Architectural Choices for Auxetic Metamaterials and their Effects on Impact Mitigation

27th Engineering Mechanics Symposium – Hotel Papendal, Arnhem

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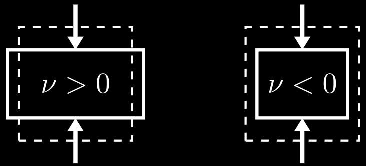
TNO TU Delft

October 22, 2024

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)

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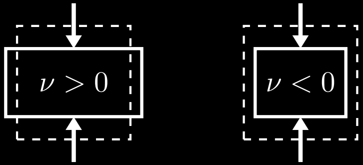

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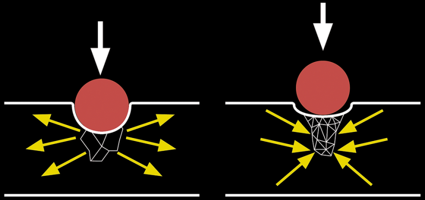

non-auxetic and auxetic material under impact (Kolken et al. 2017)

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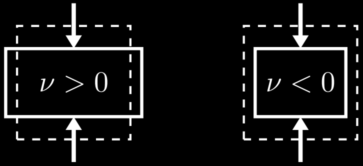
- auxetic materials are materials with a negative Poisson's ratio
  - materials that contract laterally when compressed
- promising capabilities for impact mitigation
  - natural densification at the impact location
  - better involvement of lateral material
- auxetic materials hardly found in nature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



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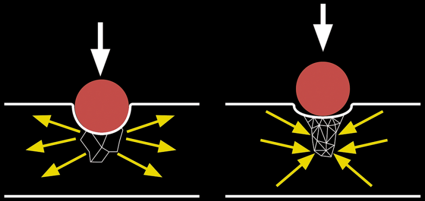

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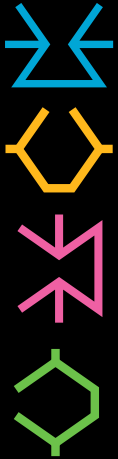

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- Stiffness and outer dimensions are kept the same:
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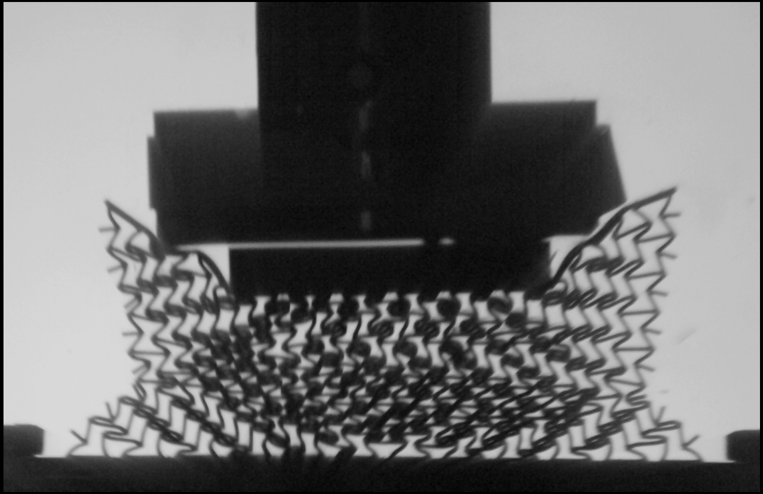
  Auxetic re-entrant honeycombs rotated by $90°$
  Conventional honeycomb in L-configuration

Experiments show higher forces for the auxetics



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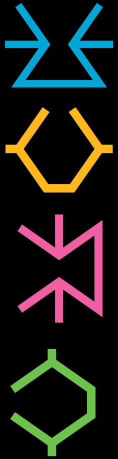

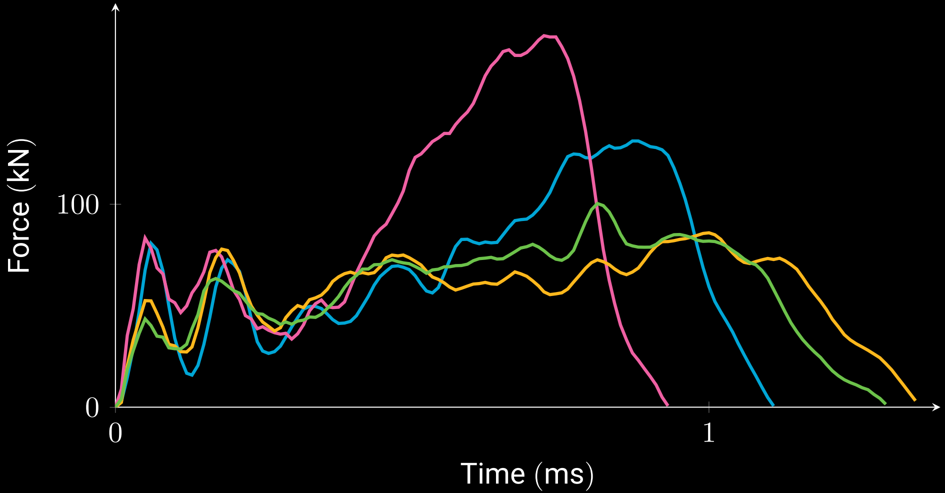

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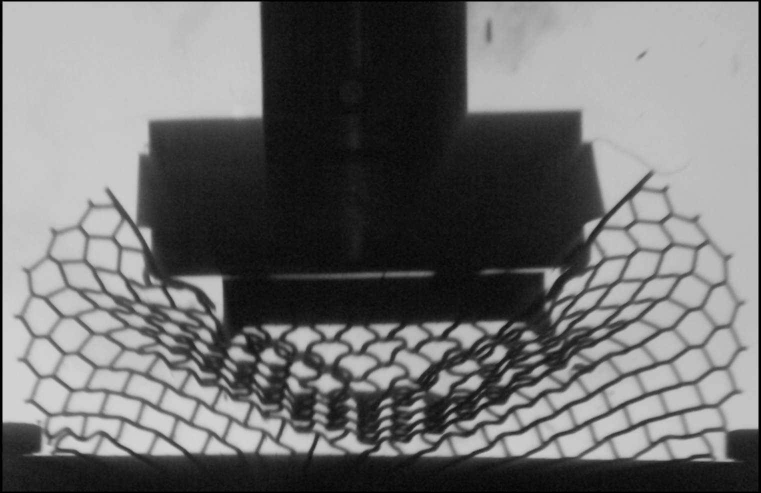

