Force Transmission and the (In)efficacy of Auxetic Metamaterials for Impact Mitigation

Til Gärtner

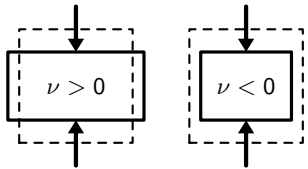
Institute of Mechanics and Computational Mechanics (IBNM)
Leibniz University Hannover

SHAPE Seminar Series

10 November 2026

Auxetic materials appear promising for impact mitigation

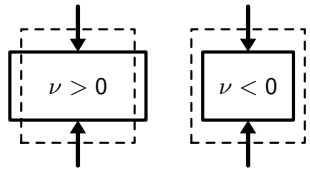
- auxetic materials are materials with a negative Poisson's ratio
  - materials that contract laterally when compressed



non-auxetic and auxetic materials
(Lim 2015)

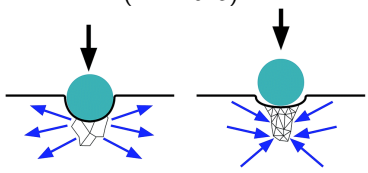
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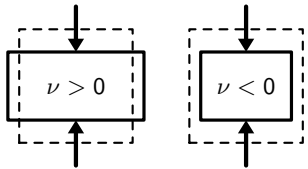
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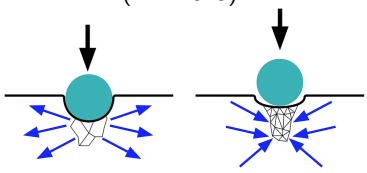
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- assumptions don't take material architecture into account
- experimental investigation of terminal ballistics intricate



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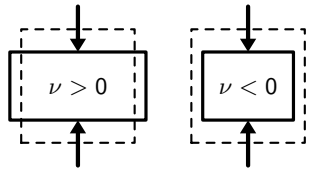


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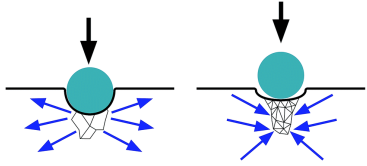
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How do mechanical metamaterials respond to high rates?



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under impact (Kolken et al. 2017)

Are Auxetics Better for Protection?

TU Delft

On the Behaviour of Architected Metamaterials under High-Rate Loading Conditions

TNO

Investigation #1

How can lattice structures be efficiently and accurately modelled using numerical tools?

Gärtner, van den Boom, et al. ***Comput. Mech.*** **(2025)**

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Investigation #4

How to efficiently predict and design the response of non-uniform lattices?

Wang, Gärtner, Aldakheel *under review*

Wang, Gärtner, Aldakheel *in preparation*

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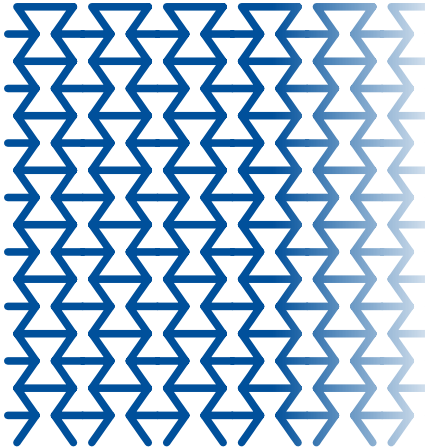
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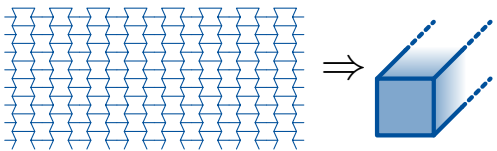
Modelling of lattices with rods to reduce runtime

