Numerical Investigation of Rate and Scale Effects in Architected Metamaterials under High-Rate Loading Conditions

8th CFRAC – Porto, Portugal

Til Gärtner[ab] S.J. van den Boom[b] J. Weerheijm[a] L.J. Sluys[a]

a. Delft University of Technology

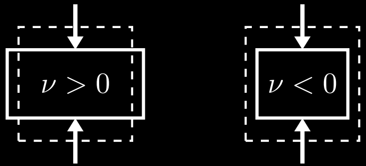
b. Netherlands Institute for Applied Scientific Research (TNO)

TNO TU Delft

04 June 2025

Auxetic materials appear promising for impact mitigation

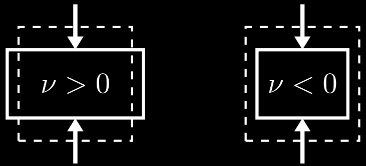
- auxetic materials are materials with a negative Poisson's ratio
  - materials that contract laterally when compressed



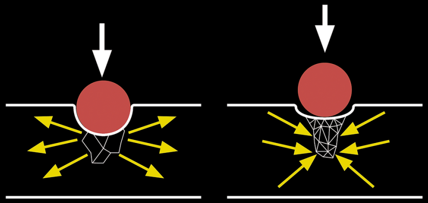
non-auxetic and auxetic materials
(Lim 2015)

Auxetic materials appear promising for impact mitigation

- auxetic materials are materials with a negative Poisson's ratio
  - materials that contract laterally when compressed
- promising capabilities for impact mitigation
  - natural densification at the impact location
  - better involvement of lateral material



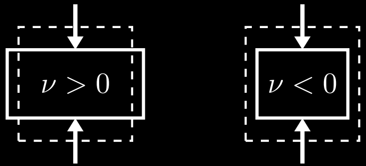
non-auxetic and auxetic materials (Lim 2015)



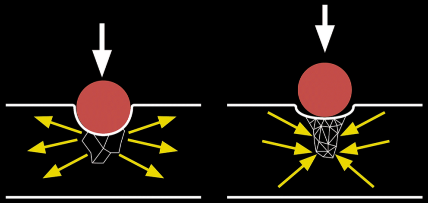
non-auxetic and auxetic material under impact (Kolken et al. 2017)

Auxetic materials appear promising for impact mitigation

- auxetic materials are materials with a negative Poisson's ratio
  - materials that contract laterally when compressed
- promising capabilities for impact mitigation
  - natural densification at the impact location
  - better involvement of lateral material
- auxetic materials hardly found in nature
- assumptions don't take material architecture into account



non-auxetic and auxetic materials (Lim 2015)



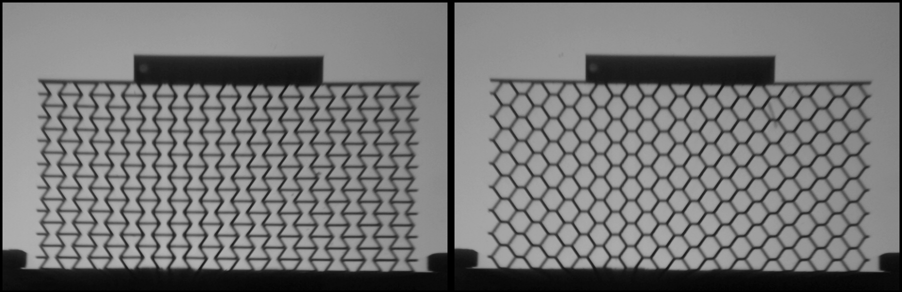
non-auxetic and auxetic material under impact (Kolken et al. 2017)

TNO TU Delft

Experiments are costly and give only limited insight

- Re-entrant and Honeycomb unit cells experimentally compared

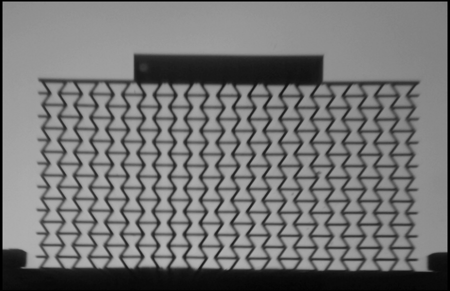
Gärtner, Dekker, van Veen, van den Boom, and Amaral *Int. J. Impact Eng.* (2025)

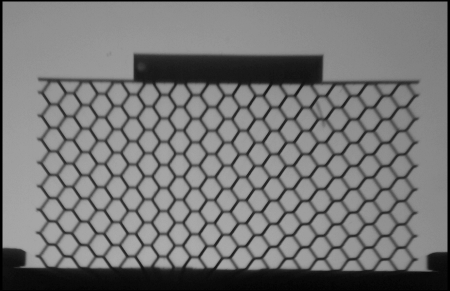


Experiments are costly and give only limited insight

- Re-entrant and Honeycomb unit cells experimentally compared
- Results indicate higher stress concentrations for negative Poisson's ratios

Gärtner, Dekker, van Veen, van den Boom, and Amaral *Int. J. Impact Eng.* (2025)

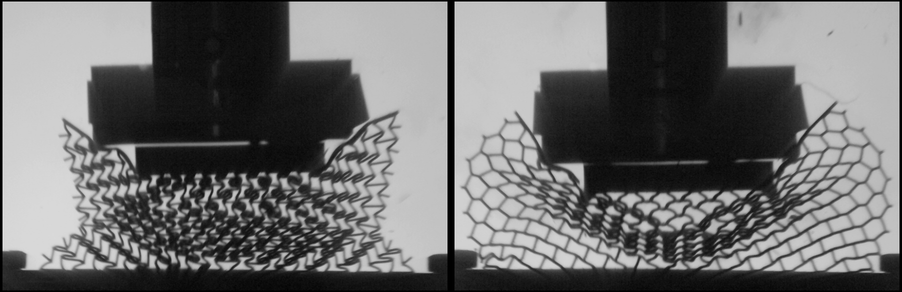




Experiments are costly and give only limited insight

- Re-entrant and Honeycomb unit cells experimentally compared
- Results indicate higher stress concentrations for negative Poisson's ratios
- Experiments allow only for global force measurements
- Experiments require elaborate equipment and skilled technicians

Gärtner, Dekker, van Veen, van den Boom, and Amaral *Int. J. Impact Eng.* (2025)



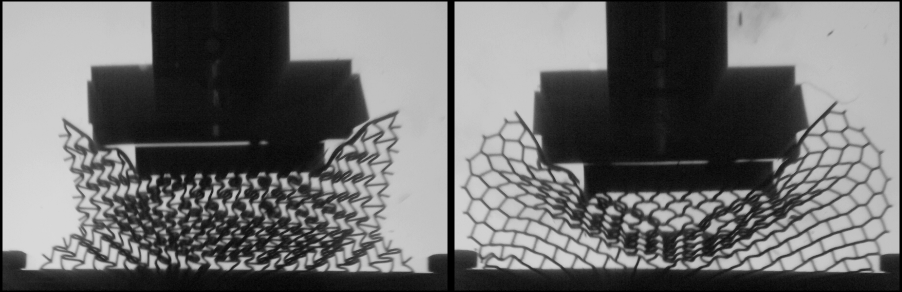
TNO TUDelft

Experiments are costly and give only limited insight

- Re-entrant and Honeycomb unit cells experimentally compared
- Results indicate higher stress concentrations for negative Poisson's ratios
- Experiments allow only for global force measurements
- Experiments require elaborate equipment and skilled technicians

