Design and modelling of active mechanical metamaterials

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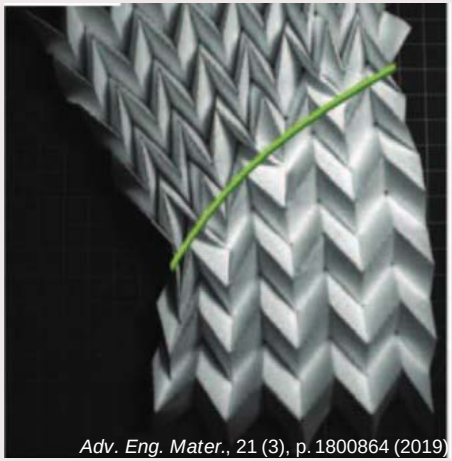
Smart materials / metamaterials

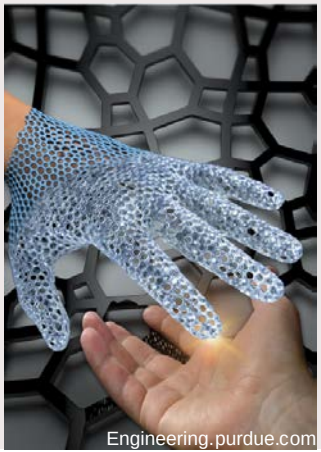
- Soft robotics
- Shape-morphing materials
- Tunable mechanical properties (stiffness, damping, band-gap)
- Biomedical applications
- Space technology
- ...

Space technology



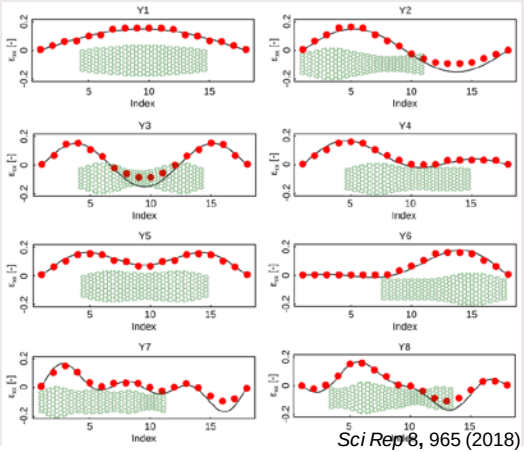
Adv. Eng. Mater., 21 (3), p. 1800864 (2019)

Soft robotics



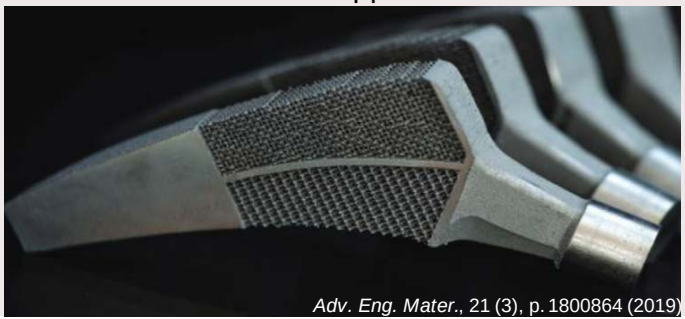
Engineering.purdue.com

Shape-morphing materials



Sci Rep 8, 965 (2018)

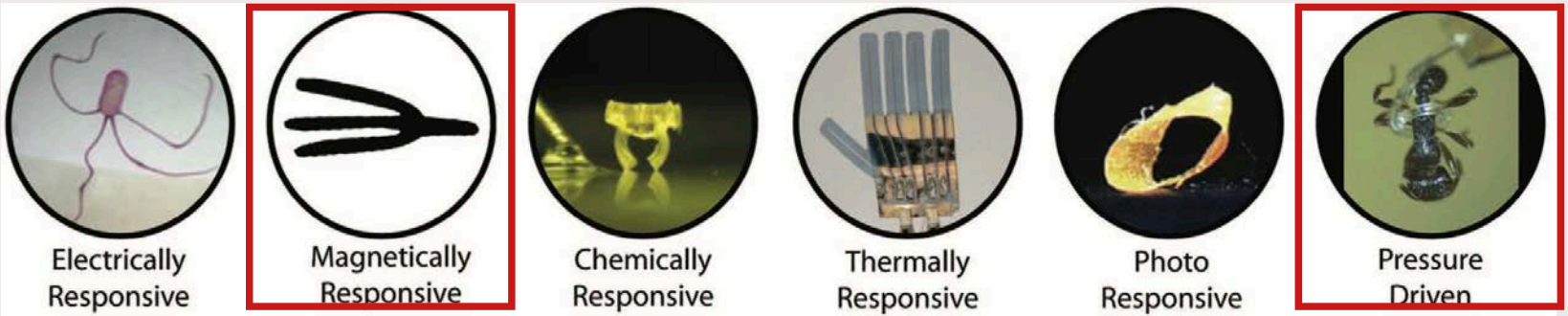
Biomedical applications



Adv. Eng. Mater., 21 (3), p. 1800864 (2019)

Focus → active mechanical metamaterials

→ Actuation mechanisms



Advanced Materials, vol. 29, no. 13, 2017

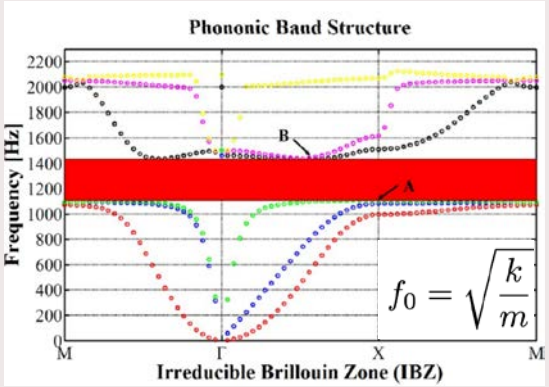
→ Change effective mechanical properties of metamaterials with a push of a button

