VARIABLE STIFFNESS COMPOSITES IN LIGHTWEIGHT AND ADAPTIVE STRUCTURES

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JUNE 14TH 2024

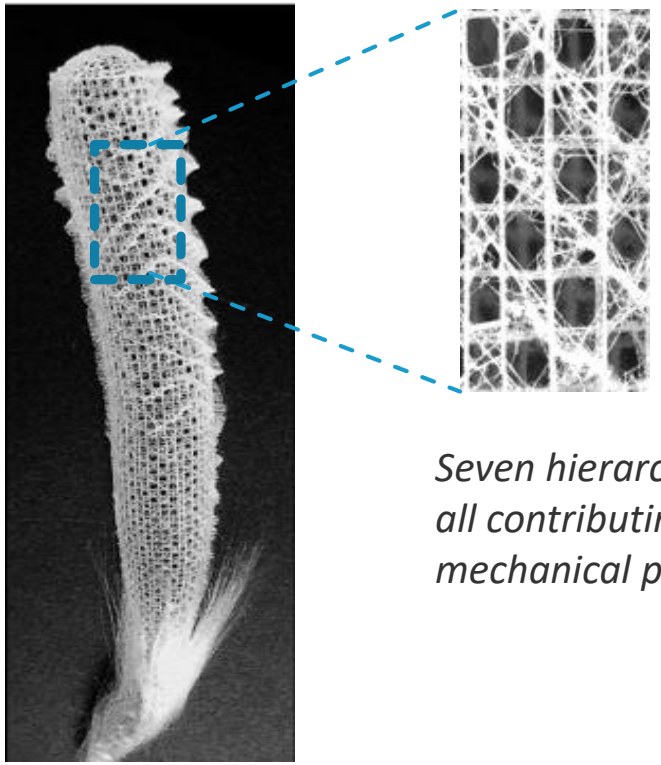
DRESDEN

CONTENT

- Geometry and Structures
- Multistability
- Active Flap of Wind Turbine Blade
- Multistable Metastructures
- Composite Lattices
- Wing Box using Tow-steered Laminates
- Future Directions
- Conclusions

GEOMETRY AND STRUCTURES

The extraordinary properties of materials found in nature often achieved through complex structures

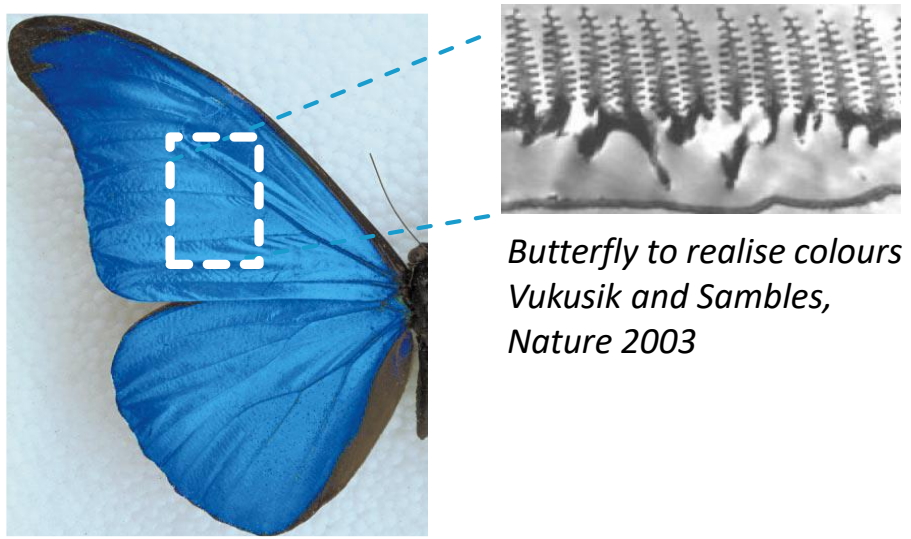


Deep-sea sponge
Euplectella aspergillum

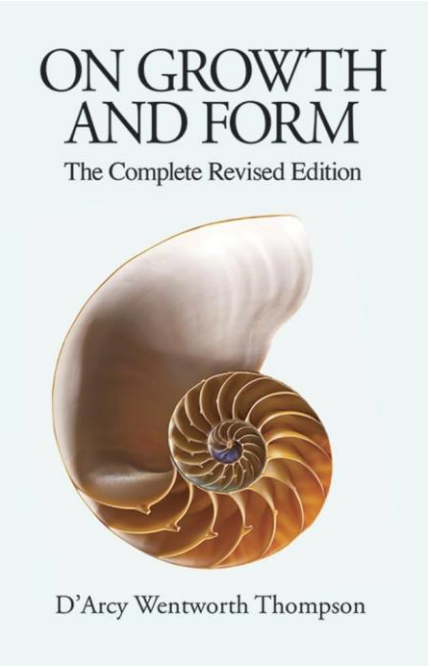
Seven hierarchical levels, all contributing to mechanical performance

Aizenberg, Weaver et al. Science 2005

Venus Flytrap : Wikimedia
Adaptive structural materials

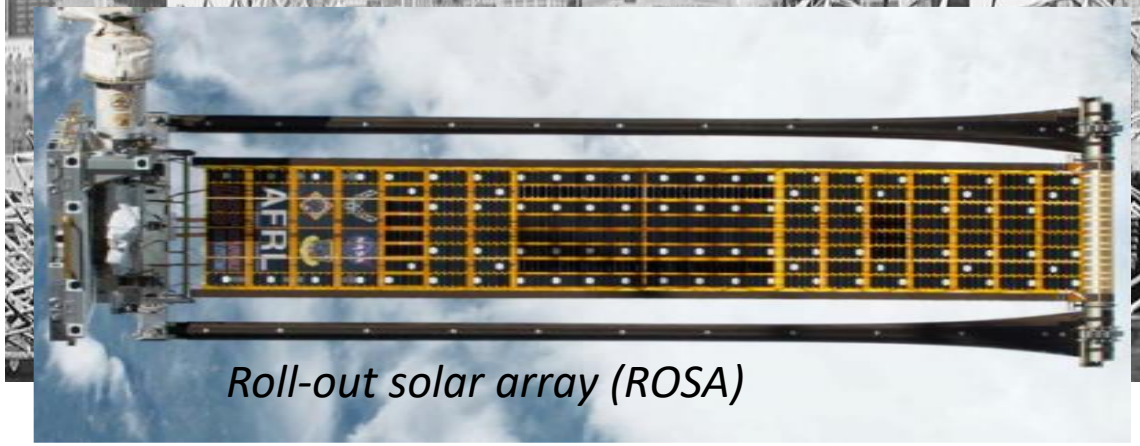


Butterfly to realise colours
Vukusik and Sambles, Nature 2003



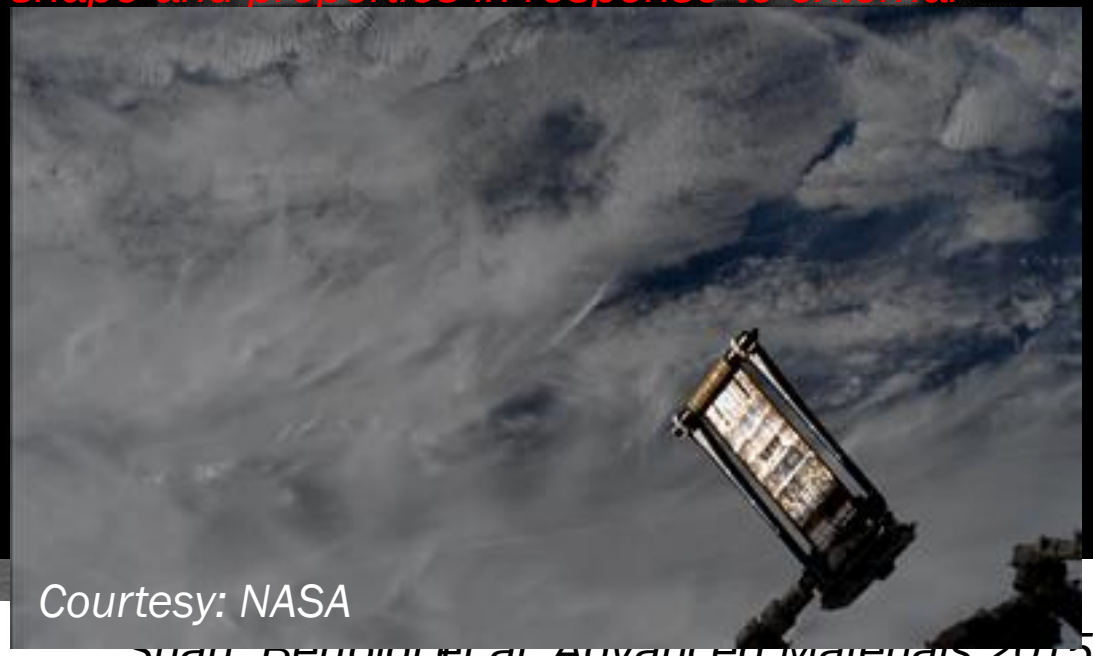
DEPLOYABLE AND ADAPTIVE STRUCTURES

- Using materials and geometry to design highly deformable structure.
- To take advantage of the large deformation to achieve new functionalities and ultimately reduce materials used.
- Exploit mechanical instabilities to achieve large shape changes-
  from buckliphobia to buckliphilia



Roll-out solar array (ROSA)

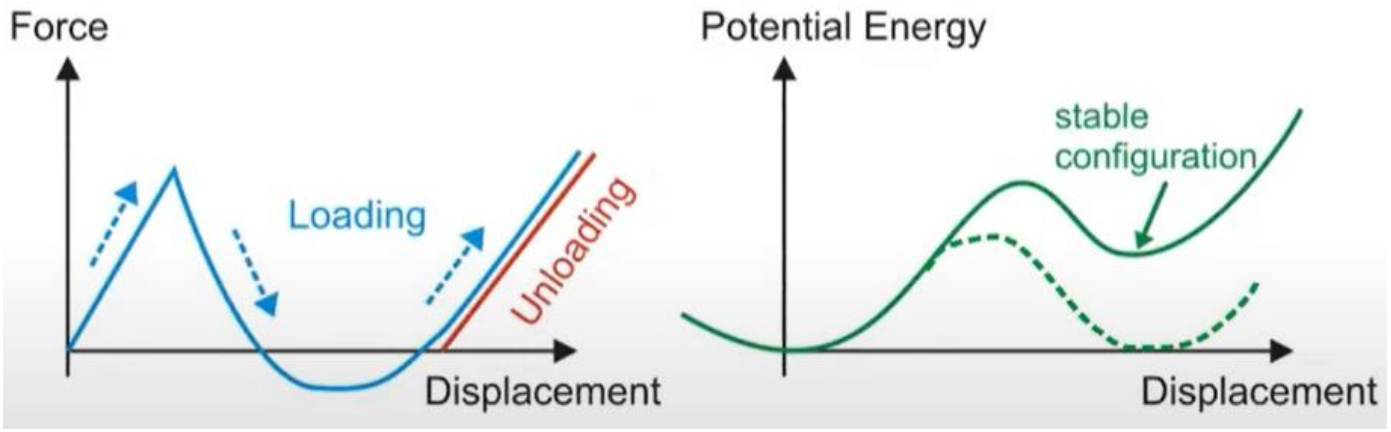
Can we exploit deformation and instabilities to design active structural materials that tune their shape and properties in response to external