⇒ *Need for computational framework*

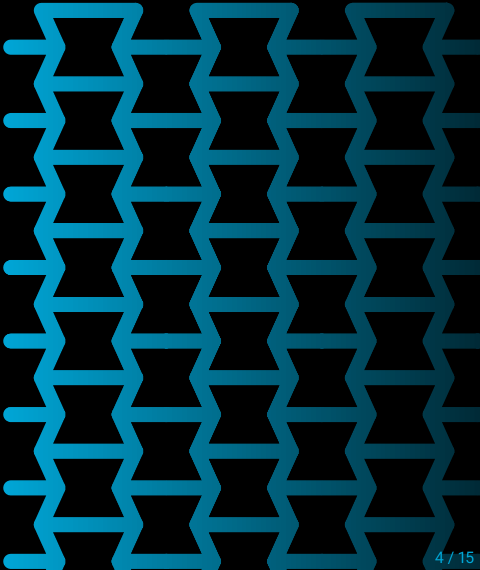
Gärtner, Dekker, van Veen, van den Boom, and Amaral *Int. J. Impact Eng.* (2025)



TNO TU Delft

Modelling of lattices with rods to reduce runtime

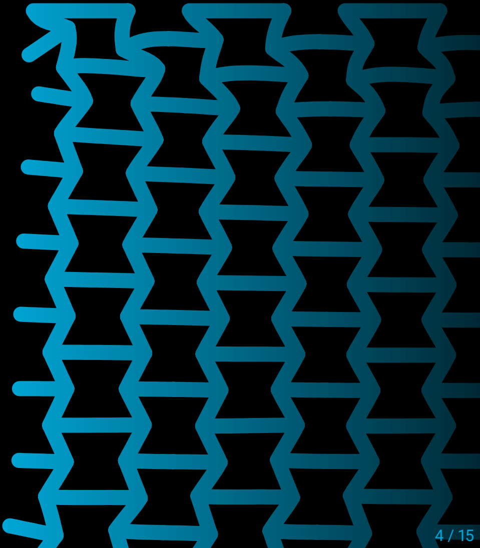
- Architectures defined as assembly nonlinear Timoshenko-Ehrenfest beams
- FE-implementation using in JEM/JIVE (C++ FE-Toolkit)



TNO TU Delft

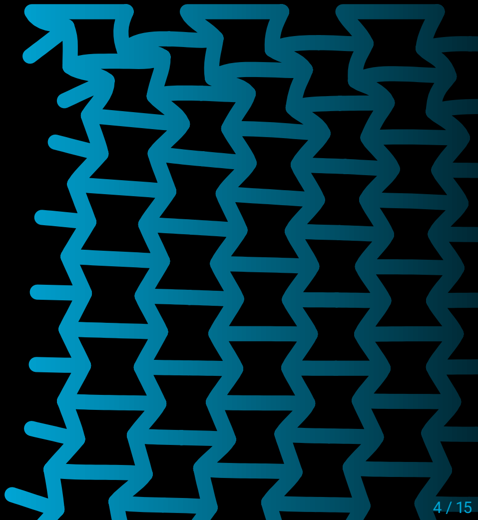
Modelling of lattices with rods to reduce runtime

- Architectures defined as assembly nonlinear Timoshenko-Ehrenfest beams
- FE-implementation using in JEM/JIVE (C++ FE-Toolkit)
- Beam-To-Beam contact using penalty parameters



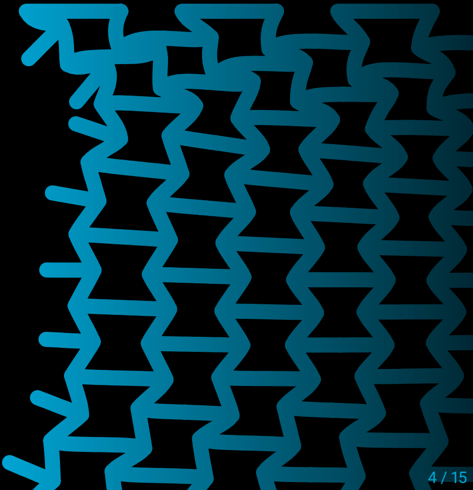
Modelling of lattices with rods to reduce runtime

- Architectures defined as assembly nonlinear Timoshenko-Ehrenfest beams
- FE-implementation using in JEM/JIVE (C++ FE-Toolkit)
- Beam-To-Beam contact using penalty parameters
- Time marching with an adaptive predictor-corrector scheme



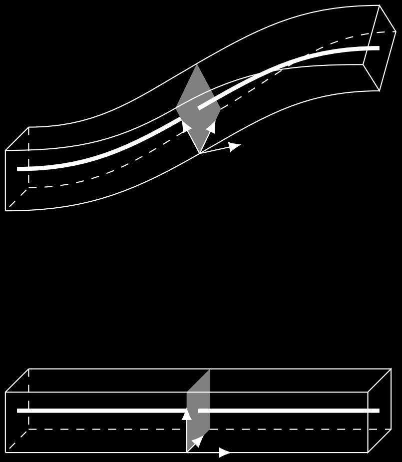
Modelling of lattices with rods to reduce runtime

- Architectures defined as assembly nonlinear Timoshenko-Ehrenfest beams
- FE-implementation using in JEM/JIVE (C++ FE-Toolkit)
- Beam-To-Beam contact using penalty parameters
- Time marching with an adaptive predictor-corrector scheme
- Elastoplasticity directly incorporated into the beam-formulation



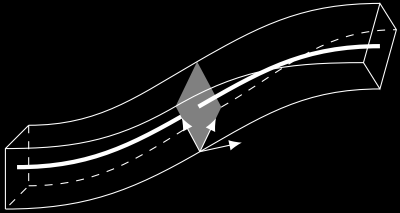
Direct modelling of elastoplasticity in beams

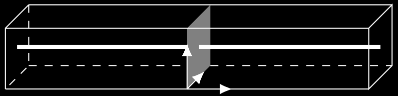
- Yield formulated in the stress resultant space
- Plastic strain prescriptors fitting the beam configuration



Direct modelling of elastoplasticity in beams

- Yield formulated in the stress resultant space
- Plastic strain prescriptors fitting the beam configuration
- J2-plasticity with isotropic hardening assumed on material scale
- Yield surface and hardening tensor obtained by Herrnböck et al. (2021; 2022)
- Isotropic hardening on material level relates to kinematic hardening on beam level



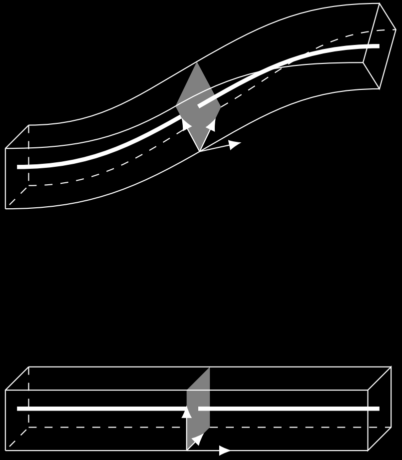


TNO TUDelft

Direct modelling of elastoplasticity in beams

- Yield formulated in the stress resultant space
- Plastic strain prescriptors fitting the beam configuration
- J2-plasticity with isotropic hardening assumed on material scale
- Yield surface and hardening tensor obtained by Herrnböck et al. (2021; 2022)
- Isotropic hardening on material level relates to kinematic hardening on beam level
- Consistent geometric scaling of the hardening tensor introduced