Focus → active mechanical metamaterials

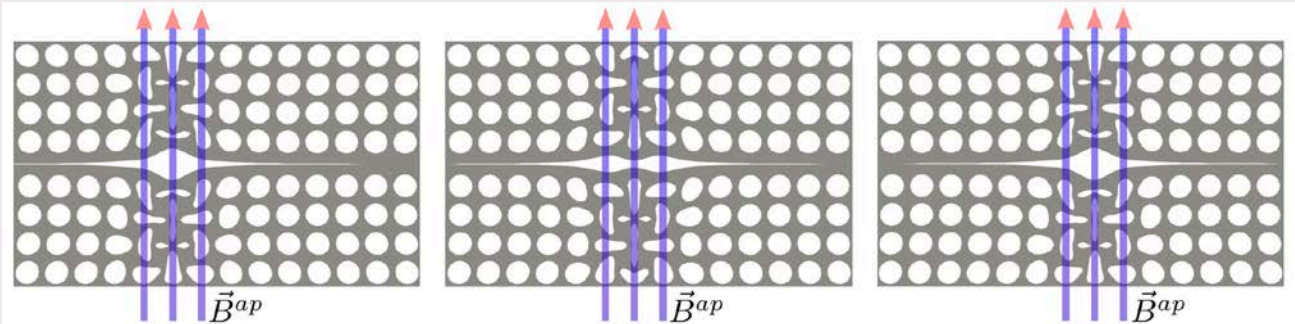
→ Tunable properties
- Stiffness
- Anisotropy
- Deformation
- …

→ Applications
- Soft robotics
- Haptics
- Positioning
- Acoustics
- …

Adjustable band gap



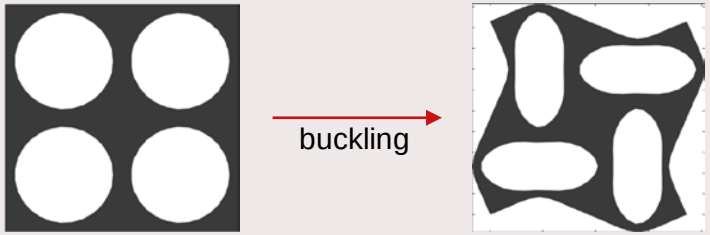
Peristaltic pump based on auxetic effect



Pneumatic actuation

- Working principle & expectations
  - Explore existing metamaterial structures
  - Distinct conformations/patterns → distinct effective properties

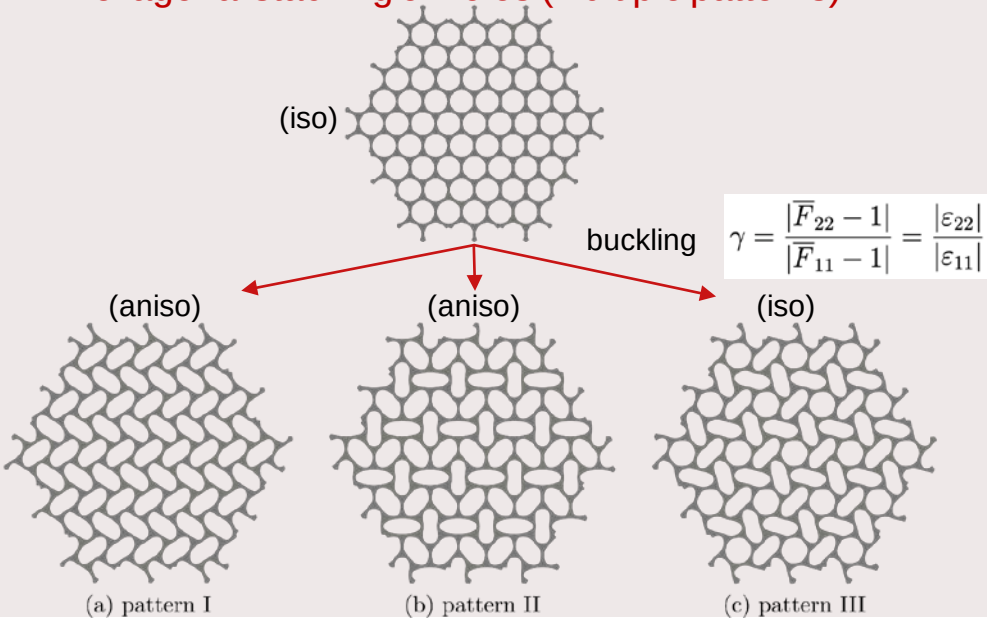
Square stacking of holes (single pattern)



Compression dominated
(aniso, stiff)

Bending dominated
(aniso, compliant)

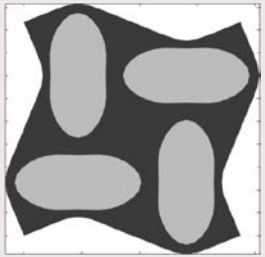
Hexagonal stacking of holes (multiple patterns)



Pneumatic actuation

- Modelling
  - Finite deformations & large strains
  - Instabilities
  - Pressure actuation

Compliant void model
(based on Casenbroon et. al, IEEE 2020)