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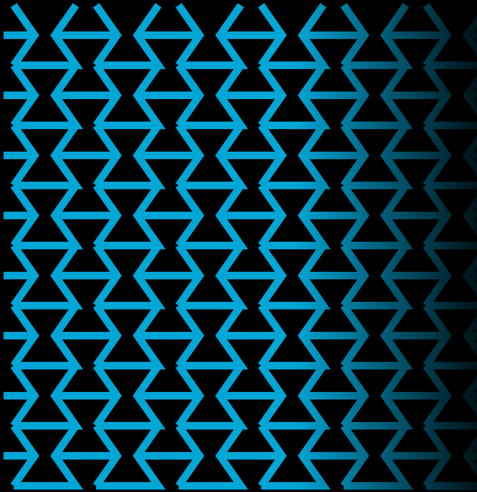
Modelling of lattices with rods to reduce runtime

- Architectures defined as assembly of rods



Modelling of lattices with rods to reduce runtime

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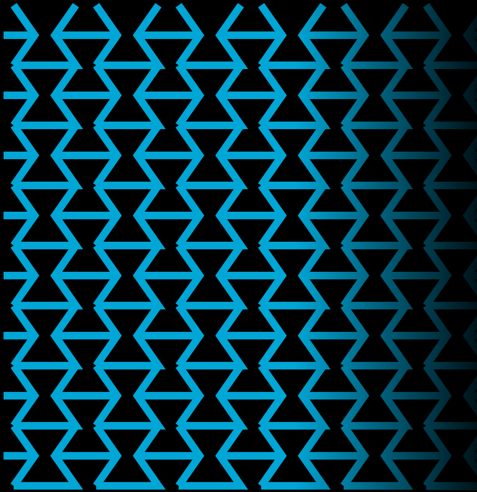
- FE-implementation of Simo-Reissner-elements in JEM/JIVE (C++ FE-Toolkit)



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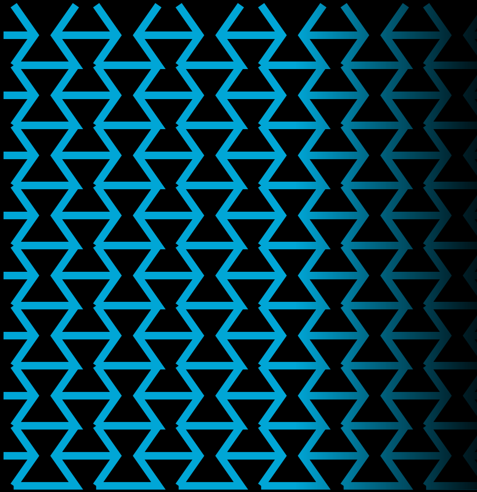

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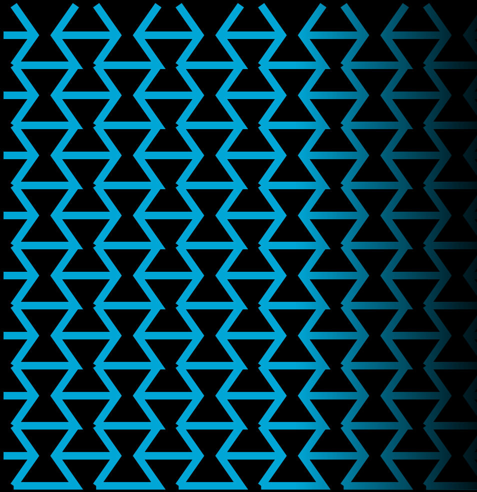
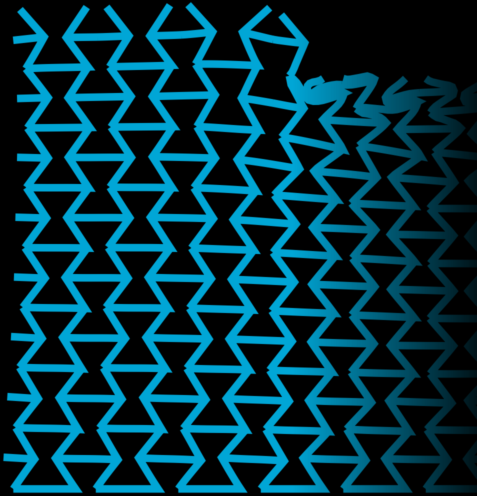
- Time marching with an explicit predictor-corrector scheme
- Time step adaptivity using a Milne-device