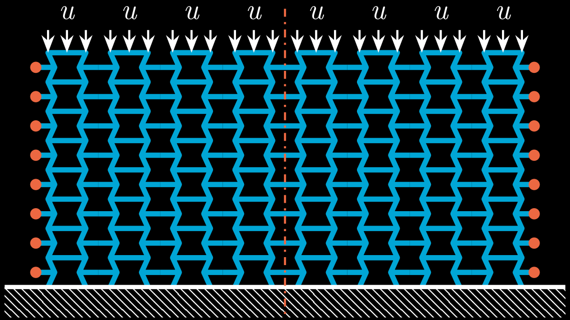
  Gärtner et al. *Comput. Mech.* 75.5 (2025)
- Size-objective formulation for the entire material model



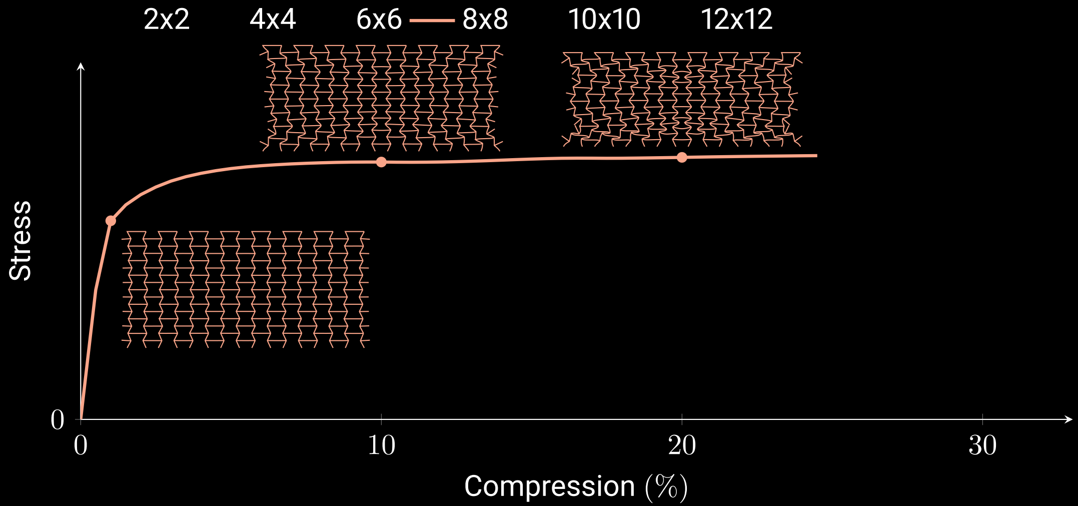
TNO TU Delft

Material testing conditions

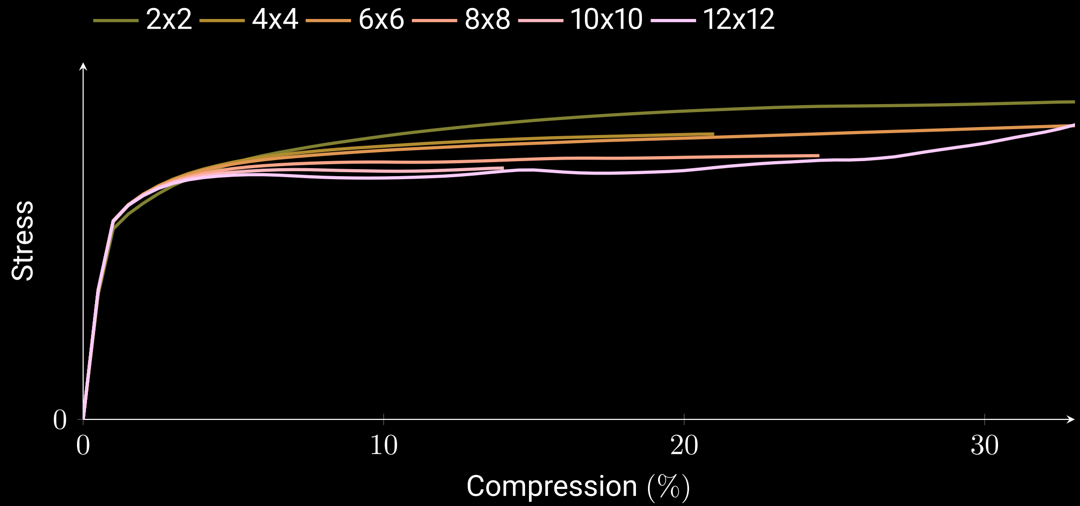
- Generic steel with $E = 210\,\text{GPa}$, $\nu = 0.3$, $\varrho = 7850\,\text{kg}\,\text{m}^{-3}$
- Presented plasticity model corresponding to J2-Plasticity with isotropic hardening
- Boundary conditions to be similar to a physical material test setup



