Shen, J., Garrad, M. S., Pirrera, A., & Groh, R. (2022). *Climbing soft robot using re-programmable metamaterial*. 11th European Solid Mechanics Conference, Galway, Ireland.

Climbing soft robot using re-programmable metamaterial

Jiajia Shen[1], Martin Garrad[2], Alberto Pirrera[1], Rainer M. J. Groh[1]
[1] *Bristol Composites Institute (BCI), Department of Aerospace Engineering,*
University of Bristol, Bristol BS8 1TR, UK
E-mail: j.shen@bristol.ac.uk, alberto.pirrera@bristol.ac.uk, rainer.groh@bristol.ac.uk
[2] *SoftLab, Bristol Robotics Laboratory, University of Bristol, Bristol BS8 1TR, UK*
E-mail: m.garrad@bristol.ac.uk

Keywords: active modal nudging; multi-stability; mode switching

Buckling-driven metamaterials are increasingly being exploited for novel functionality in soft robotics as shape-adaptation and exotic constitutive behaviour can be tailored by controlling the nonlinearity of individual unit cells [1]. Extensive work has been done on tailoring the post-buckling behaviour of metamaterials through geometry/material modification before fabrication [2, 3], also known as 'modal nudging' [4]. In this work, we demonstrate the re-programmability of metamaterials after fabrication through the use of embedded actuators.

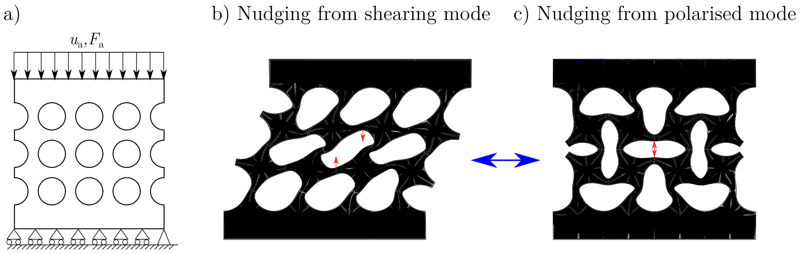


Fig. 1: (a) Original geometry and boundary conditions of the re-programmable metamaterial. (b, c) Stable post-buckling modes with the active nudging forces (red arrow) applied to achieve mode switching.

To design the metamaterial we use an in-house generalised path-following solver [5] that explores the complete post-critical bifurcation landscape of a buckling-driven latticed metamaterial comprising an elastomeric matrix with an embedded square array of circular holes. With the full bifurcation landscape at hand, and multiple stable states in the post-critical regime, we propose an active modal nudging technique that switches the latticed metamaterial between two distinct configurations—a shearing mode and a polarized mode—through a pair of concentrated forces applied in the central hole. The applied actuation leads to a sudden mode change by means of a snap-through instability. Based on the ability to interchange between two stable states, a soft robotic climber is manufactured and its effectiveness verified through demonstration tests. The conducted work sheds light on programming the behaviour of soft metamaterials through embedded actuators after manufacturing, which will further enrich the design space of mechanical metamaterials and their application in soft robotics.

References

[1] S. Janbaz, F. S.L. Bobbert, M. J. Mirzaali, and A. A. Zadpoor. Ultra-programmable buckling-driven soft cellular mechanisms. *Mater. Horizons*, 6(6):1138–1147, 2019.

[2] B. Haghpanah, H. Ebrahimi, D. Mousanezhad, J. Hopkins, and A. Vaziri. Programmable Elastic Metamaterials. *Adv. Eng. Mater* , 18(4):643–649, 2016.

[3] E. Medina, P. E. Farrell, K. Bertoldi, and C. H. Rycroft. Navigating the landscape of nonlinear mechanical metamaterials for advanced programmability. *Physical Review B*, 101(6):1–6, 2020.

[4] B. S. Cox, R. M.J. Groh, D. Avitabile, and A. Pirrera. Modal nudging in nonlinear elasticity: Tailoring the elastic post-buckling behaviour of engineering structures. *J. Mech. Phys. Solids* , 116:135–149, 2018.

[5] R. M. J. Groh, D. Avitabile, and A. Pirrera. Generalised path-following for well-behaved nonlinear structures. *Comput. Meth. Appl. Mech. Eng.*, 331:394–426, 2018.

University of BRISTOL
Bristol Composites Institute

Reconfigurable latticed metamaterial using active modal nudging

Jiajia Shen, Martin Garrad, Qicheng Zhang, Alberto Pirrera, **Rainer M.J. Groh**

ROYAL ACADEMY OF ENGINEERING

The Leverhulme Trust

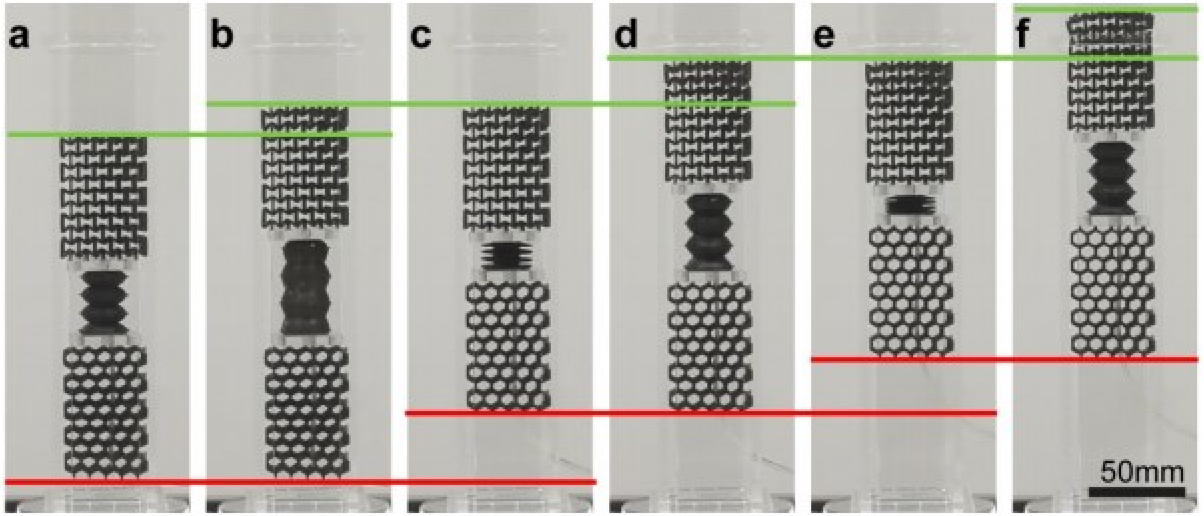
Outline

- Background
- Problem definition
- Active nudging
- Demonstration example—crawling soft robot
- Conclusion

Background

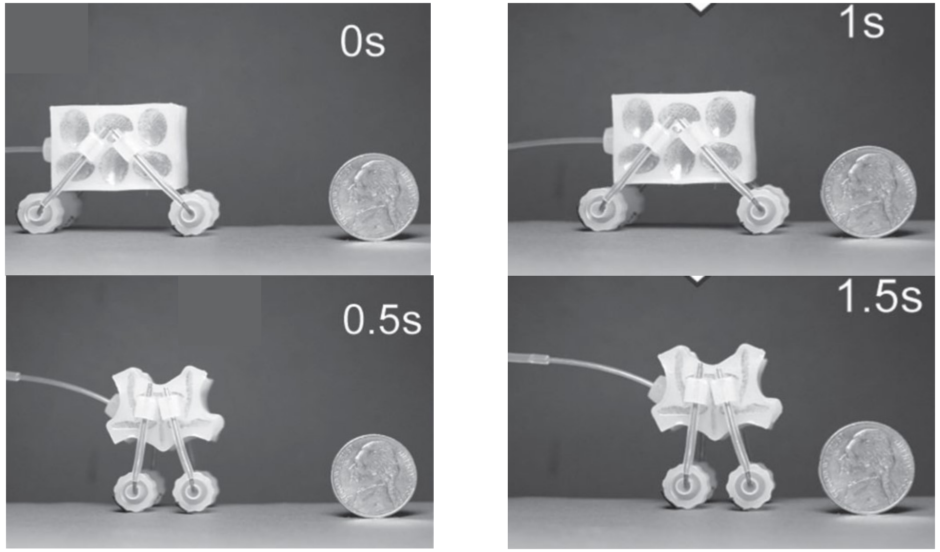
- Rich nonlinearity for programming
- Multi-stable equilibria with distinct deformation profiles

➢ A soft metamaterial robot inchworm climber



Mark, Andrew G., et al. **ICRA**, IEEE, 2016.