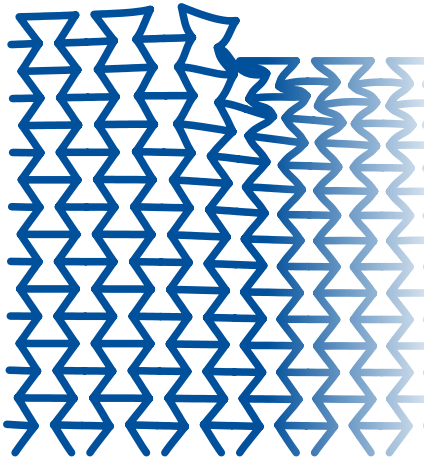
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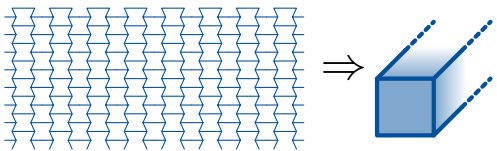
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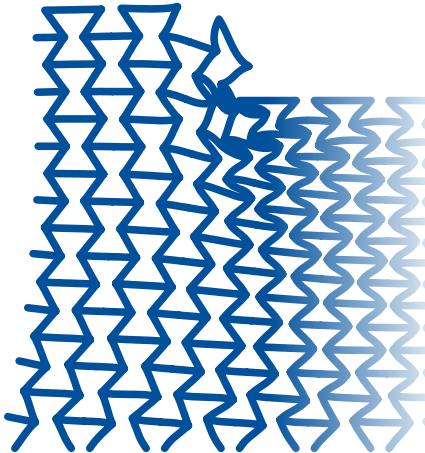




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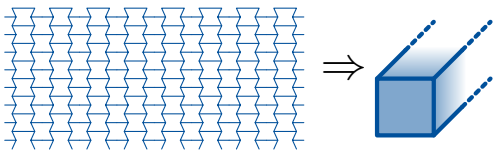
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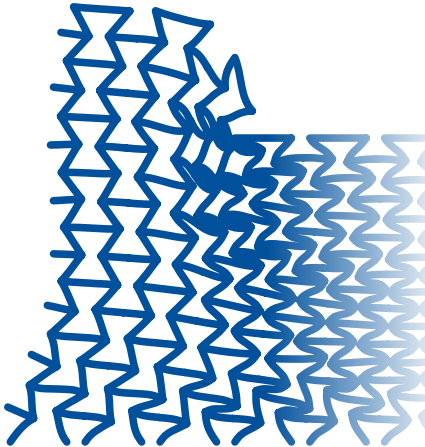




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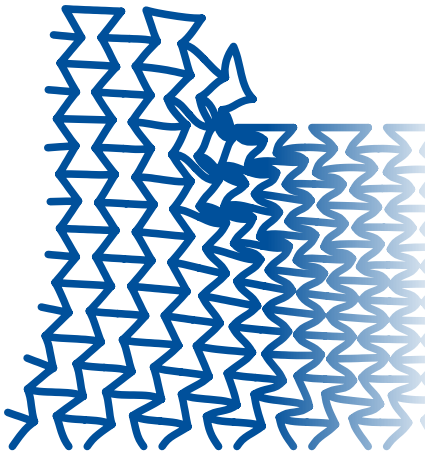
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- Time step adaptivity using a Milne-device





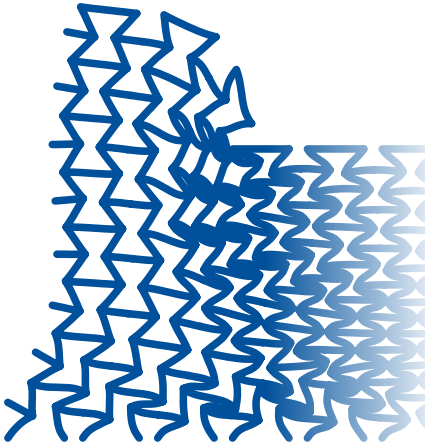
Fast computation of geometrically nonlinear beams