Localization in static compression of the re-entrant patch

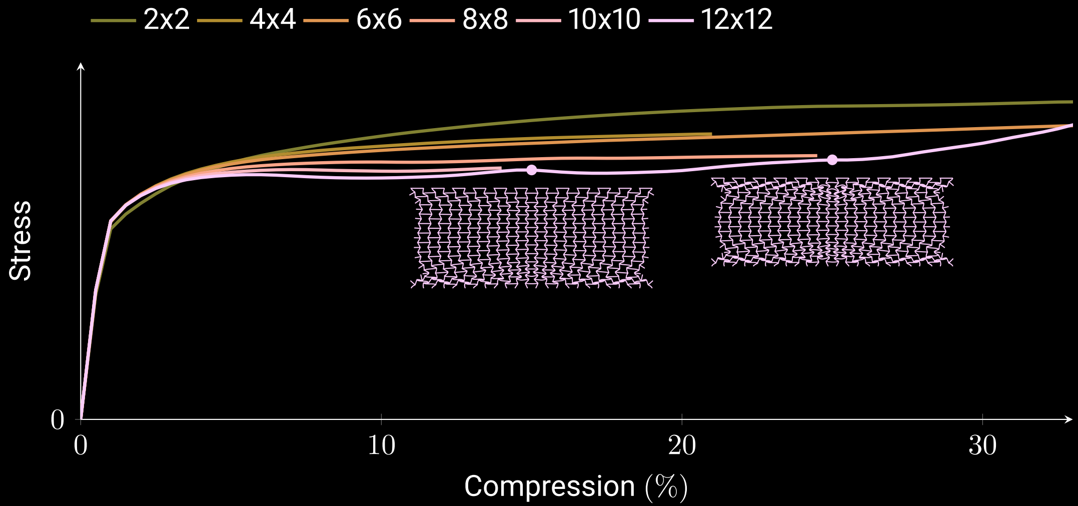


Localization in static compression of the re-entrant patch



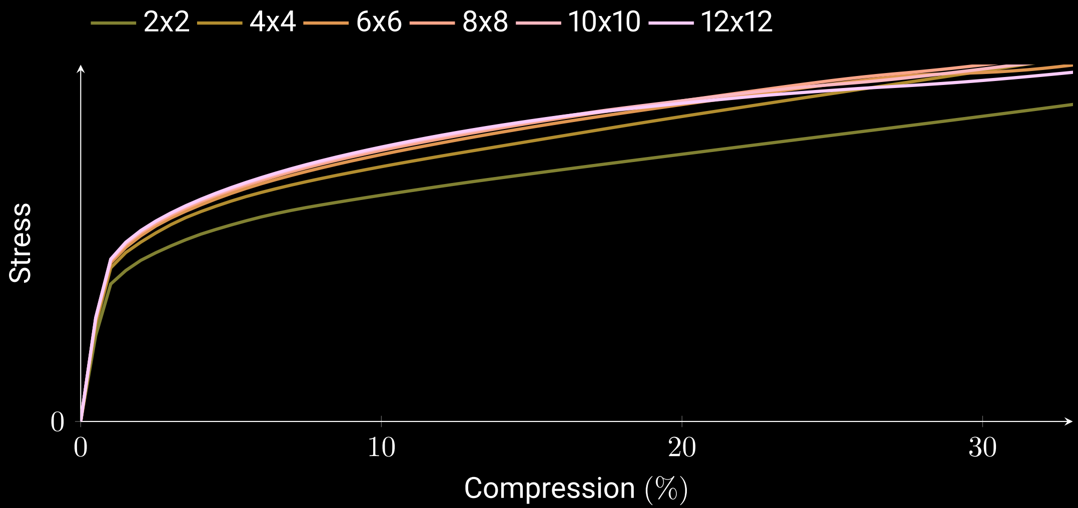
TNO TUDelft

Localization in static compression of the re-entrant patch

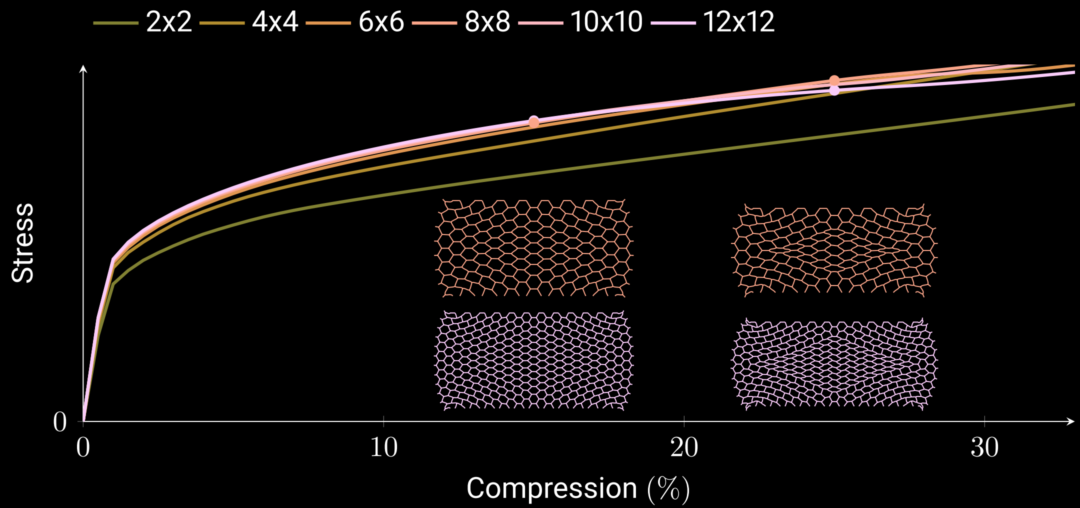


TNO TU Delft

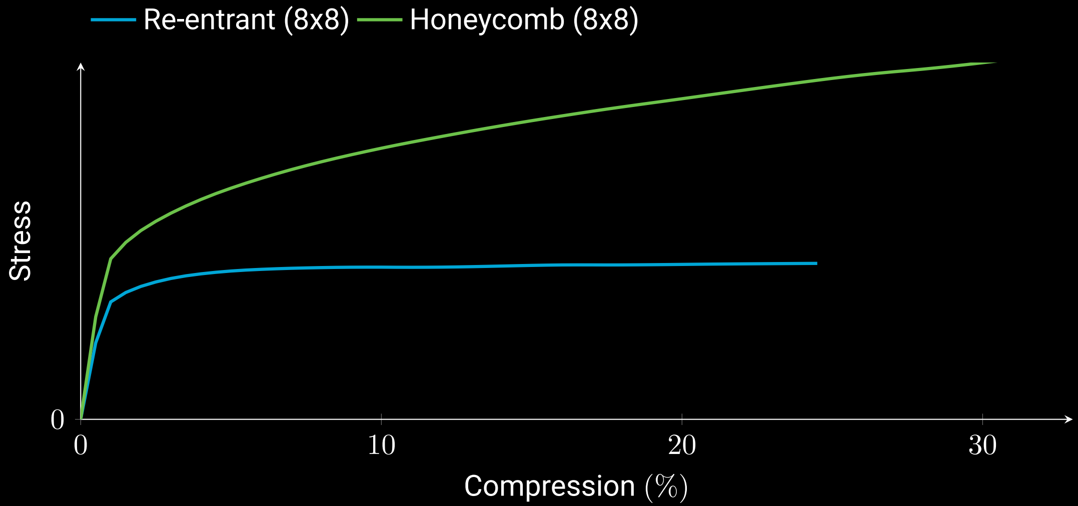
Honeycomb patches deform homogeneously



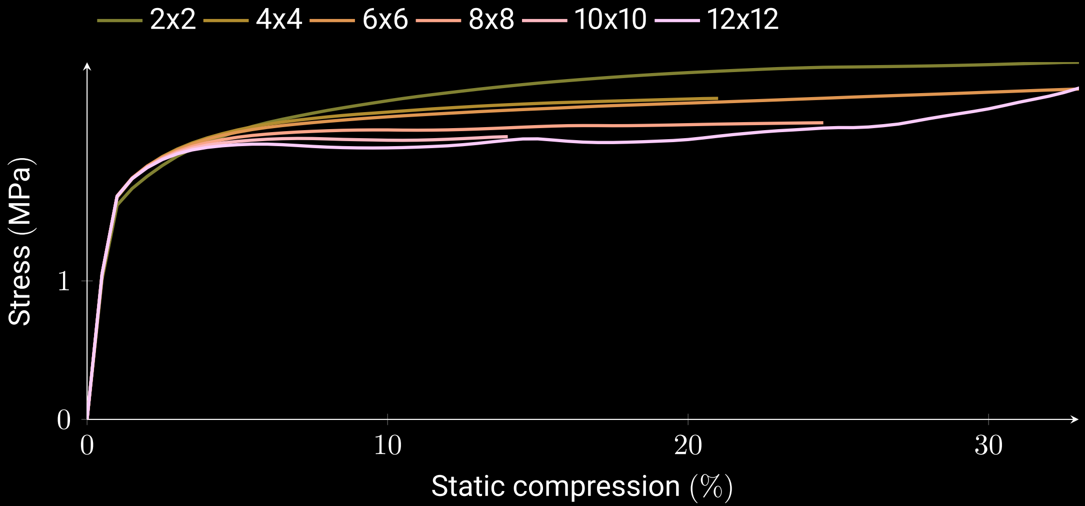
