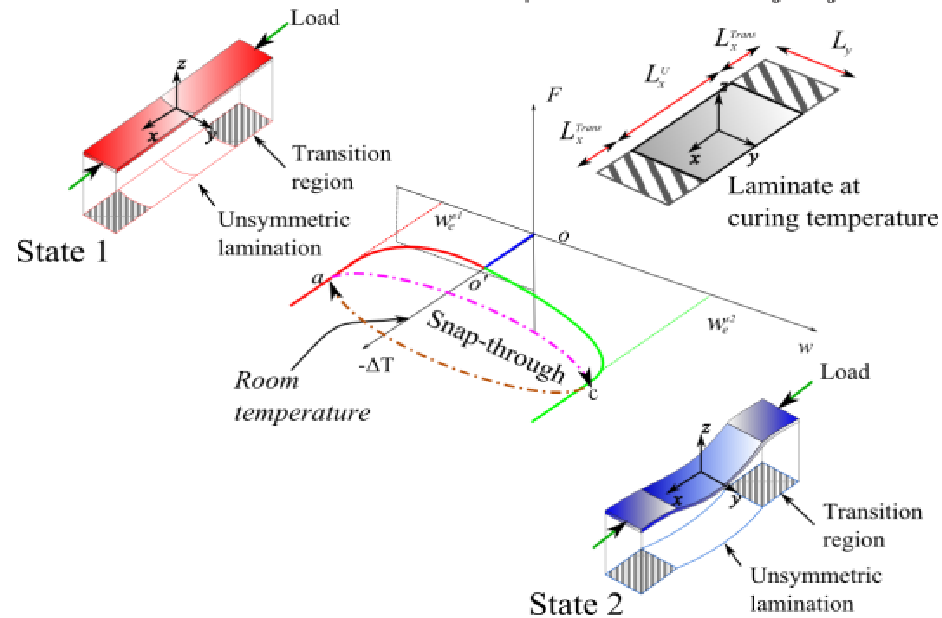
- Multi-stability is been exploited for achieving large deformations
- Multi-stable structures
  - Reduced actuator systems weight and complexity due to bi-stability

State 1 *Configuration morphing* ⟷ *State 2*



Daynes et al. 2009

Structural response variability



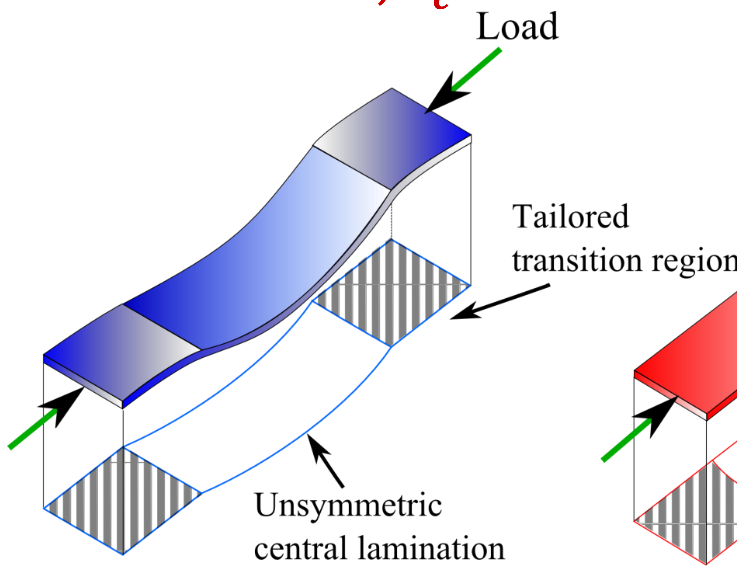
- Stable states exhibit different structural directional response

- Ratio between:

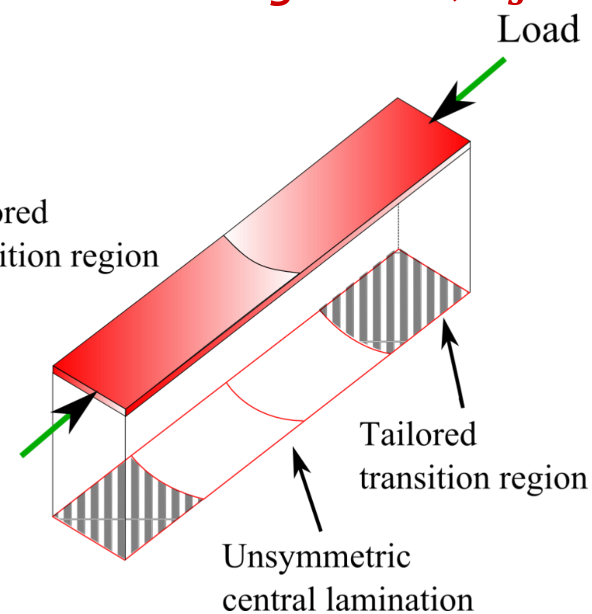
$$k_s / k_c$$

Obtained stiffness variability

Curved state, k_c



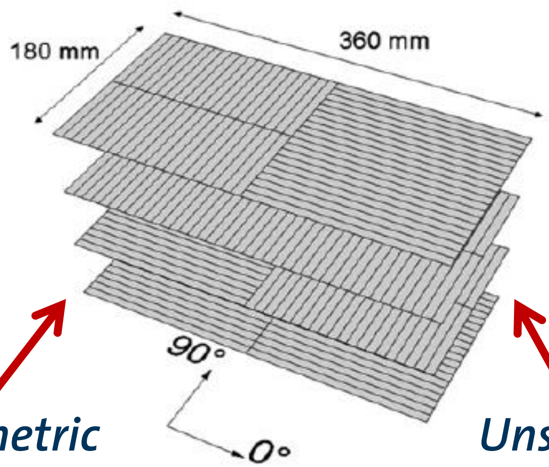
Straight state, k_s



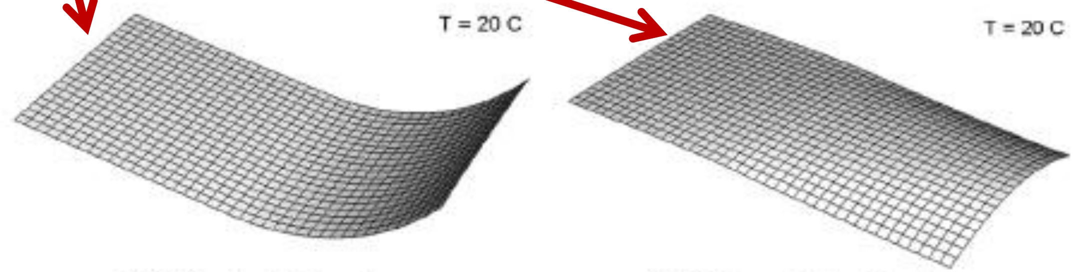
Previous embeddable configurations: cantilevered plates

- Thermally introduced multi-stable with simple cantilever lay-outs as shown below are already investigated:

Can be clamped



Symmetric *Unsymmetric*



(a) First stable shape (b) Second stable shape

Fig. 11. Numerical equilibrium shapes.