Fast computation of geometrically nonlinear beams

- Six DOFs along the beam-axis
- Resulting in six strain prescriptors



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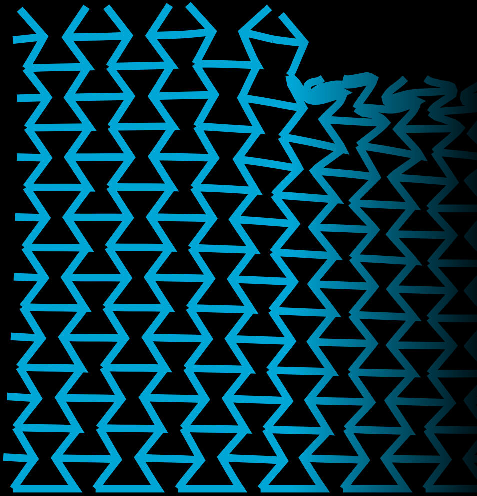
- Steel as material ($E = 210\,\text{GPa}$, $\nu = 0.265$)



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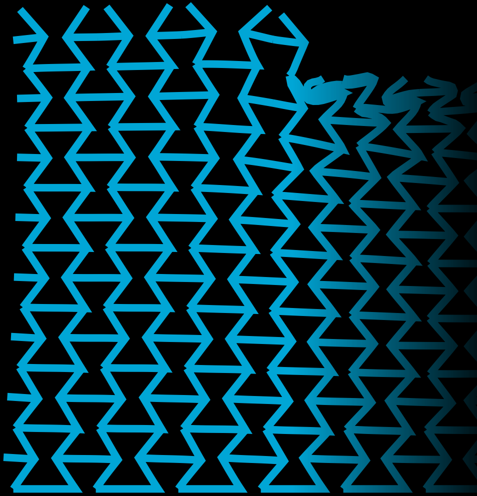

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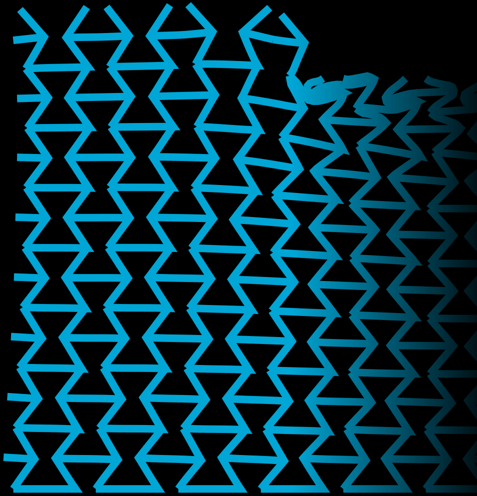
- Possibilty to model elastoplasticity on the beam-level
- Approach suggested by Smriti et al. 2018, 2020



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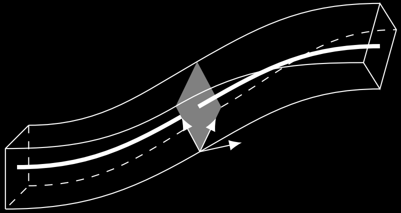
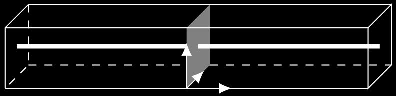
Further speed-up with beam-type elasto-plasticity

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





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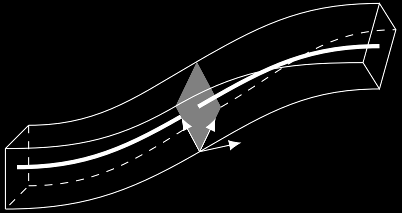
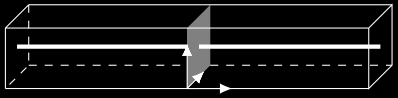
- Yield surface and hardening tensor obtained by Herrnböck et al. 2021, 2022
- Isotropic hardening on material level relates to kinematic hardening on beam level





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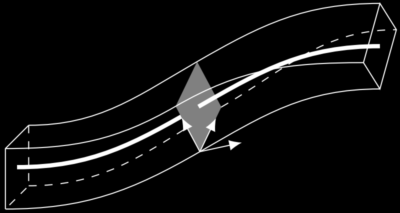
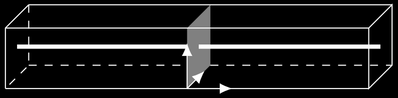
- Isotropic hardening on material level relates to kinematic hardening on beam level
- Consistent geometric scaling of the hardening tensor introduced

  Gärtner et al. *Computational Mechanics* accepted for publication (2024)
- Size-objective formulation for the entire material model





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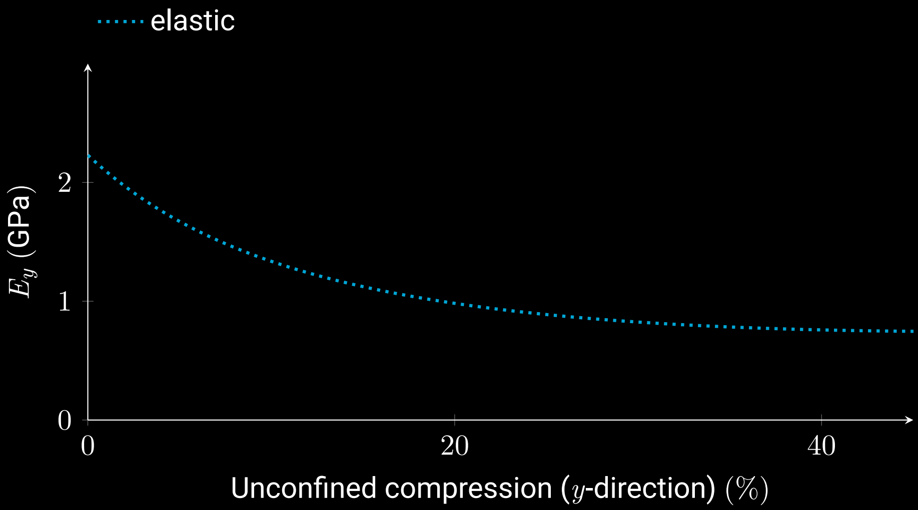
Changes in geometry lead to changes in stiffness



