Modelling Impact Behaviour of Auxetic Meta-Materials using Geometrically Nonlinear Lattices

GACM 2022

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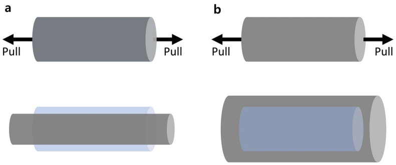
September 15, 2022

Impact Behaviour of Auxetic Materials

- auxetic materials are materials with a negative Poisson's ratio
  - materials that contract laterally when compressed



non-auxetic and auxetic rods under tension
(Cho, Seo, and Kim 2019)

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  - natural densification at the impact location
  - higher shear wave speed
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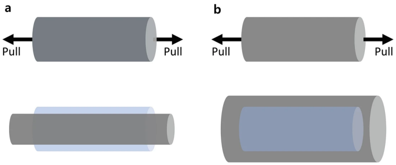

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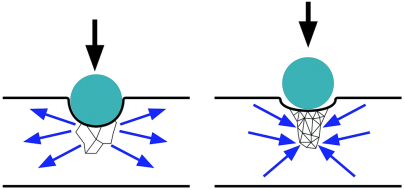

non-auxetic and auxetic material under impact (Kolken and Zadpoor 2017)

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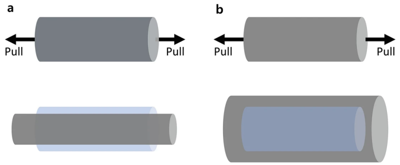
- auxetic materials hardly found in nature



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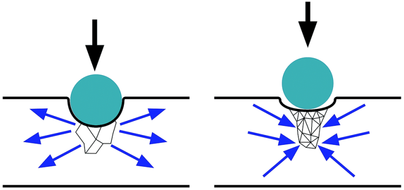

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Design of Auxetic Materials

- targeted design possible with lattice structures
- two main working mechanisms to create the auxetic effect

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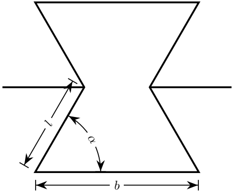
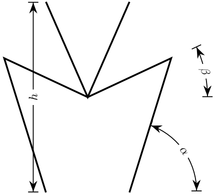


re-entrant
honeycomb



double arrowhead

Design of Auxetic Materials

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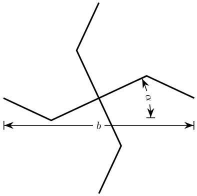
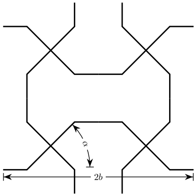


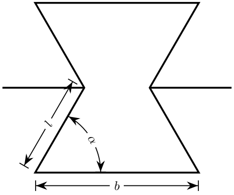
chiral structure



anti-chiral structure

Design of Auxetic Materials

- targeted design possible with lattice structures
- two main working mechanisms to create the auxetic effect
  - folding structures (potentially strong auxeticity)
  - rotating structures (limited auxeticity)
- goal of this investigation:
  elastic comparison of different architectures at high strains and strain rates



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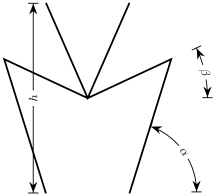

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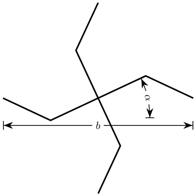

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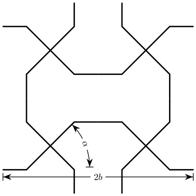
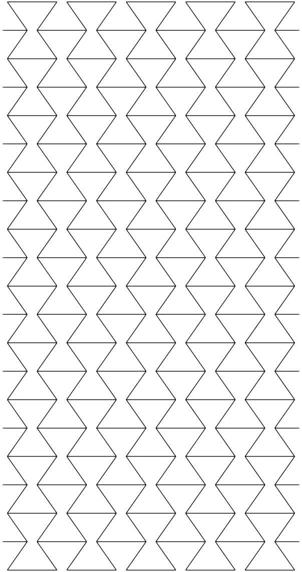


anti-chiral structure

Lattice Simulation

- architectures defined by assembly of rods



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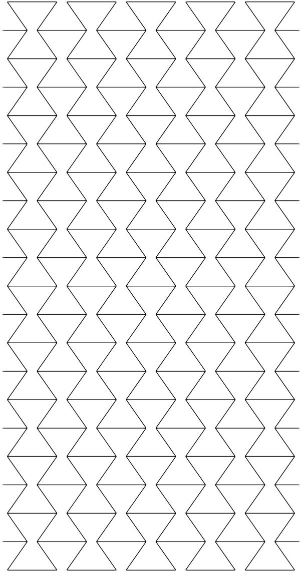
Lattice Simulation