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



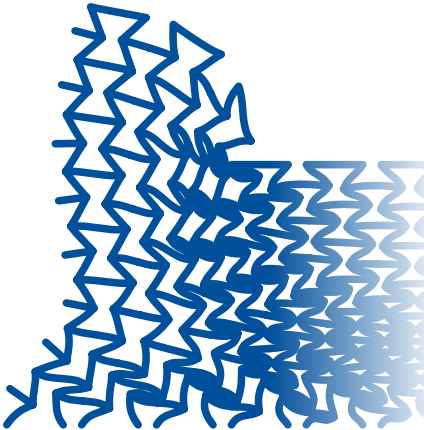
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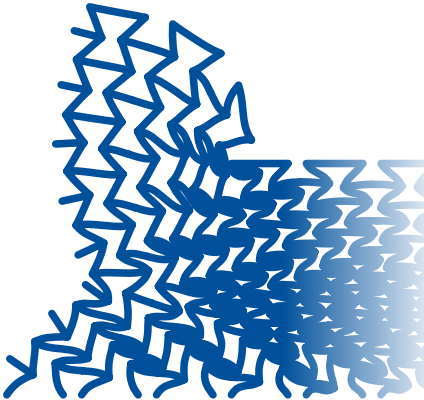
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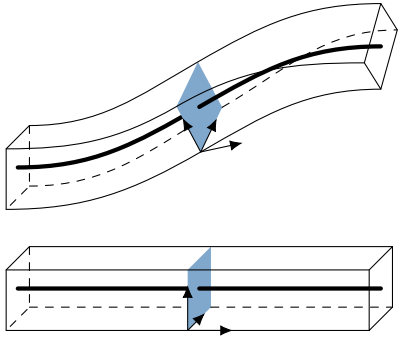
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- Modelling elastoplasticity on the beam-level
- Introduction of consistent geometric scaling into the hardening formulation

Gärtner, van den Boom, et al. *Comput. Mech.* 75 (2025)



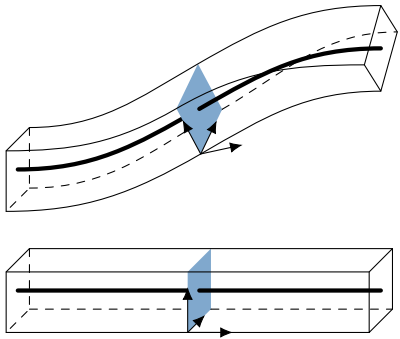
Further speed-up with beam-type elasto-plasticity

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



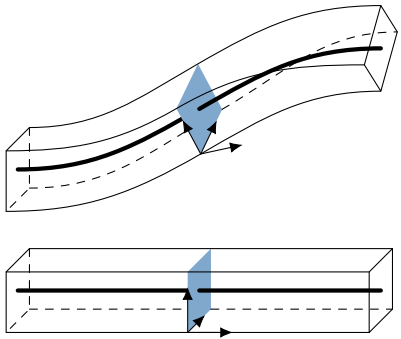
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- Isotropic hardening on material level relates to kinematic hardening on beam level



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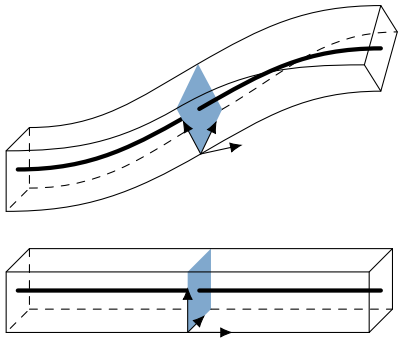
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$\Rightarrow$ Size-objective formulation for the entire material model

Are Auxetics Better for Protection?

On the Behaviour of Architected Metamaterials under High-Rate Loading Conditions

Investigation #1

How can lattice structures be efficiently and accurately modelled using numerical tools?

Geometrically nonlinear beams contribute to a numerically efficient method for the modelling of lattice structures and allow for inclusion of material non-linearities, contact, and proper geometric scaling in an accurate manner.