Gärtner et al. *Mechanics of Materials* 191 (2024)

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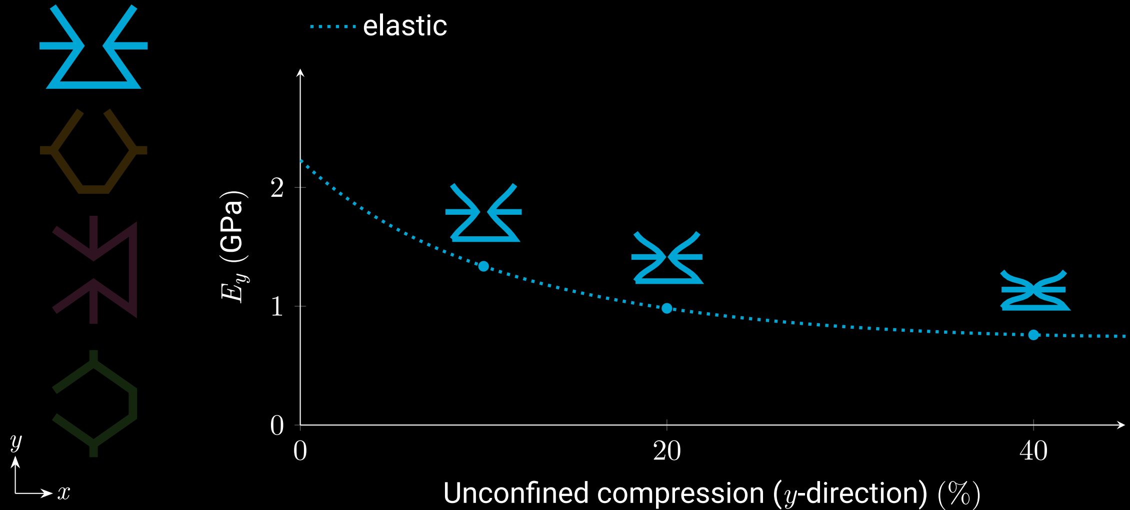

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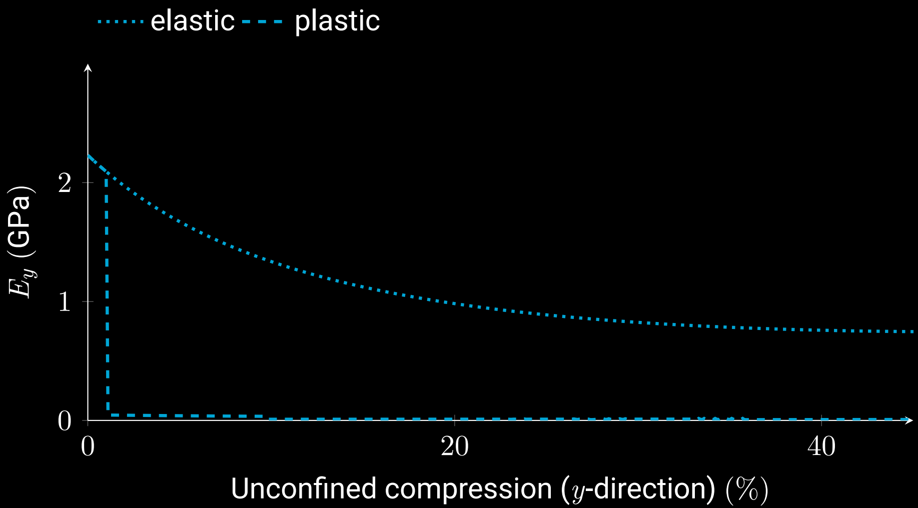
Plasticity leads to free hinging of the joints