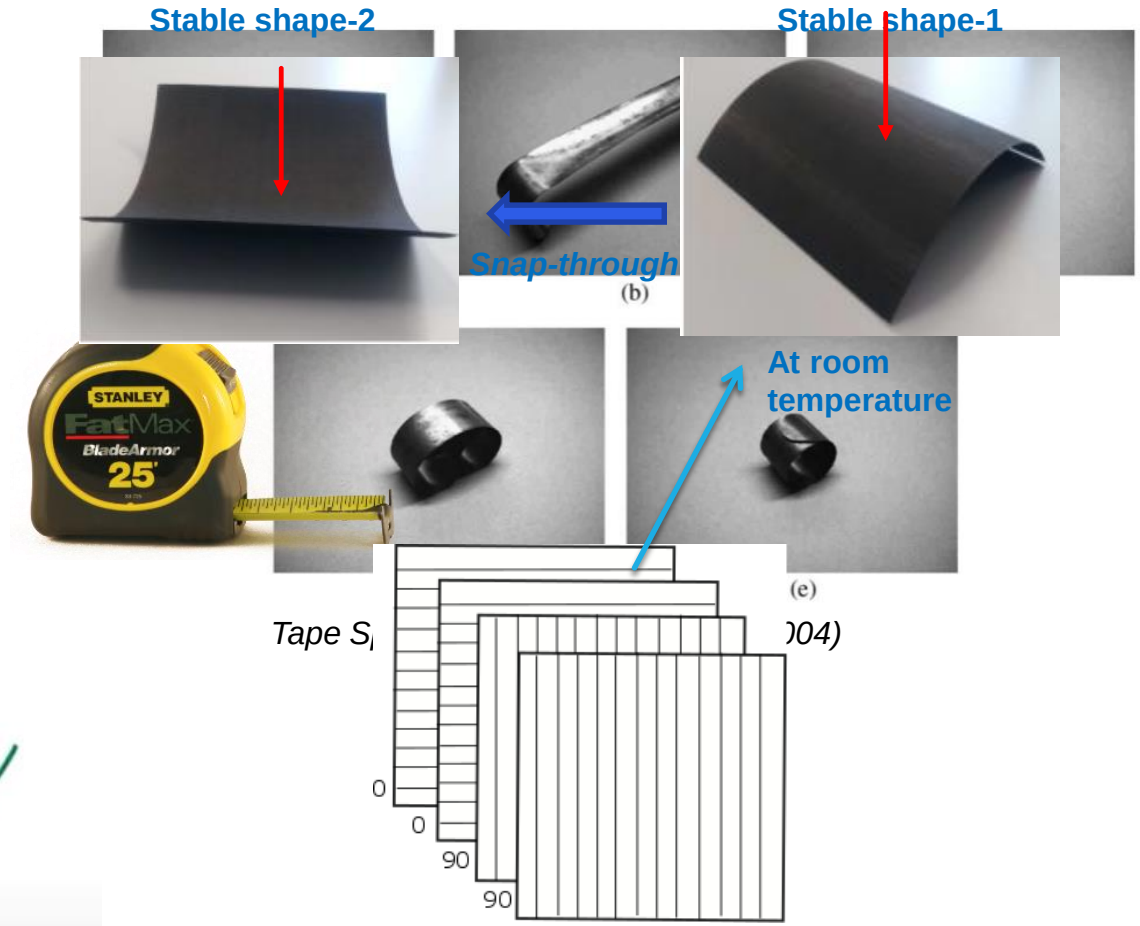

Courtesy: NASA

Shan, Bertoldi et al. Advanced Materials 2015

MULTISTABLE STRUCTURES

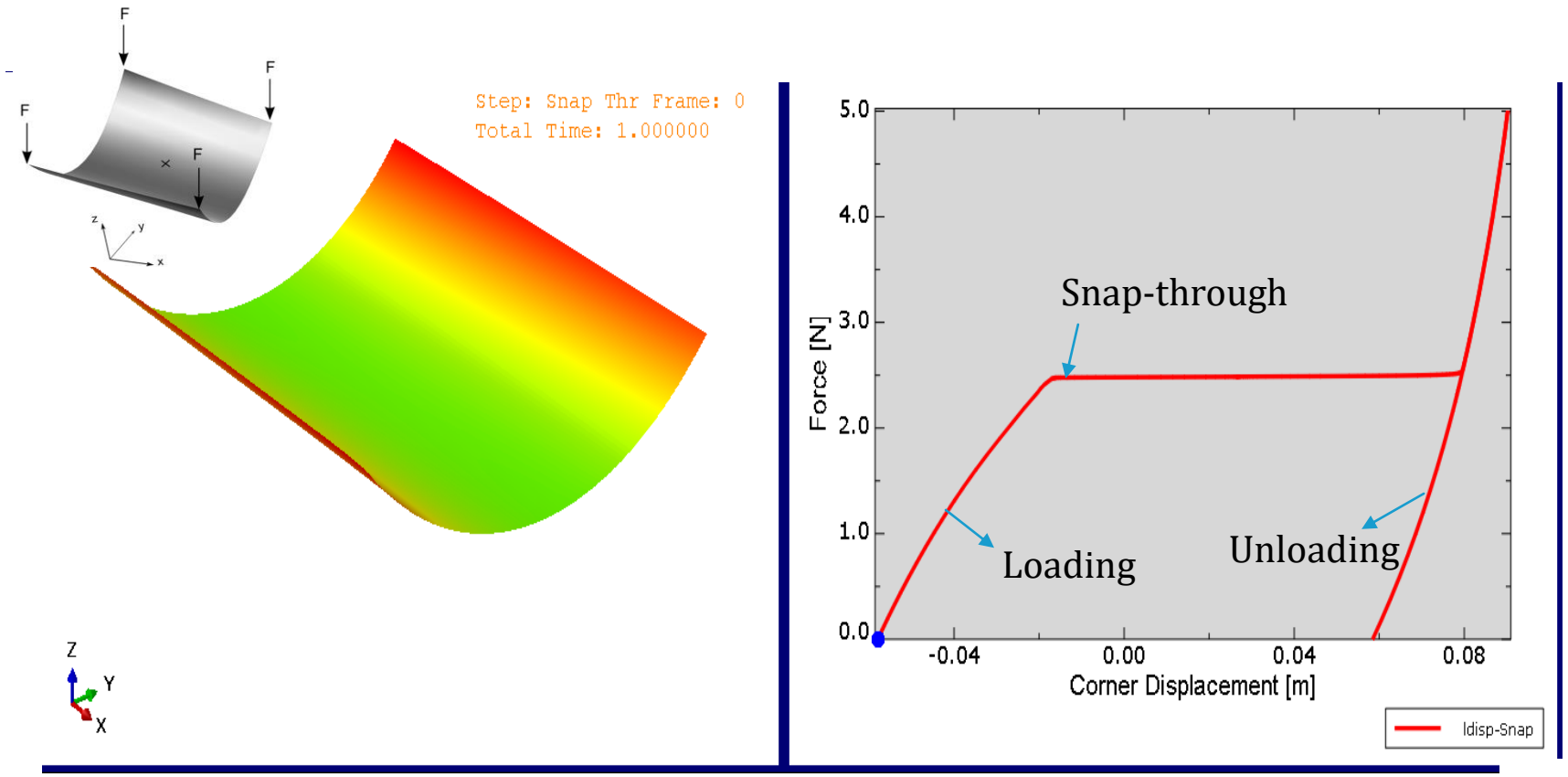
- Structures having multiple stable shapes
- Continuous supply of force not required to hold either of the shapes
- Energy/force required just to snap from one shape to another
- Engendered by geometrical features or subjecting anisotropic materials to residual stress, prestressing

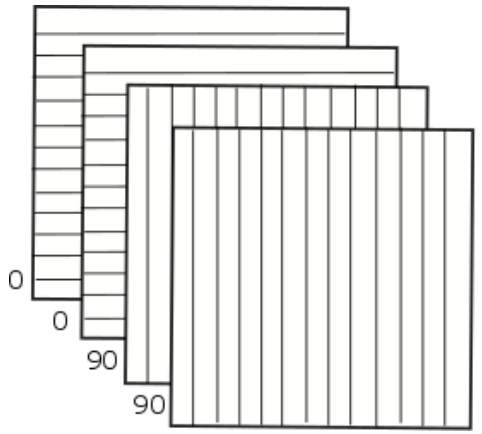




Flat unsymmetric fiber reinforced laminates heated to curing temperature

SNAP-THROUGH ANALYSIS

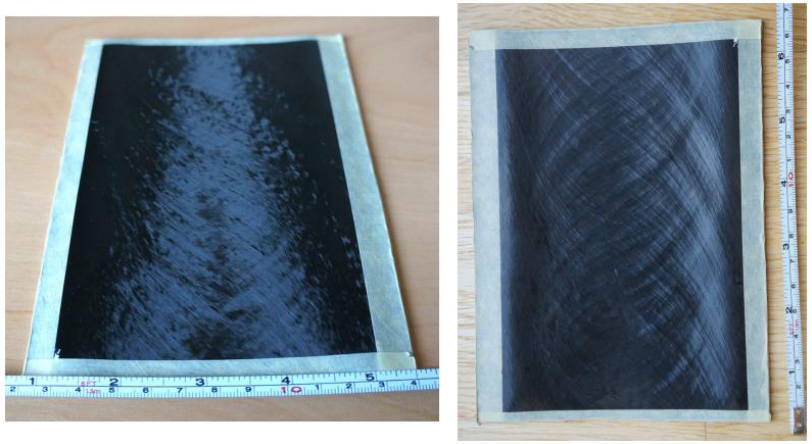




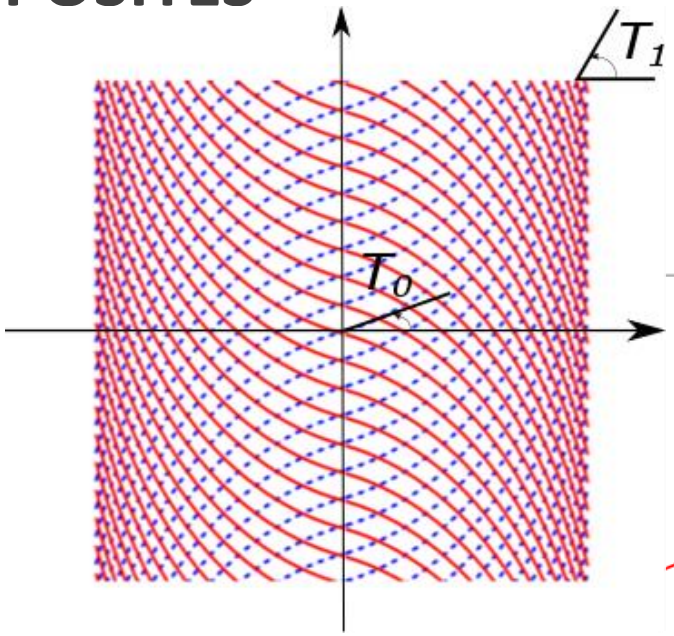
Unsymmetric cross-ply laminate

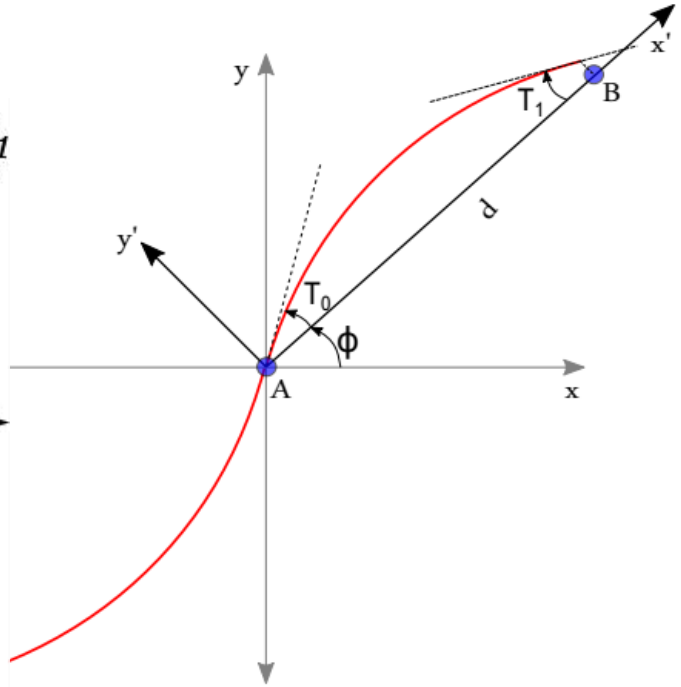
Static finite element analysis allowing geometrical nonlinearity

VARIABLE STIFFNESS (VS) COMPOSITES



Curvilinear fiber paths using AFP (Weaver et al 2009)





- Unlike traditional fiber placements, fiber direction is varied spatially
- Enhance design space for generating multistable shapes
- How does the multistable shapes change?
- Is it possible to tailor energy landscape and the snap-through loads

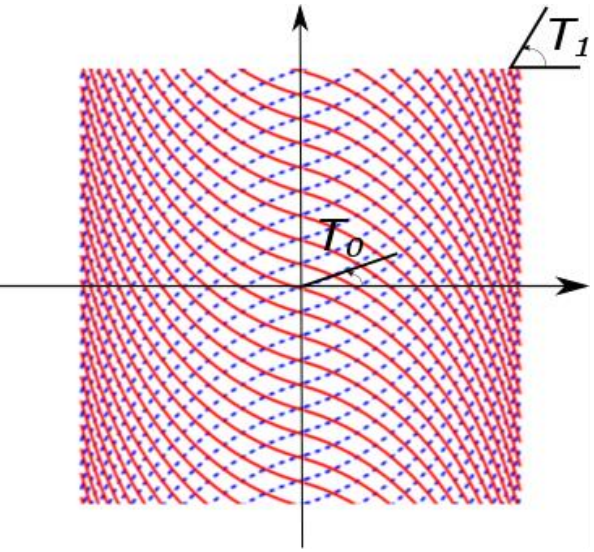
$$\phi\langle T_0|T_1\rangle$$

$$\theta(x') = \begin{cases} \phi + \frac{(T_0 - T_1)x'}{d} + T_0, & \text{for } -d \le x' \le 0 \\ \phi + \frac{(T_0 - T_1)x'}{d} + T_0, & \text{for } 0 \le x' \le d \end{cases}$$

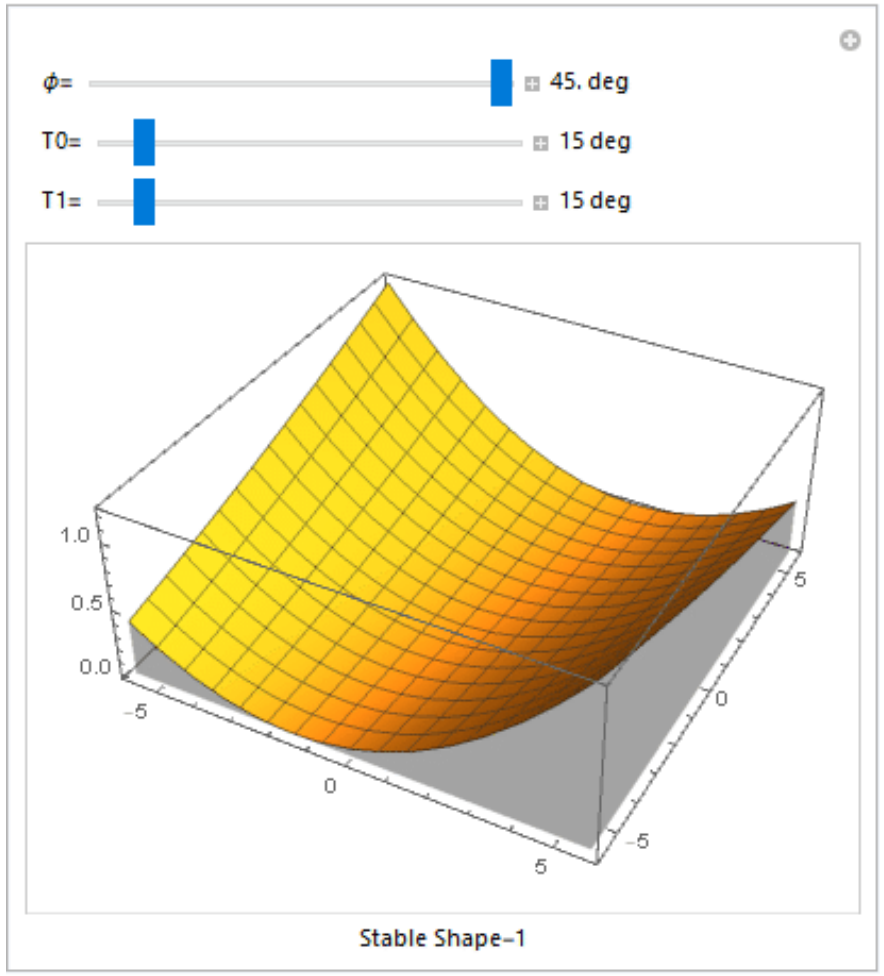
Linear variation of fiber from center to a specified point