Honeycomb patches deform homogeneously



Non-auxetic patch is stiffer

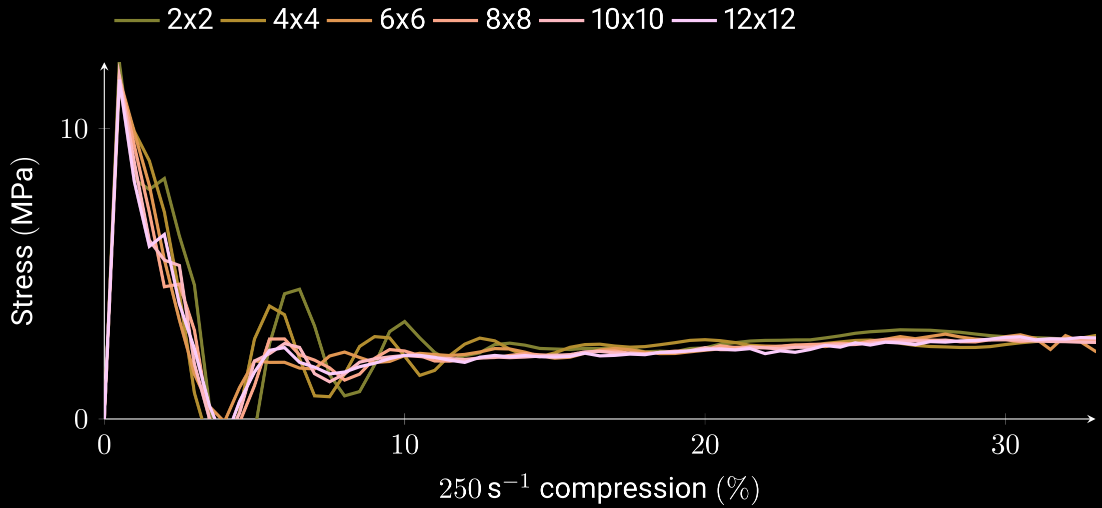


Embrittlement for faster rates in the re-entrant patch

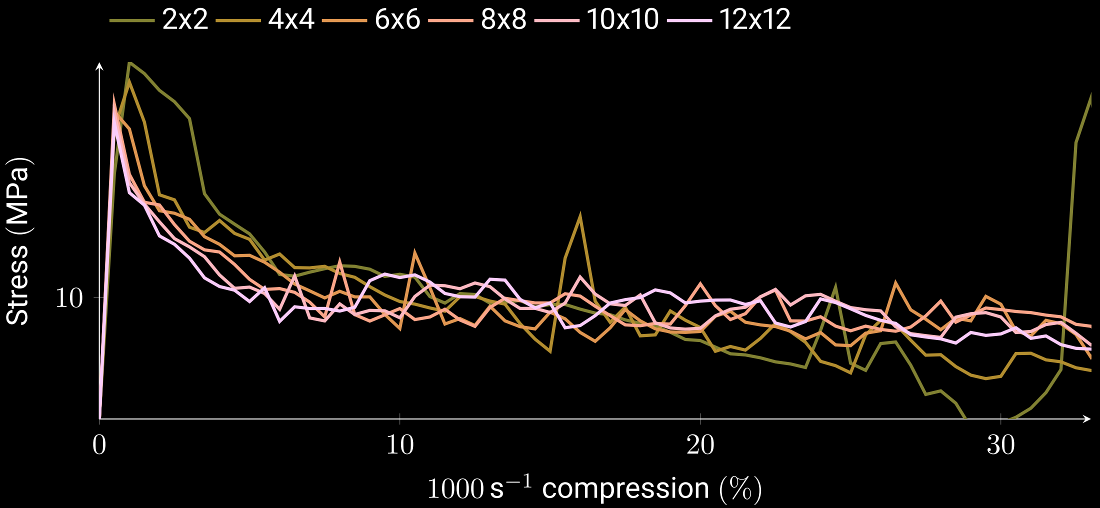


TNO TU Delft

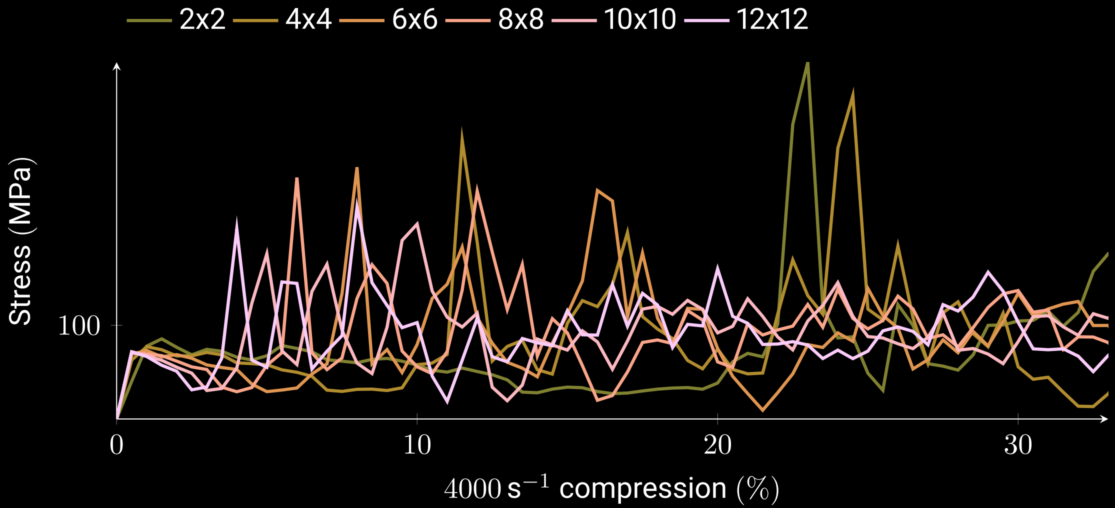
Embrittlement for faster rates in the re-entrant patch



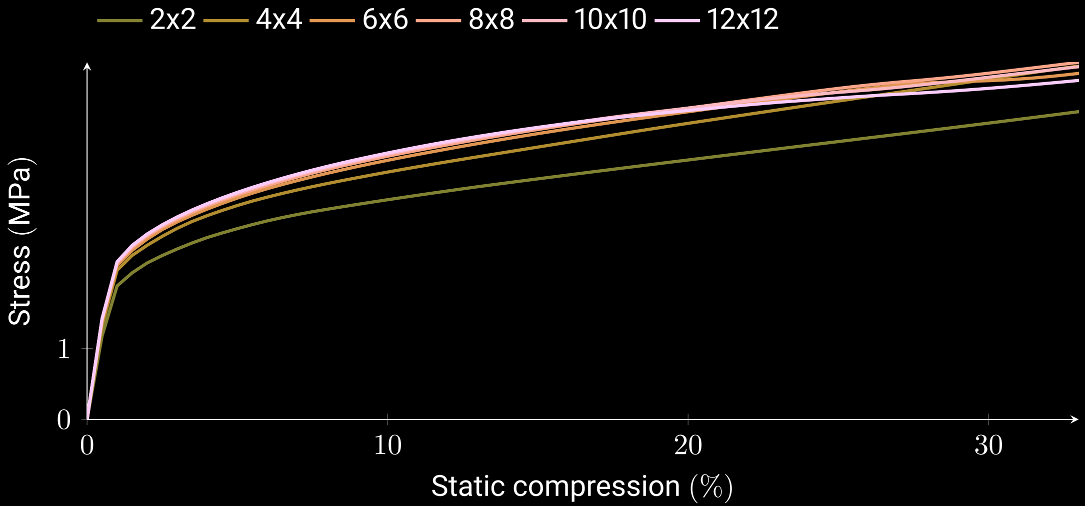
Embrittlement for faster rates in the re-entrant patch