- architectures defined by assembly of rods
- rods represented as geometrically nonlinear Timoshenko Beams
- FE-Implementation in JEM/JIVE[1]



[1] C++ FE-Toolkit

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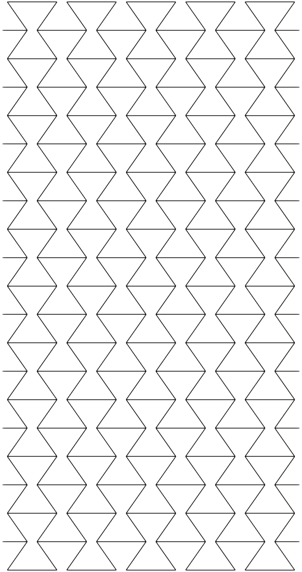
- time marching using a two step semi-explicit scheme



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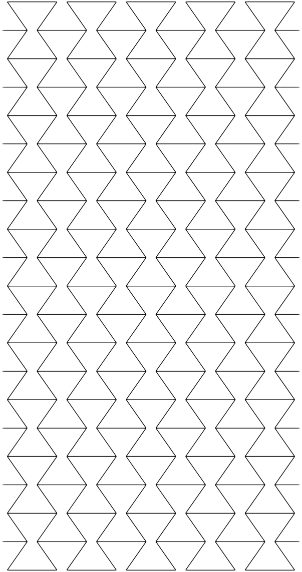
- FE-Implementation in JEM/JIVE[1]
- for first investigation purely elastic material behaviour
- time marching using a two step semi-explicit scheme
- 2D static, 2D dynamic, and 3D static verification successful
- promising comparison with first experiments



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Setup of Investigation

- investigation of six different architectures tuned to two sets of equal linear properties

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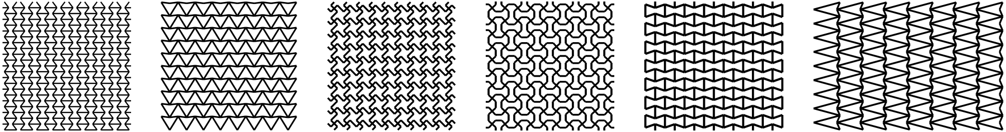
- Young's modulus of $20\ \mathrm{kPa}$ and density of $1570\ \mathrm{kg\ m^{-3}}$



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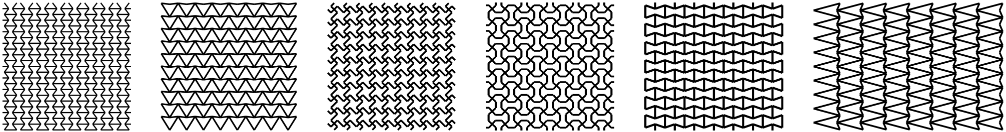

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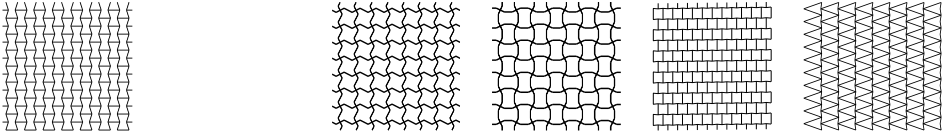
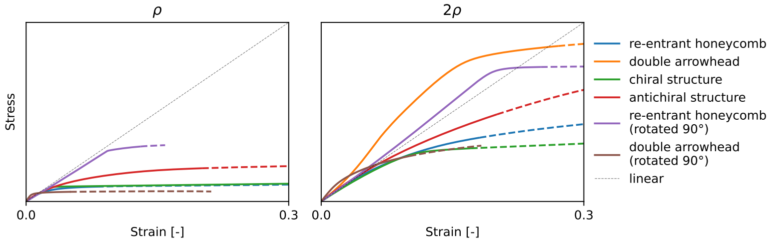