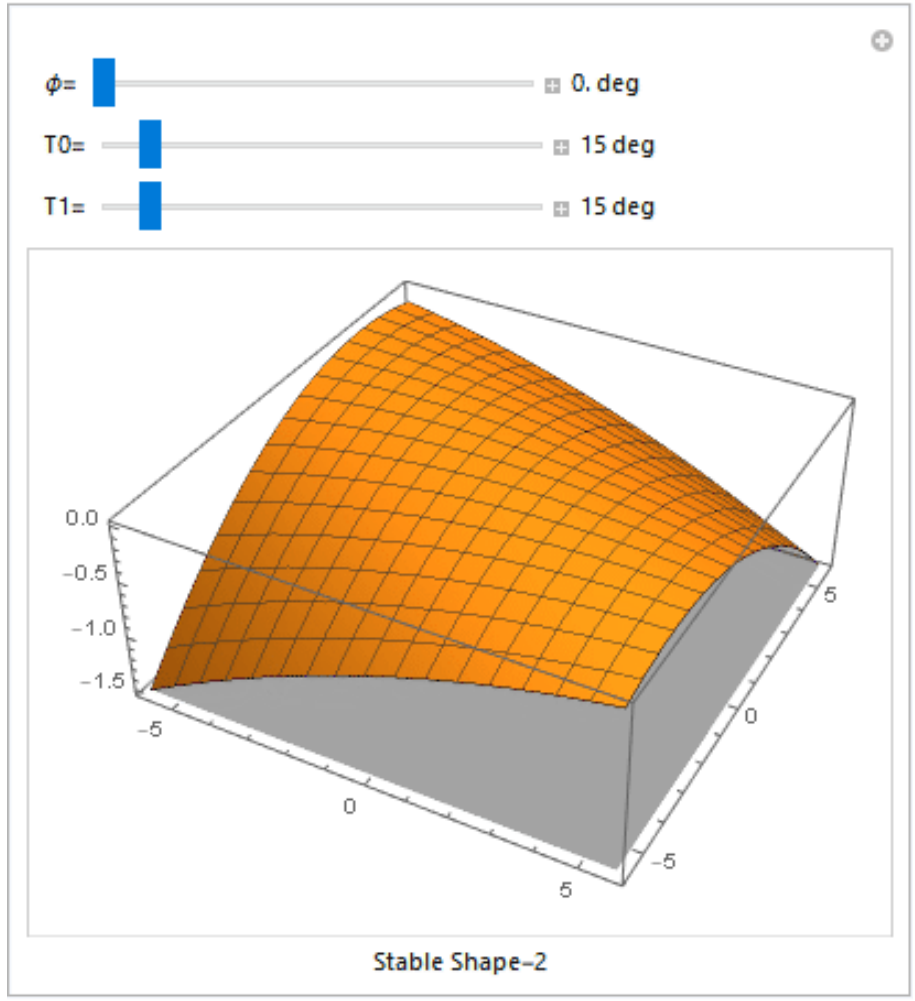
DIVERSE STABLE SHAPES FROM VS LAMINATES

Obtained shapes after thermal cool-down for different parameters of VS laminates



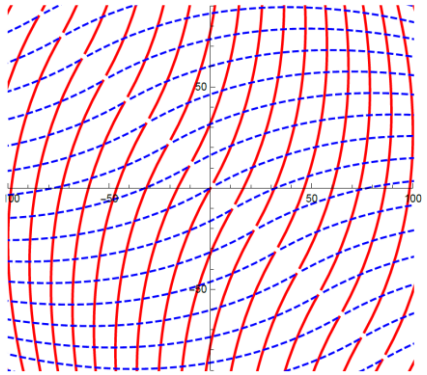
Variable Stiffness Laminates



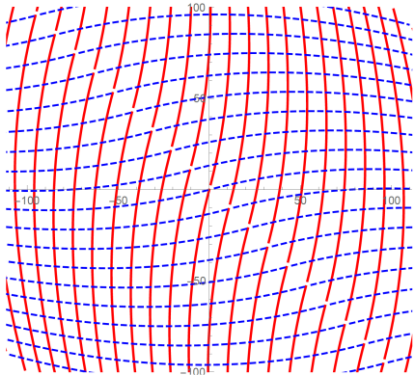


Haldar et al. 2018, Composite Structures

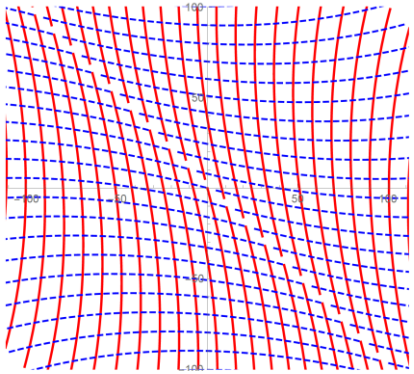
TAILORING USING MULTISTABLE VS LAMINATES



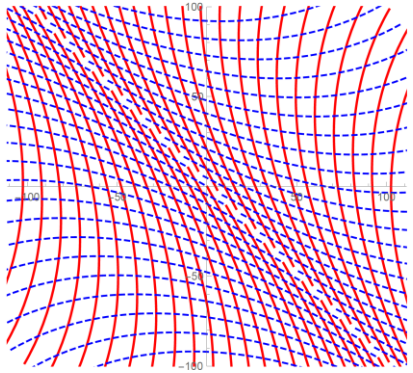
VS-1



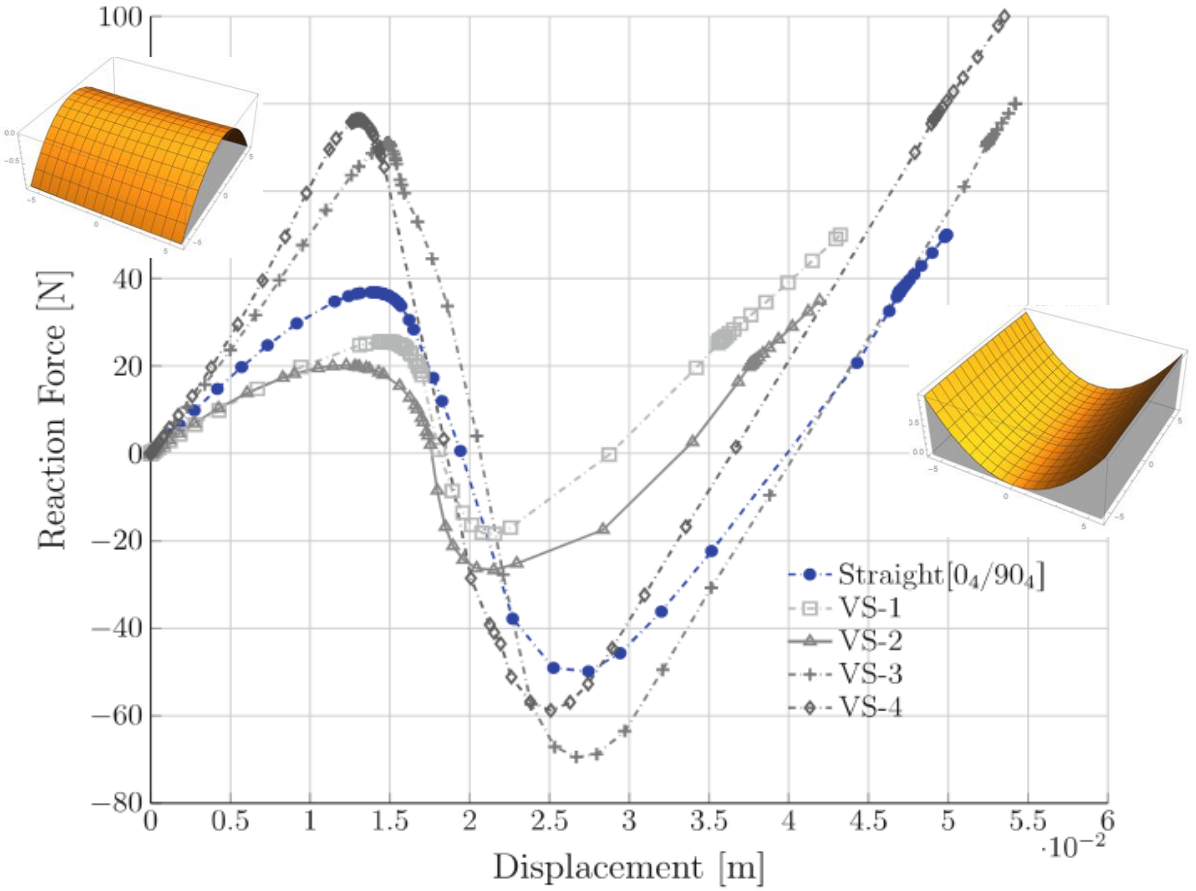
VS-2



VS-3



VS-4



Tailoring snap-through loads

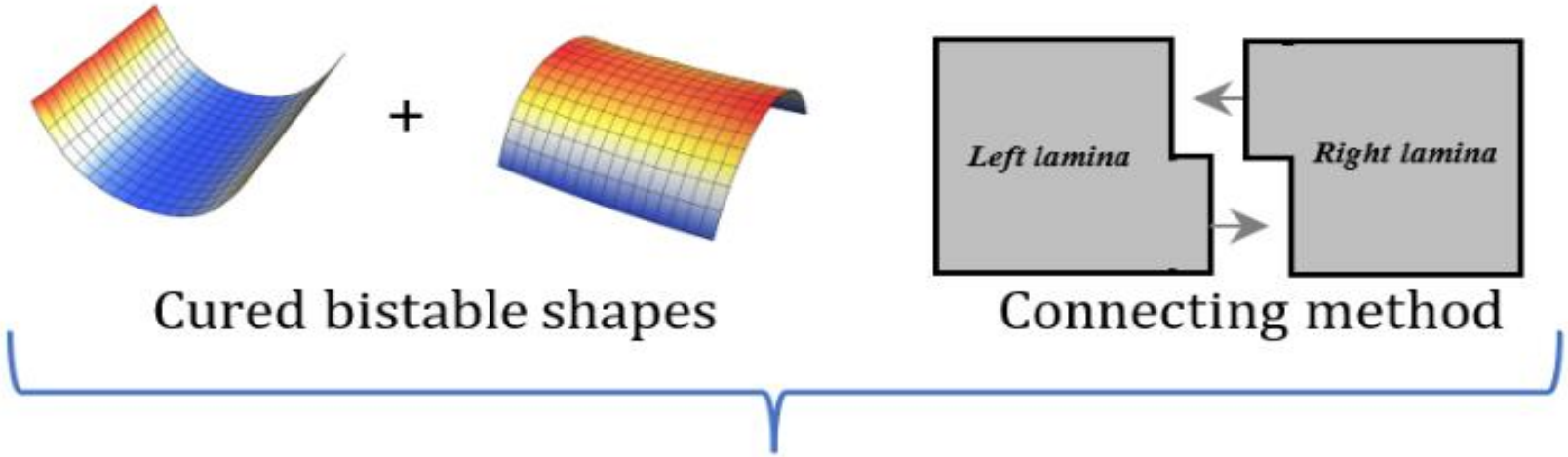
Haldar et al. 2018, Springer, Book Chapter

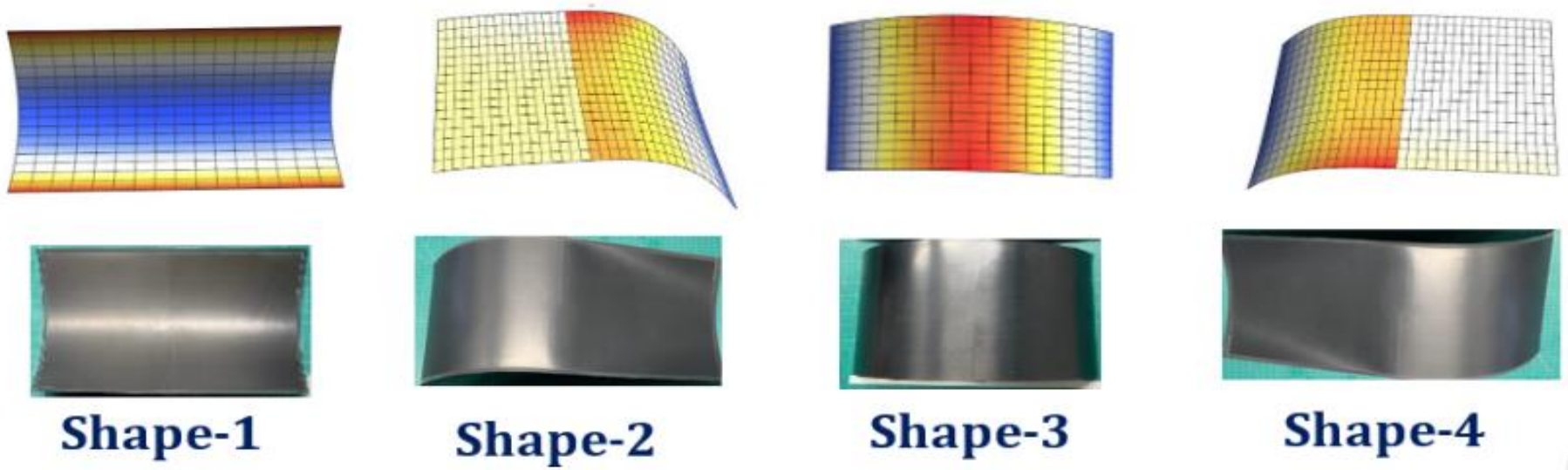
MANUFACTURING VS LAMINATES

- Cutting Strips from prepreg in linearly varying angle
- Shape measurements taken from 3D scanner

Anilkumar, Haldar 2023 et al. (Composite-A), submitted

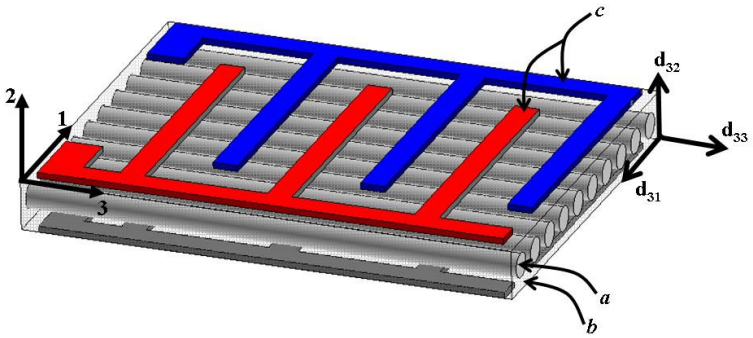
CONNECTED LAMINATES: FROM BISTABILITY TO MULTISTABILITY