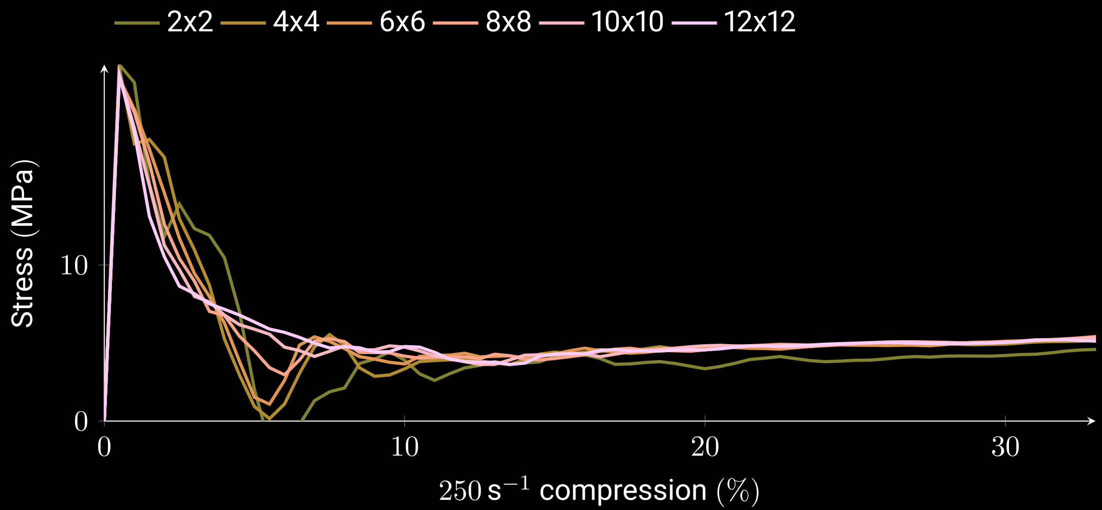
Embrittlement for faster rates in the re-entrant patch



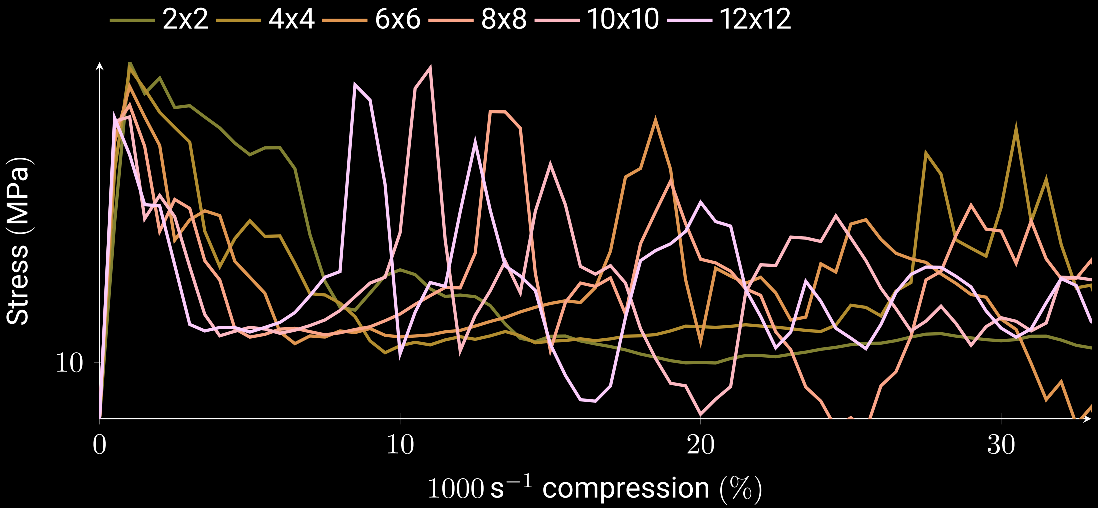
Embrittlement for faster rates in the honeycomb patch



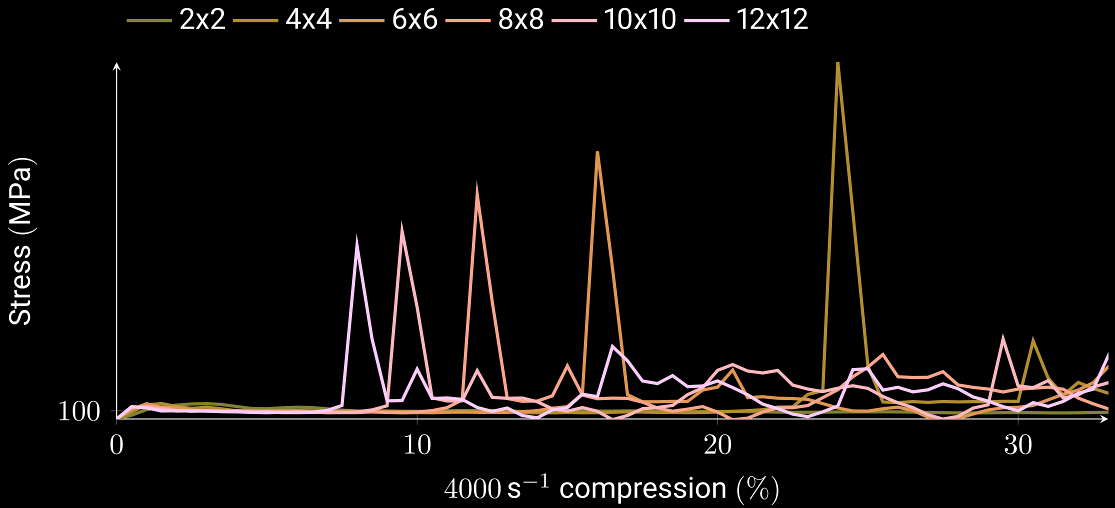
Embrittlement for faster rates in the honeycomb patch