Lay-out *curved* *straight*

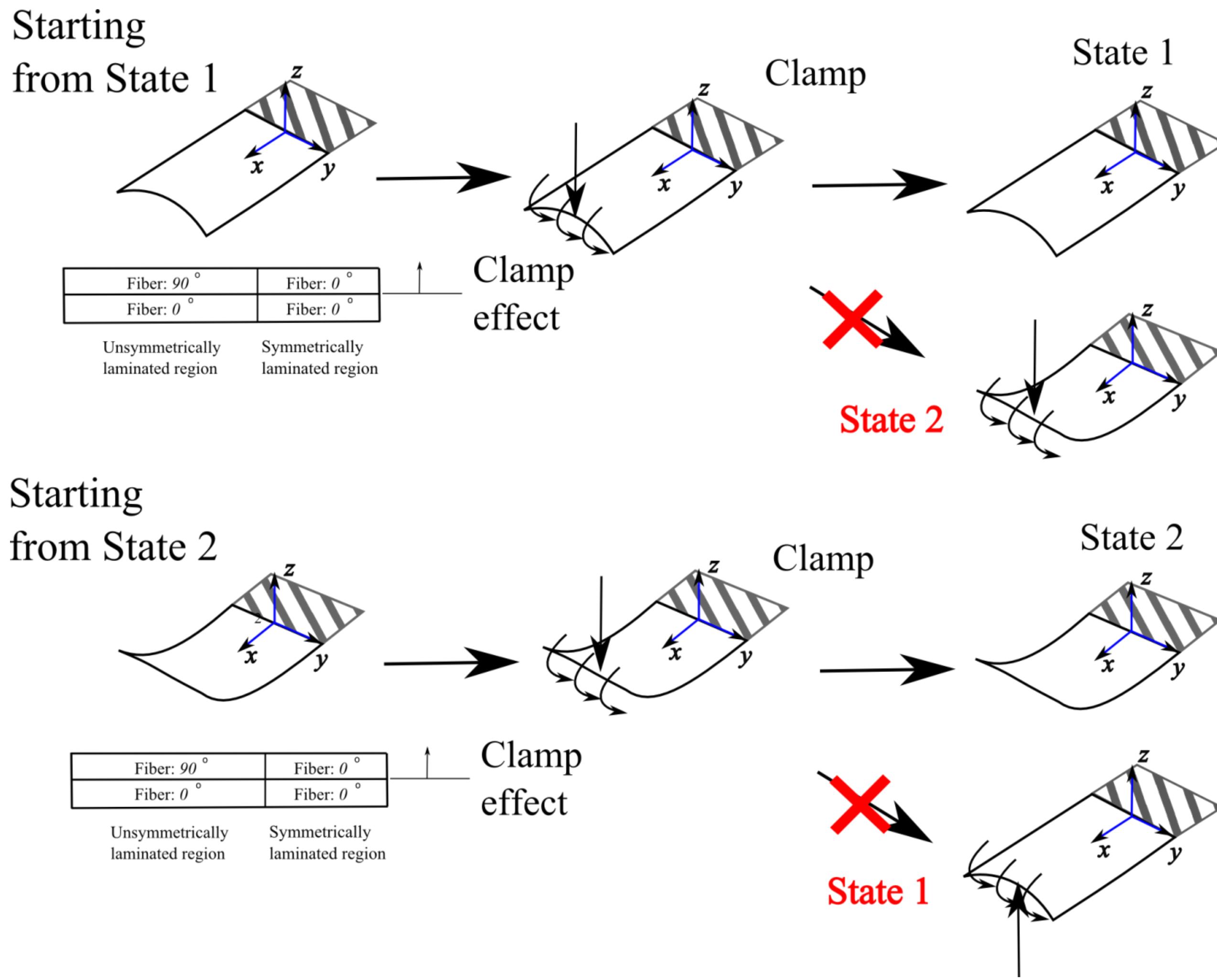
- Symmetric part causes smooth reduction of curvature

[Analysis of thermally induced multistable composites, F. Mattioni, 2007]

Embedding multi-stable components

- For the cantilevered configuration:
  - Simply clamping the other edge results in loss of multi-stability

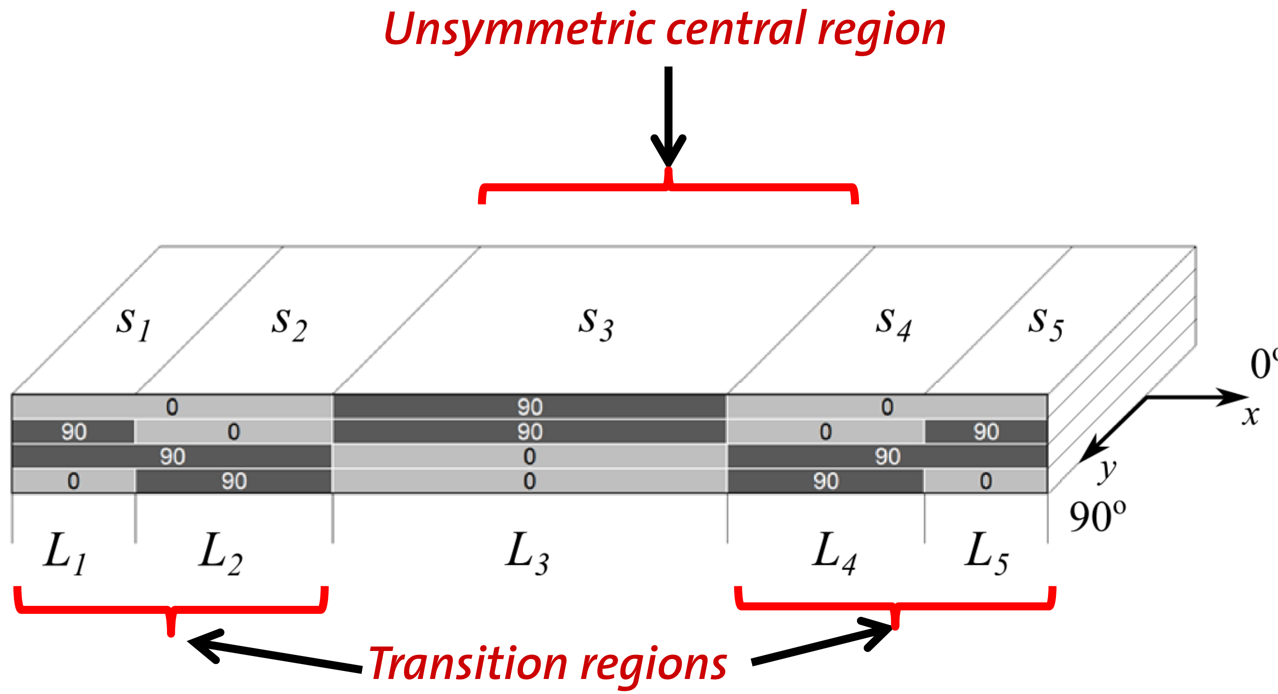
- New lay-out required

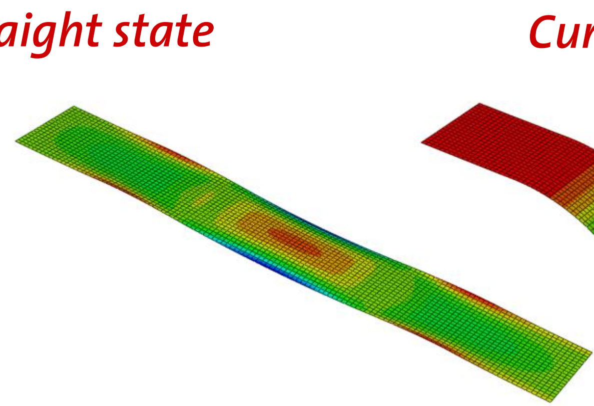


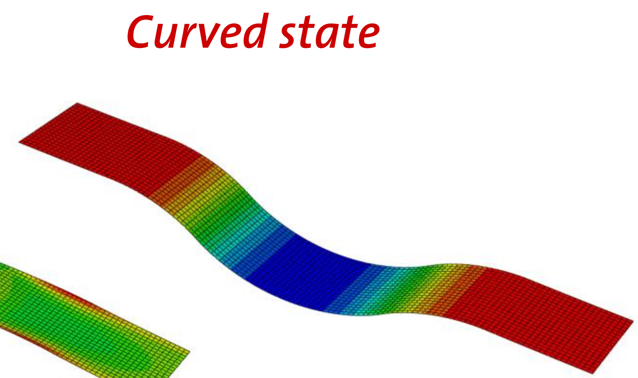
Novel lay-out design

- Introduction of an elastic boundary condition on either side of a main central unsymmetric section

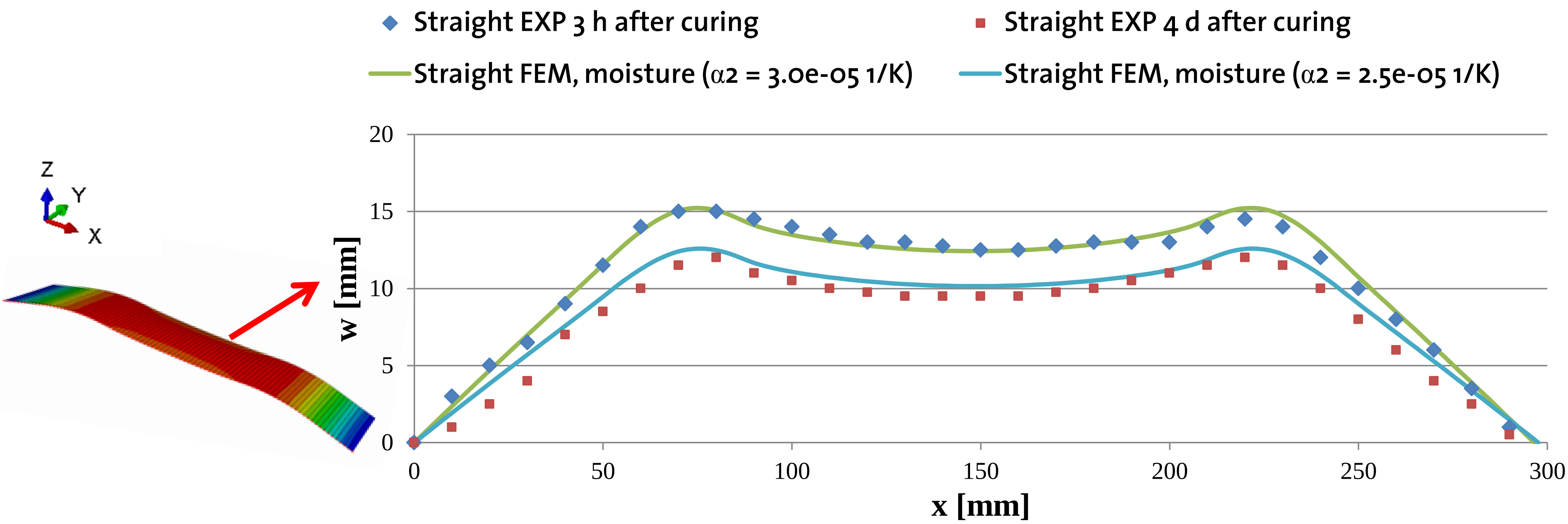
- Transition regions allow for:
  - Maintaining multi-stability when embedded by clamping both short edges