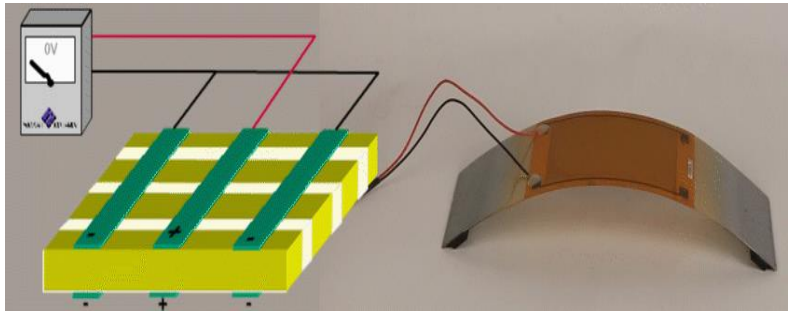


Attada, Haldar et al. Composite Science and Technology, 2022

MORPHING USING MACRO FIBER COMPOSITE (MFC) ACTUATORS

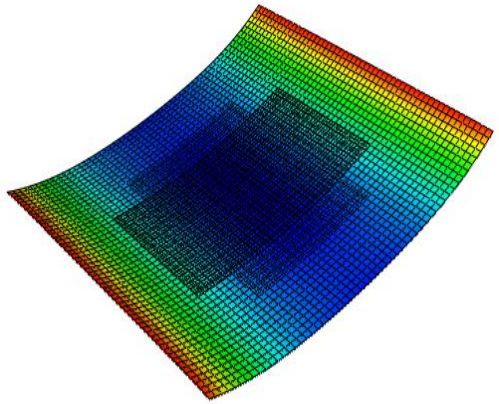


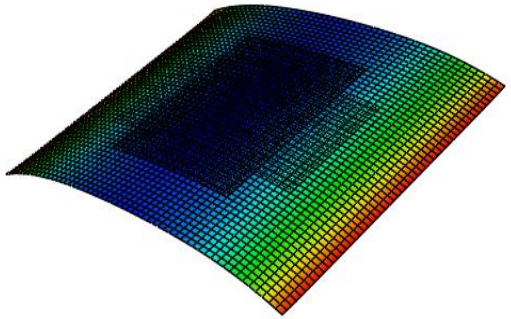
Schematic of an MFC actuator showing unidirectional piezoelectric fiber alignment (a) epoxy matrix (b) interdigitated electrodes (*Williams et al. 2014).*



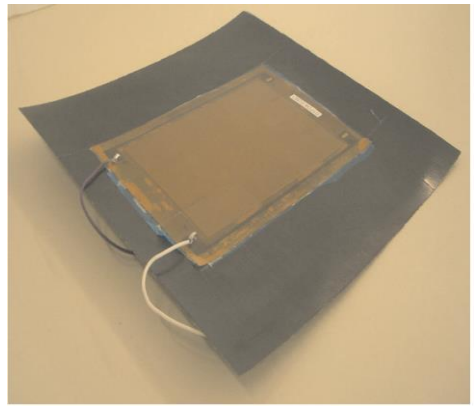
Working of MFC actuators

(www.smart-material.com)

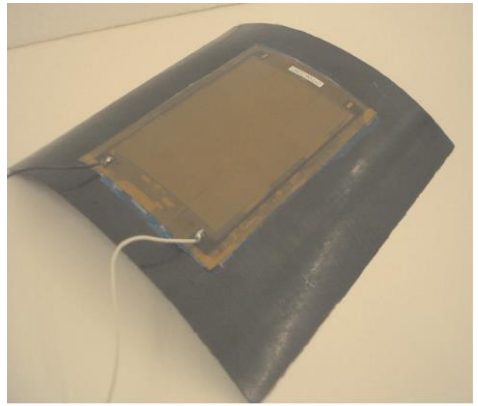




Operating limit:
+1500 V to −500 V



Laminate in first stable shape

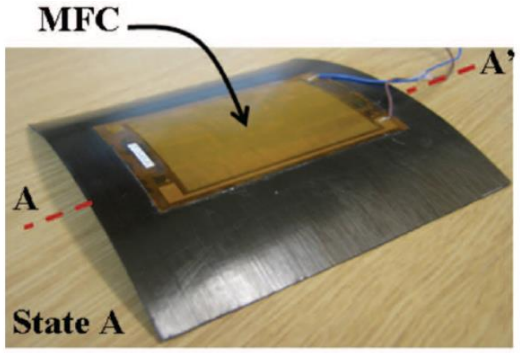


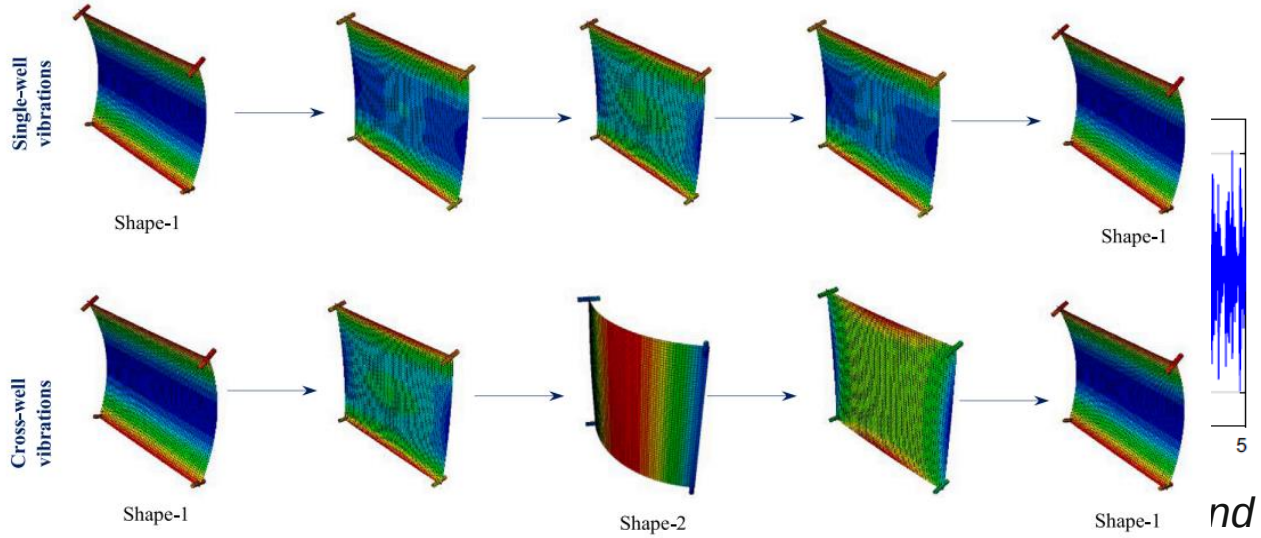
Laminate in second stable shape

NON-LINEAR ENERGY HARVESTING

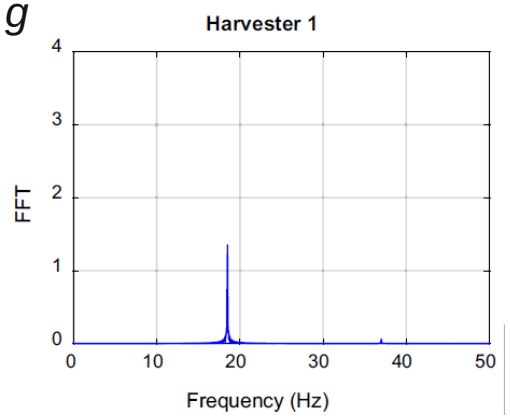
- Linear harvesters work only near the resonant frequencies
- Respond to broader frequency band
- Respond non-proportionately t

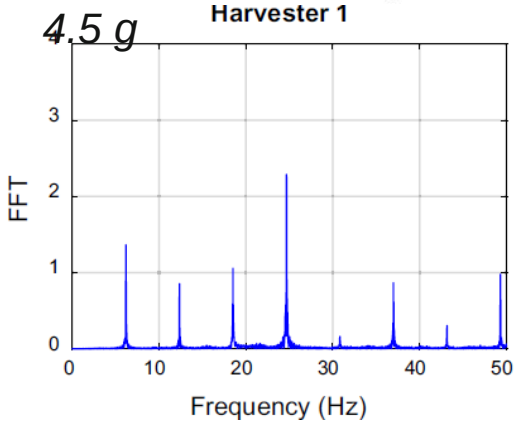
Anilkumar, Haldar et al 2023





freq *nd magnitude of*
1.5 g *4.5 g*

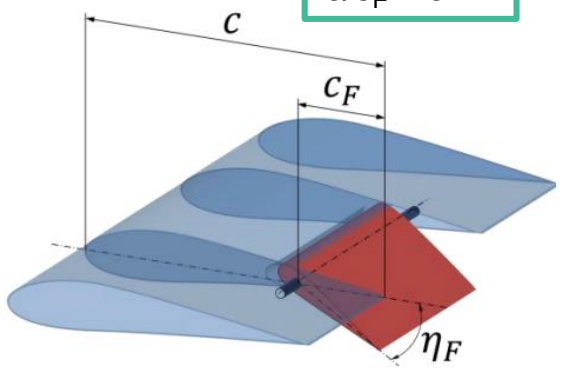




APPLICATION : MORPHING TRAILING EDGE FLAP OF A WIND TURBINE BLADE

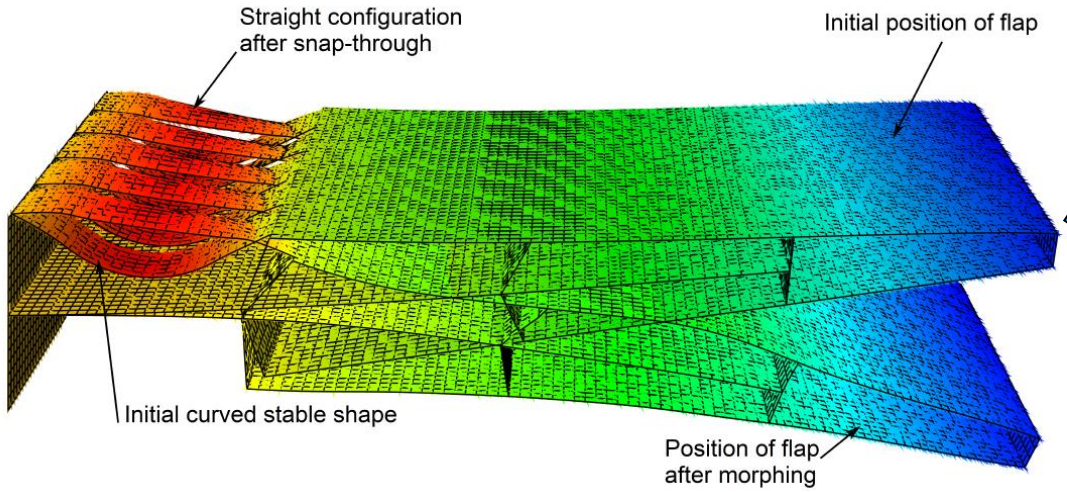
- Radius: 82 m and hub radius: 2 m
- Rated speed of 7.5 MW wind turbine is 11m/s
- Rotor speed : 1.05 rad/s

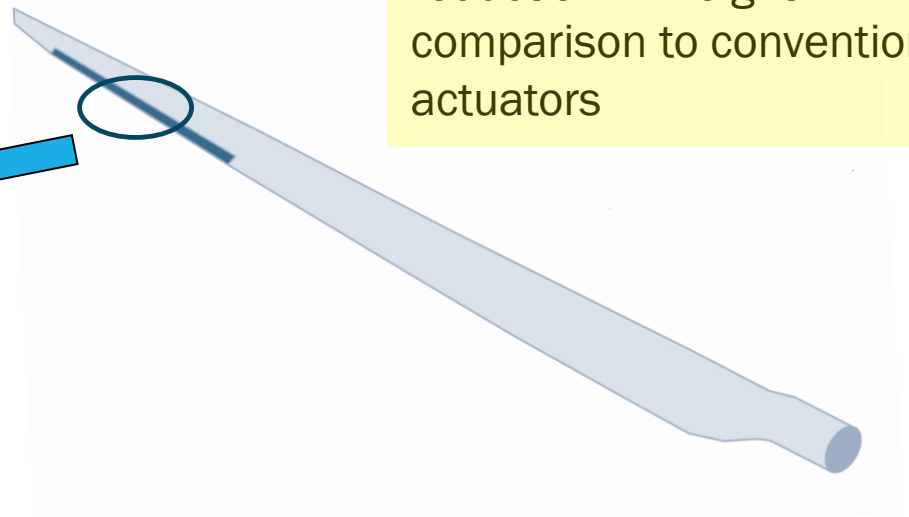
c ≈ 1.5 m
$c/c_F = 0.2$



Continuous supply of energy is not required to hold the deflected shape of the flap

Haldar et al. (Patent): Combination of several bistable elements for an integrated multistable system **DE 10 2018 115 476 B4, 02/2020**