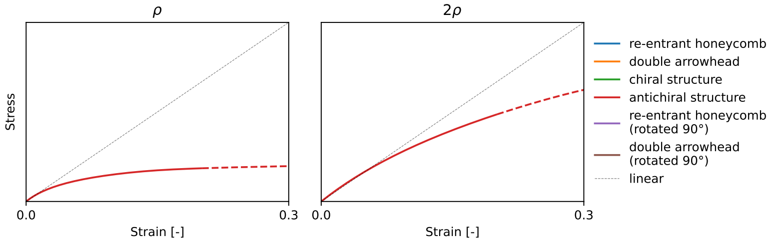
Differences in Density

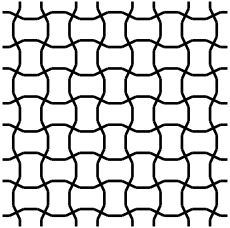


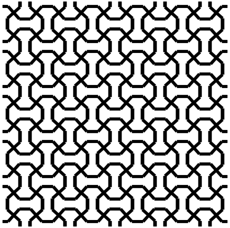
stress-strain curves for different architectures at different densities

- denser structures preserve existing properties better

Differences in Density







stress-strain curves for different architectures at different densities

- denser structures preserve existing properties better
- denser structures derive larger part of their stiffness from bending

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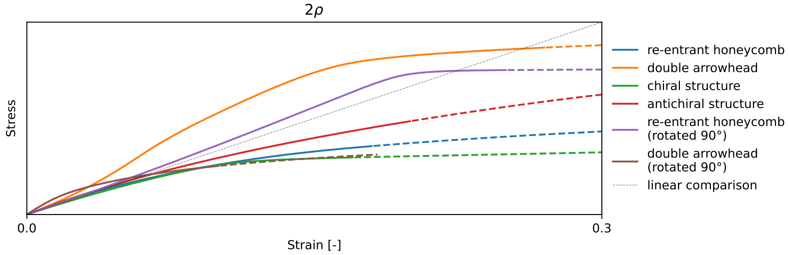
Effects of Vertical Beams



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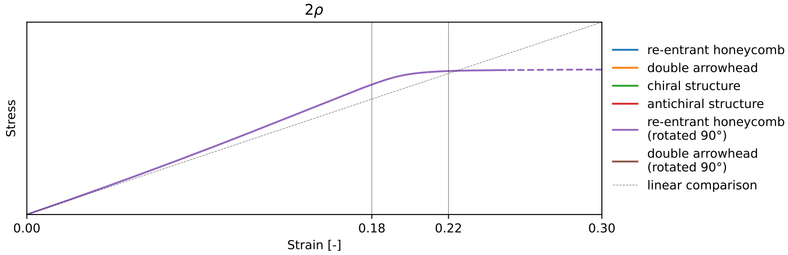

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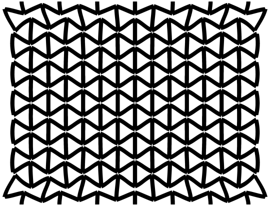
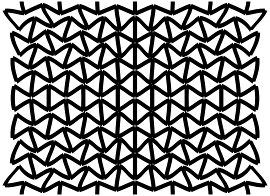
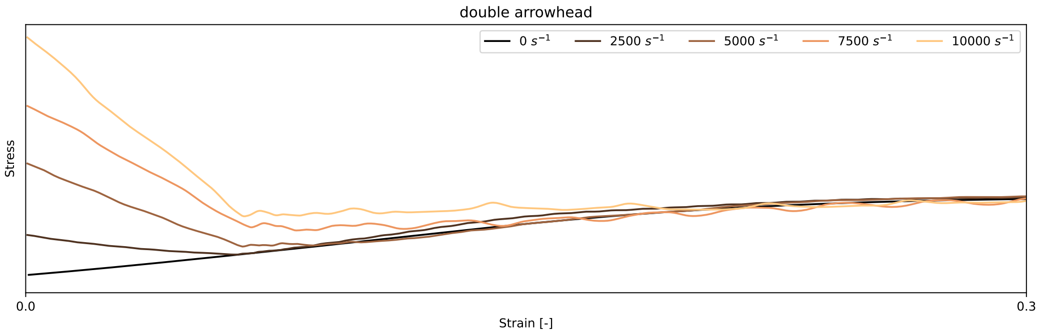




- structures with vertical beams exhibit stiffer behavior
- buckling in those structures results in a rapid decline in stiffness