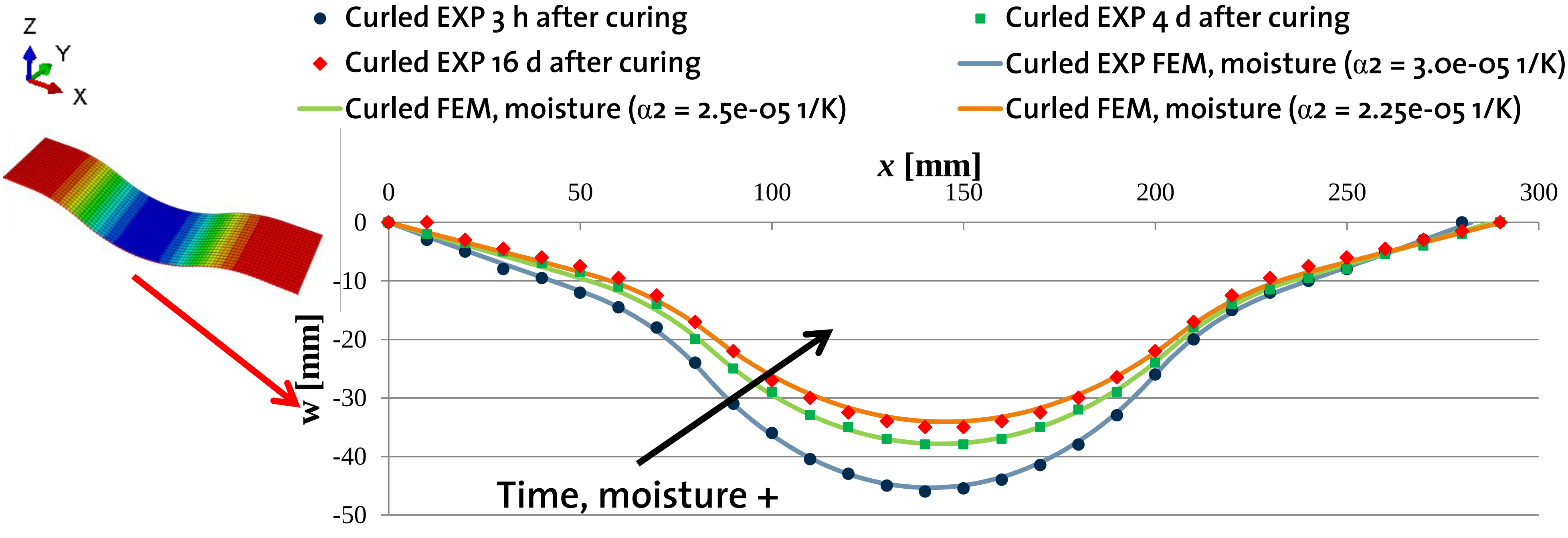


Stable configurations: straight state



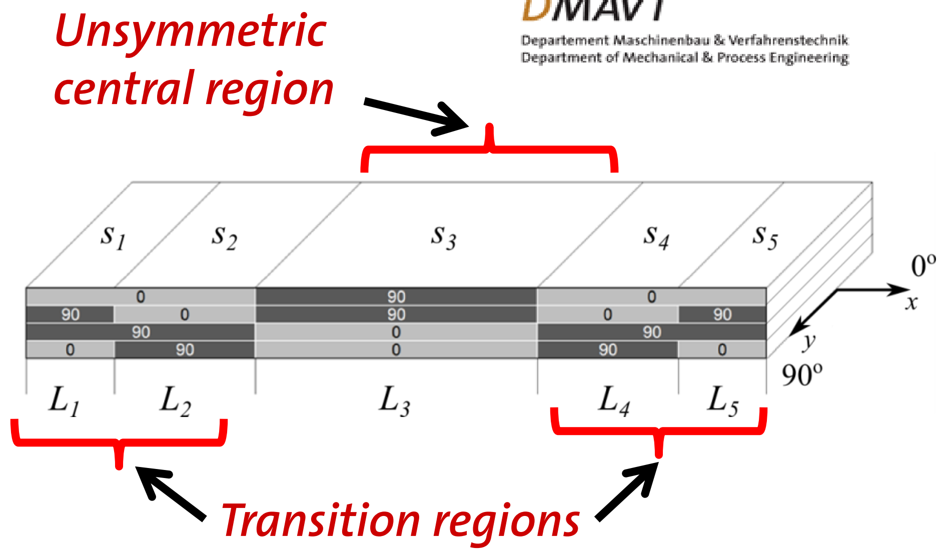
- All produced specimens showed a multi-stable behaviour
- Moisture expansion (time dependent) has a significant influence to the shape and can be considered with a reduction of the thermal expansion coefficient in the FEA
- For the further FEA validation the α_2 is chosen according to this data

Stable configurations: curved state



- Good agreement achieve for shape prediction for both stable states

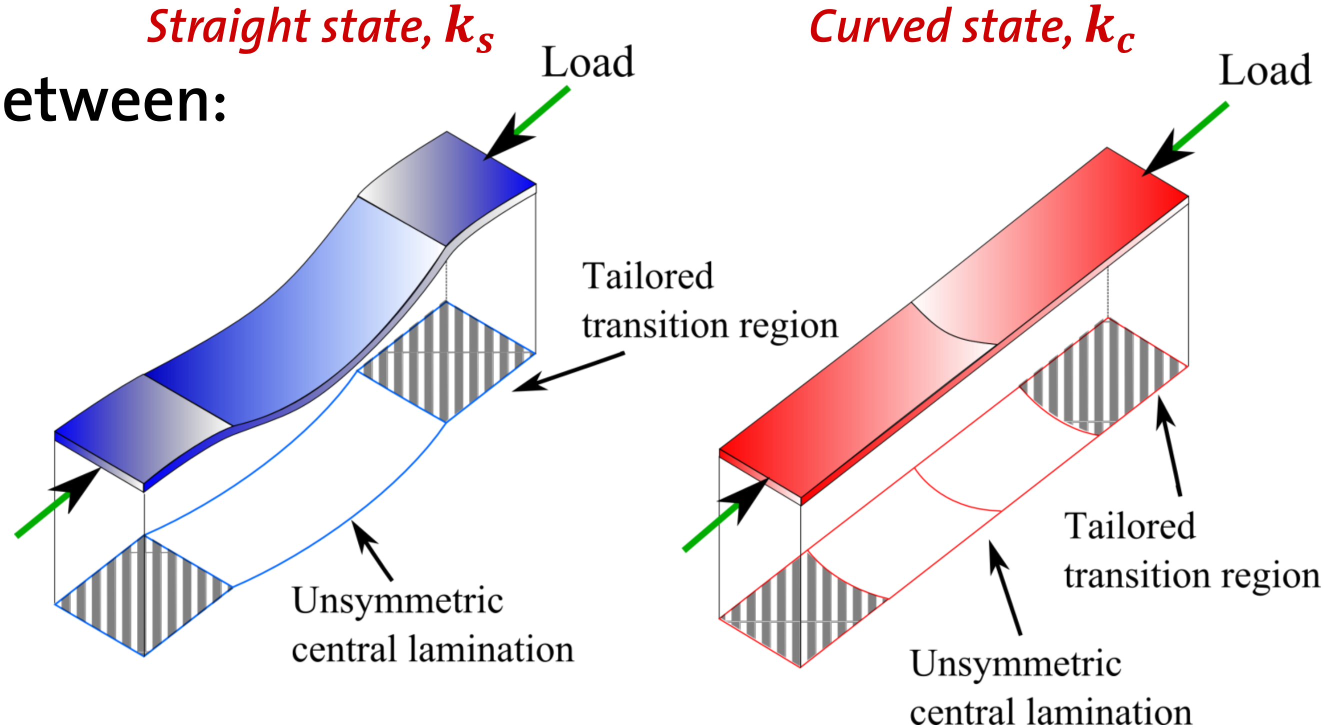
Longitudinal stiffness tests



- Show variability in structural response between states
- Objective ->ratio between:

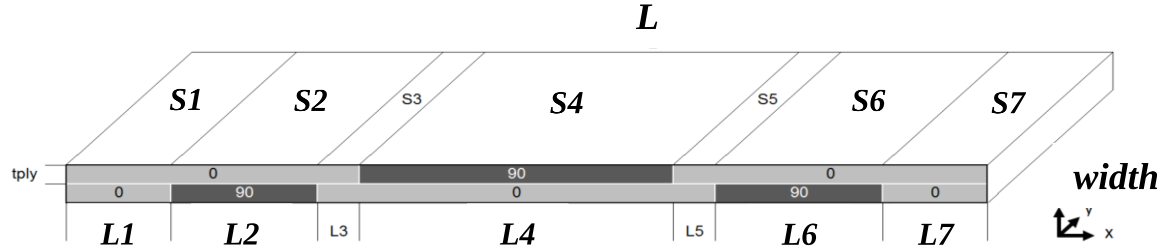
$$k_s / k_c$$

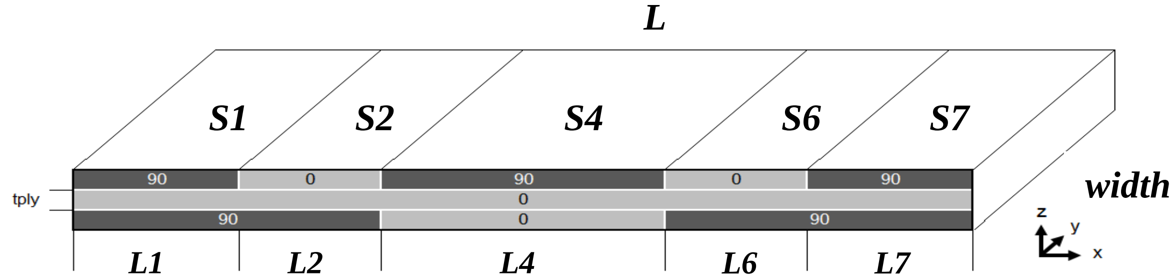
- Lay-out design
  - Region length
  - Region lay-up

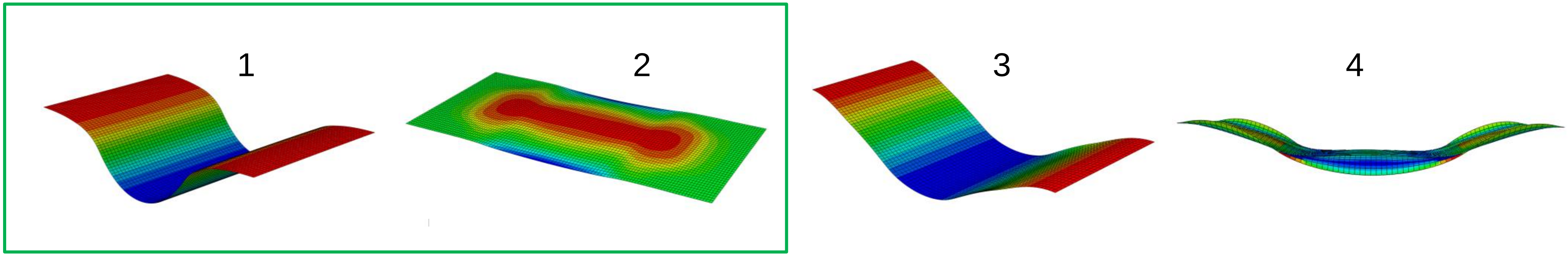


Parameter study: stiffness variability

- Lay-out designs are studied:
  - Two ply
  - Three ply
- 4 different shapes are found:







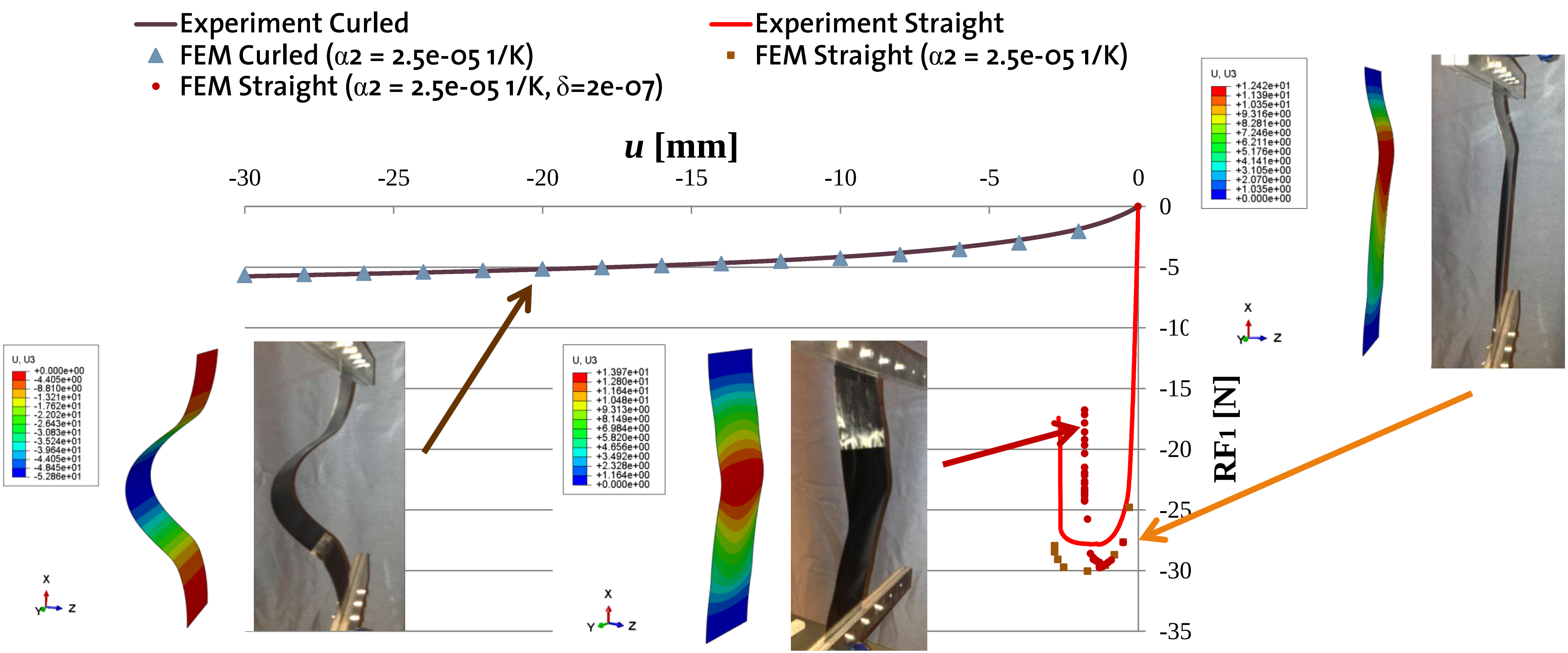
Parameter study – results

- The longitudinal stiffness is investigated with a simulated compression test.