Gärtner, van den Boom, et al. ***Comput. Mech.*** **(2025)**

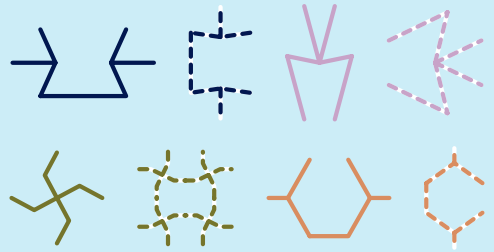
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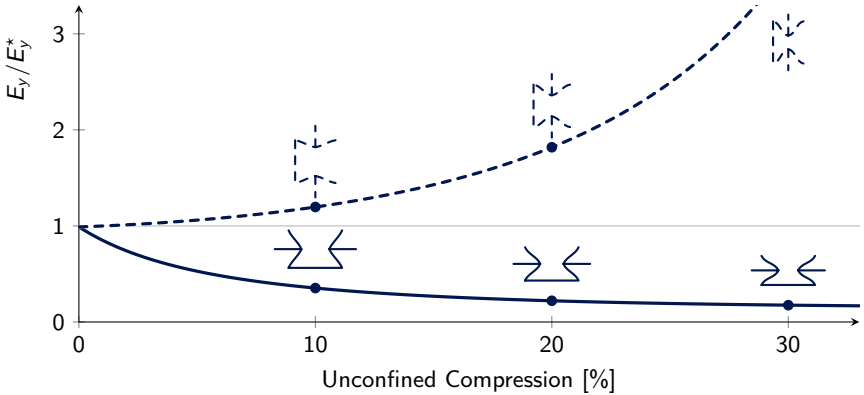
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How does the Poisson effect influence energy absorption in architected materials?



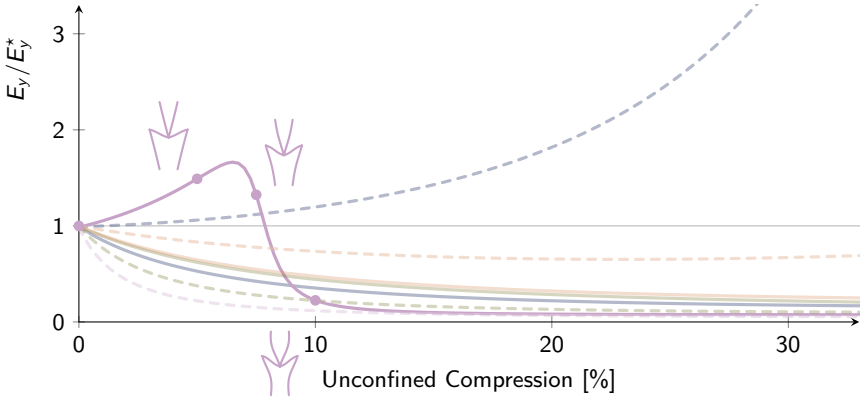
Change in E_y due to Loading-Direction of Beams