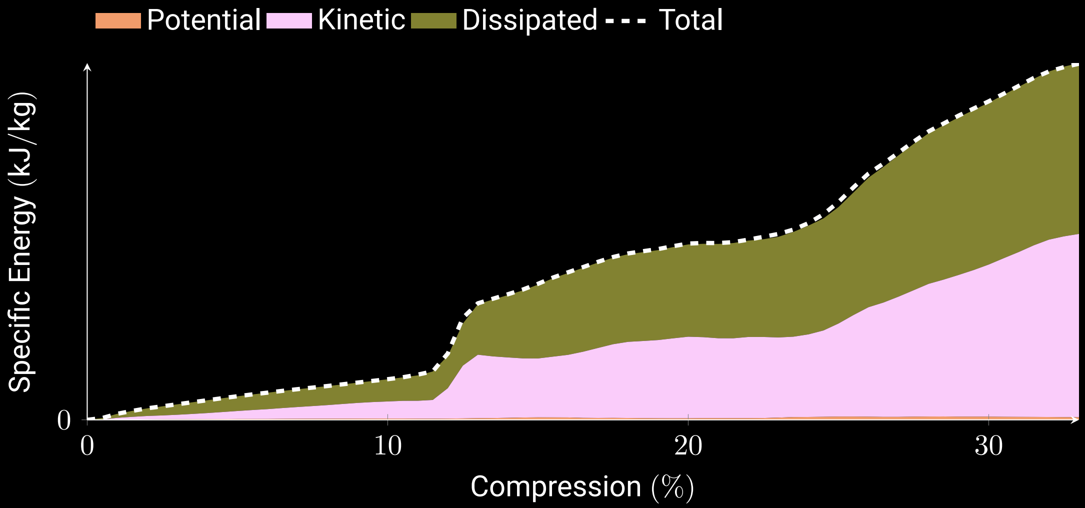
Embrittlement for faster rates in the honeycomb patch



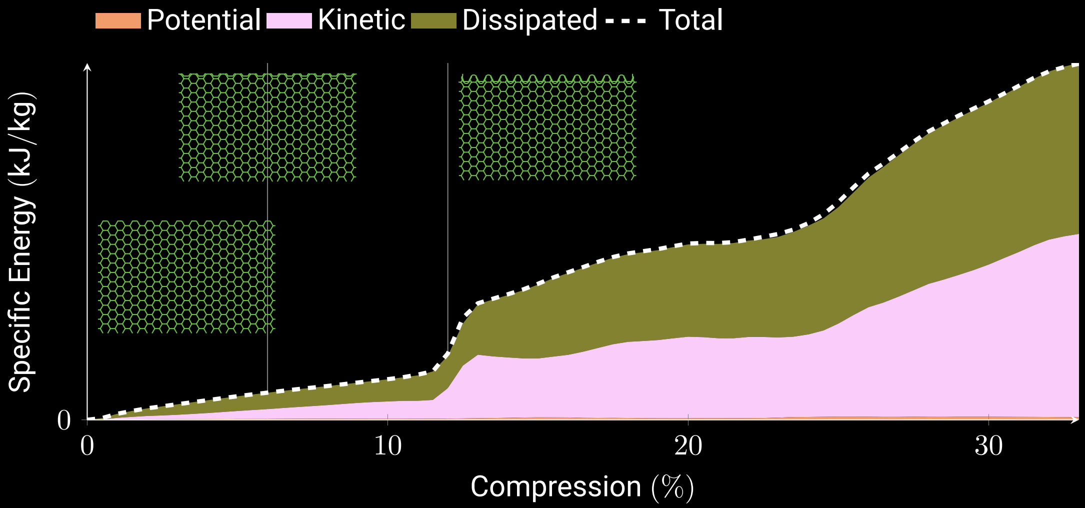
Embrittlement for faster rates in the honeycomb patch



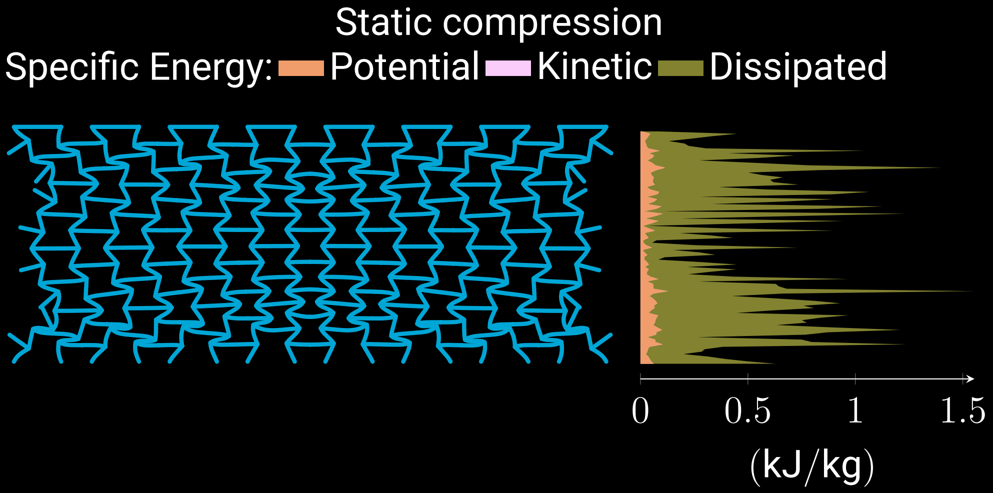
Peaks in stress-strain curve explained by kinetic energy (8x8)



Peaks in stress-strain curve explained by kinetic energy (8x8)