➢ A soft robotic walker



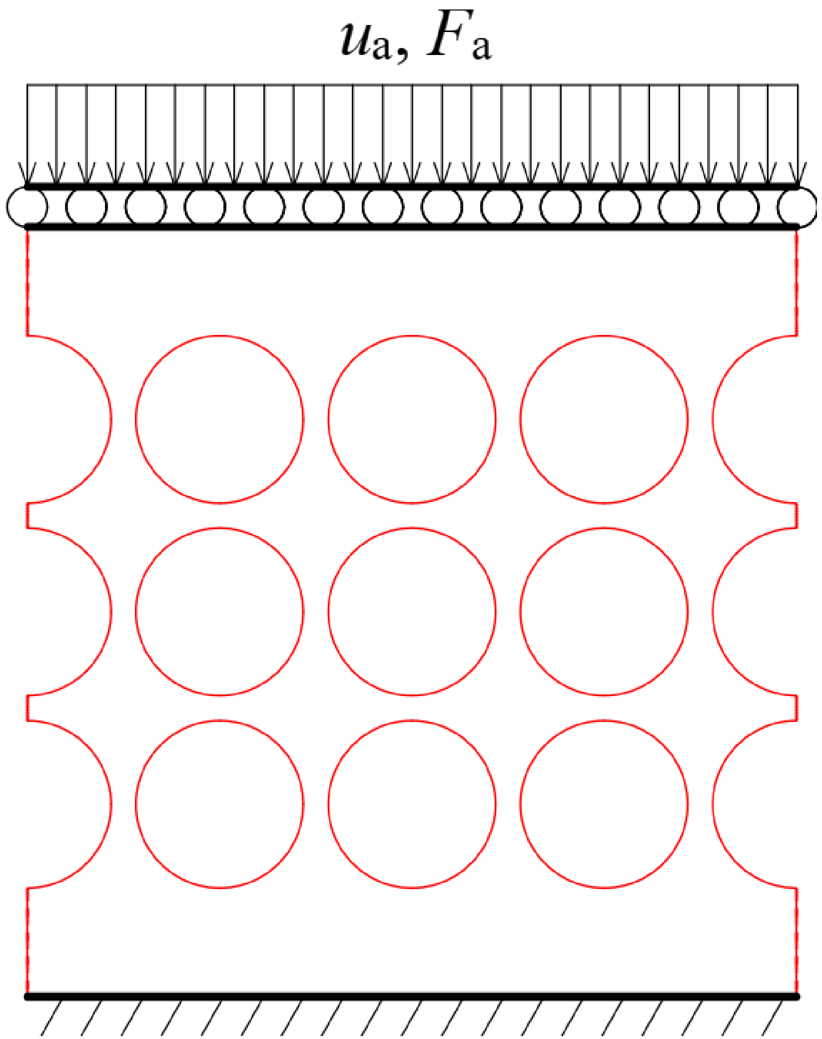
Yang, et al. **Adv. Mater**. 27.41 (2015): 6323-6327.

Problem definition

- Design philosophy of existing metamaterial-based soft robots: shape change from pre-buckling state to post-buckled state.
- *Multi-stability*: can we achieve shape shifting between *different stable post-buckling modes* through *a secondary loading?*
- Since the secondary loading is generally very small compared with primary loading, we define it as active *modal nudging*[1].

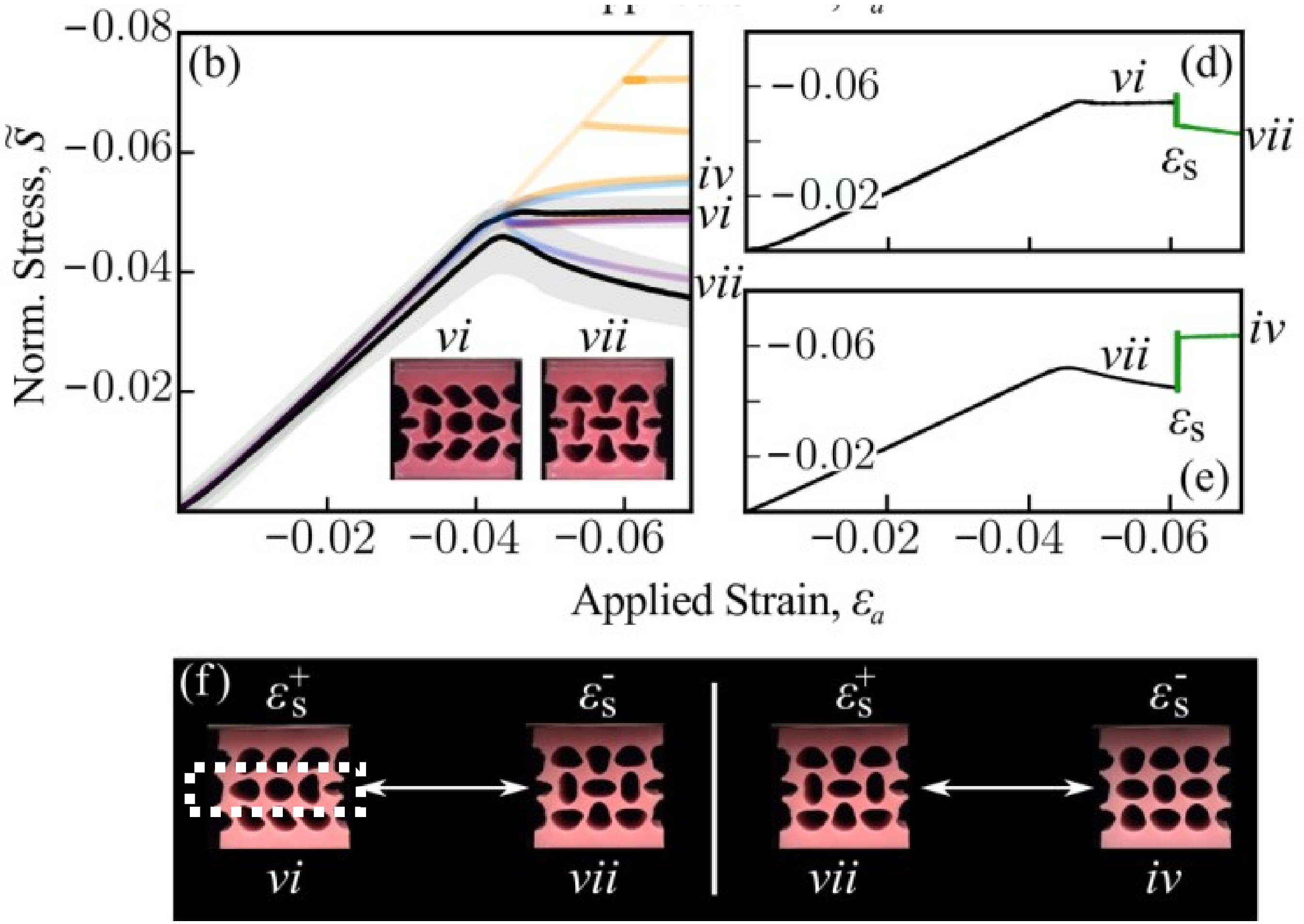
[1] Cox, B. S., et al. (2018) Modal nudging in nonlinear elasticity: tailoring the elastic post-buckling behaviour of engineering structures. **JMPS**. 116: 135-149.