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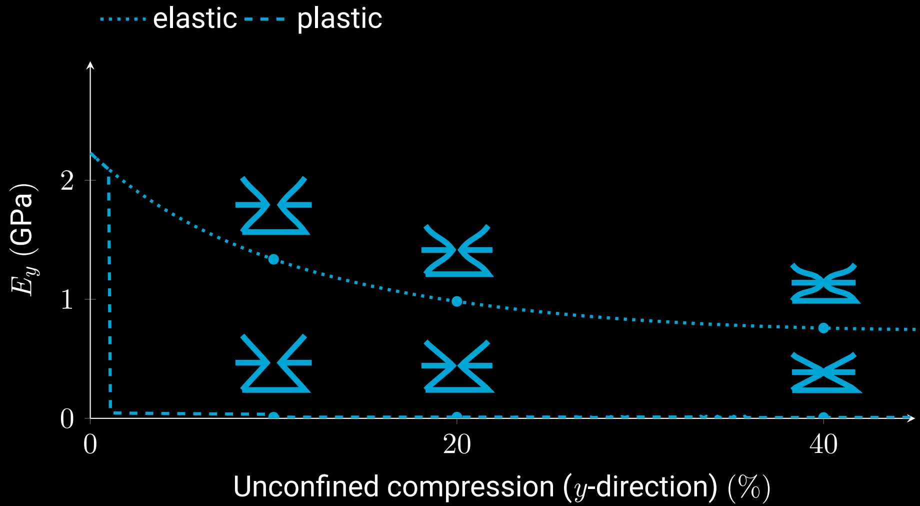
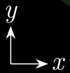
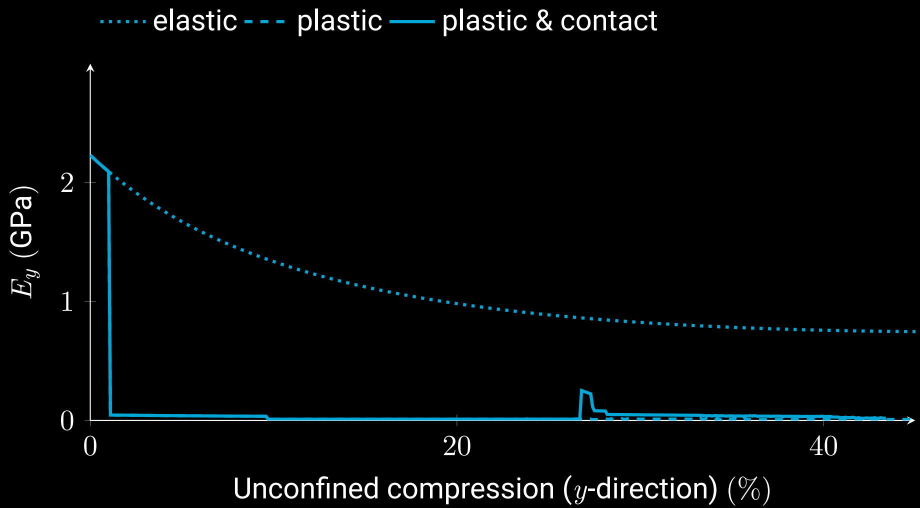
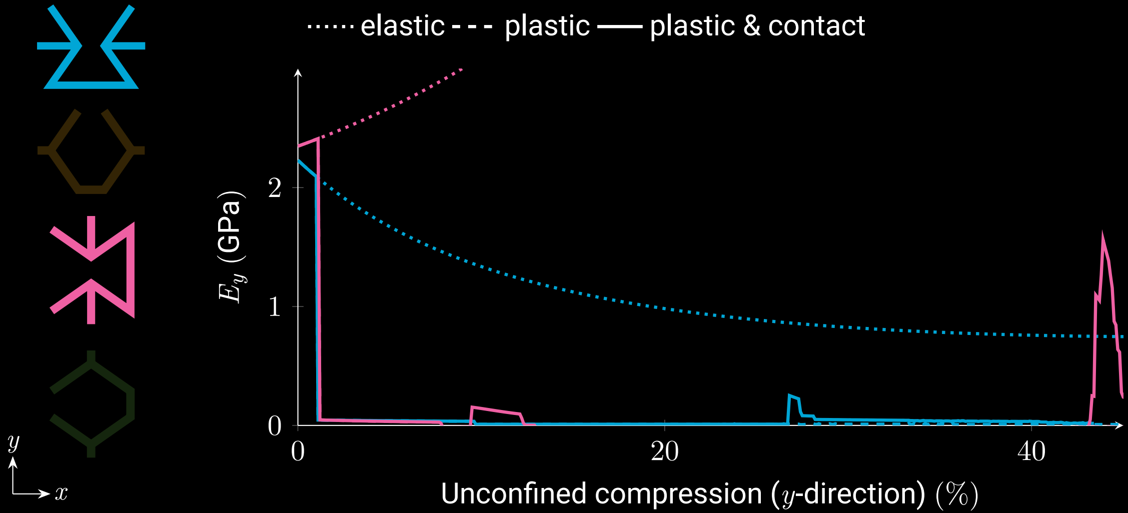