Specimen	1	2	3	6	7	9	11	12	13	14	19
Chart	14	15	16	17	18	19	20	21	22	23	24
Plies	2	2	2	2	2	2	2	2	2	3	3
$k_{straight}$ [N/mm]	19.97	11.53	3.81	89.00	159.20	84.35	117.83	180.96	166.30	9.83	7.57
k_{cuvled} [N/mm]	0.36	0.24	0.12	2.25	1.44	2.26	3.59	2.30	1.14	4.83	6.77
$k_{straight}/k_{curved}$ [-]	55.57	47.77	31.27	39.60	110.4	37.36	32.80	94.12	145.52	2.03	1.12
L [mm]	450.0	450.0	450.0	300.0	300.0	300.0	280.0	280.0	280.0	450.0	400.0
width [mm]	225.0	150.0	75.0	225.0	150.0	225.0	225.0	150.0	75.0	225.0	150.0
L4/L2 [-]	2	2	2	3	3	2	4	4	4	2	2

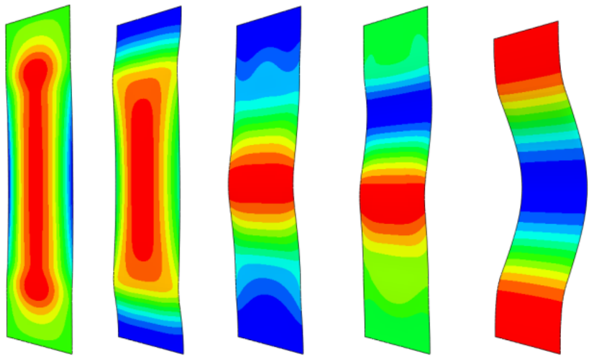
- A significant change in stiffness can be seen in each case, best results for ***2 ply***

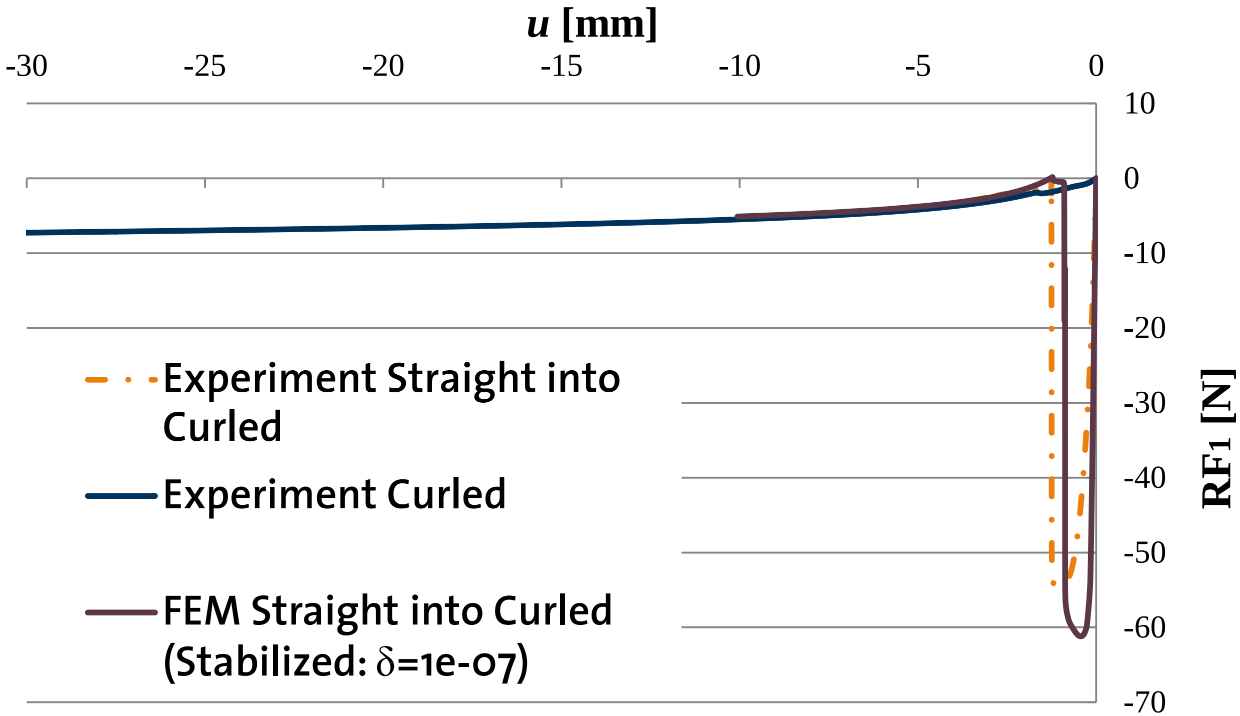
Experimental validation – Longitudinal stiffness (1)



- The experimental data are in good agreement to the FE simulation
- STABILIZED option is need to simulate the post-buckling behaviour

Experimental validation – Longitudinal stiffness (2)

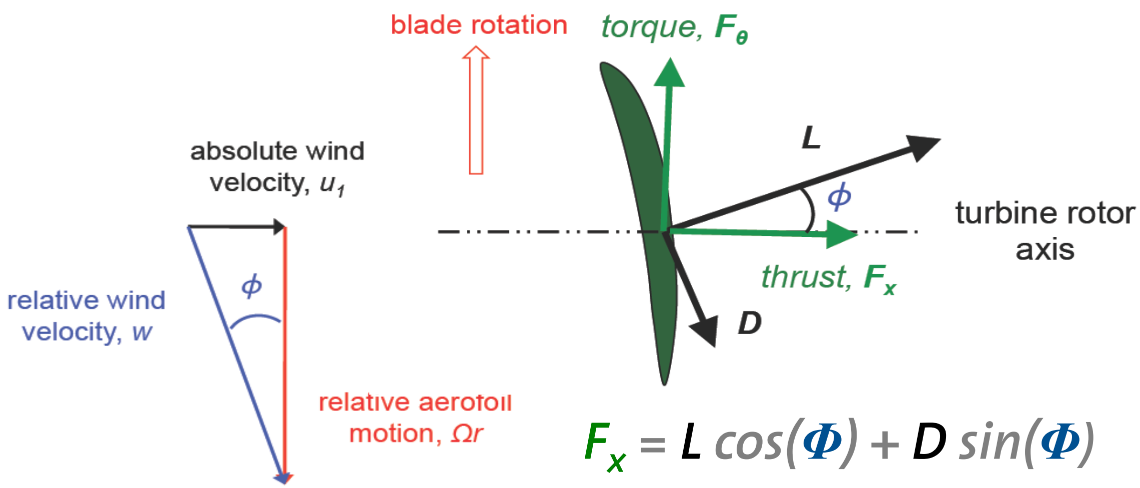




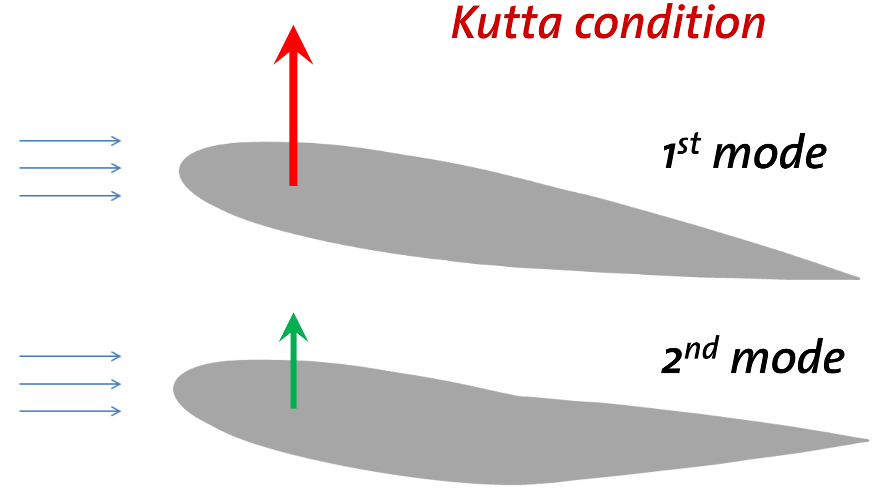
- Snaps from straight into curled state by introducing in-plane loads
- Snap instead of buckling → "*Fail Safe*"

Load alleviation mechanism

- GOAL: passive load alleviation for wing structures: wind turbine blades
  - Protection for rapidly changing aerodynamic : gusts
- Requirement for bending stiffness an strength can be reduced
  - Save costs and weight, an increased fatigue life
- IDEA: reducing the thrust by decreasing the camber of the airfoil (maintain low drag)