Problem definition



- Latticed metamaterial with a 3 by 3 square array of circular holes under uniform compression with the **top edge** moving freely in the *horizontal* direction:
  - Identify all stable post-buckling modes
  - Find an effective nudging approach to switch between them
  - Design/manufacture a crawling soft robot

Previous work by Medina et al (2020)



From Ref [1]

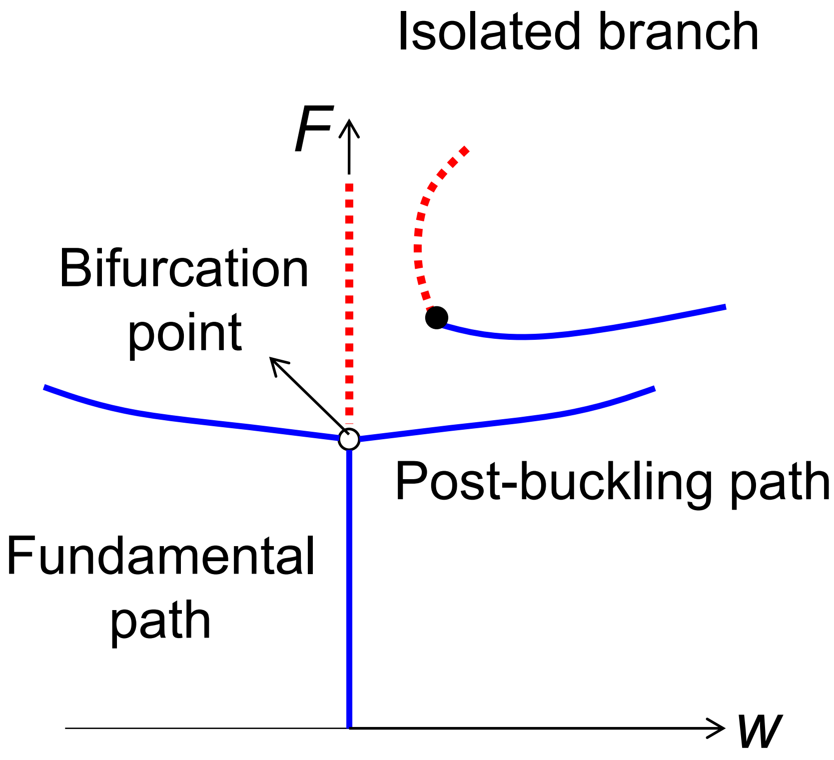
- Both top and bottom edges are fixed horizontally.
- Stable *shear* and *polarized* modes are observed.
- Deformation mainly *localized* in the *middle* layer with relatively small amplitude. Not suitable for climbing robot.

University of BRISTOL
Bristol Composites Institute

[1] Medina, E. et al. (2020) Navigating the landscape of nonlinear mechanical metamaterials for advanced programmability." PRB 101.6: 064101.

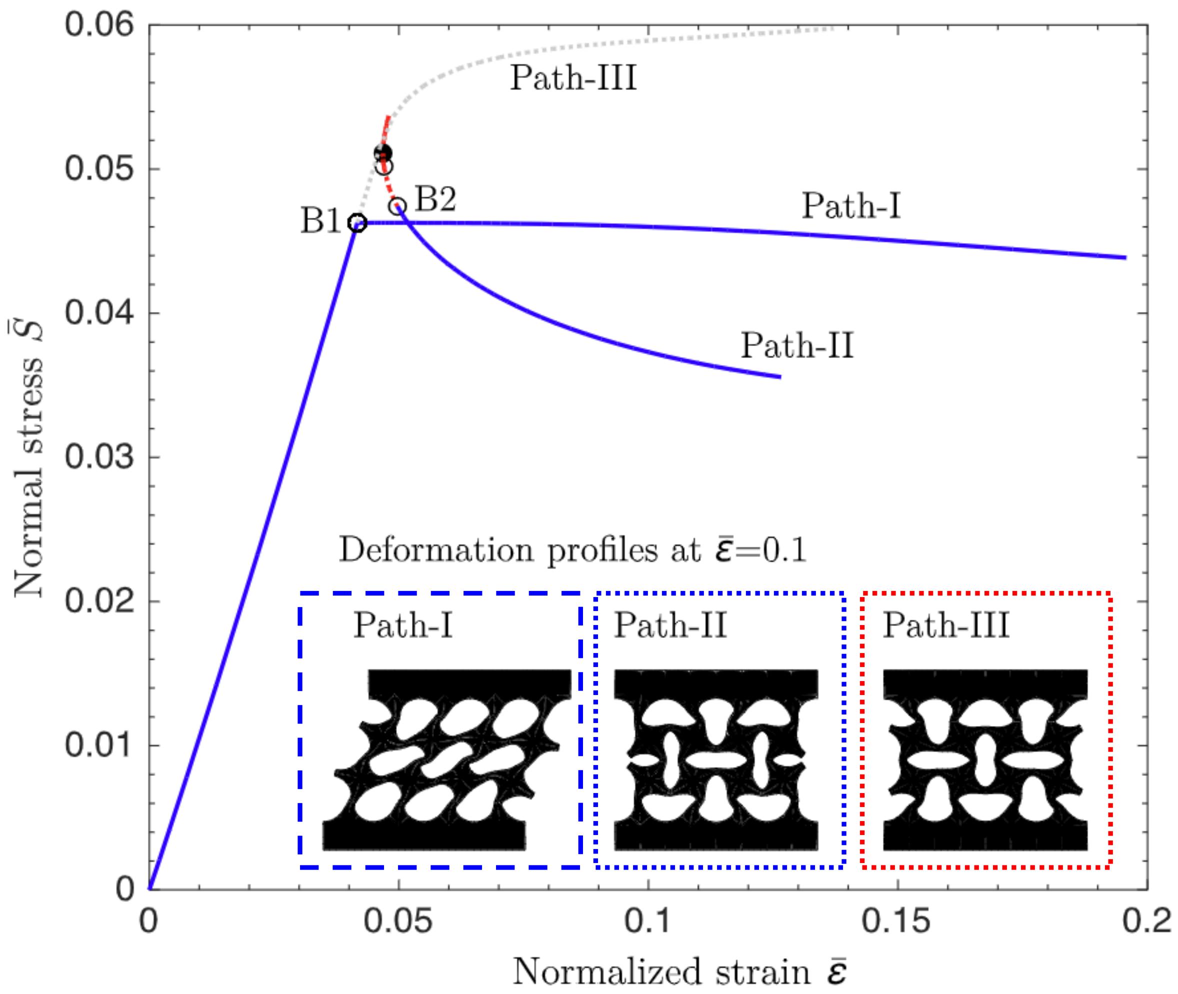
Methods

- FE model
  - 2D *plane strain* element
  - *Compressible* Neo-Hookean hyperelastic model
- Generalized path-following solver[1]
  - Pin-point critical points
  - Switch branch
  - Locate isolated equilibria using deflation/homotopy method



[1] Groh, Avitabile, & Pirrera. (2018). Generalised path-following for well-behaved nonlinear structures. CMAME, 331, 394-426.

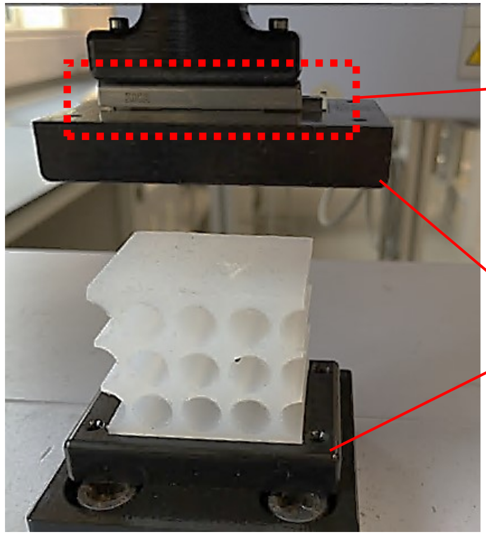
Equilibrium manifold of latticed metamaterial



- 3 stable post-buckling modes:
  2 *shear* modes (mirror-symmetric)
  + 1 *polarized* mode.
- For 'perfect' baseline geometry,
  - stable *shear* mode is on the *natural* loading path
  - stable *polarized* mode is on the *isolated* path, separated from fundamental path by an energy barrier