Energy densities

Base material (matrix)

$$\Psi^{bb}(I_1, I_3) = c_1(I_1 - 3) + c_2(I_1 - 3)^2 - 2c_1 \log(J) + \frac{\kappa}{2}(J-1)^2 \longrightarrow \boldsymbol{\sigma}^{bb} = \frac{2}{J}\frac{\partial \Psi^{bb}}{\partial I_1}\boldsymbol{B} + \frac{\partial \Psi^{bb}}{\partial J}\boldsymbol{I}$$

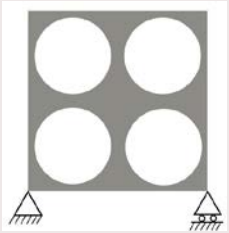
Air material (actuation)

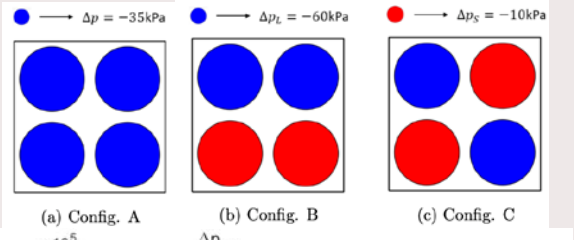
$$\Psi^{void}(\boldsymbol{F}) = \Delta p J \longrightarrow \boldsymbol{\sigma}^{void} = J^{-1}\boldsymbol{P}^{void} \cdot \boldsymbol{F}^T = \Delta p J^{-1} J \boldsymbol{F}^{-T} \cdot \boldsymbol{F}^T = \Delta p \boldsymbol{I}$$

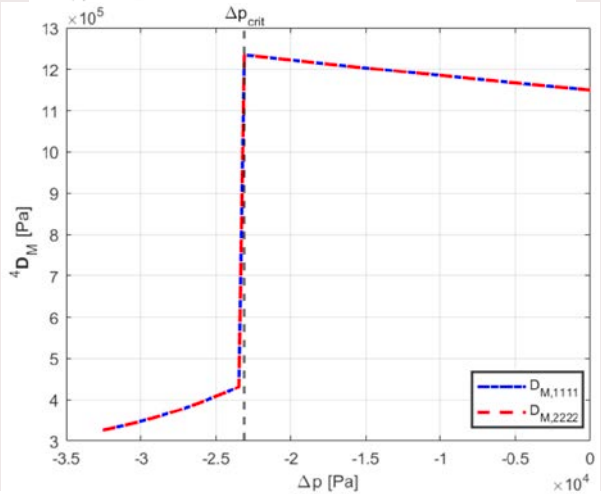
Standard TL FEM with Modified Newton (instabilities & bifurcation)

Pneumatic actuation

- Square stacking of holes
  →Pattern transformation driven by average pressure

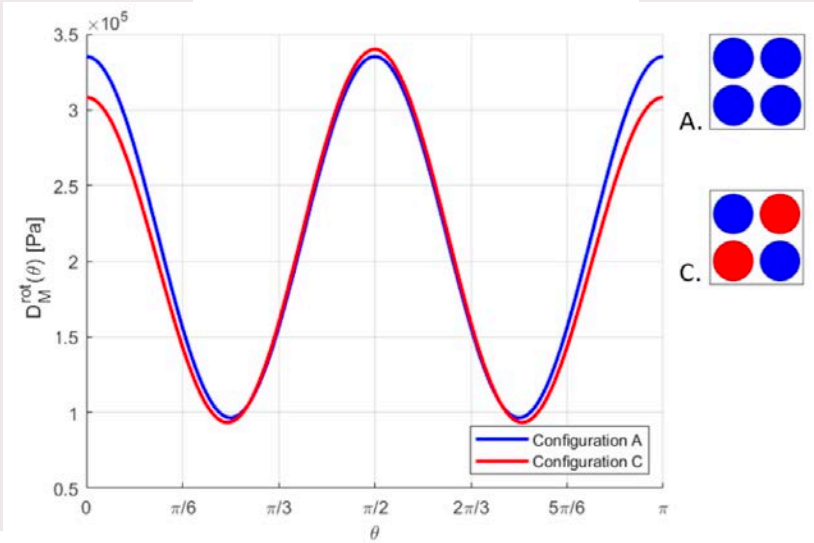






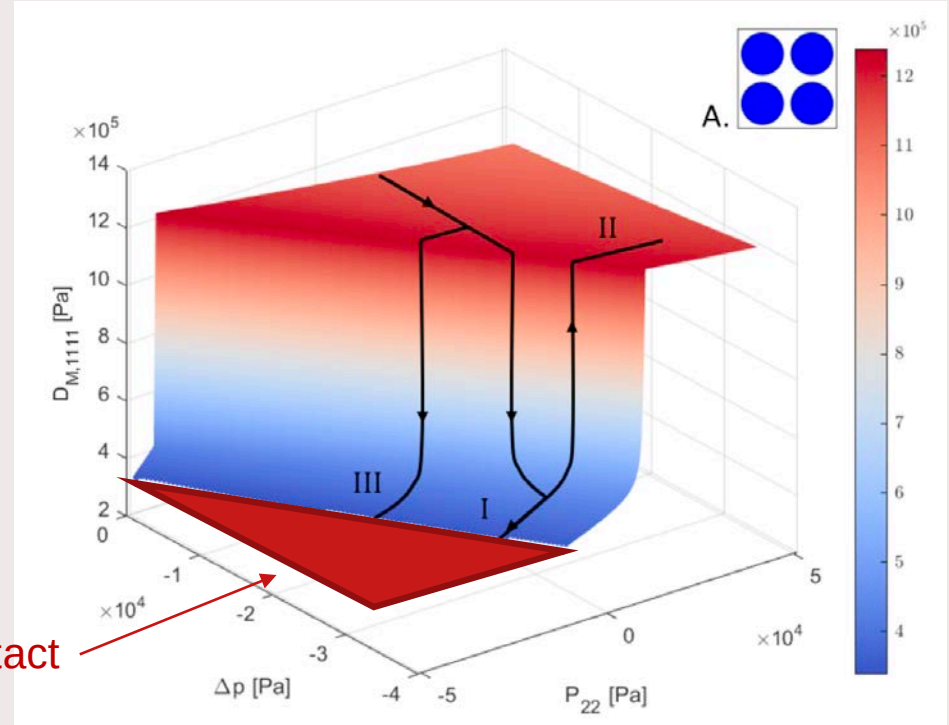
$$D_M^{rot}(\theta) = \boldsymbol{M}(\theta) : {}^4\boldsymbol{D}_M : \boldsymbol{M}(\theta),$$