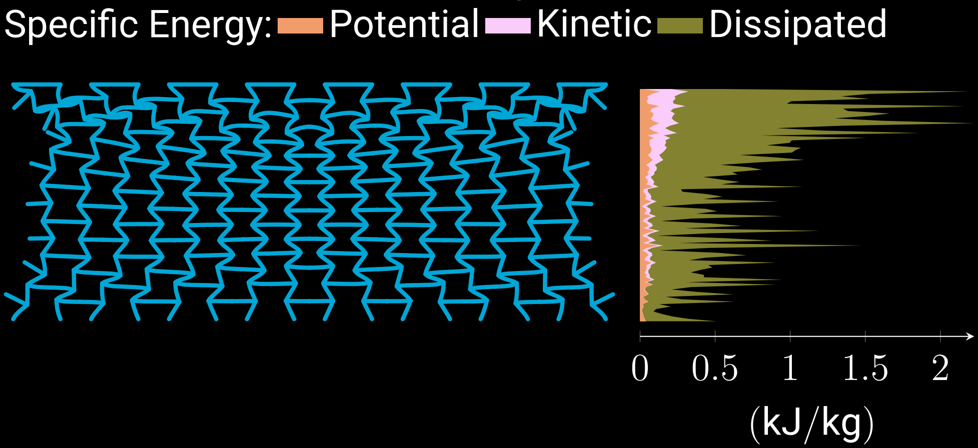


Energy localize with the deformation

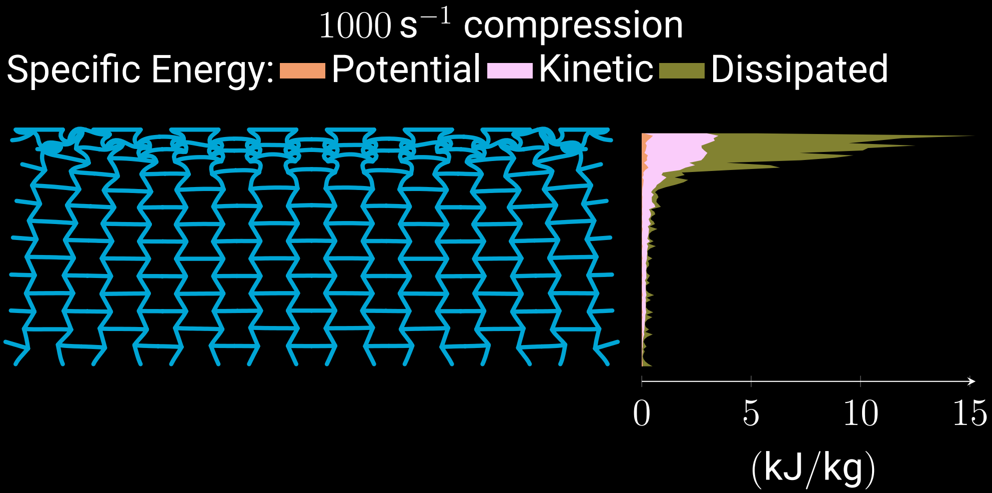


Energy localize with the deformation

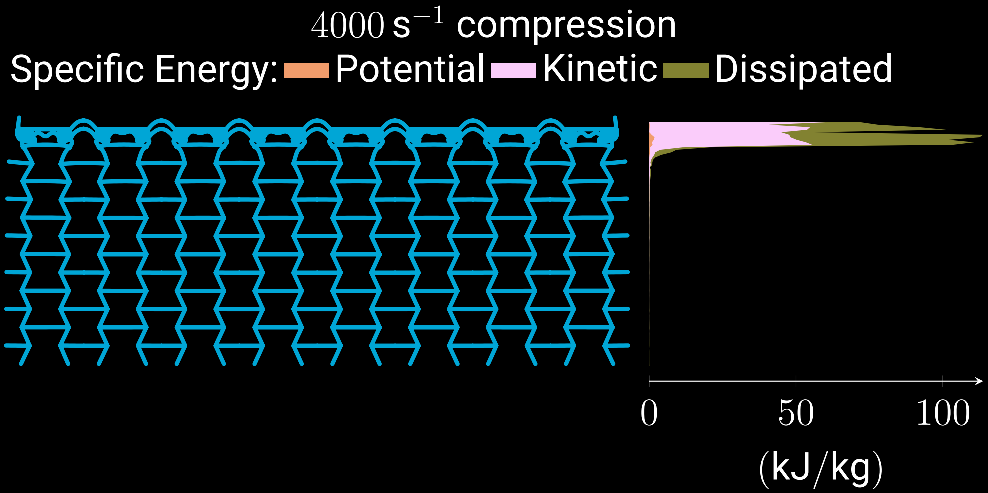
$250\,\mathrm{s}^{-1}$ compression



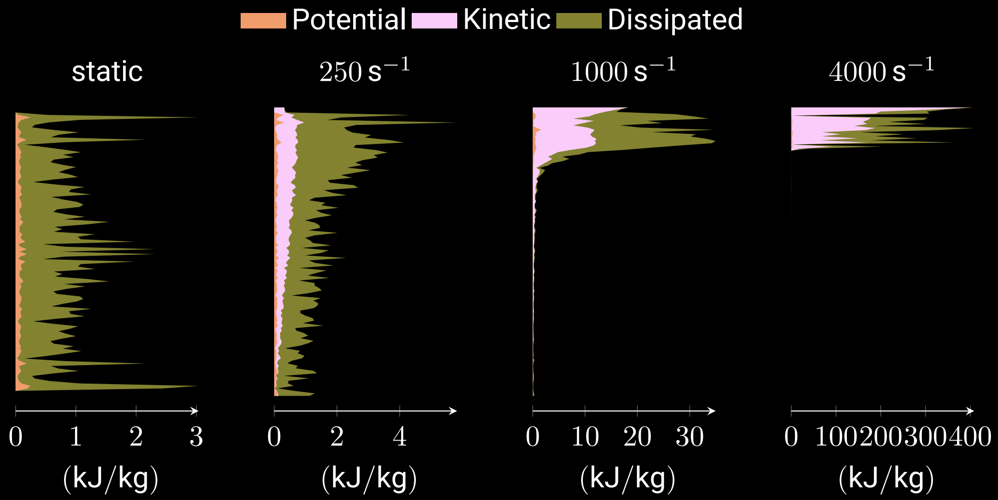
Energy localize with the deformation



Energy localize with the deformation

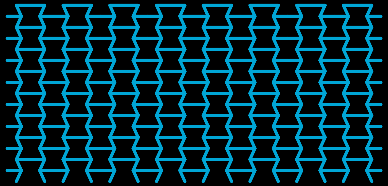


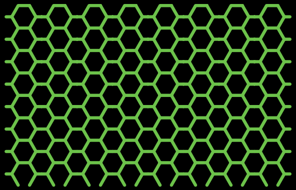
Similar behaviour in the honeycomb patch



Conclusions

- Auxetic honeycombs show a softer behaviour than conventional honeycombs
- The softening effect is related to the localization of deformation
- No localization observed for the conventional honeycombs

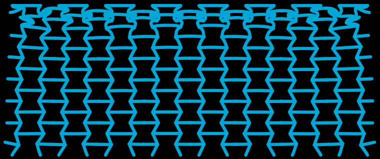


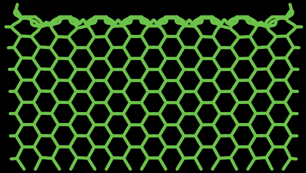


TNO TUDelft

Conclusions

- Auxetic honeycombs show a softer behaviour than conventional honeycombs
- The softening effect is related to the localization of deformation
- No localization observed for the conventional honeycombs
- Dynamic compression promotes localization near the compressing edge
- Both structures show similar behaviour during dynamic compression

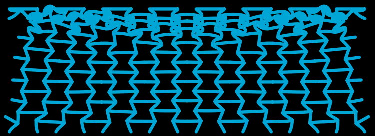


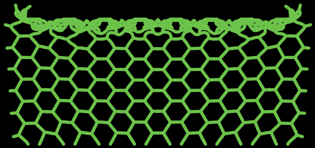


TNO TU Delft

Conclusions

- Auxetic honeycombs show a softer behaviour than conventional honeycombs
- The softening effect is related to the localization of deformation
- No localization observed for the conventional honeycombs
- Dynamic compression promotes localization near the compressing edge
- Both structures show similar behaviour during dynamic compression
- Dependence of stresses on microstructural size during dynamic loading





TNO TU Delft

Thank you!

Comments?

References I

[1] Teik-Cheng Lim. *Auxetic Materials and Structures*. Engineering Materials. 2015.

[2] H. M. A. Kolken and A. A. Zadpoor. “Auxetic mechanical metamaterials”. In: *RSC Adv.* 7 (9 2017), pp. 5111–5129.

[3] Til Gärtner, Richard Dekker, Dennis van Veen, Sanne J. van den Boom, and Lucas Amaral. “(In)Efficacy of Auxetic Metamaterials for Impact Mitigation”. In: *Int. J. Impact Eng.* (2025).

[4] Ludwig Herrnböck, Ajeet Kumar, and Paul Steinmann. “Geometrically exact elastoplastic rods: determination of yield surface in terms of stress resultants”. In: *Comput. Mech.* 67.3 (2021).

[5] Ludwig Herrnböck, Ajeet Kumar, and Paul Steinmann. “Two-scale off-and online approaches to geometrically exact elastoplastic rods”. In: *Comput. Mech.* 71.1 (2022).

References II

[6] Til Gärtner, Sanne J. van den Boom, J. Weerheijm, and L. J. Sluys. "A strategy for scaling the hardening behavior in finite element modelling of geometrically exact beams". In: *Comput. Mech.* 75.5 (May 2025), pp. 1471–1482.