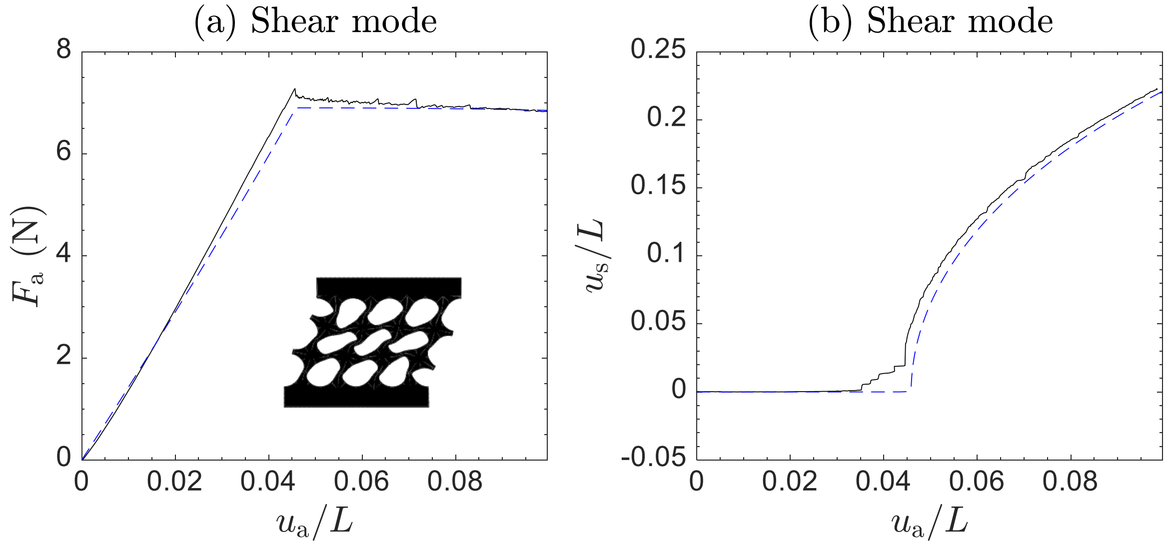
Validation of the FE model

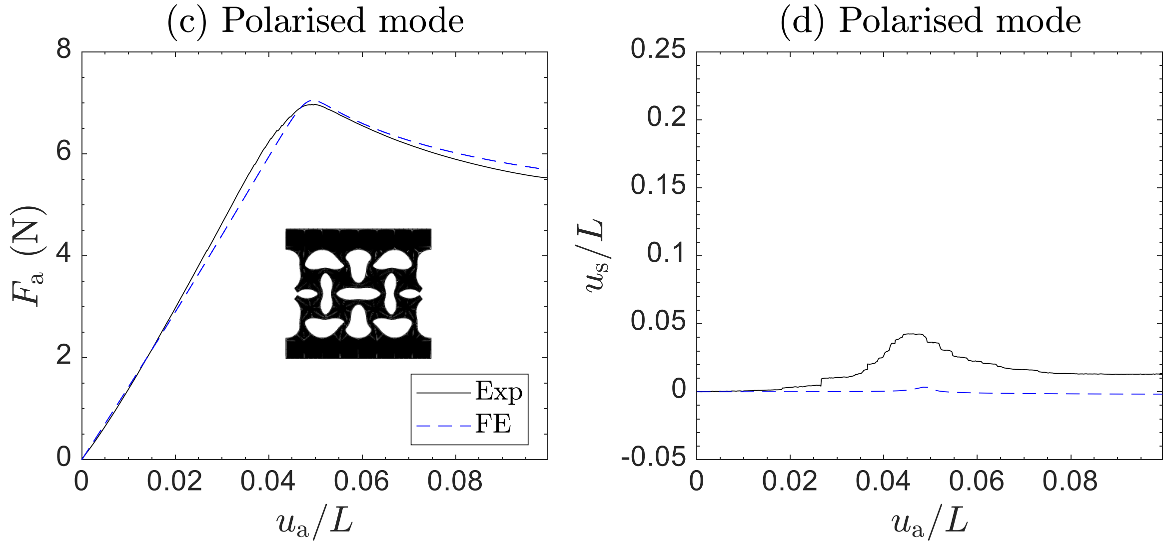
- Experimental setup
  - Smooth glide at the top loading edge
  - Sample size: 50 mmx50 mmx40mm(depth)
  - Cast silicon: Dragon Skin™ 10
  - Loading rate: 5 mm/min
  - Video gauge to measure shear disp.