Contact has little influence on the further behavior



Plasticity can induce buckling



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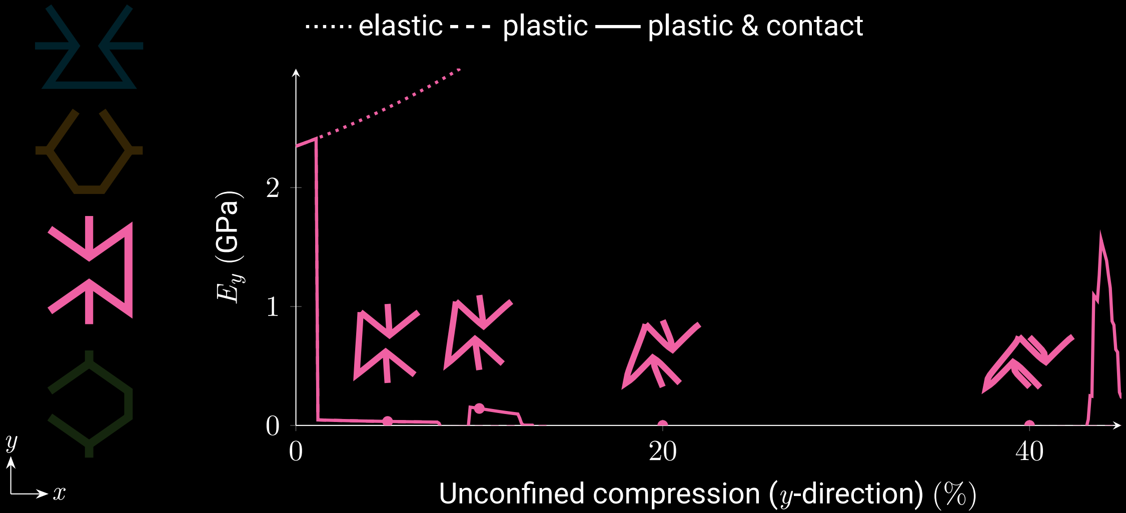
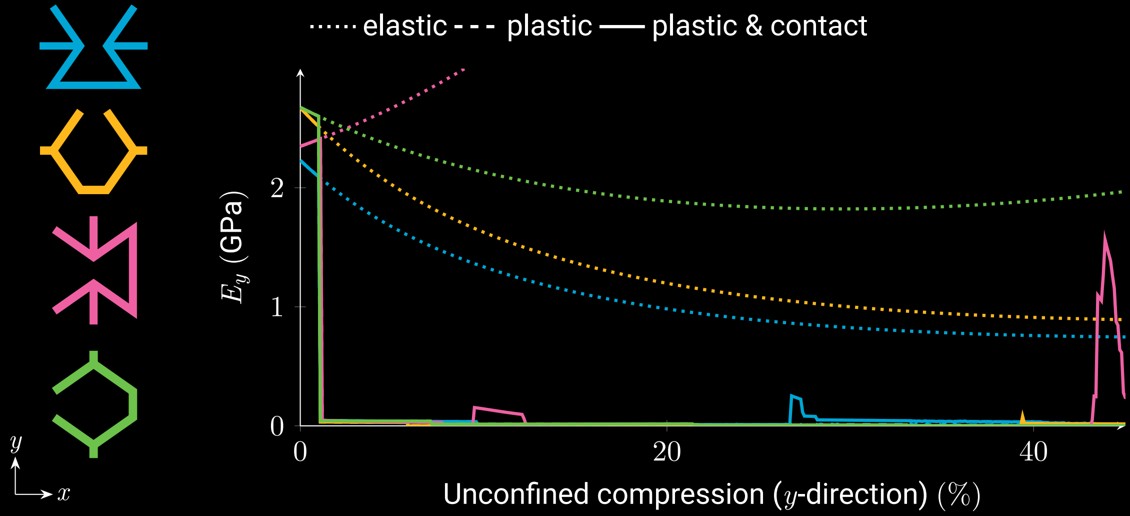
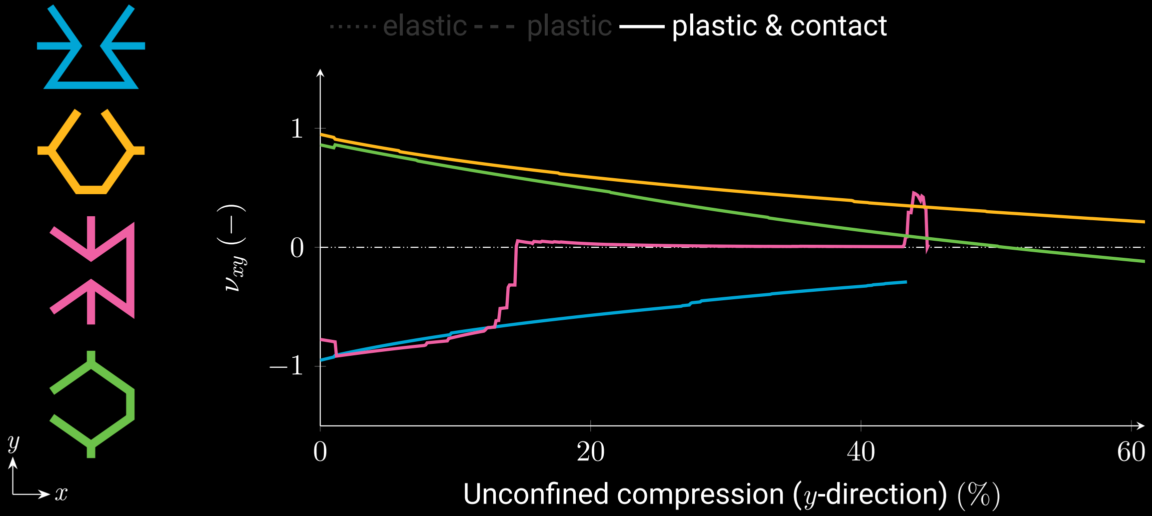


Development of stiffness differs for architectures

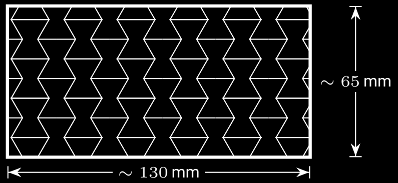


Poisson's ratio tends to 0 with compression



Impact compression tests

- Impact simulation conducted with patches of $\sim 130\,\text{mm} \times 65\,\text{mm}$



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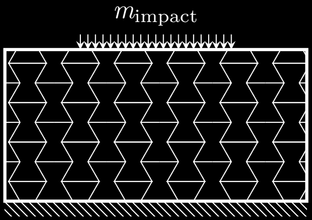
- Apply the impact at the middle patch $65\,\mathrm{mm}$ wide



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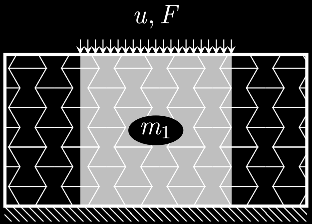
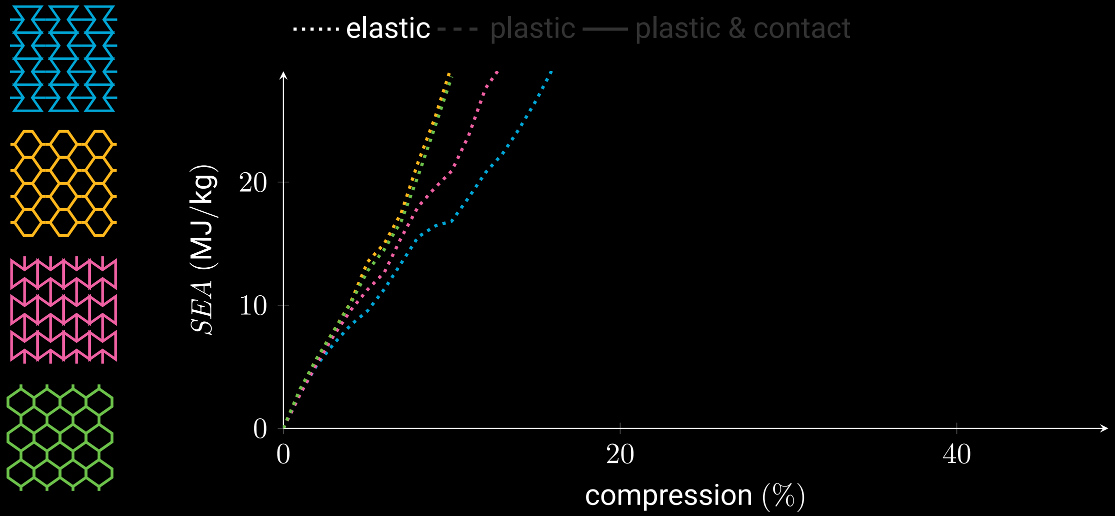
- Evaluating force over the middle patch
- Evaluating the specific energy absorption (SEA)