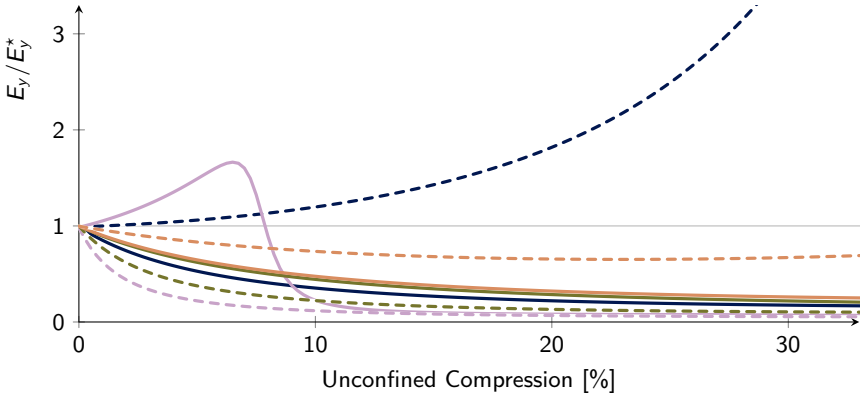
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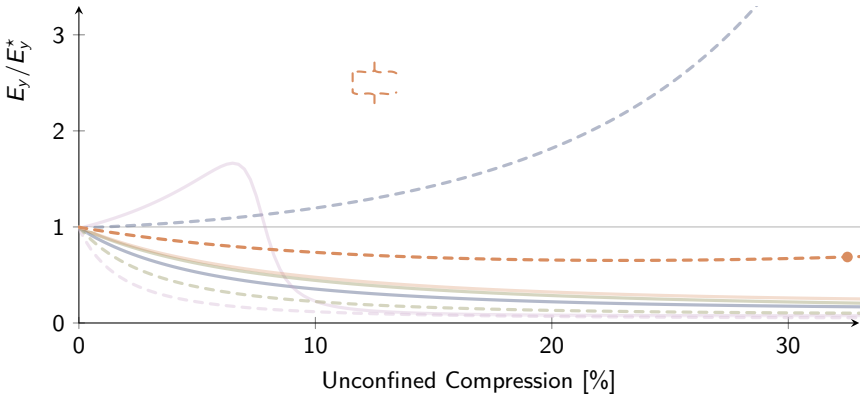
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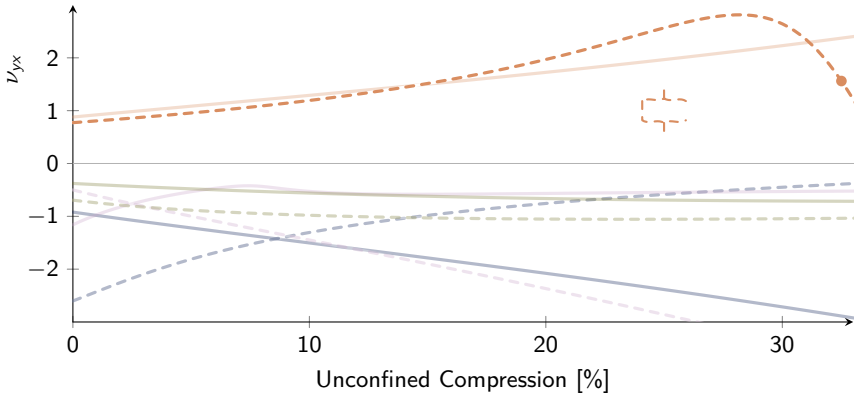
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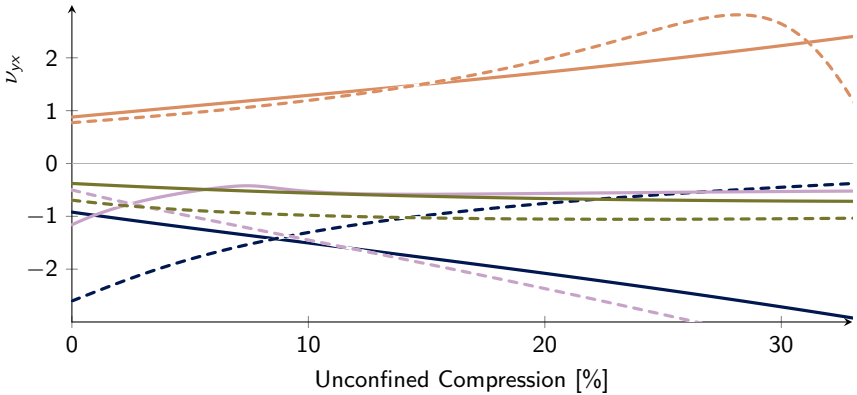
Influence of Geometry on Poisson's Ratio





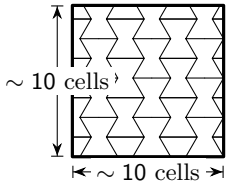
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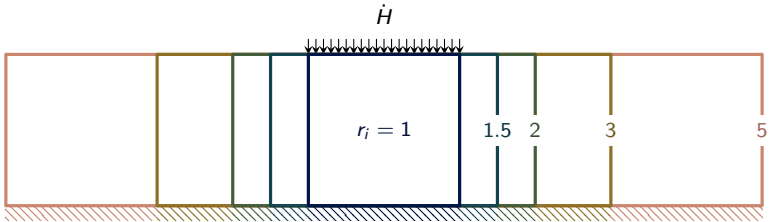
Setup for Impact Simulation