Large Strain Rate Effects



different impact speeds

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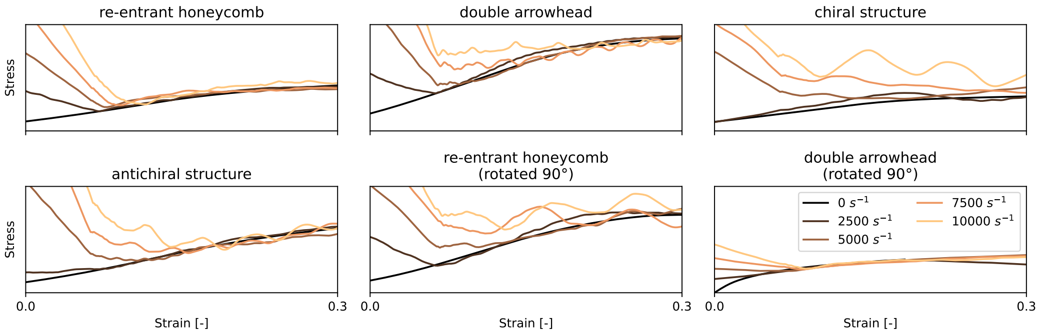

different impact speeds on different architectures

- higher strain rates lead to higher resistance at the immediate impact
- most cases: constant plateau stress
- *chiral* and *rotated re-entrant* show dependency on velocity

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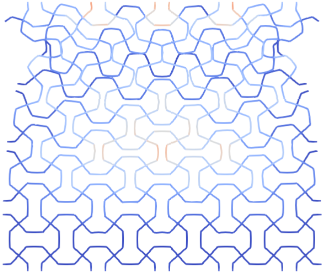
Effect of Surrounding Material



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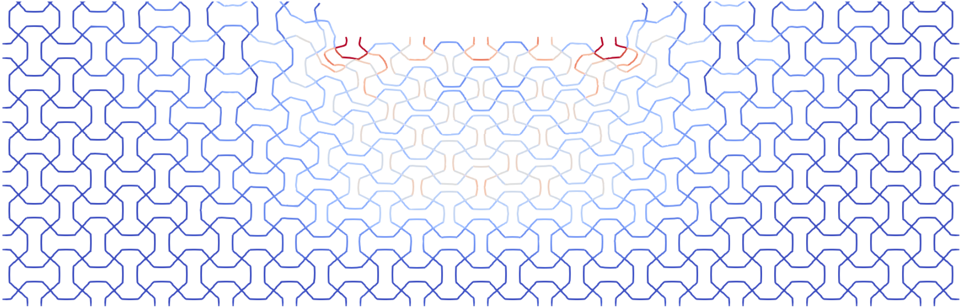

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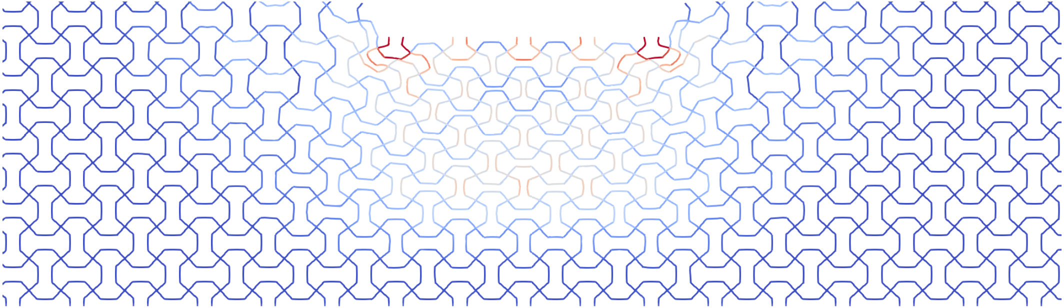

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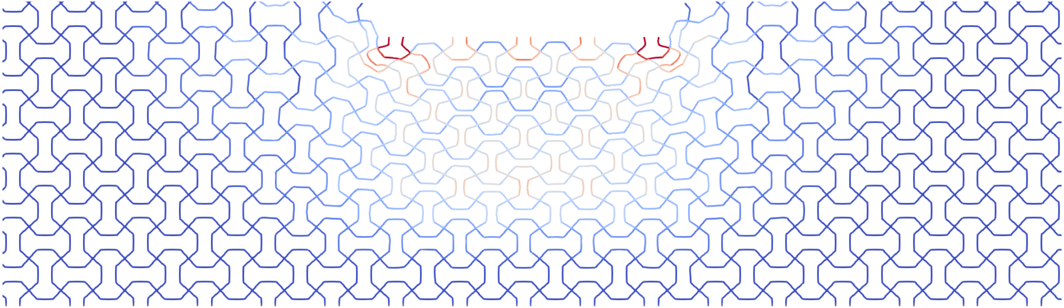