$$\text{SEA} = \frac{1}{m_1} \int F \,\mathrm{d}u$$



Impact Tests – Influence of material nonlinearities



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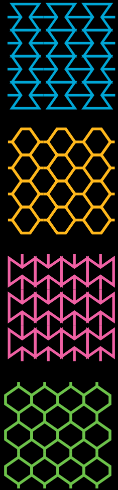

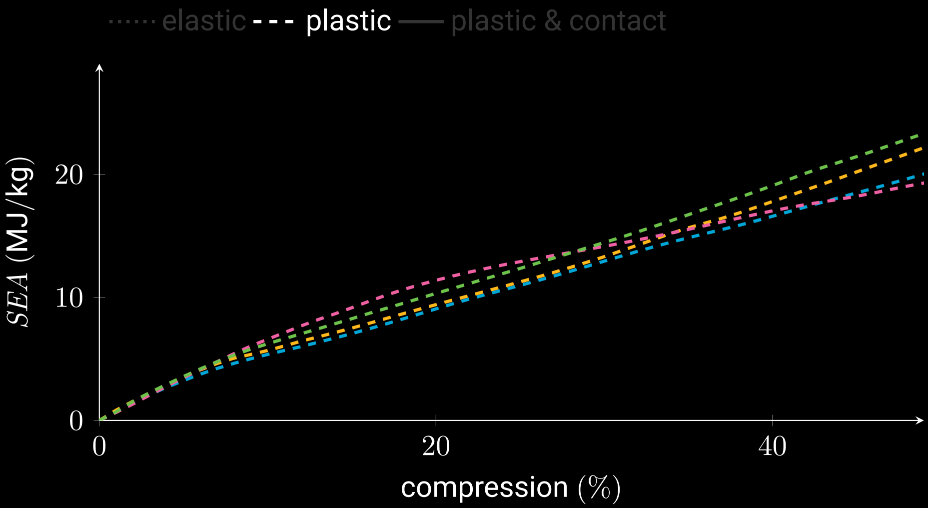

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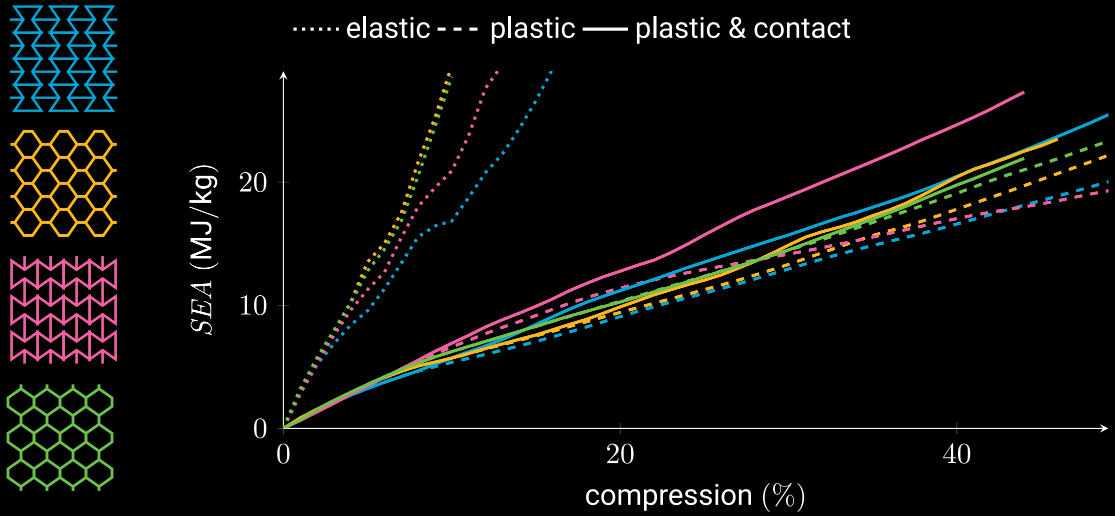