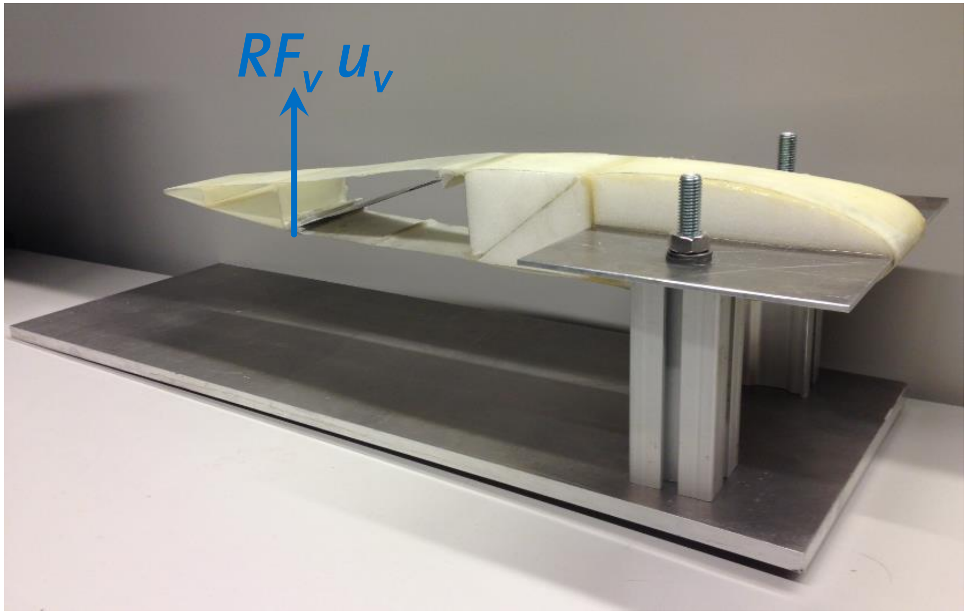


$$F_x = L\cos(\Phi) + D\sin(\Phi)$$



Integration into wider structure -1st Demonstrator

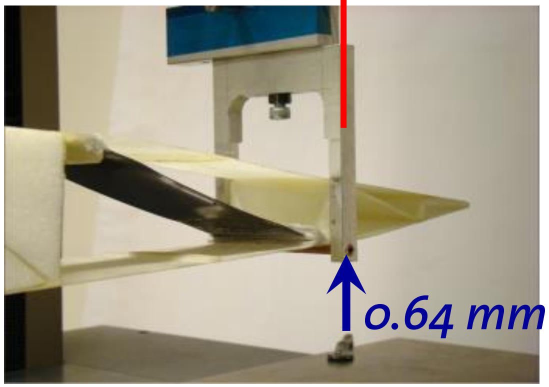
Passive load alleviation aerofoil: inextensible skin

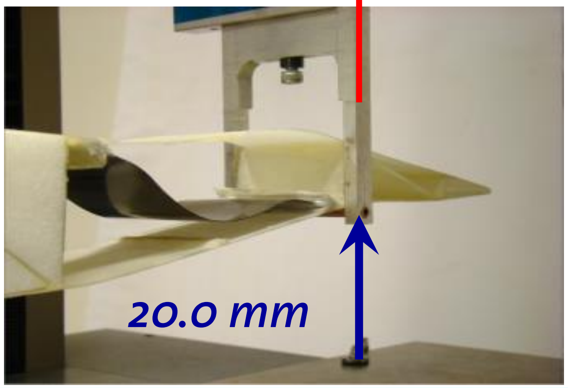


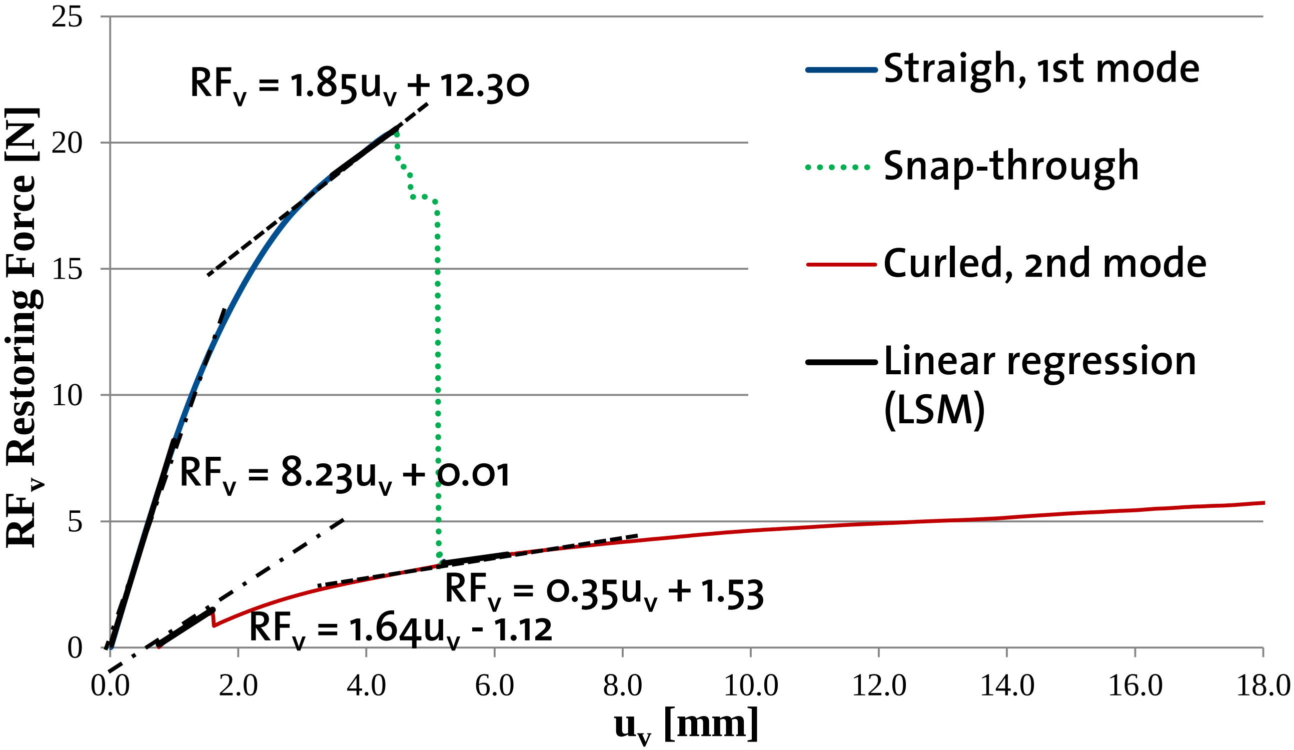
- NACA 0012, chord length 500 mm
- Skin and conventional rib
  - GFRP
  - 0.5 mm thickness
- Front reinforced with foam
  - Assumed to be rigid
- Reaction force of a pressure load of the compliant part is assumed to be acting at the second web at the bottom skin

Integration into wider structure - 1st Demonstrator

- Experimental Testing







- **Stiffness variability:**
  - Small displacements $\rightarrow$ $\left. k_s / k_c \right|_{small} = 5$
  - Large displacements $\rightarrow$ $\left. k_s / k_c \right|_{large} = 5.5$

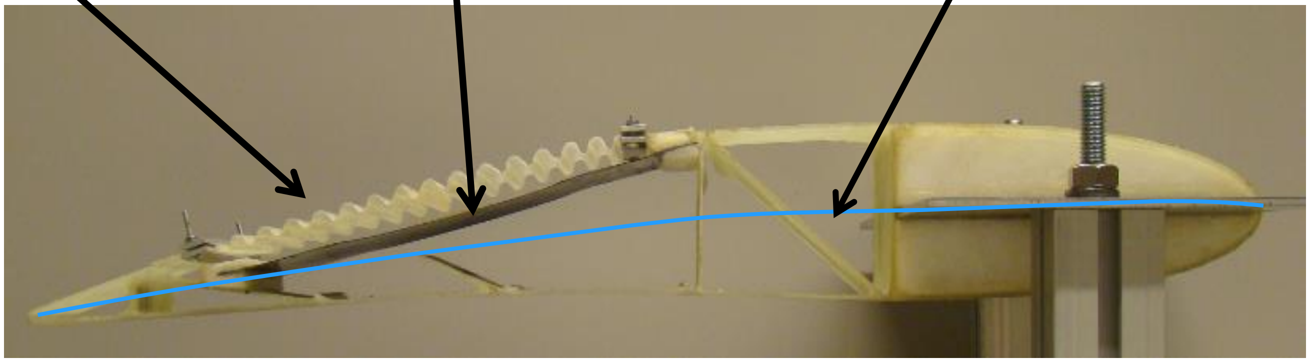
Integration into wider structure - 2nd Demonstrator