$$\boldsymbol{M}(\theta) = \begin{bmatrix} \cos^2(\theta) & \sin(\theta)\cos(\theta) \\ \sin(\theta)\cos(\theta) & \sin^2(\theta) \end{bmatrix}$$



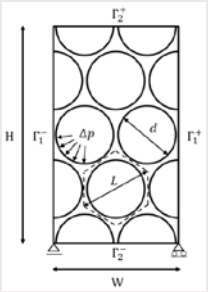
Pneumatic actuation

- Square stacking of holes
  → Actuation Δp + external load P_{22}

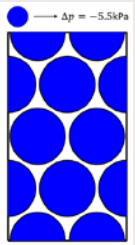


Pneumatic actuation

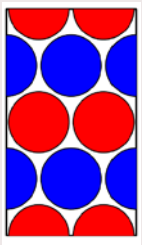
- Hexagonal stacking of holes
- Switchable stiffness
- Switchable directionality (anisotropy) 0°, ±60°



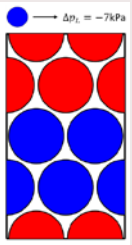
A: Pattern 3



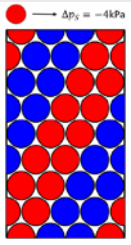
B: Pattern 2



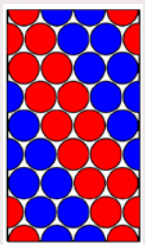
C: Mode 1 = Pattern 1

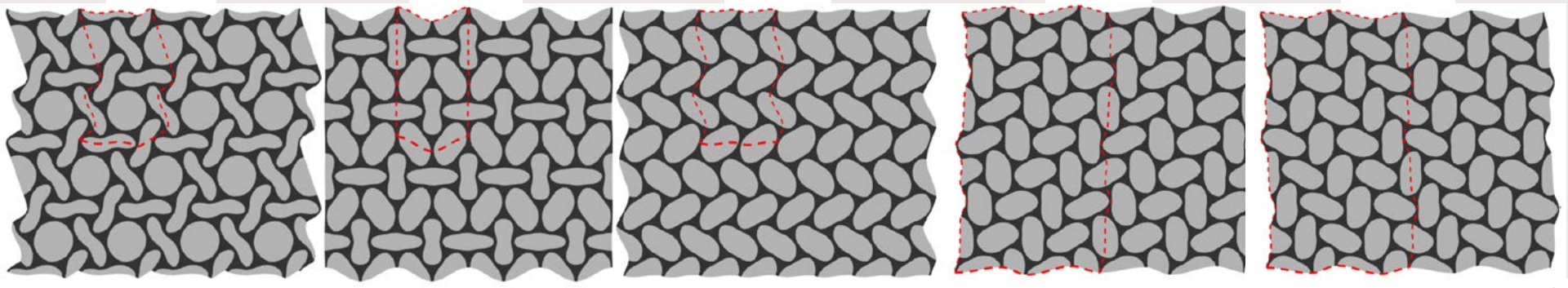


D: Mode 2



E: Mode 3



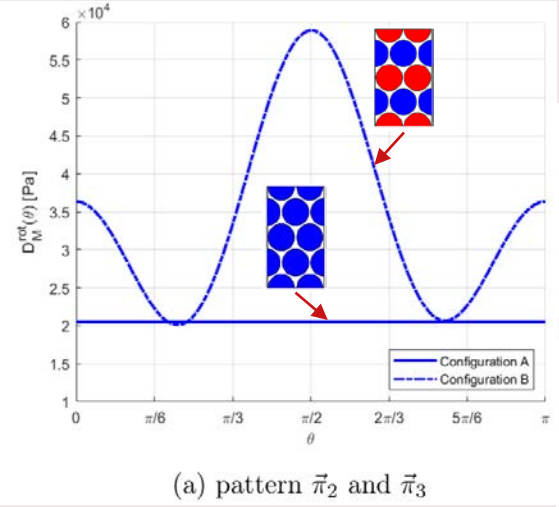


TU/e

Pneumatic actuation

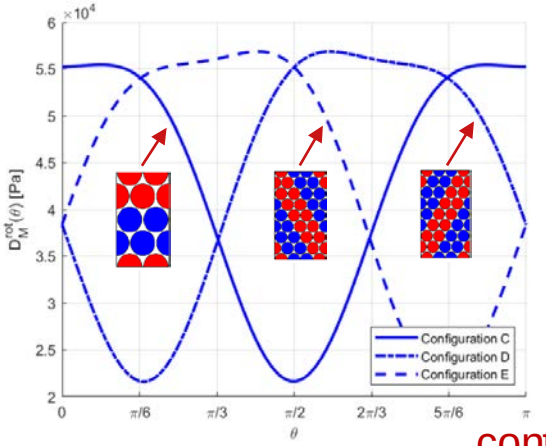
- Hexagonal stacking of holes

Switchable anisotropy: A, B



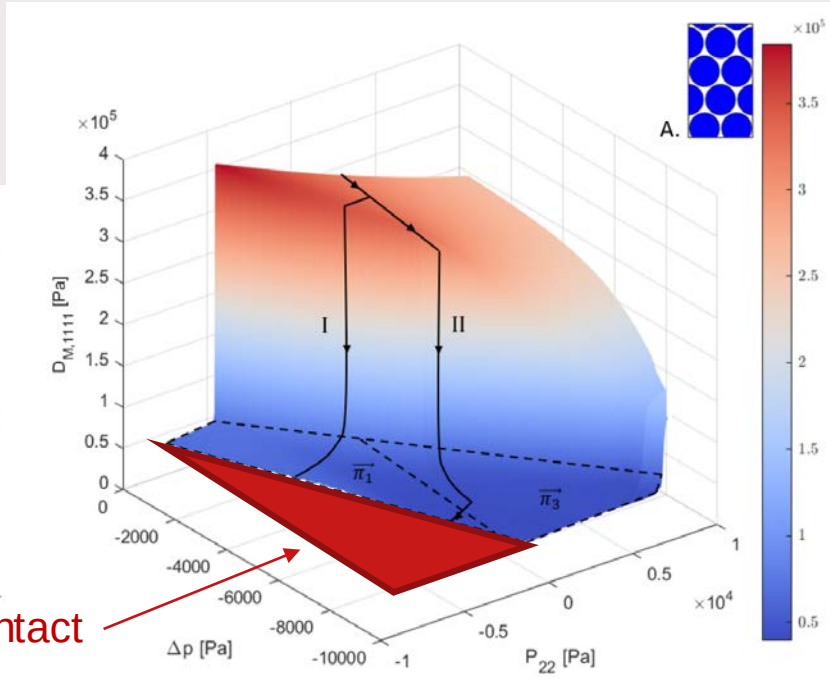
(a) pattern $\vec{\pi}_2$ and $\vec{\pi}_3$

Switchable anisotropy: C, D, E