- impact simulation conducted with patches of $\sim 10 \times 10$ unit cells



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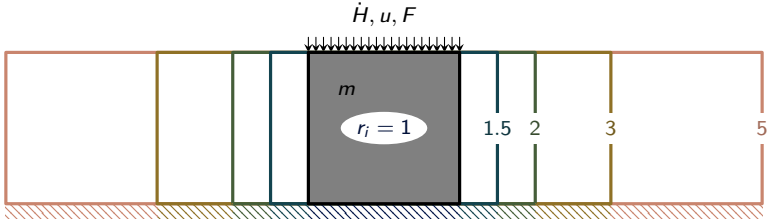
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- different compression speeds $\dot{H}$
- different localization ratios r_i



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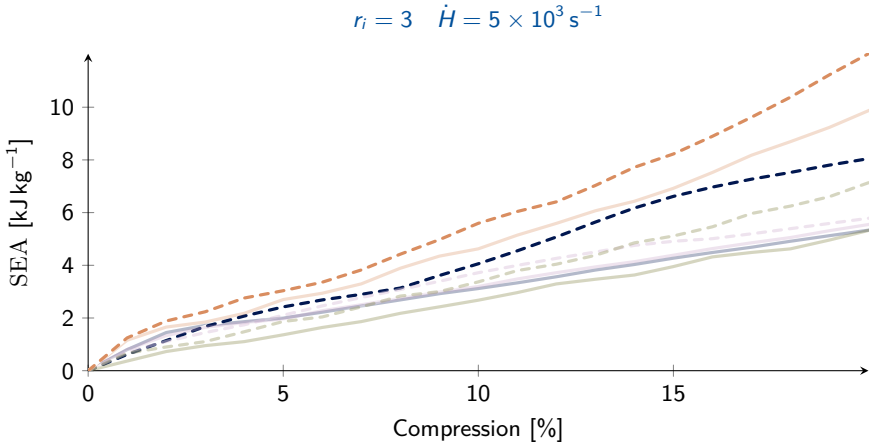
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$$\mathrm{SEA} = \frac{1}{m} \int F \, \mathrm{d}u$$