Smooth glide

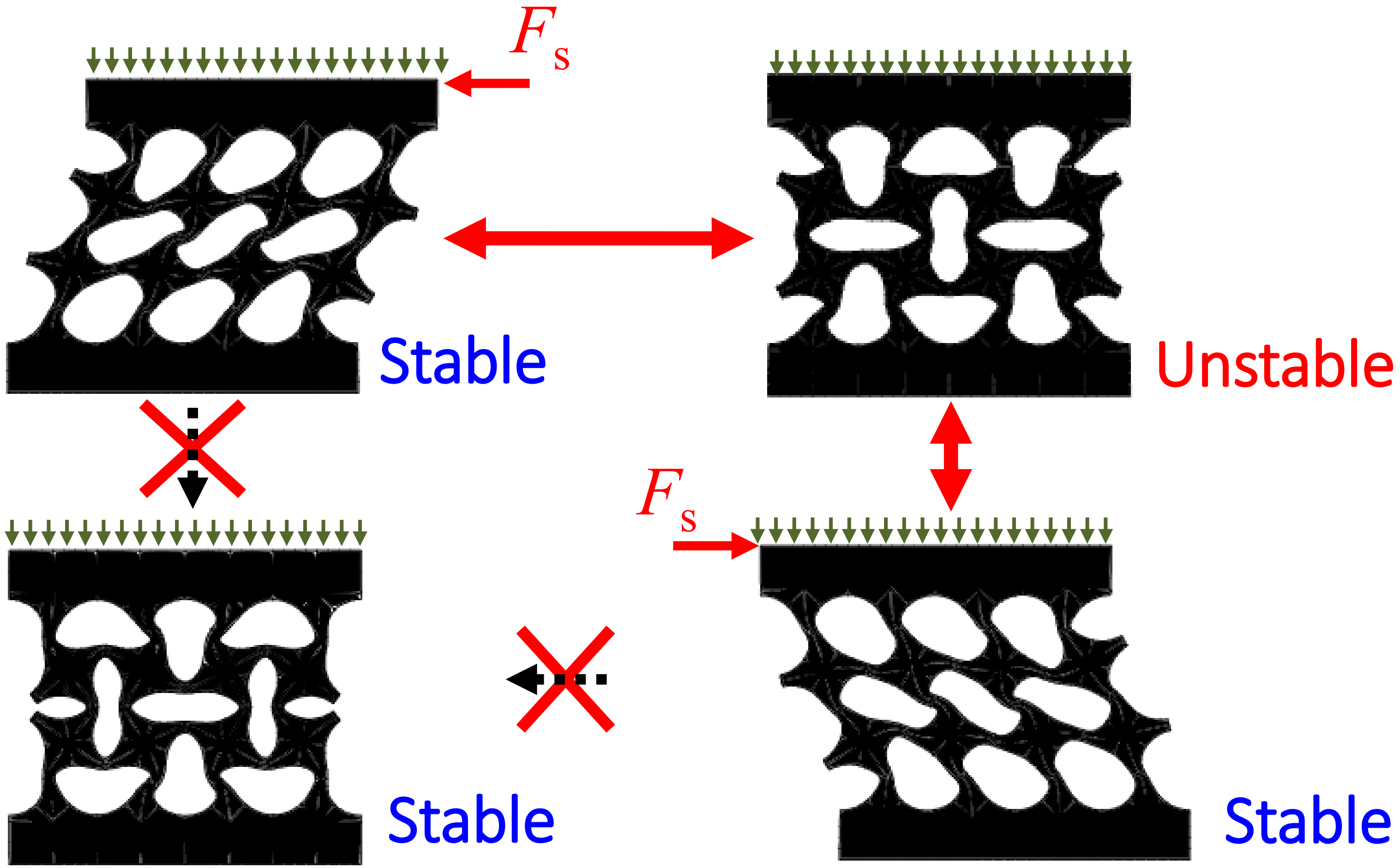
Fixtures



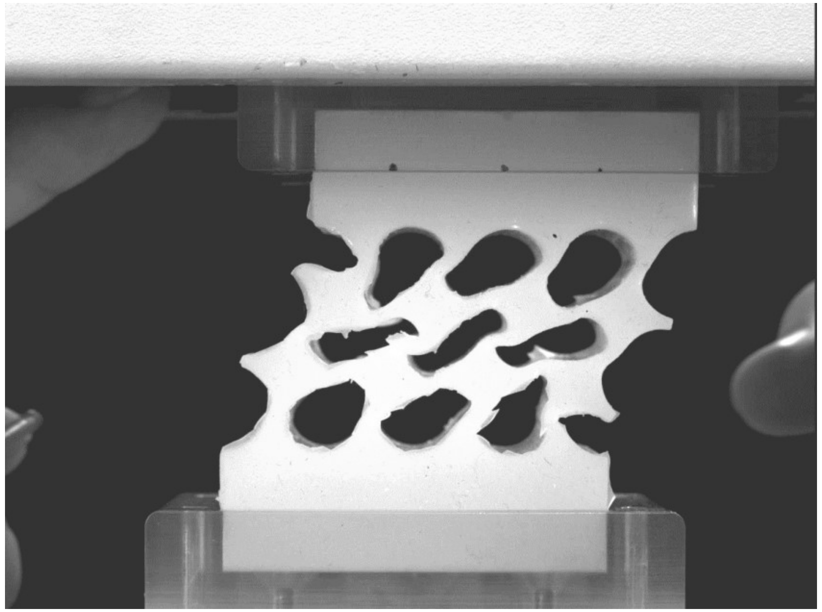


Mode switch between distinct stable equilibria

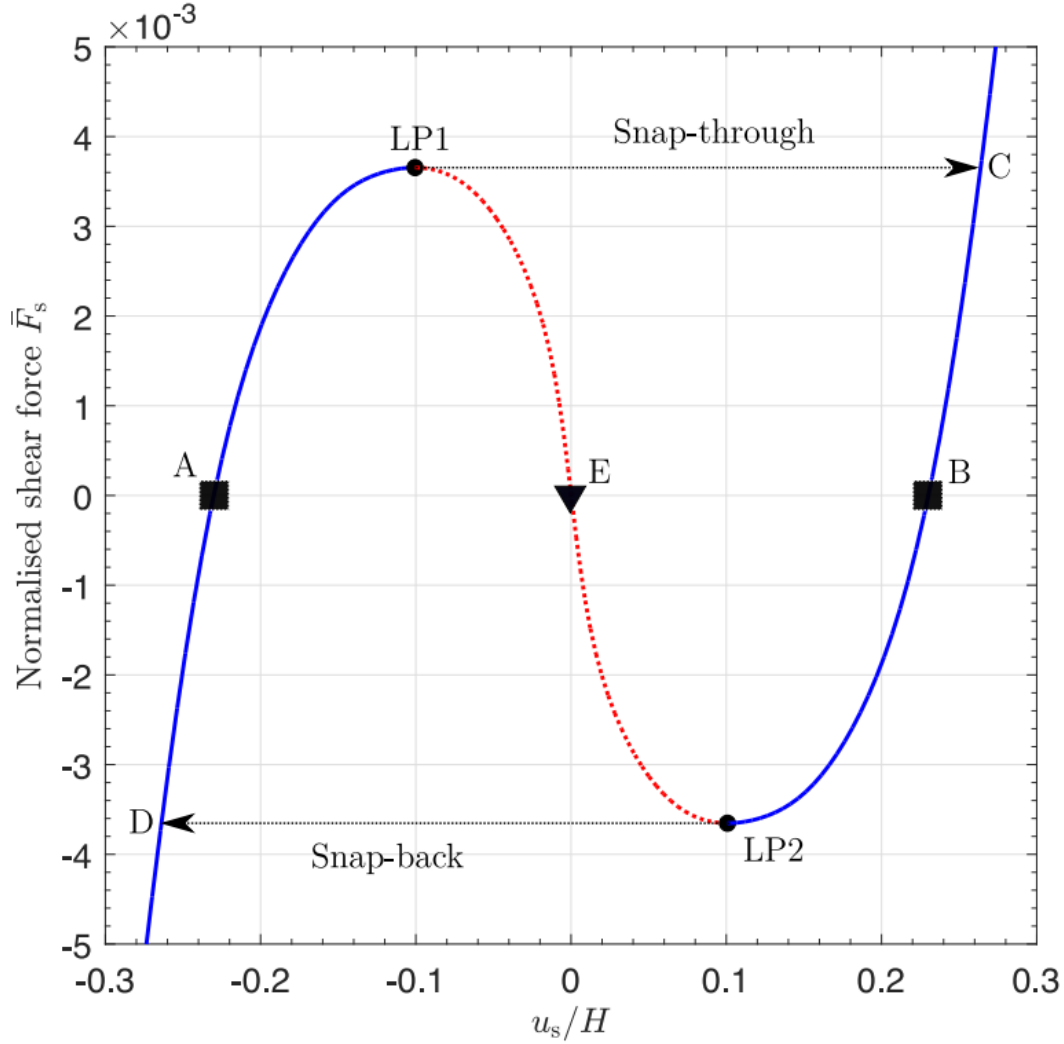
- Nudging using the shear force at the top edge