(b) pattern $\vec{\pi}_1$

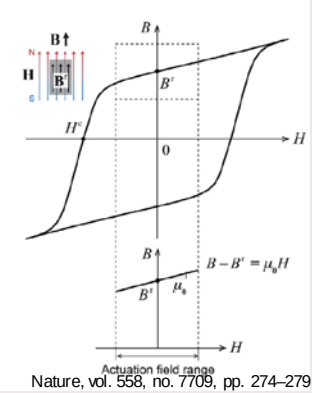
Stiffness evolution for various loading paths: A



contact

Magnetic actuation

- 3D printing of hard-magnetic & soft-elastic materials
- Design remanent magnetization & applied magnetic field



Nature, vol. 558, no. 7709, pp. 274–279

Energy density

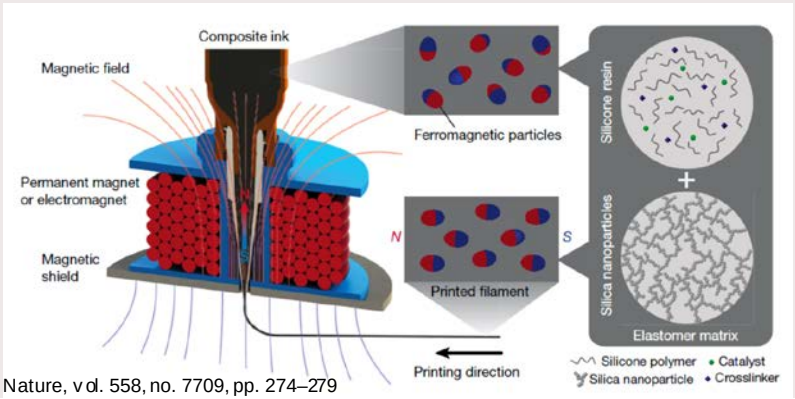
$$\widetilde{W}(\boldsymbol{F}, \vec{B}^{ap}) = \widetilde{W}^{mech}(\boldsymbol{F}) + \widetilde{W}^{mag}(\boldsymbol{F}, \vec{B}^{ap})$$

$$W^{mag}(\vec{B}^{ap}) = -\mu_0^{-1} \vec{B}^r \cdot \vec{B}^{ap}$$

$$\boldsymbol{P}(\boldsymbol{F}, \vec{B}^{ap}) = \boldsymbol{P}^{mech}(\boldsymbol{F}) + \boldsymbol{P}^{mag}(\vec{B}^{ap}) = \frac{\partial \widetilde{W}^{mech}(\boldsymbol{F})}{\partial \boldsymbol{F}} - \mu_0^{-1} \vec{B}^{ap} \otimes \vec{\vec{B}}^r$$

Standard TL FEM

3D printing



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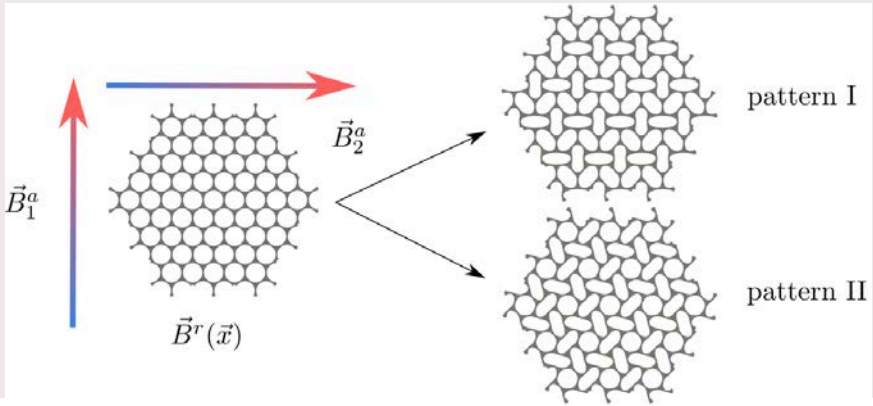
Printed microstructure subjected to a background magnetic field