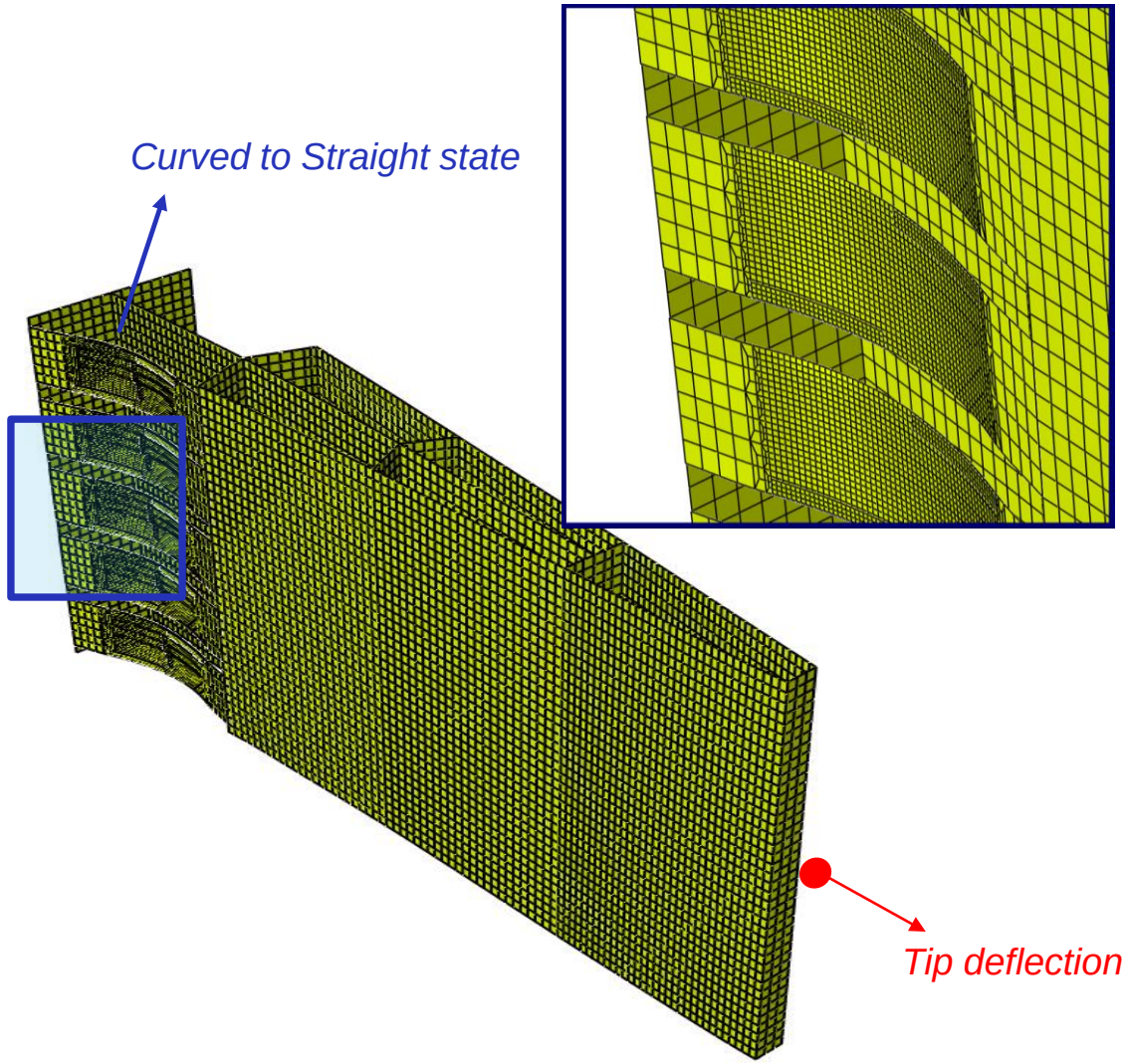


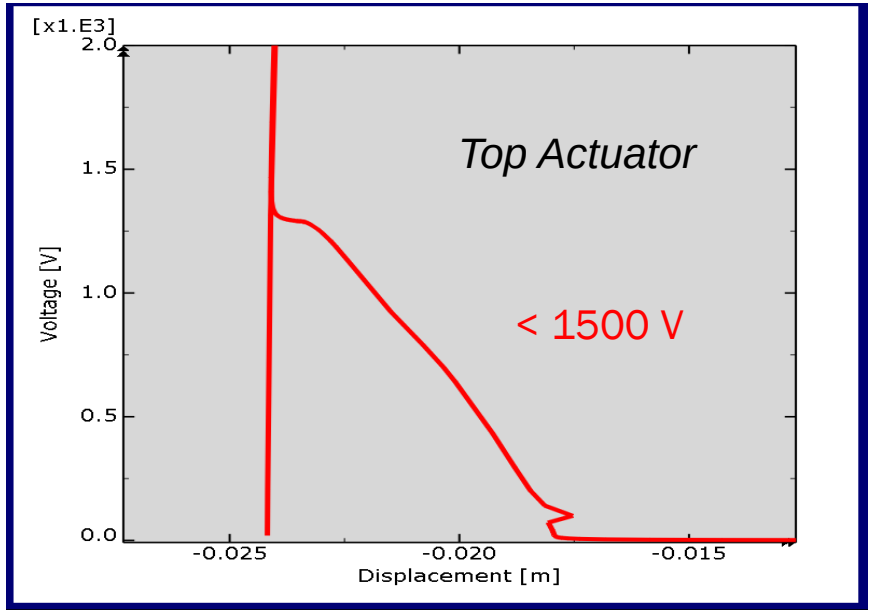
Simple efficient design with reduction in weight in comparison to conventional actuators

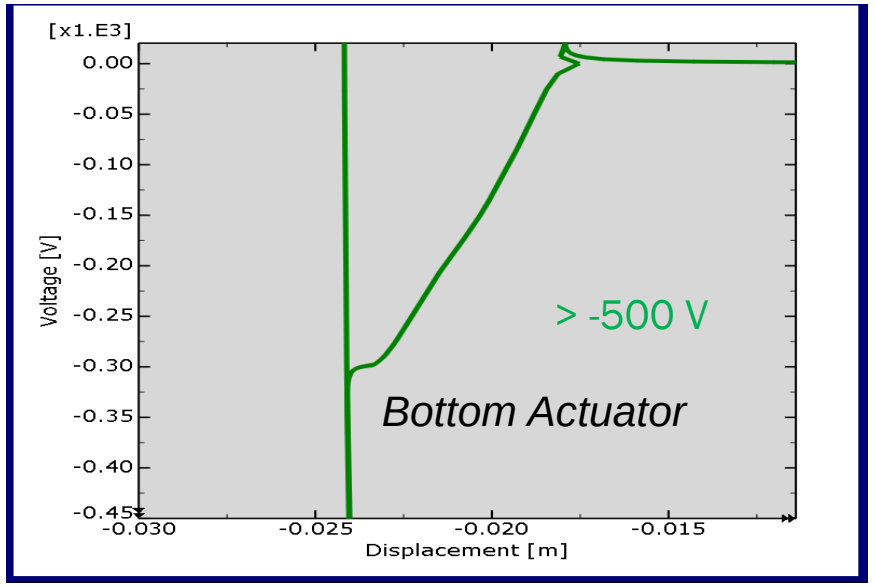
Trailing edge flap from SmartBlades project, DLR Germany

Haldar et al. 2020, AIAA Journal

MORPHING FLAPS WITH ACTUATORS

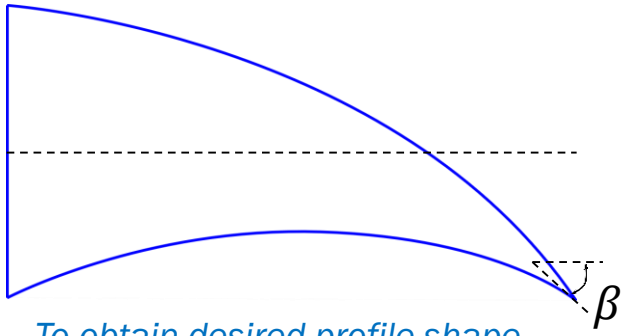




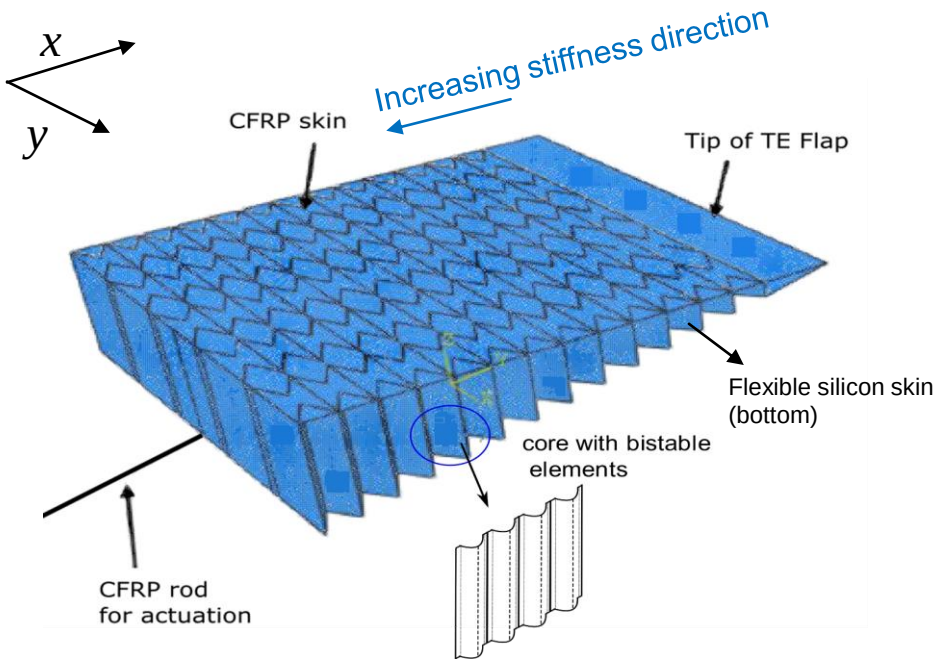


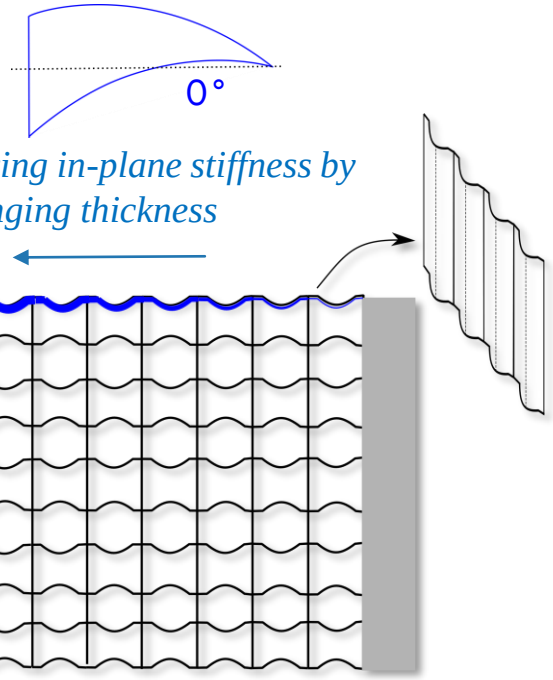
Haldar et al. (Patent): Combination of several bistable elements for an integrated multistable system DE 10 2018 115 476 B4, 02/2020