- in most cases little difference between amount of surrounding material
- no clear dependency of surrounding material effect on strain rate
- local impact offers more resistance compared to global impact
  - impact energy dispersed laterally

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Towards 3D Auxetic Structures

- thus far only 2D structures investigated
- 3D structures could amplify effects of surrounding material

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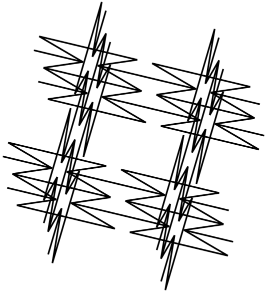
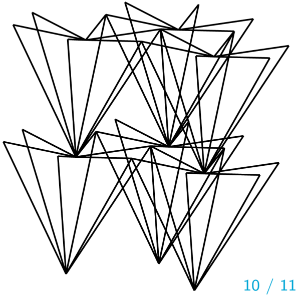
  - hexagonal or trigonal assembly is transversely isotropic in linear regime
  - moving to 3D not trivial for (anti)chiral structures





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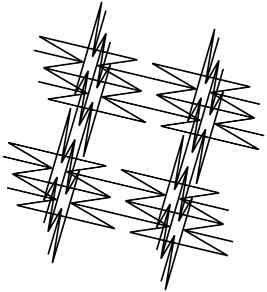
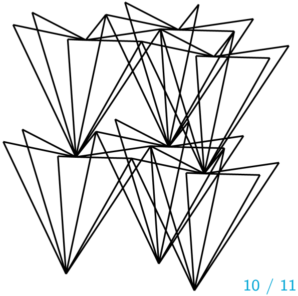
- nonlinear investigations pending





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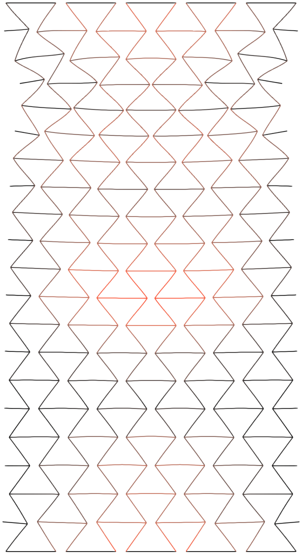
Conclusion



- FE-Toolbox to analyse lattice structures set up

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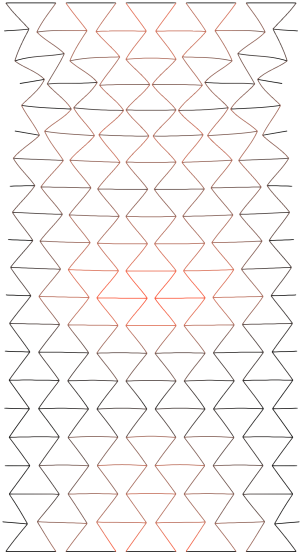
Conclusion



- FE-Toolbox to analyse lattice structures set up
- Analysis of nonlinear and dynamic properties of different auxetic architectures conducted
  - otherwise equal, but denser structures show beneficial properties even in static behaviour
  - vertically folding structures stiffen initially later buckling results in sharp decrease of stiffness
  - it is possible to generate an artificial strain rate dependency
  - auxeticity demonstrates benefits when impact is surrounded with more material

Thank you!