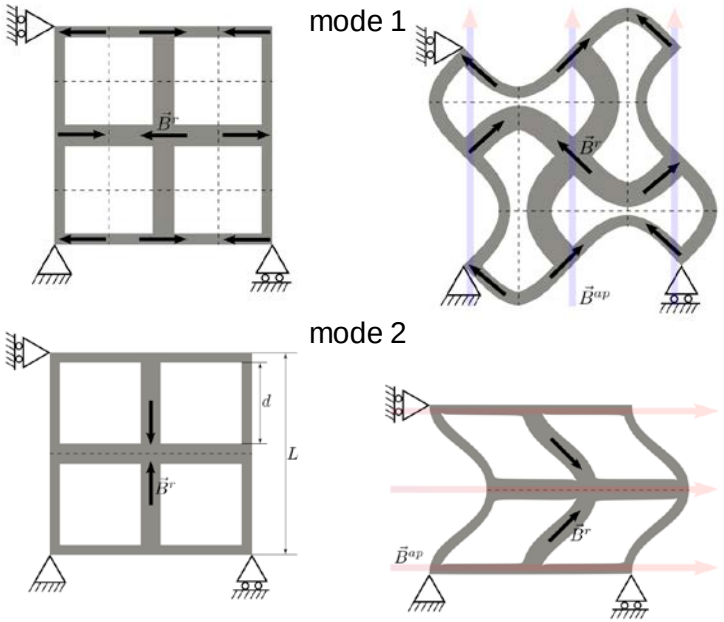


Magnetic actuation

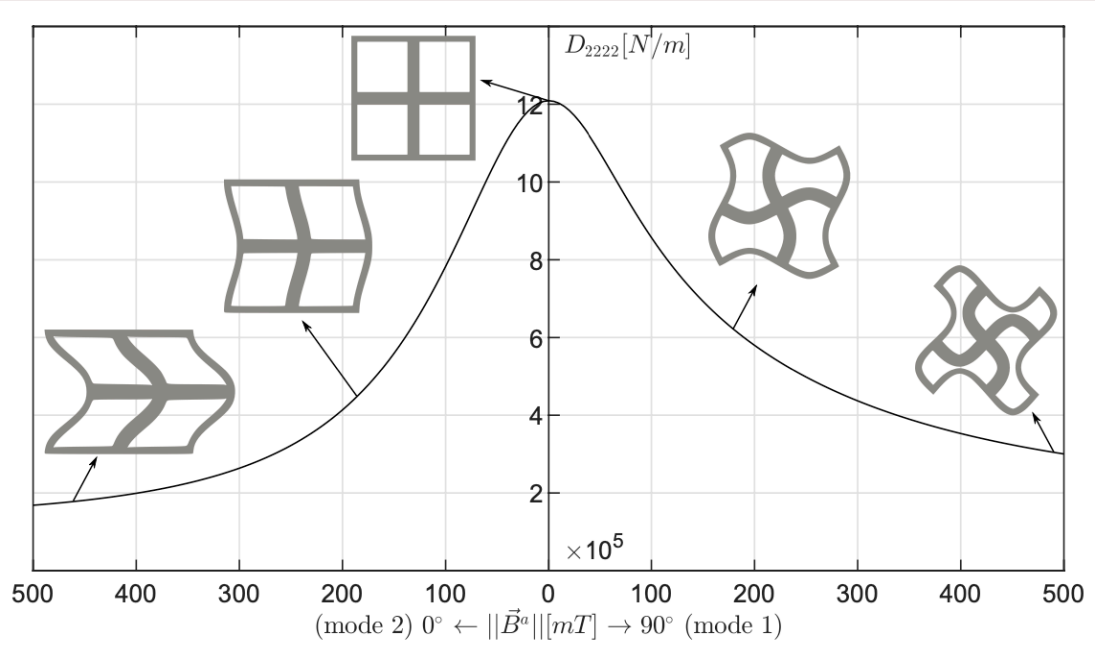
- Square stacking of holes: patterning modes

$$\underline{\underline{K}}_{tan} = \underline{\underline{K}}_{mat} + \underline{\underline{K}}_{geo}$$ → No contribution of magnetics to stiffness (unlike mechanical/pneumatic actuation)