MORPHING FLAP USING MULTISTABLE METASTRUCTURE

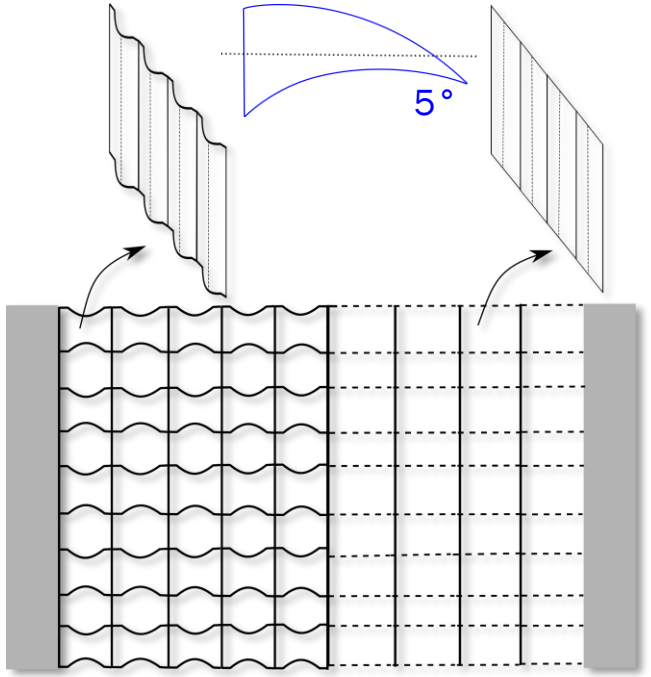


To obtain desired profile shape

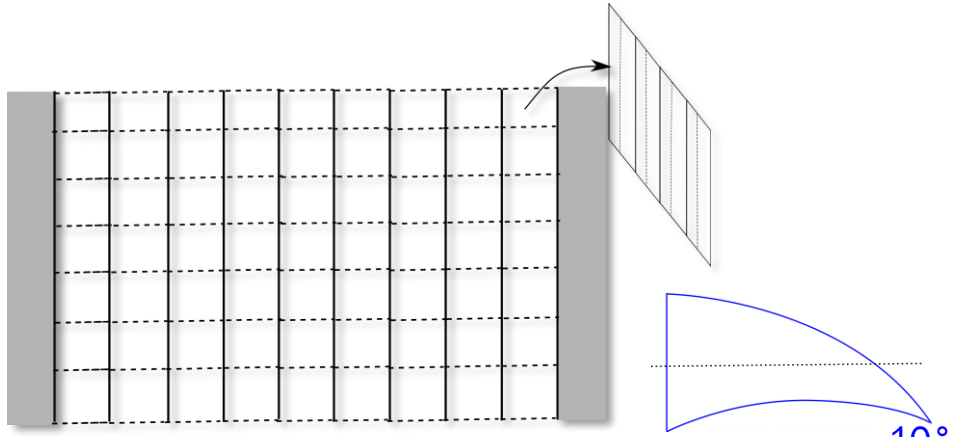




Folded configuration

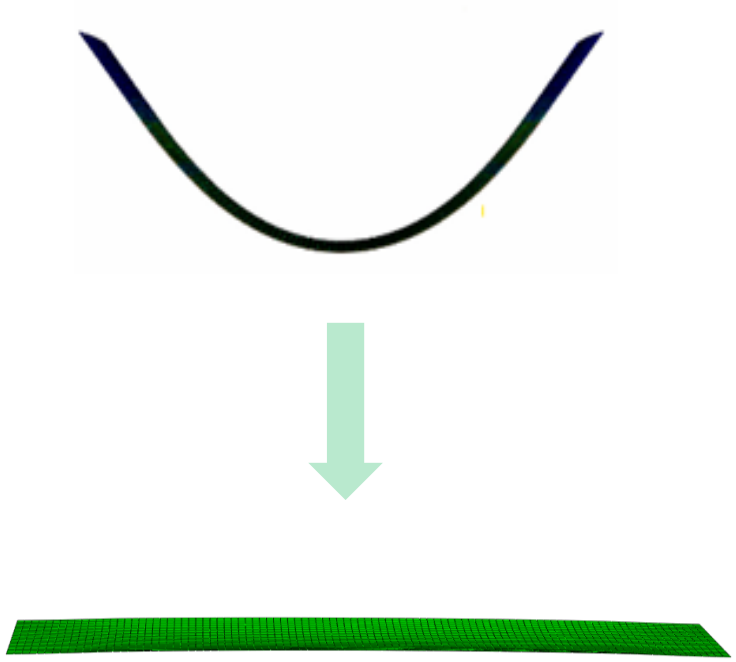


Half retracted configuration

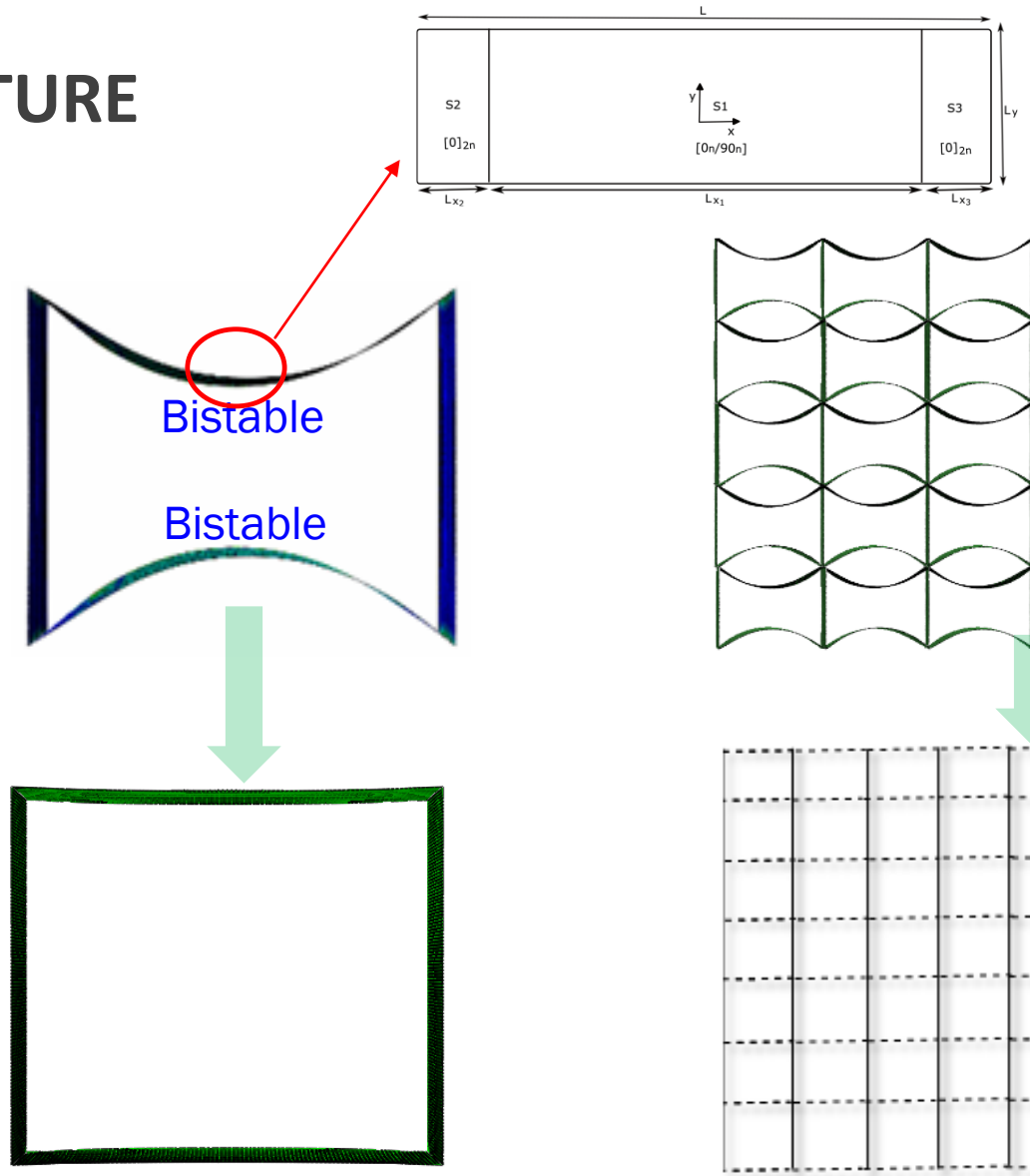


Full retracted configuration

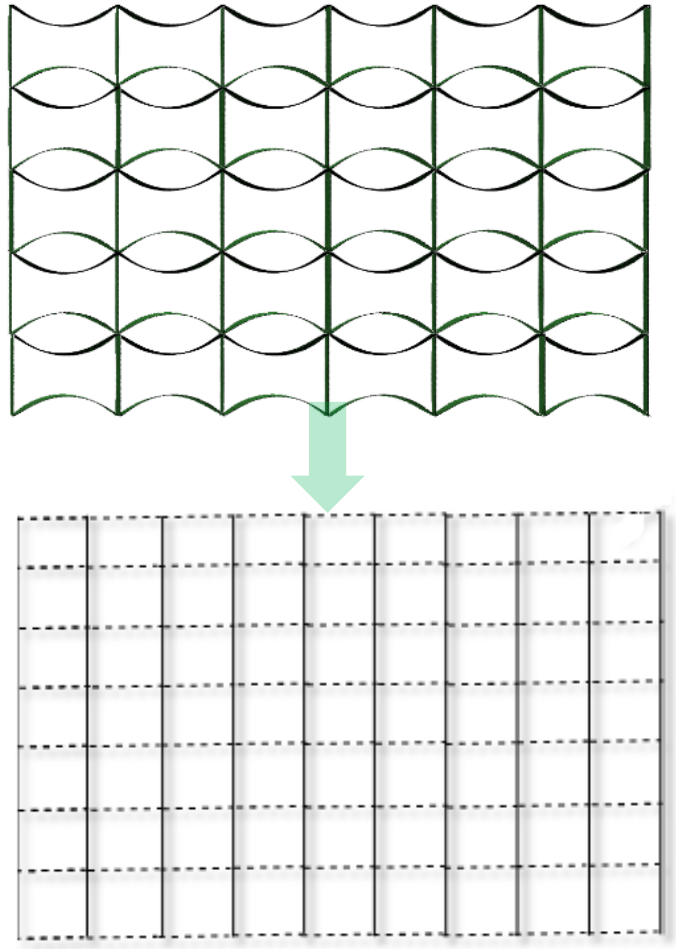
MULTISTABLE METASTRUCTURE



Level I

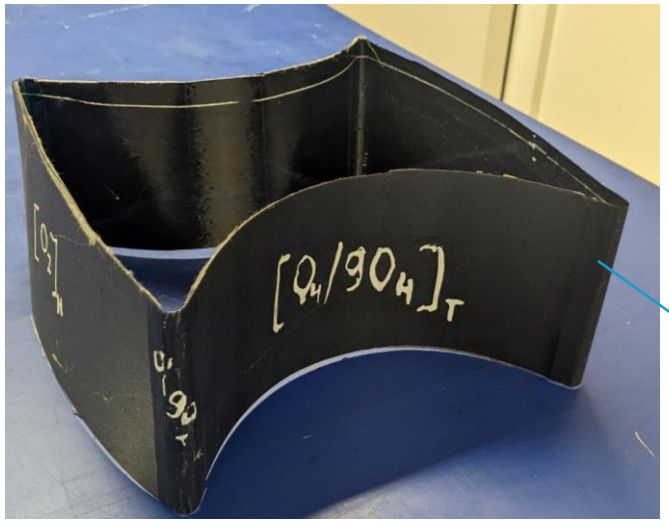


Level II



Level III

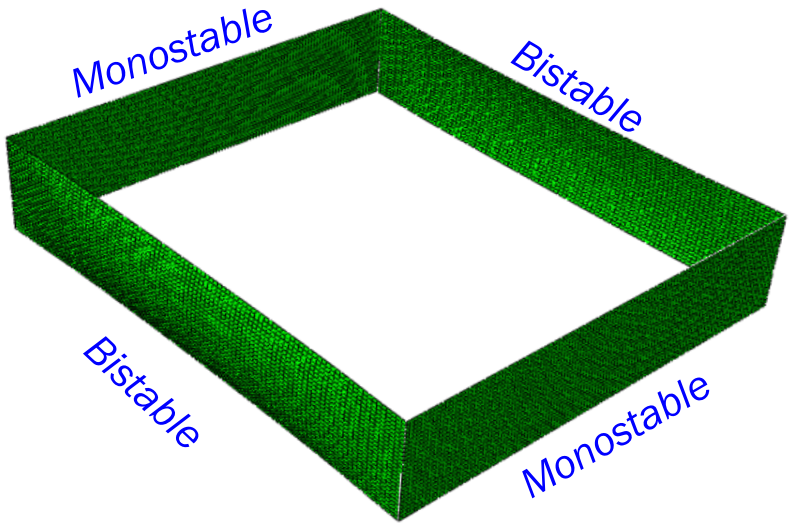
MULTISTABLE METASTRUCTURE

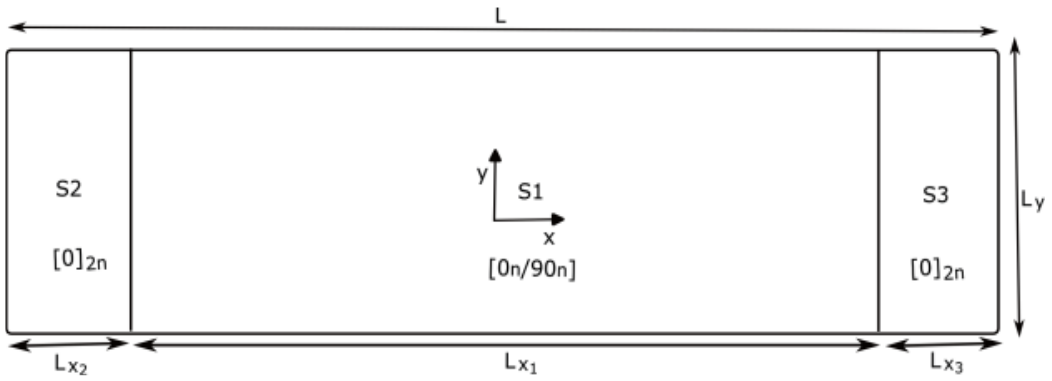


Corner hinges using thin laminates

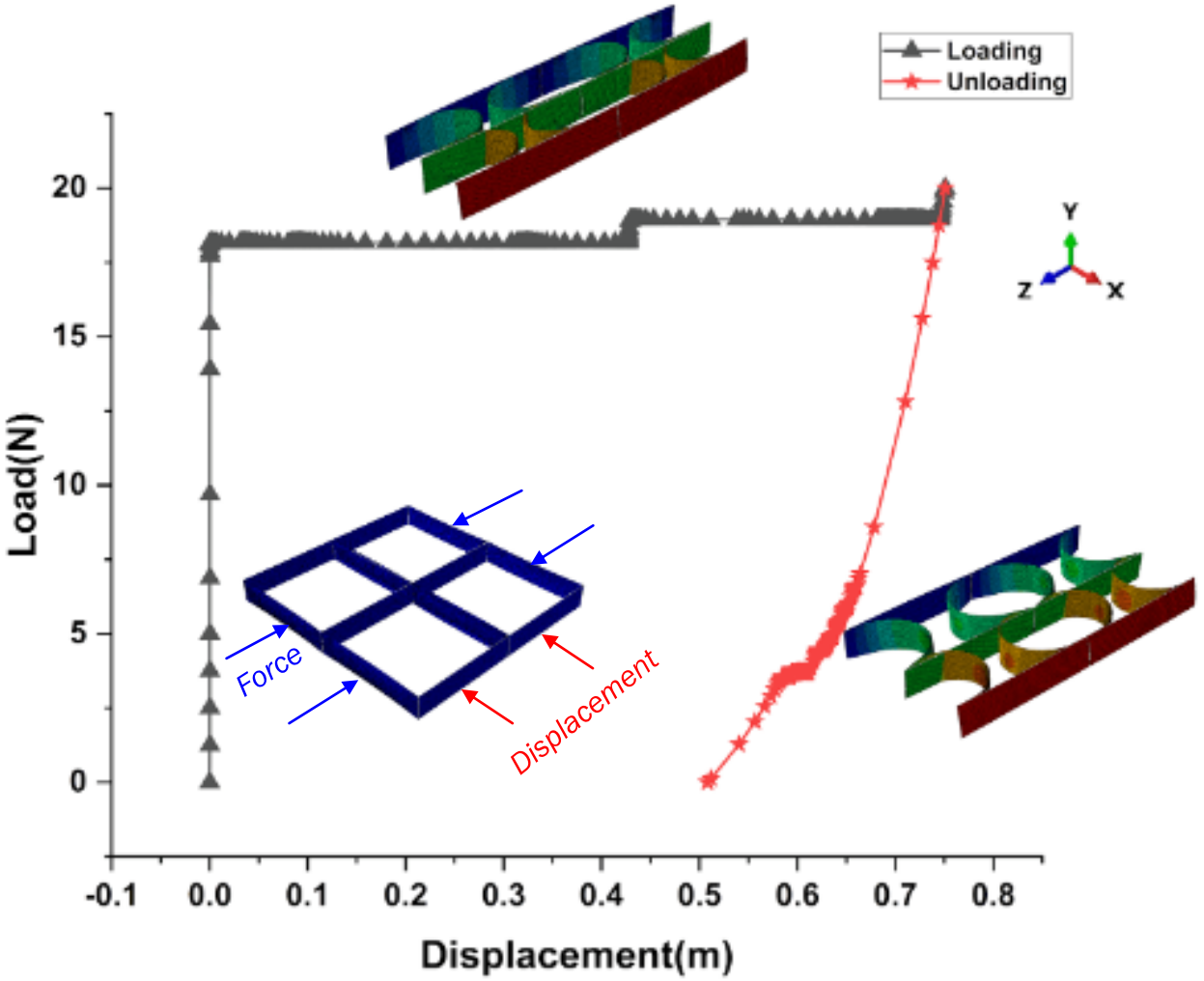
- Large deformation due to change in change in bistable shapes
- Tailored stiffness of the lattice in its respective stable configuration