- Improved demonstrator

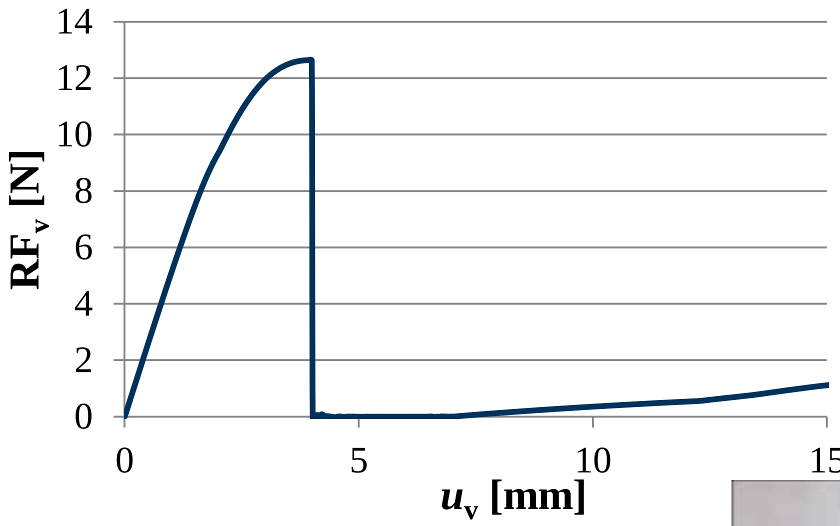
Corrugation [2] for proper aerodynamic shape:
Extensible skin

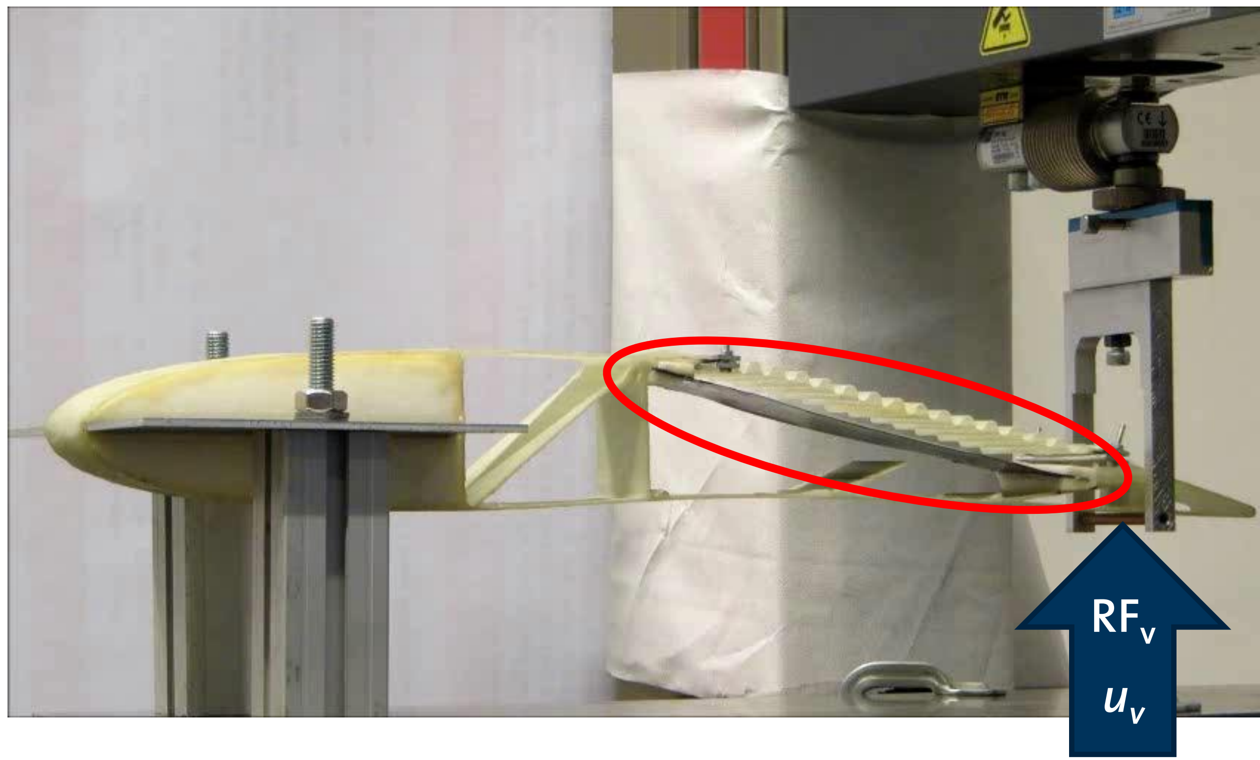
Restriction of 2nd mode:
Increased stiffness

Cambered aerofoil in 1st mode

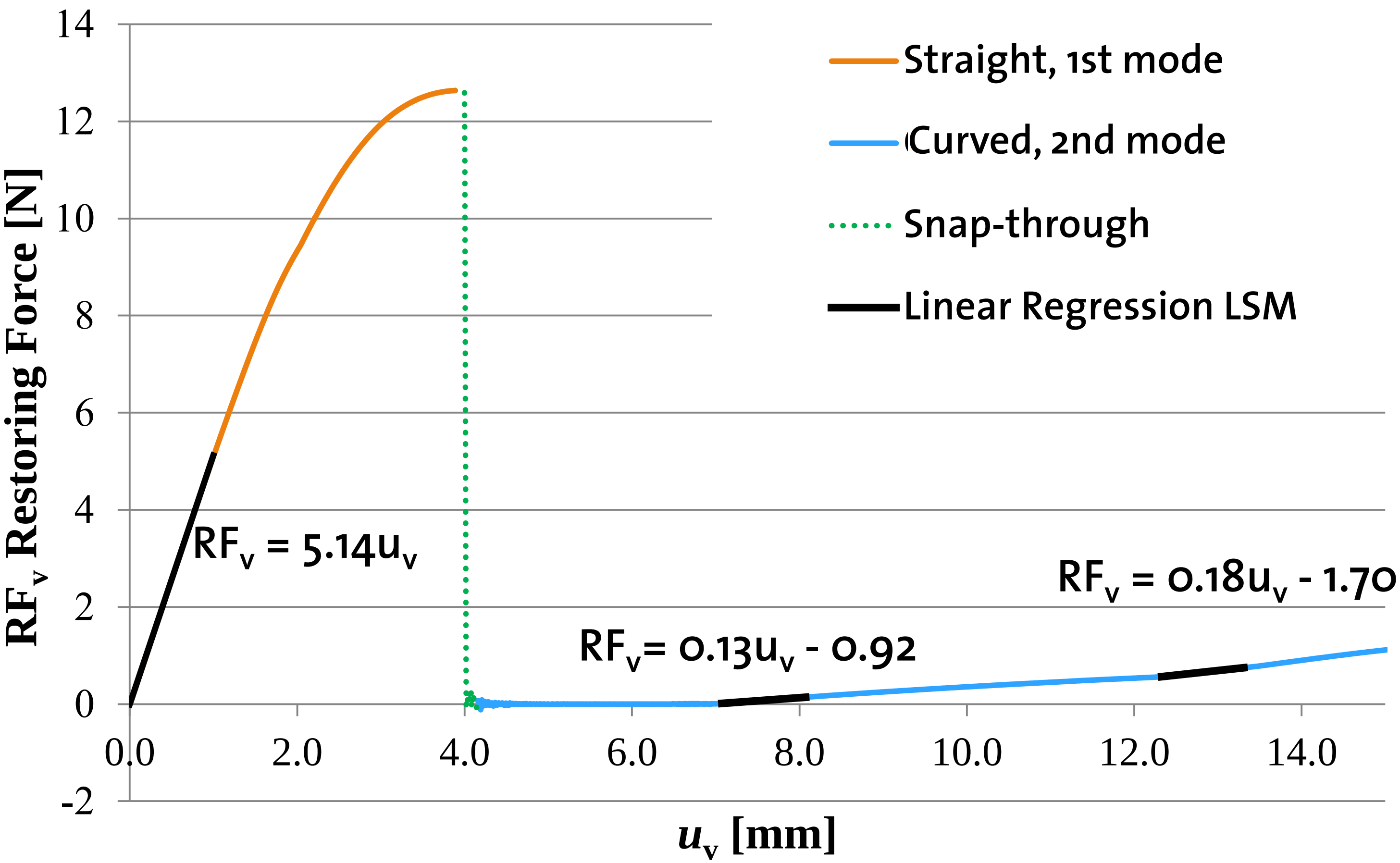


[2] U. Stebler, Construction of a 3-D Compliant Wing demonstrator, ETH Zurich: Semester Thesis, 2013.