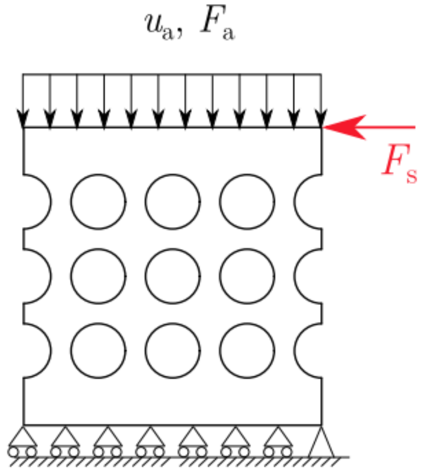


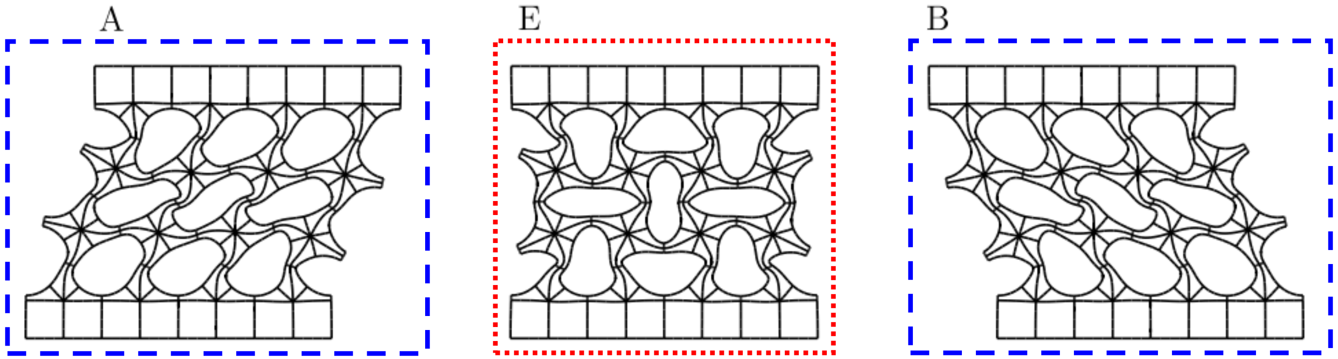
Demo experiment



Nudging path: shear force at the top edge



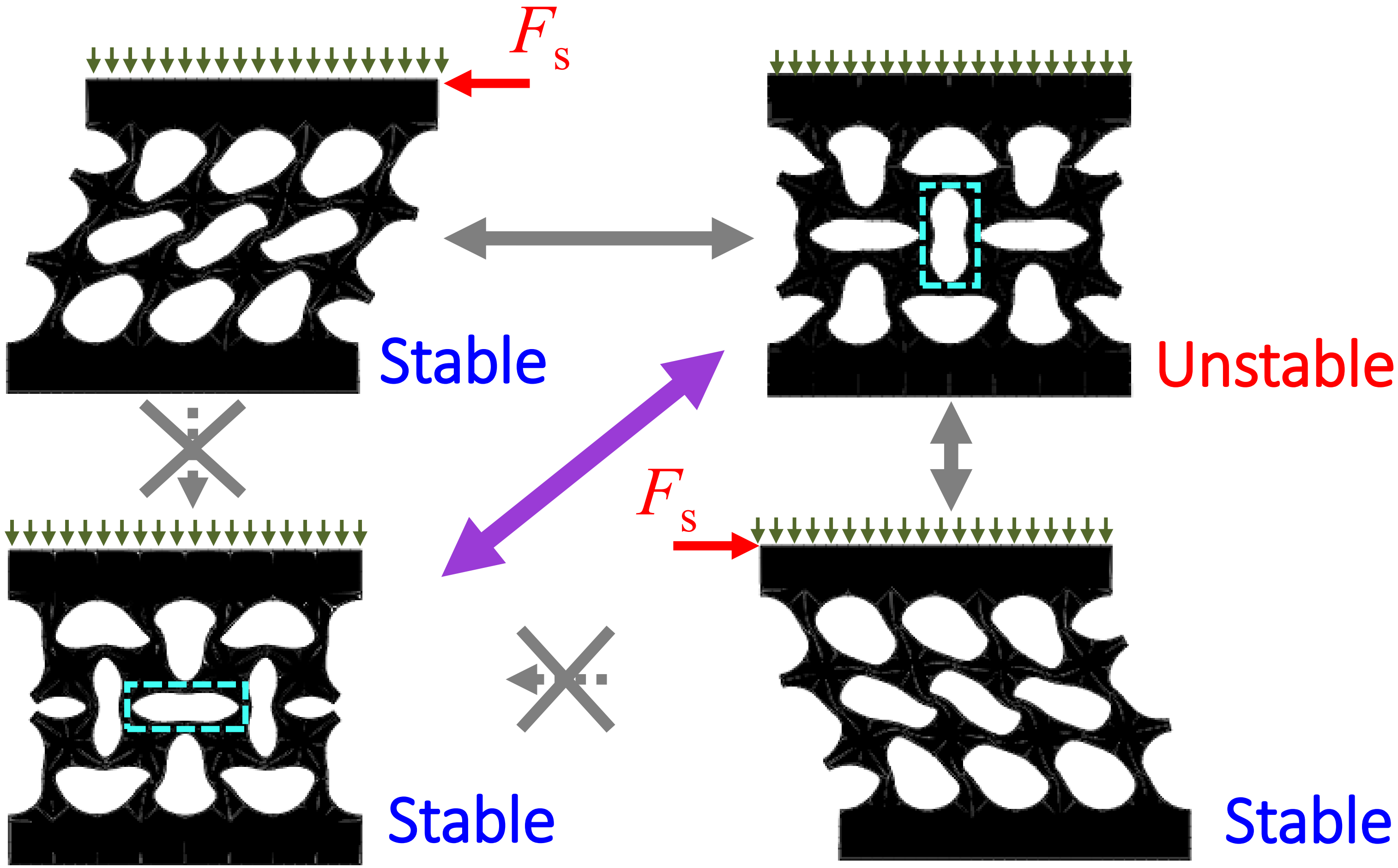




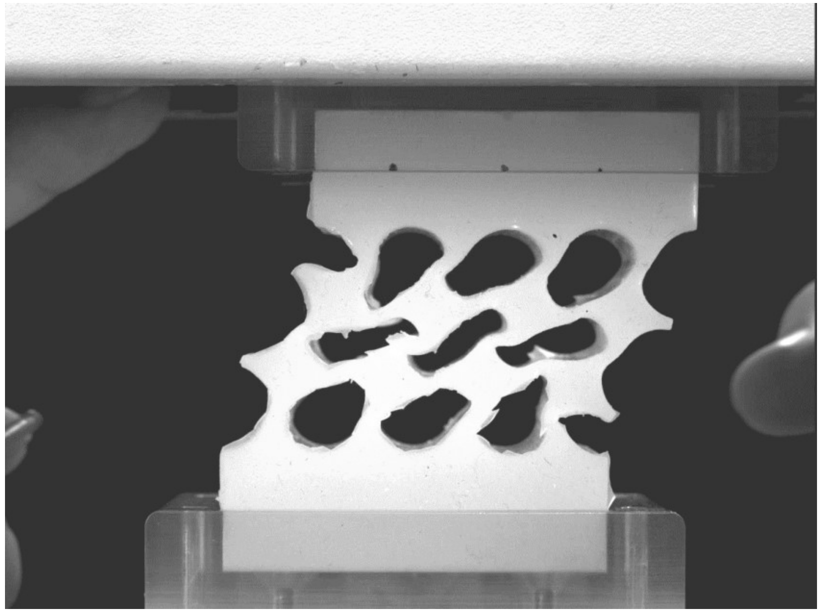
- $F_{s,LP1}$ is about 1/10 of $F_{a,cr}$

Mode switch between distinct stable equilibria

- Nudging using the shear force at the top edge



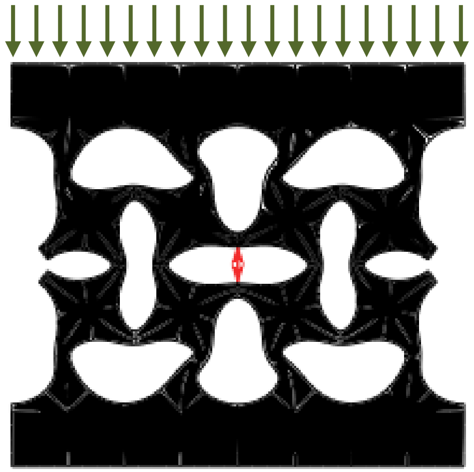
Demo experiment



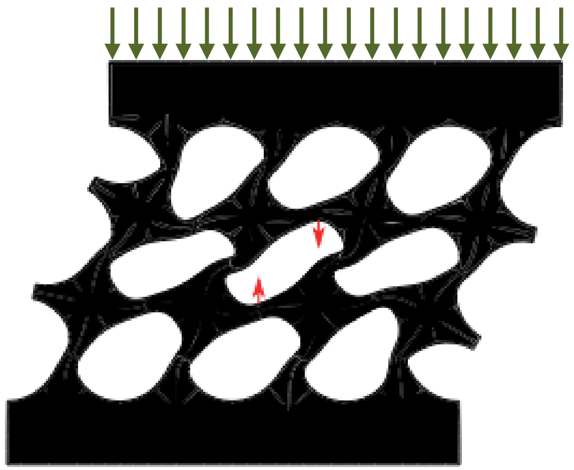
Mode switch and shape control authority

- A pair of vertical forces applied at the *central* hole can nudge the latticed metamaterial between stable *polarized* mode and *shear* mode.