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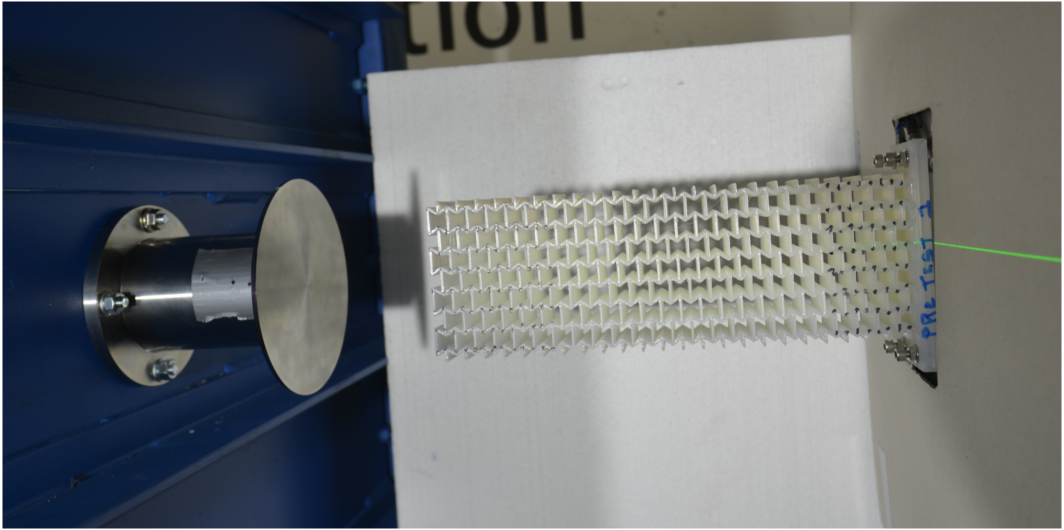
References I

Cho, Hyeonho, Dongsik Seo, and Do-Nyun Kim (2019). "Mechanics of Auxetic Materials". In: *Handbook of Mechanics of Materials*. Ed. by Siegfried Schmauder et al. Singapore: Springer Singapore, pp. 733–757. DOI: 10.1007/978-981-10-6884-3_25.

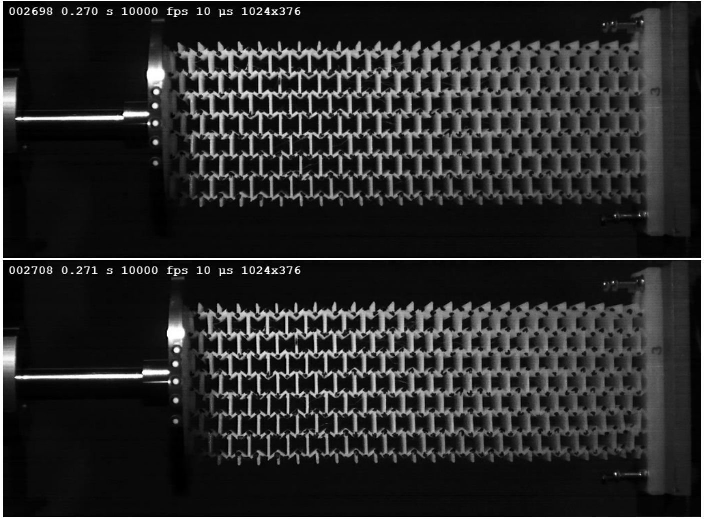
Kolken, H. M. A. and A. A. Zadpoor (2017). "Auxetic mechanical metamaterials". In: *RSC Adv.* 7 (9), pp. 5111–5129. DOI: 10.1039/C6RA27333E.

Simo, J.C. and L. Vu-Quoc (1986). "A three-dimensional finite-strain rod model. part II: Computational aspects". In: *Computer Methods in Applied Mechanics and Engineering* 58.1, pp. 79–116. DOI: 10.1016/0045-7825(86)90079-4.

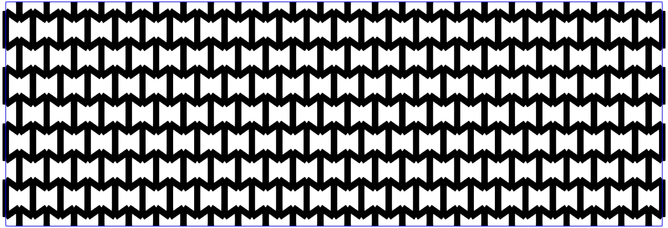
Experiment I

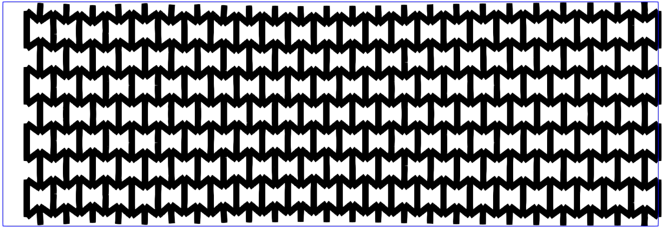


Experiment II



Experiment III





Experiment IV