14
12
10
8
6
4
2
0
RF_v [N]
0
5
10
15
u_v [mm]


RF_v
u_v

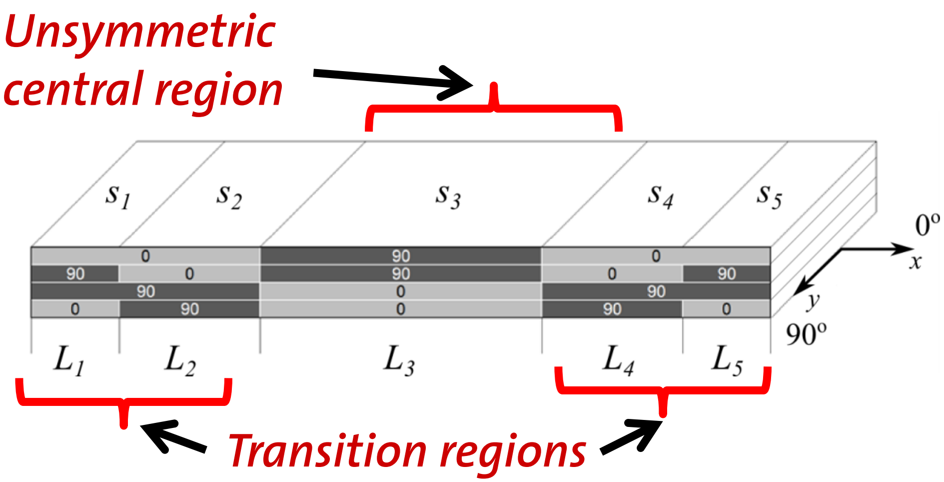
Integration into wider structure - 2nd Demonstrator



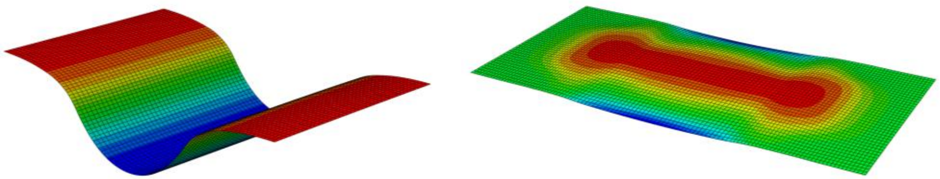
$$k_s/k_c\Big|_{small} \approx 40$$

Conclusions

- Embeddable variable stiffness elements exploiting multi-stability are realised through a novel lay-out featuring symmetric unsymmetric regions are presented

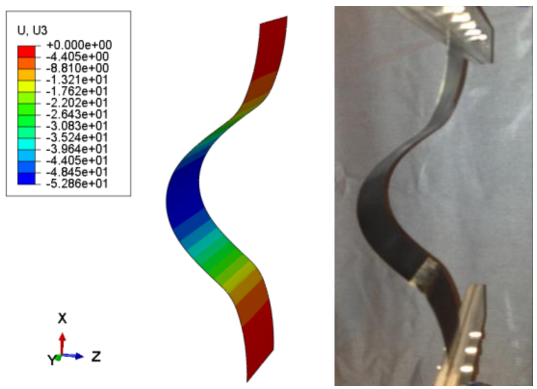


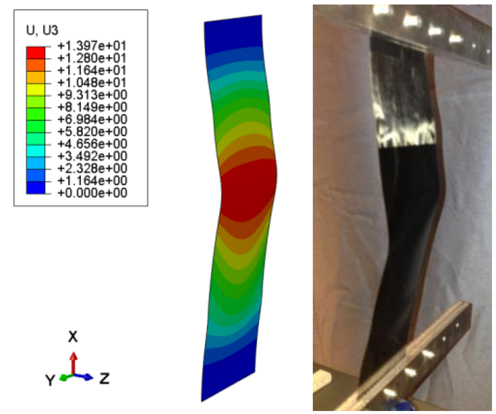
- Parameter study:
  - Adequate lay-out design shows multi-stability with a significant change in stiffness in different states
  - The stiffness can be tailored



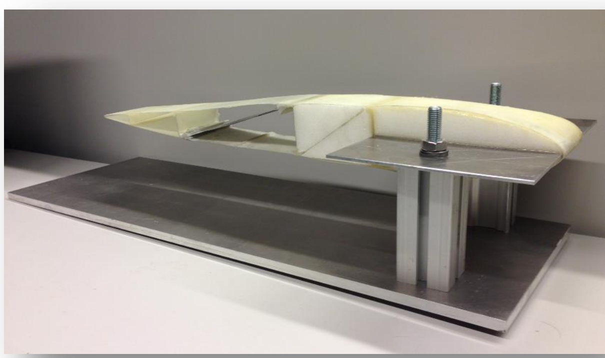
Conclusions

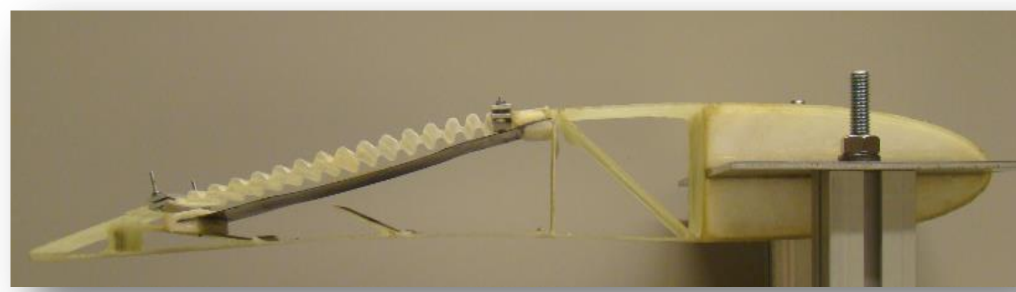
- Experimental validation show good agreement to FE results:
  - Shape
  - Compression test
  - Snap-through





- Two demonstrator proving feasibility of using bi-stable variable stiffness elements for load alleviation in lift generating structures





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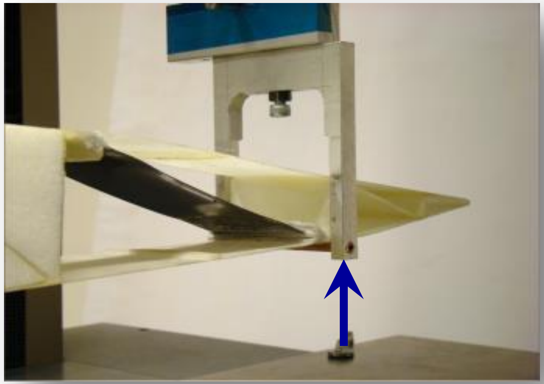
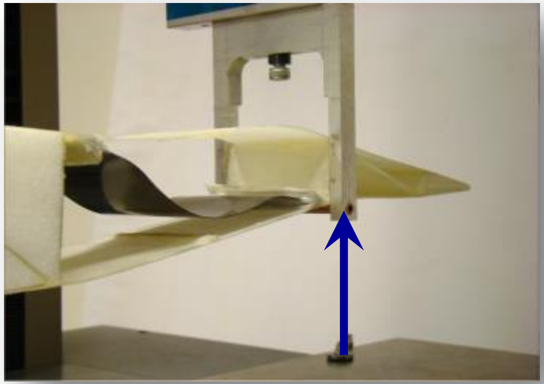
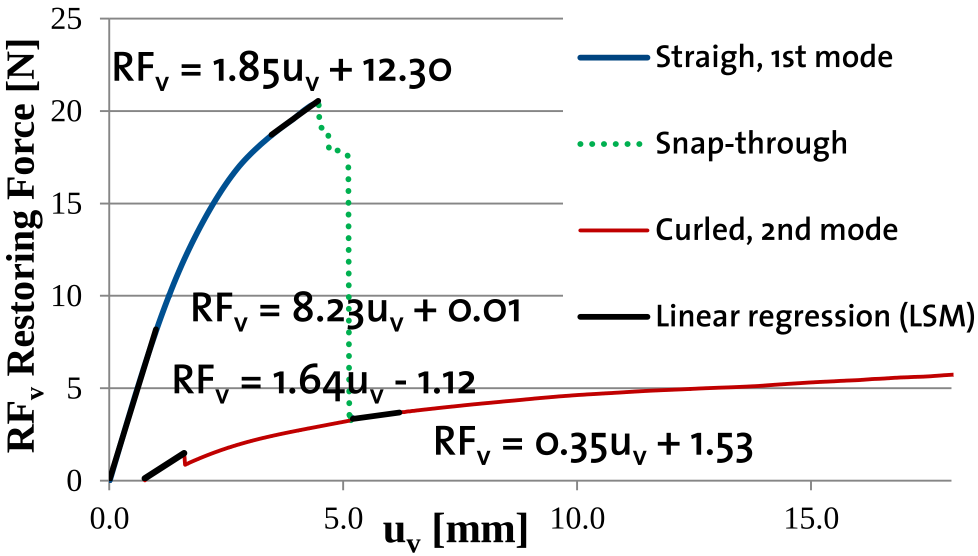




Questions?



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