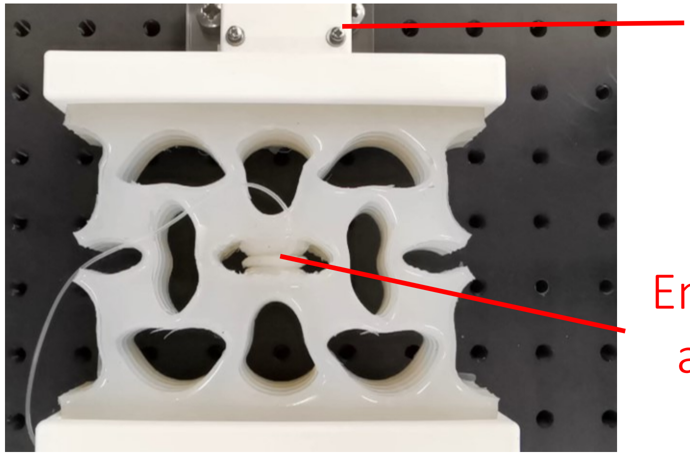
a) Nudging from polarized mode



b) Nudging from shear mode



c) Demo experiment



Smooth glide

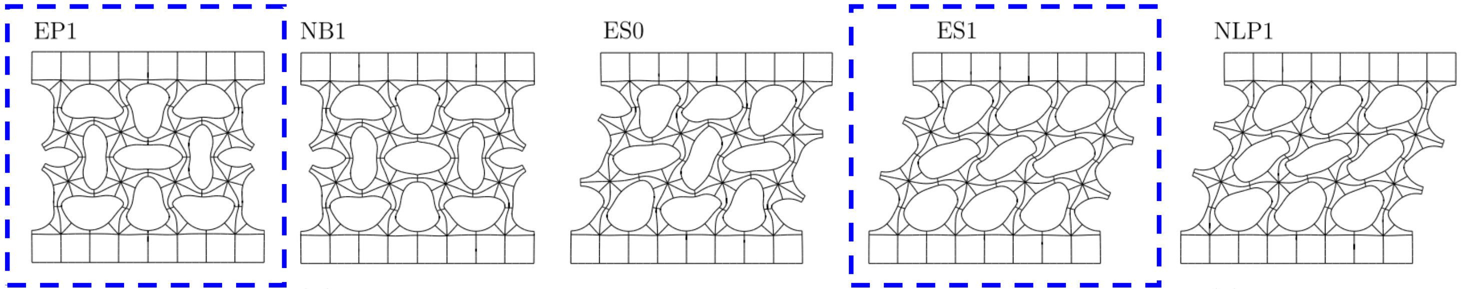
Embedded actuator

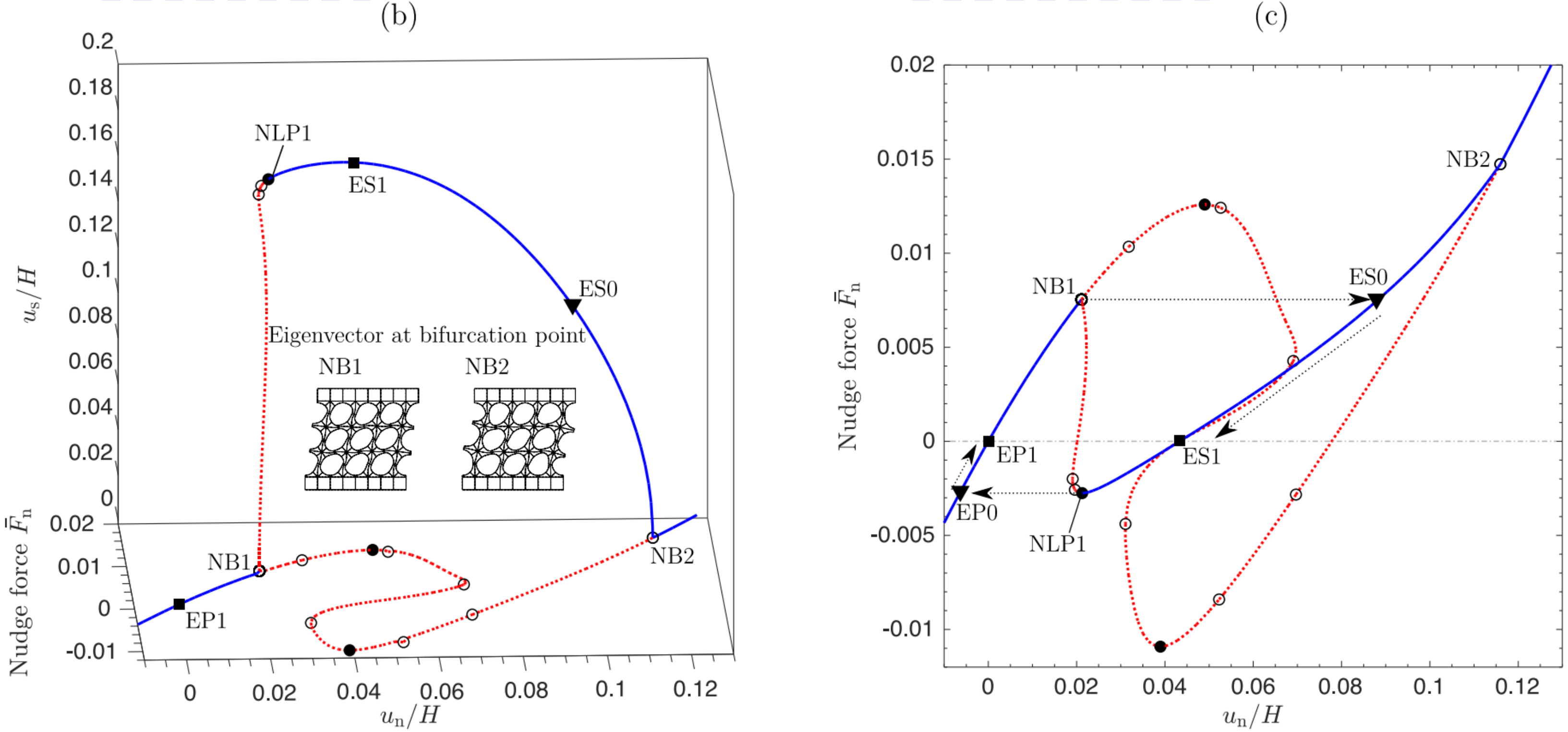
- Shape control [1] in the deformation of the central hole is key to the success of active modal nudging.

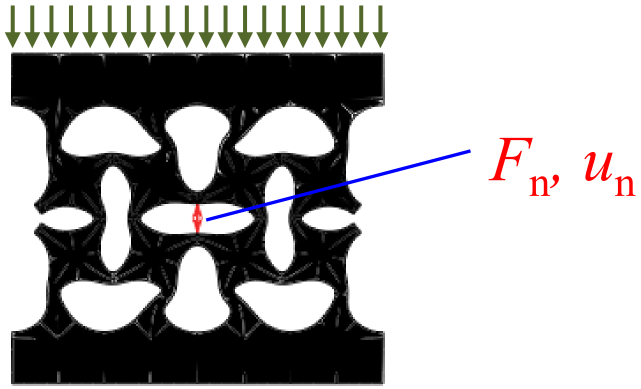
[1] Neville, R. M., et al. (2018) Shape control for experimental continuation. **PRL**. 120.25 : 254101.