Magnetization profiles

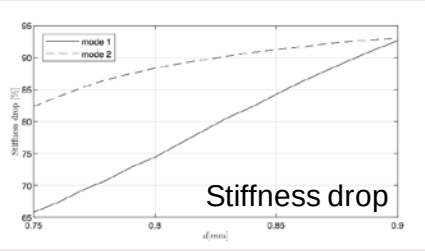


Combined response for 0° and 90° applied magnetic field

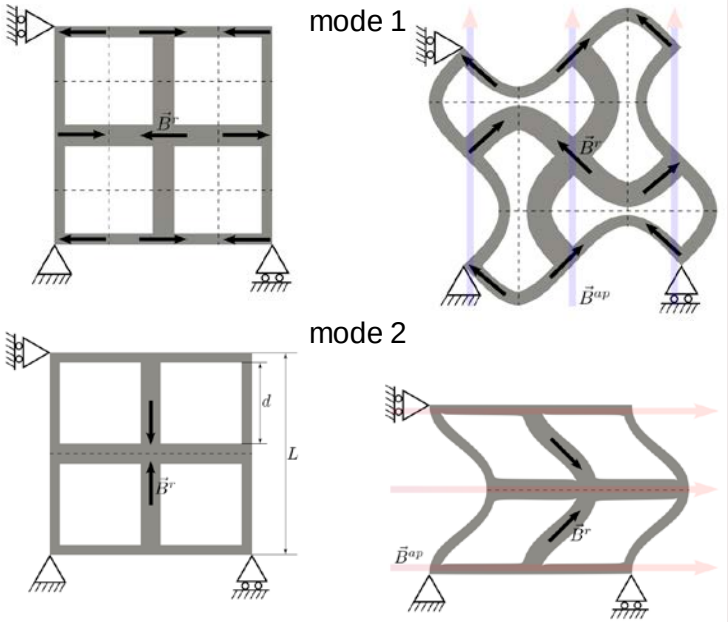


Magnetic actuation

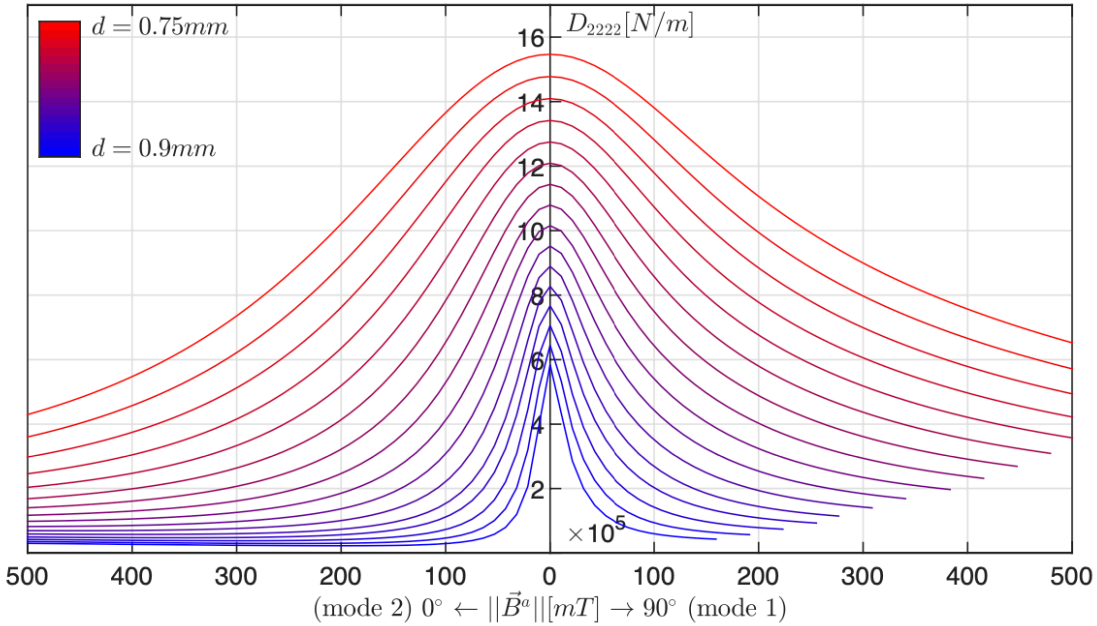
- Square stacking of holes: stiffness drop



Magnetization profiles



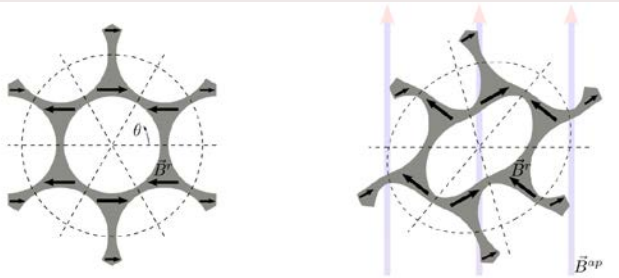
Effective stiffness for various hole sizes d (unit cell size l = 1)