MULTISTABLE METASTRUCTRE





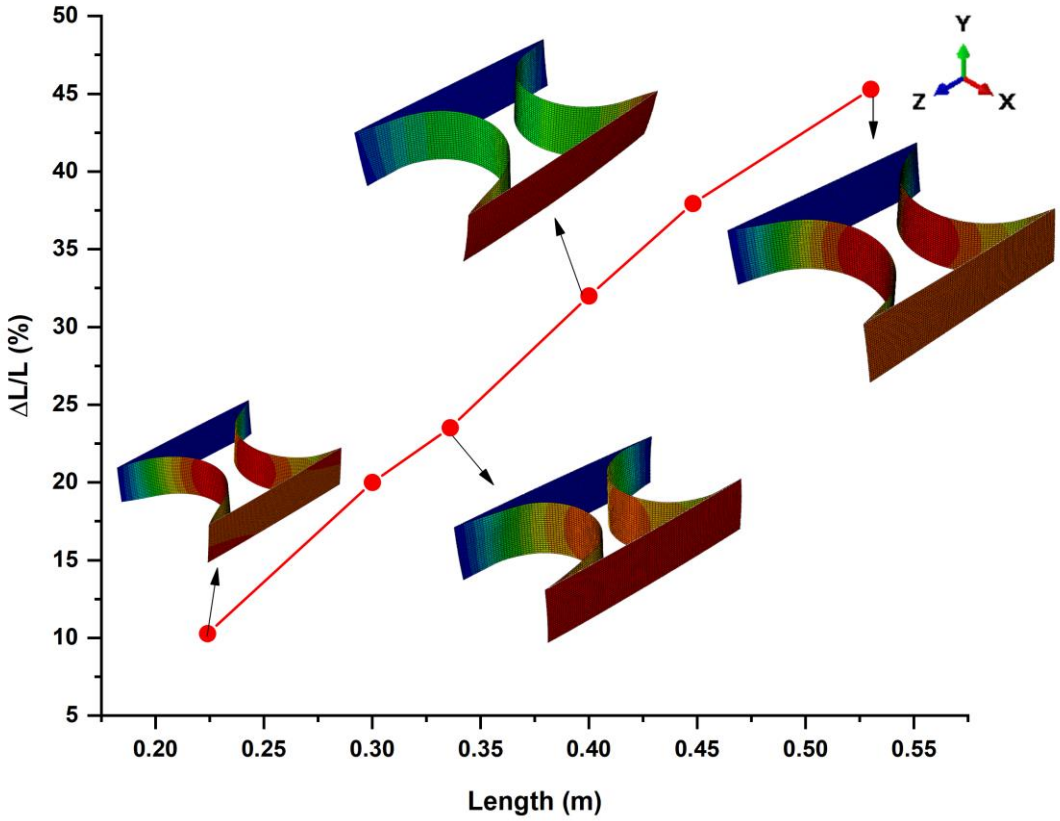
Multi-sectioned laminate

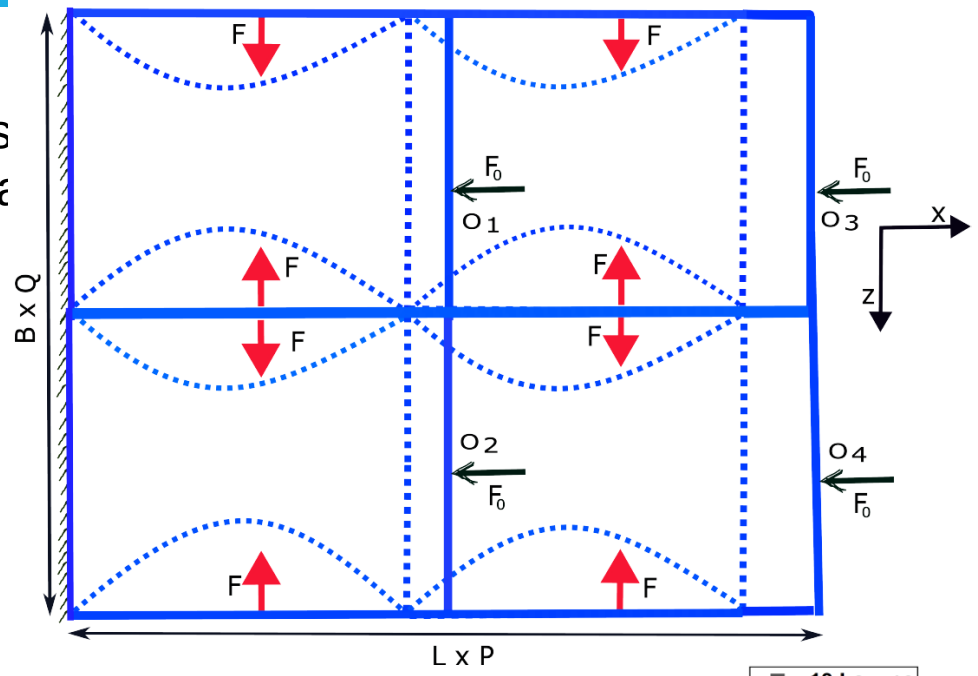


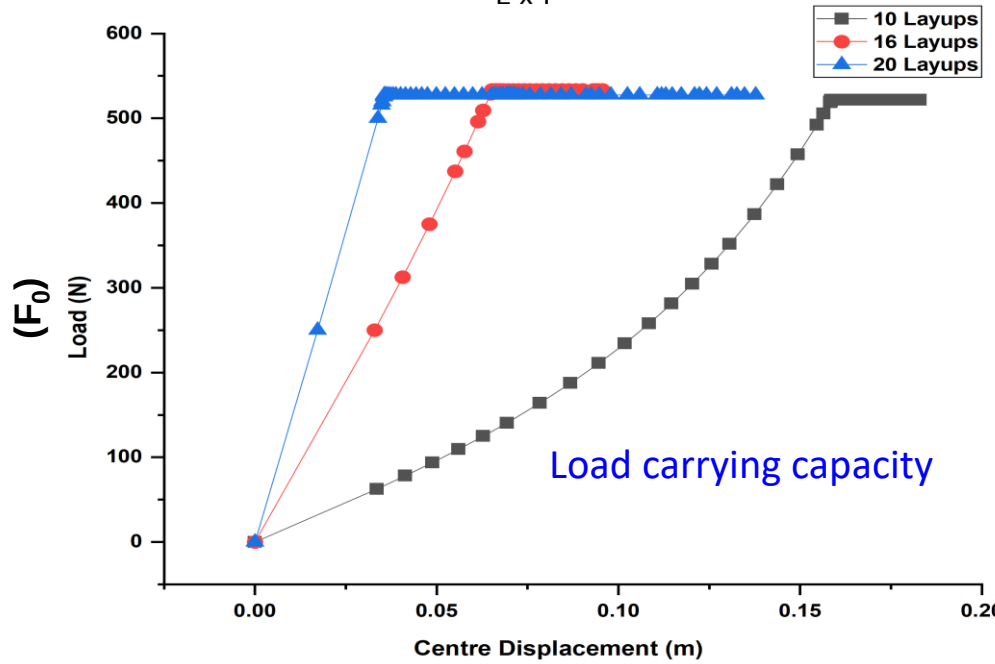
2X2 Lattice

PARAMETRIC STUDY

F: Load on bistable plates
$\mathbf{F_0}$: Load of monostable pla

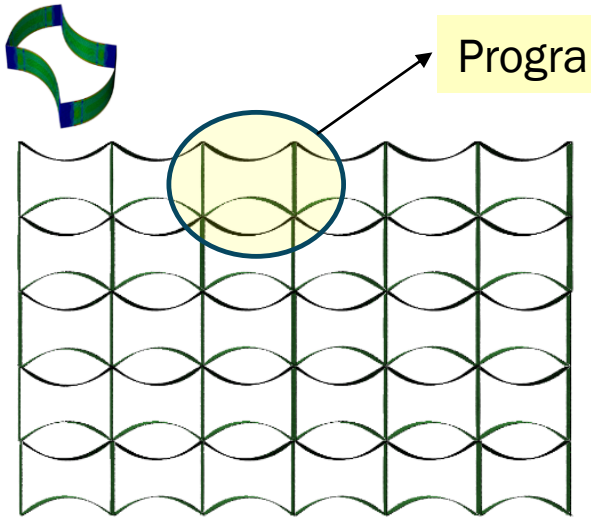






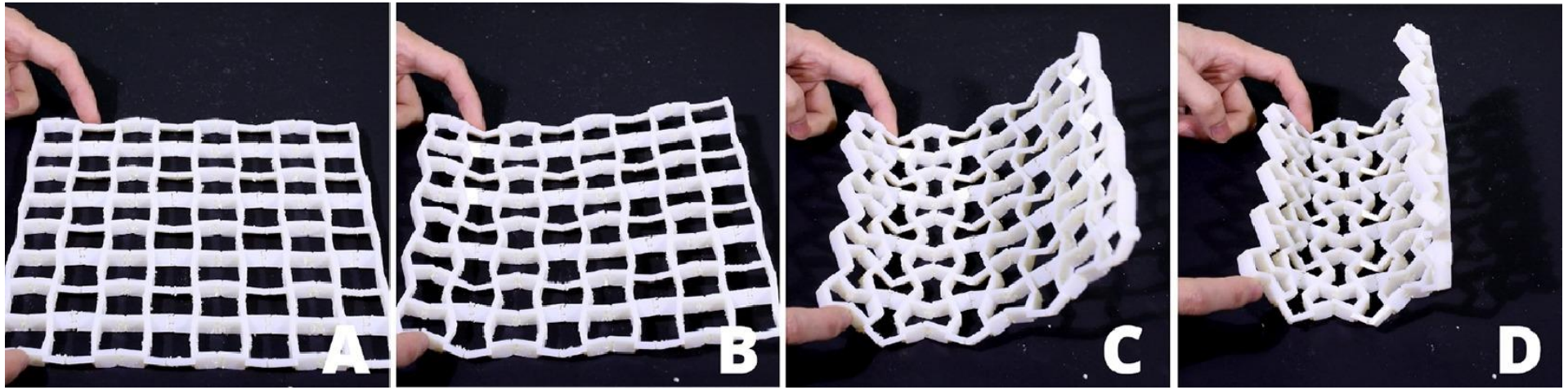
Aspect ratio: 5, t = 0.524 mm (n = 2)
70% unsymmetric sections