Nudging path: pair of vertical forces in the central hole

(a) Deformation profiles at selected equilibria during active nudging

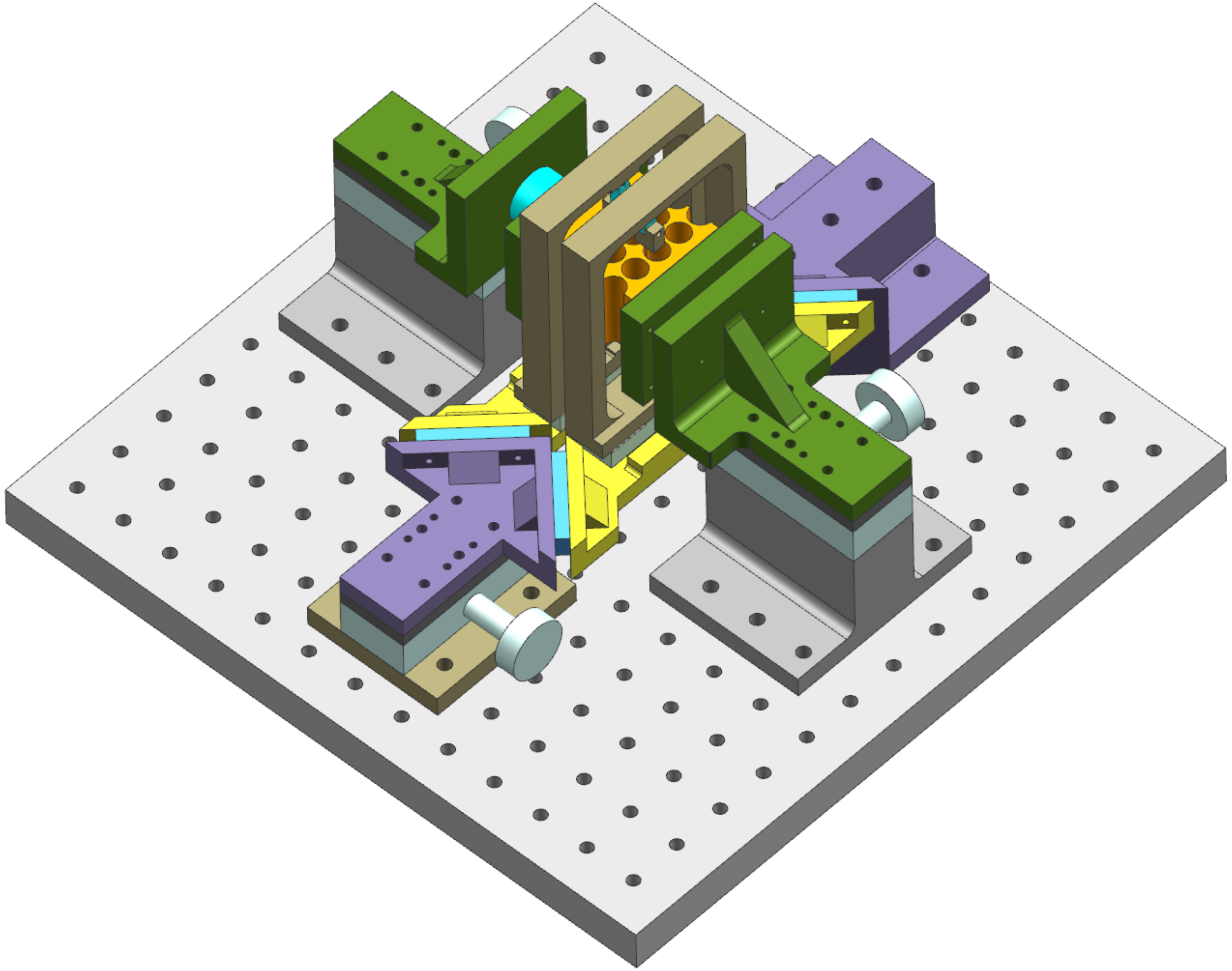






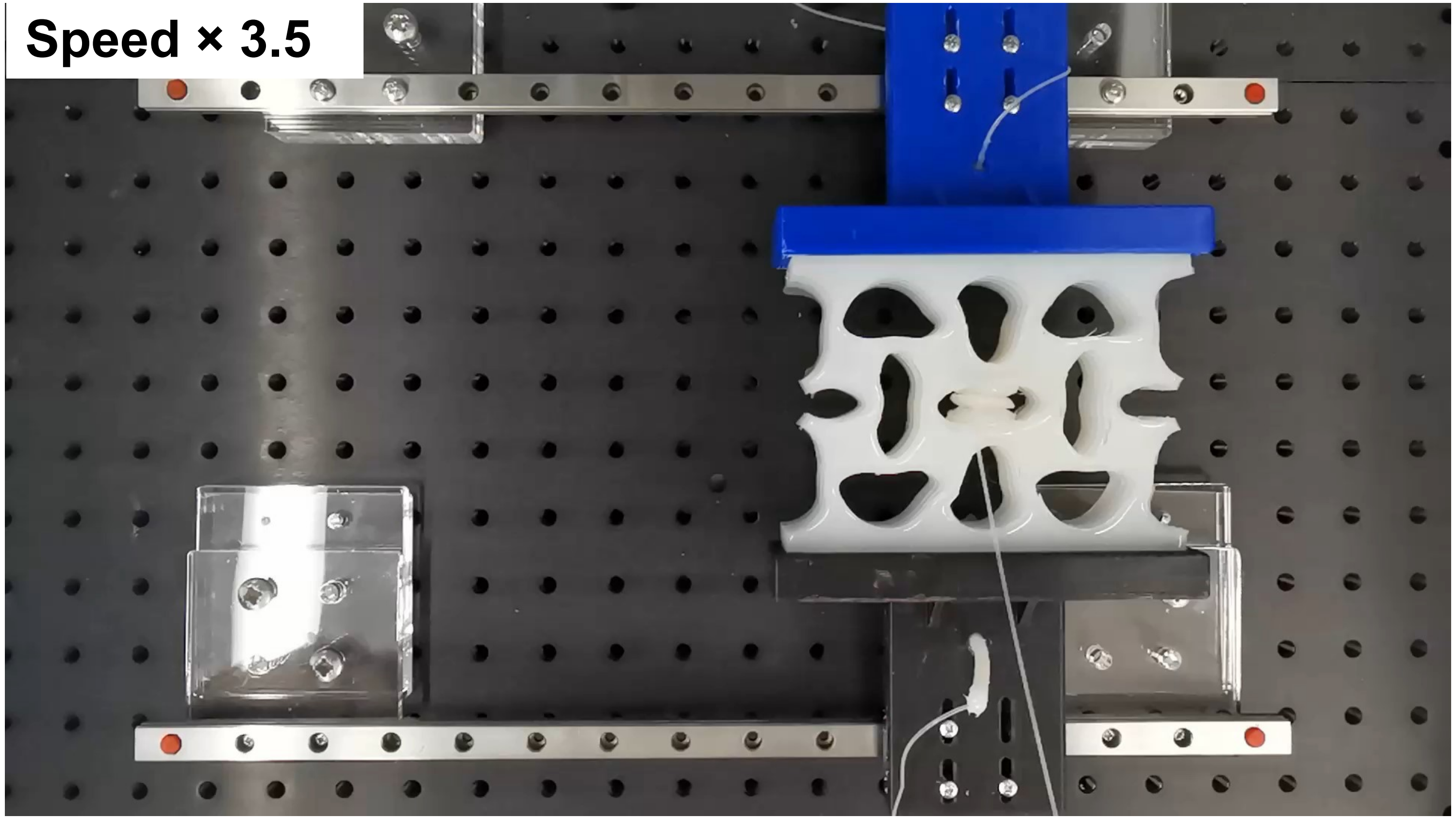
- Symmetry breaking/restoration accompanied by snap-through instability
- P->S requires more energy than S->P

Test rig for active nudging test



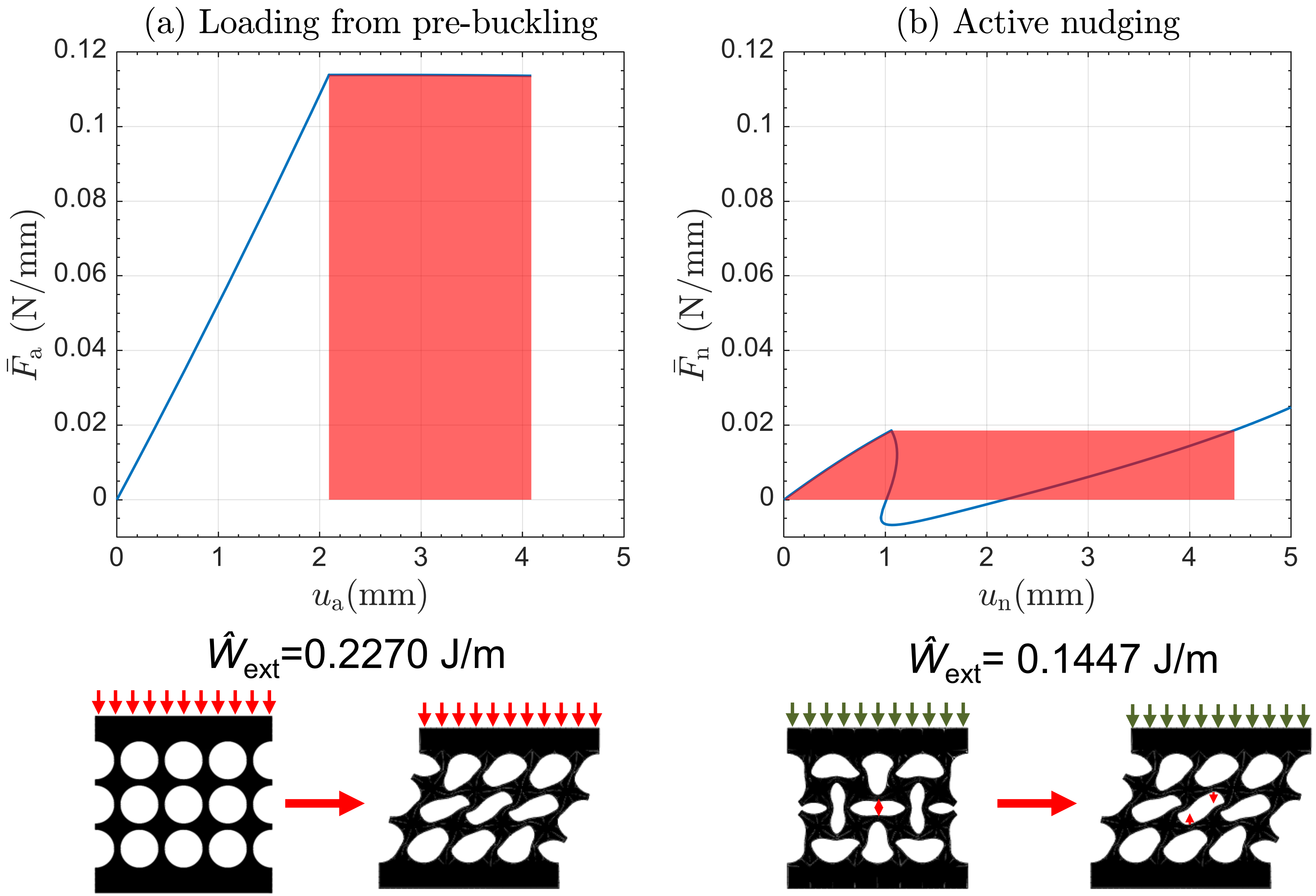
- Bi-axial loading system
- Green: apply the pre-compression force
- Purple (wedge + glide system): apply the pair of vertical *active nudging* force in the central hole

Crawling robot demo—`Moving cheese’



- Pneumatic bellow as actuator in the central hole
- Asymmetric friction mechanism on the connectors with glides

Energy efficiency comparison



$\hat{W}_{\rm ext}$=0.2270 J/m

$\hat{W}_{\rm ext}$= 0.1447 J/m

- Save more than **35%** of energy to achieve the same amplitude of shape shifting compared with *loading from pre-buckling state*.
- Parts of the input energy transformed to *dynamic effects* arising from snap-through instability, leading to much faster response.

Conclusion

- Generalised path-following technique[1] to identify all stable post-buckling modes and solve the active nudging path.
- An embedded actuator, with shape control authority, can achieve the mode switch between the stable polarized and shear modes.
- A crawling soft robot based on the active modal nudging mechanism is manufactured and tested.
- Higher energy efficiency and faster response speed compared with traditional buckling-induced shape shifting metamaterial.

[1] Groh, Avitabile, & Pirrera. (2018). Generalised path-following for well-behaved nonlinear structures. CMAME, 331, 394-426.

University of BRISTOL

Bristol Composites Institute

Thanks for your attention.

Q&A

Contact us:

Jiajia Shen: j.shen@bristol.ac.uk

Martin Garrad: m.garrad@bristol.ac.uk

Rainer Groh: Rainer.Groh@bristol.ac.uk

bristol.ac.uk/composites

ROYAL
ACADEMY OF
ENGINEERING

The Leverhulme Trust