Magnetic actuation

- Hexagonal stacking of holes: patterning modes

Mode φ_1

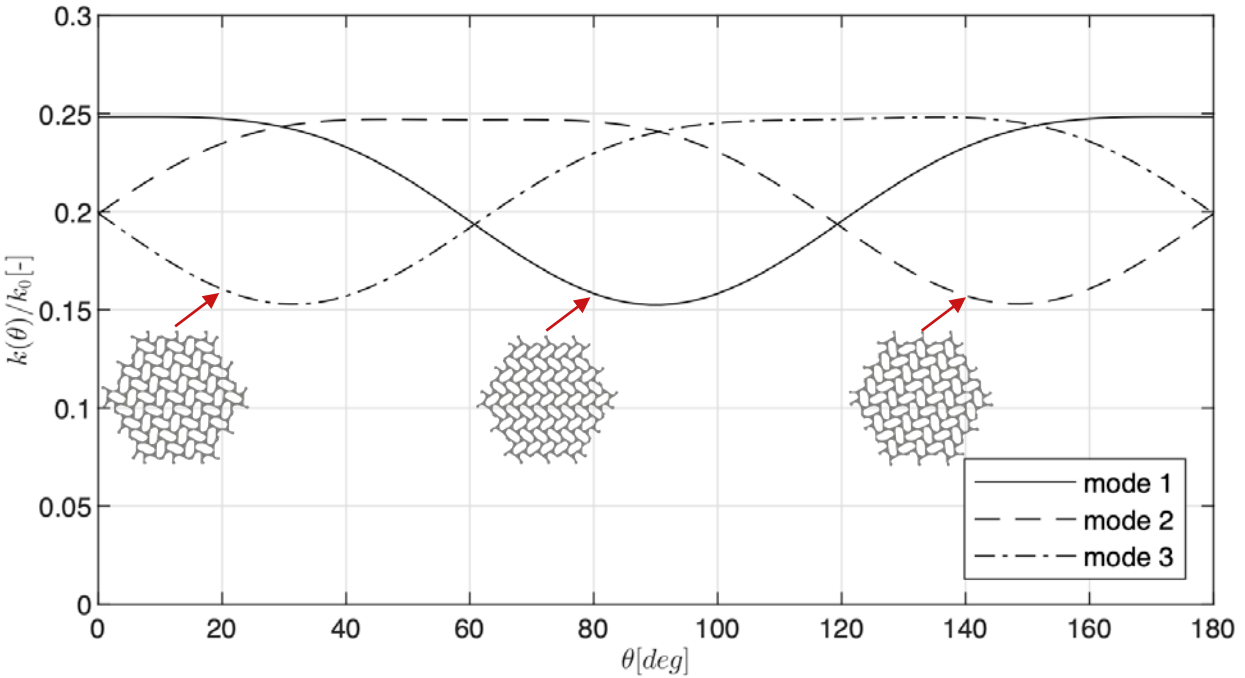


Modes 2 and 3 → rotation by ±60°

Patterns:

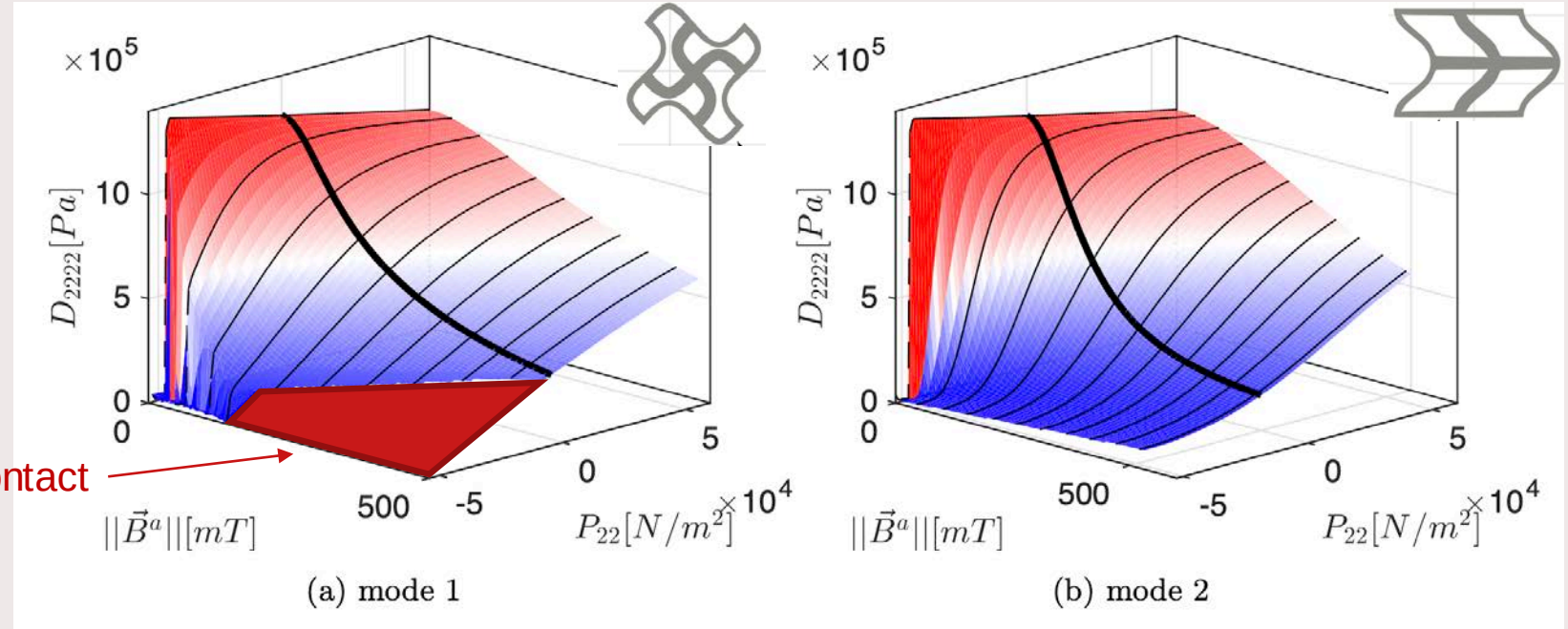
$$\vec{\pi}_1 = \vec{\varphi}_1,$$
$$\vec{\pi}_2 = \vec{\varphi}_2 + \vec{\varphi}_3,$$
$$\vec{\pi}_3 = \vec{\varphi}_1 + \vec{\varphi}_2 + \vec{\varphi}_3$$

Anisotropy of individual modes



Magnetic actuation

- Mechanical loading



Conclusions & Outlook

- Conclusions
  - Active metamaterials – computational proof of concept
  - Pneumatic/magnetic actuation
  - Switchable stiffness & anisotropy

- Outlook
  - Manufacturing and experimental testing
  - Design and modelling
    - Targeted design – engineering & mathematical (optimization)
    - Contact
    - Other types of actuation (mechanical, light, etc.)

Thank you for your attention!