PROGRAMMING LATTICES FOR TARGET SHAPE



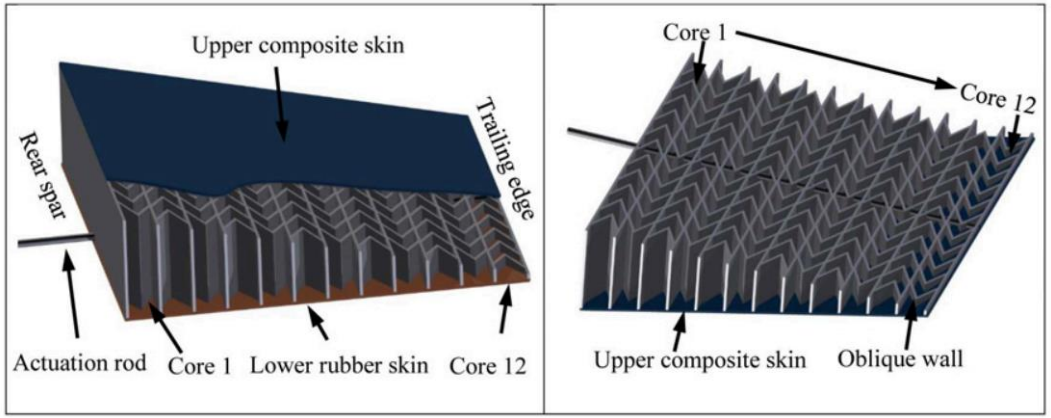
Target shape

Where both the configurations flat and 3D are multistable

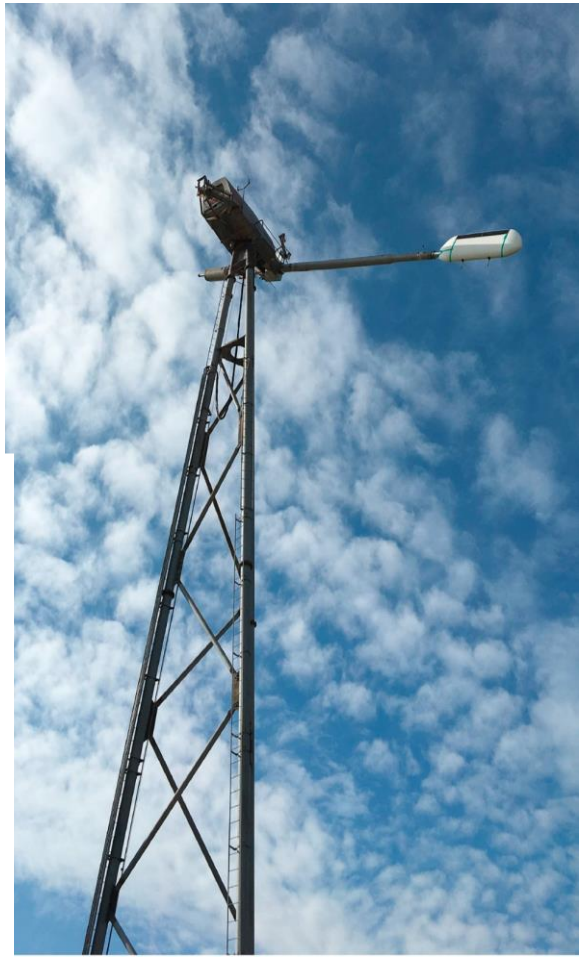


Ou et al. 2018

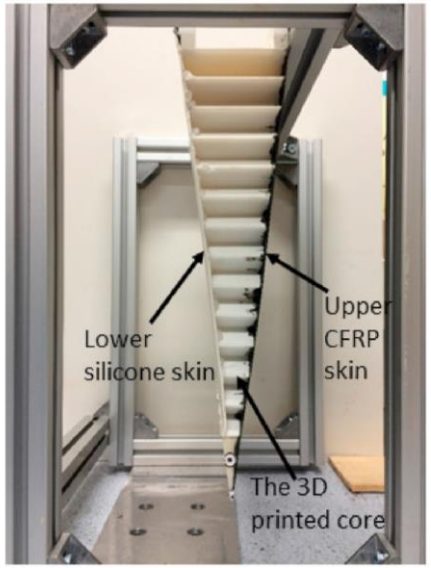
MORPHING ROTOR BLADE



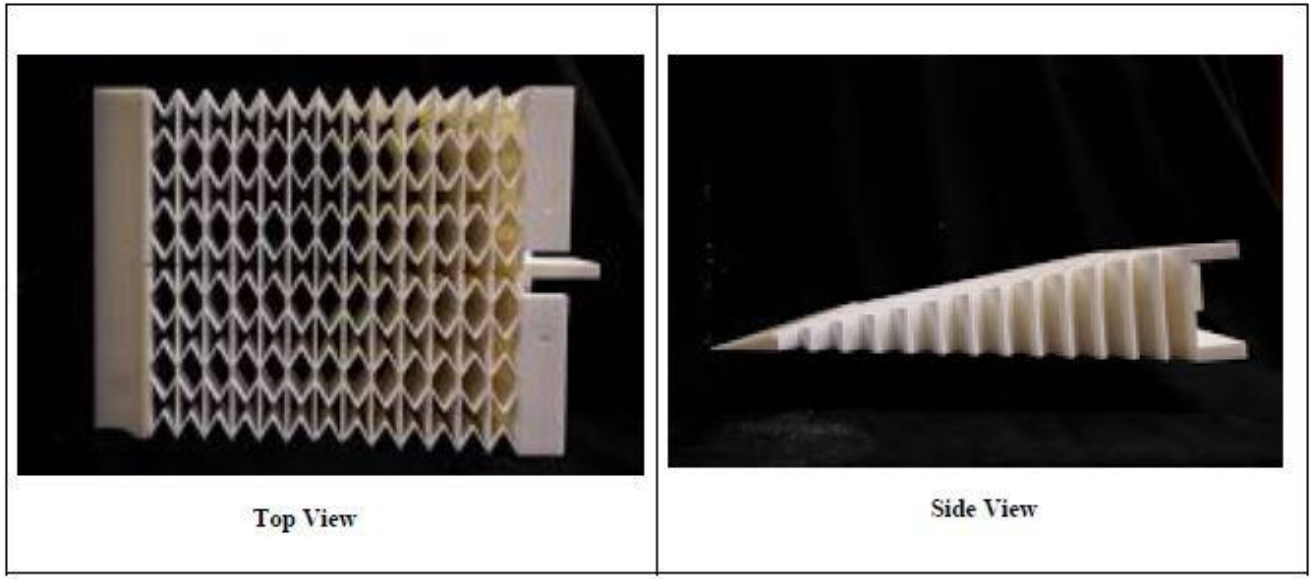
Integrated actuation mechanism



Testing rig

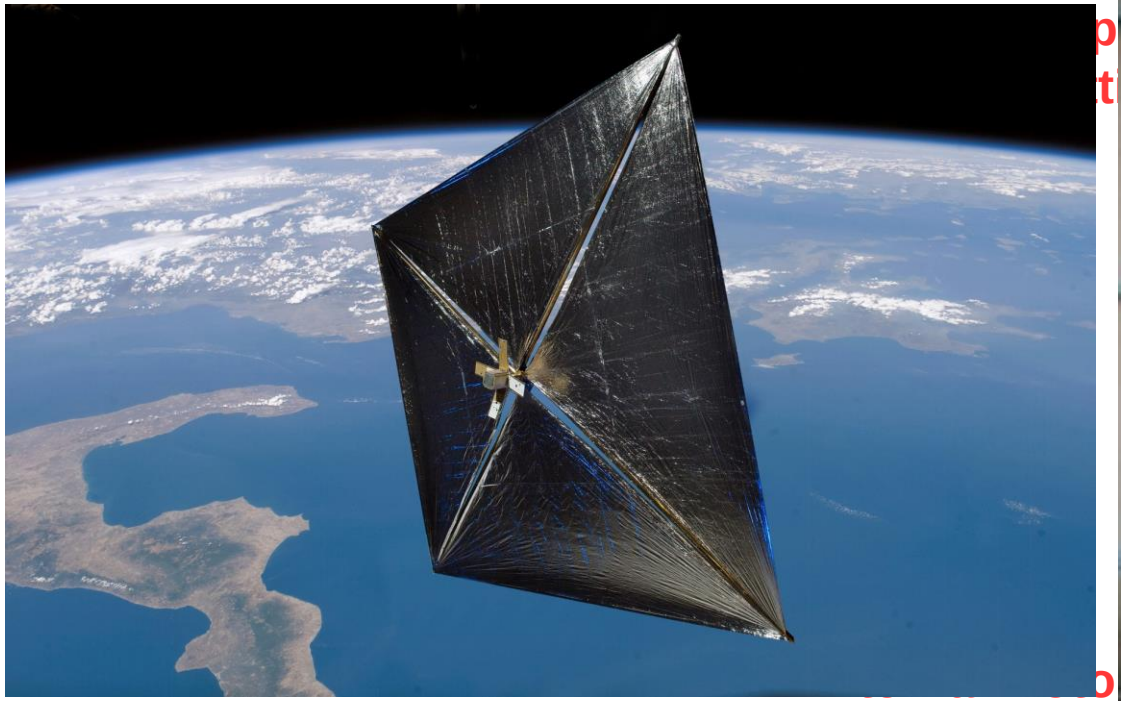


(a) Side view of the demonstrator



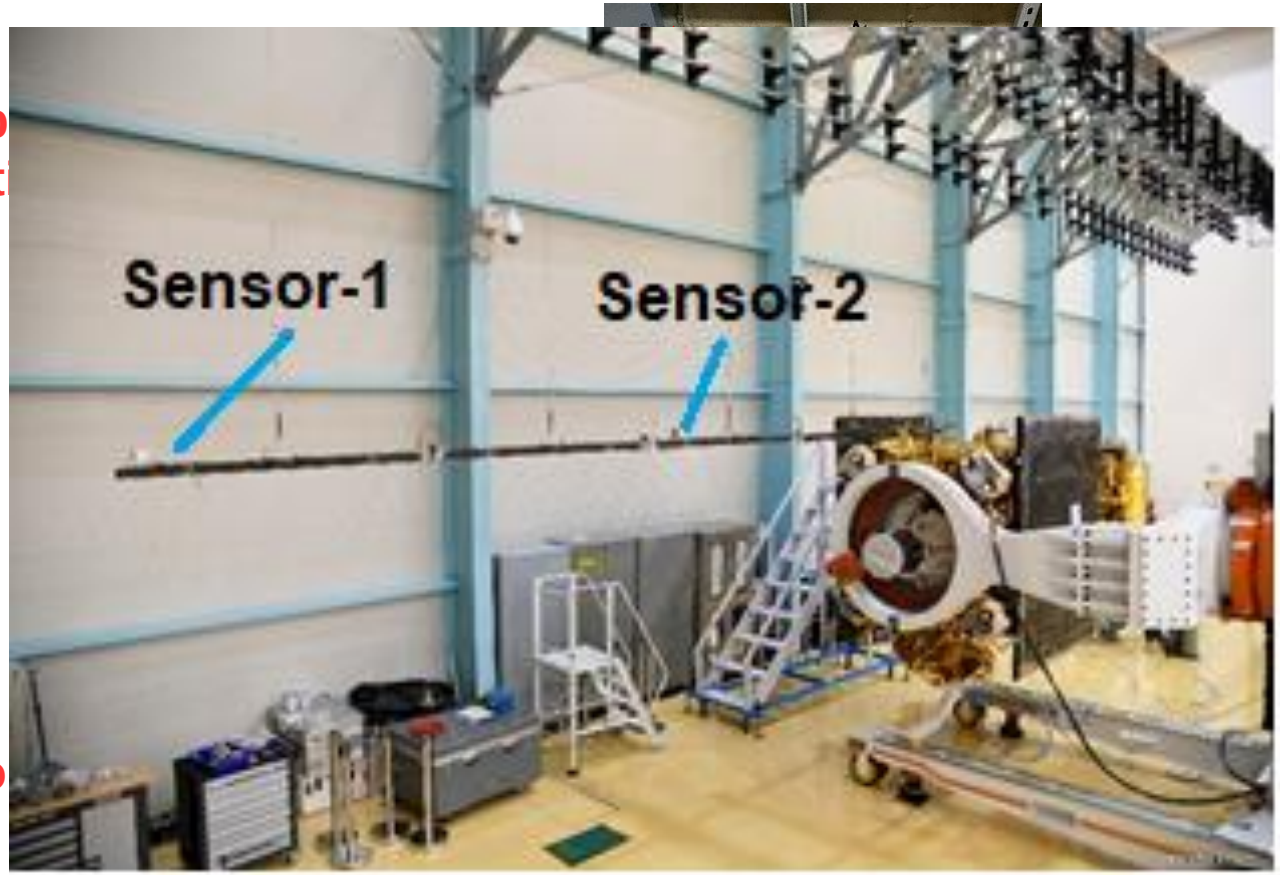
DEPLOYABLE BOOM: MARKET LEADING PACKING EFFICIENCY AND STRUCTURAL EFFICIENCY

Deployed State

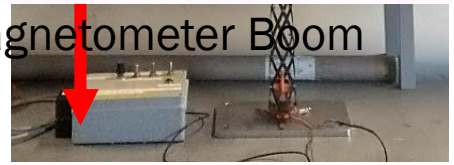


NASA's solar sail system

"Morphing composite cylindrical lattices with enhanced bending stiffness", Materials & Design, 2022



ISRO's Aditya-L1 Magnetometer Boom



DEPLOYABLE LATTICES

Composite cylindrical lattice morphing from stowed to deployed state

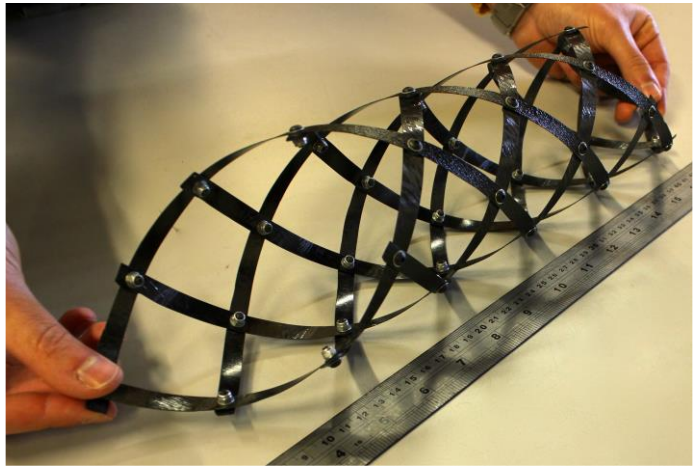
Curved composite strips after autoclave curing

[0/0/90/0/0] CFRP Laminate

McHale et al. 2020

Stable

Stable



Unstable

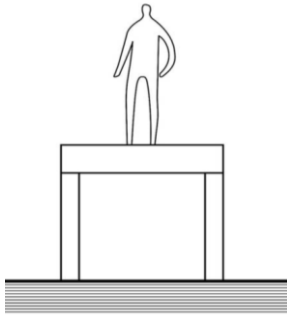
Multistable fiber reinforced composite lattices

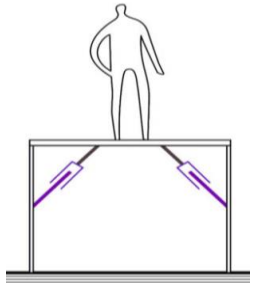
Pirrera et al. 2013

CONCLUSIONS

Thin Elastic structures → Geometry + Materials → Function

Energy efficient adaptive structures
Gennatore et al. 2021





DESIGN

Metamaterials, composites, lattices, origami

Theory, computational model, and optimisation

FABRICATION

Rapid Prototyping, Composite Manufacturing

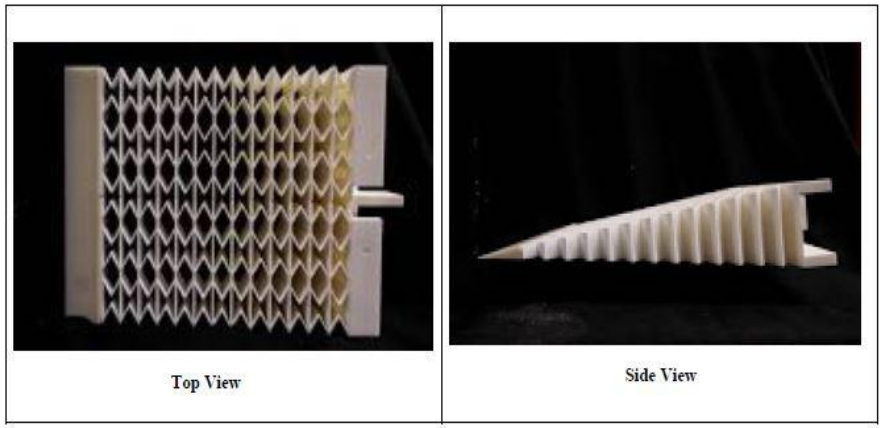
3D printing, Autoclave curing, Pultrusion, Laser scoring, folding

CHARACTERIZATION

Experiments

Mechanical Testing, Measurements, Geometrical characterisation (3D scanning)

Roll-Out Solar Array (ROSA) - NASA



Morphing Wind turbine flap (Ai, Weaver, Azarpeyvand 2017)

ACKNOWLEDGEMENT

The presenter would like to thank the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 945168 and Science Foundation Ireland (SFI) under the grant number 12/RC/2278_P2 for funding this project (FORMULA). I would like to also thank Bernal Institute, University of Limerick, Ireland for hosting me to carry out this project.

THANK YOU