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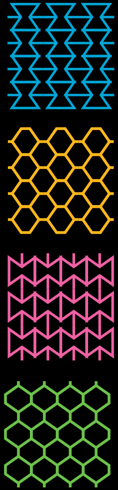
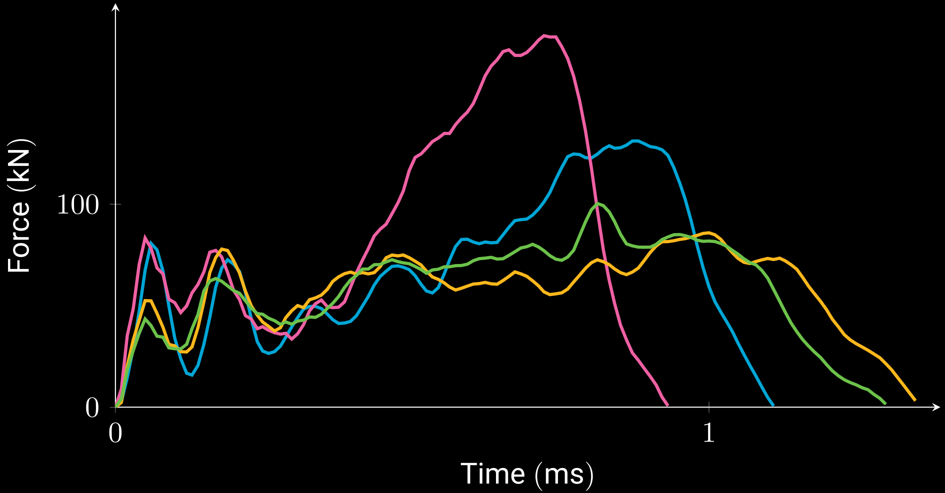
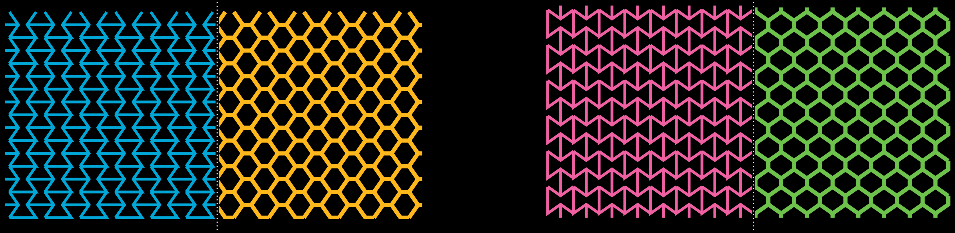




Conclusions

- Lattice materials as such do not follow linear continuum assumptions



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- Lattice materials as such do not follow linear continuum assumptions
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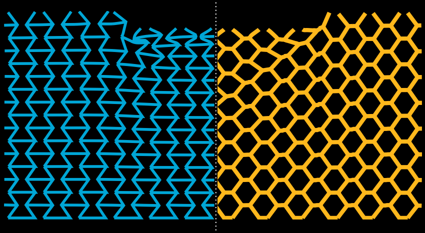

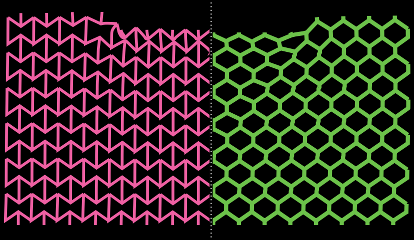

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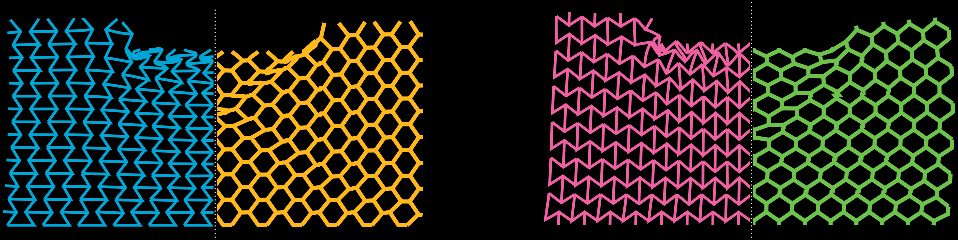
  $\Rightarrow$ Dependency on architecture under investigation



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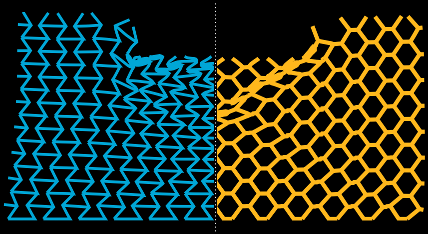
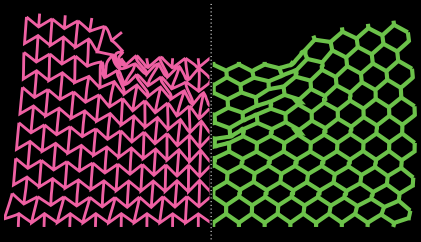
  $\Longrightarrow$ Dependency on architecture under investigation
- Auxetic structures lead to temporal and spatial concentration of forces

  $\Longrightarrow$ Have a look at the poster as well!

  Gärtner, Dekker, van Veen, van den Boom, and Amaral *publication in preparation*





Thank you!

Comments?

References I

[1] Teik-Cheng Lim. *Auxetic Materials and Structures*. Engineering Materials. Singapore: Springer Singapore, 2015.

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

[3] Smriti, Ajeet Kumar, Alexander Großmann, and Paul Steinmann. “A thermoelastoplastic theory for special Cosserat rods”. In: *Mathematics and Mechanics of Solids* 24.3 (2018).

[4] Smriti, Ajeet Kumar, and Paul Steinmann. “A finite element formulation for a direct approach to elastoplasticity in special Cosserat rods”. In: *International Journal for Numerical Methods in Engineering* 122.5 (2020).

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

References II

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

[7] 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: *Computational Mechanics* (2024). accepted for publication.

[8] Til Gärtner, S. J. van den Boom, J. Weerheijm, and L. J. Sluys. “Geometric effects on impact mitigation in architected auxetic metamaterials”. In: *Mechanics of Materials* 191 (2024), p. 104952.

[9] Til Gärtner, Richard Dekker, Dennis van Veen, Sanne J. van den Boom, and Lucas Amaral. “(In)Efficacy of Auxetic Metamaterials for Impact Mitigation: Investigations of Energy Absorption and Force Distribution”. publication in preparation. 2024.