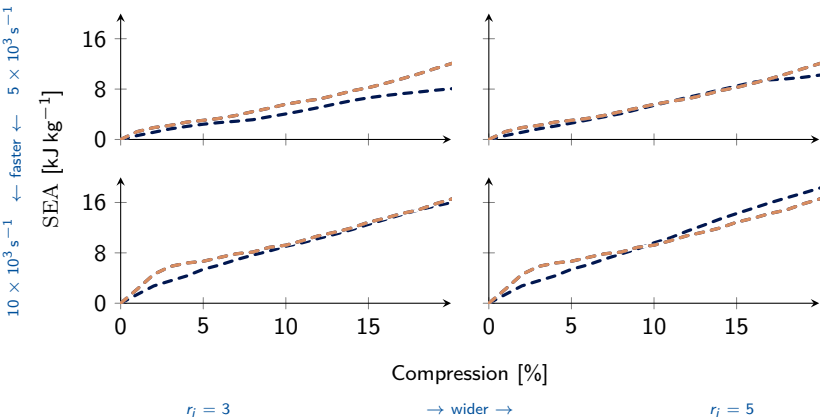


No Benefit of Auxeticity in Moderate Localization



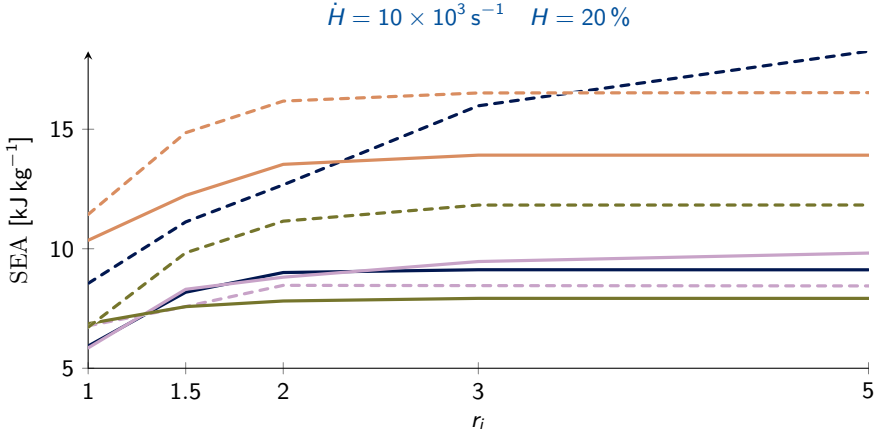


Benefit arises upon Severe Localization & Higher Strain Rates



Re-entrant Honeycomb performs better upon Severe Localization





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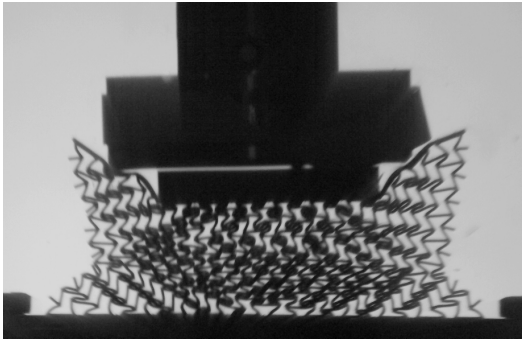
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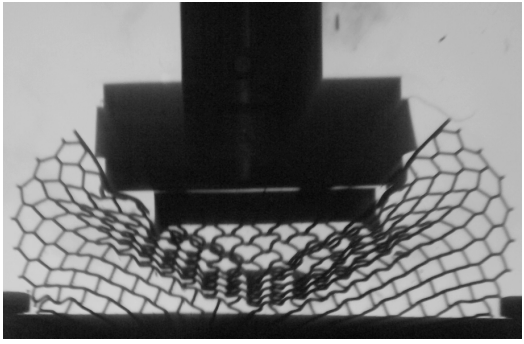
The Poisson effect in itself does not influence the energy absorption capacity of an architected material.

Gärtner, van den Boom, et al. ***Mech. Mater.*** **191 (2024)**

Gärtner, Dekker, et al. ***Int. J. Impact Eng.*** **206 (2025)**

All architectures able to stop an impact → effect on structure





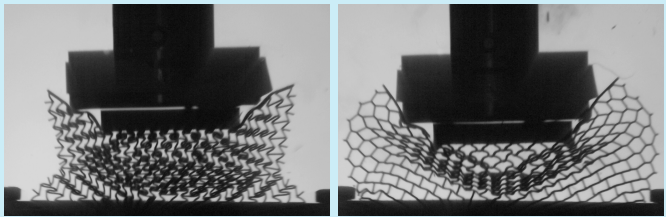
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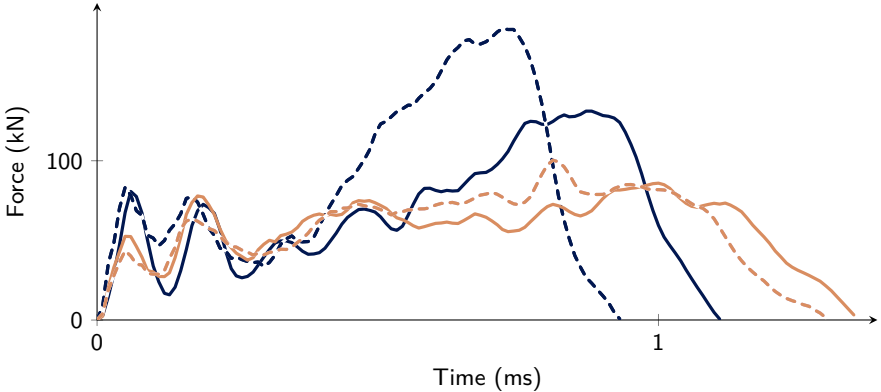
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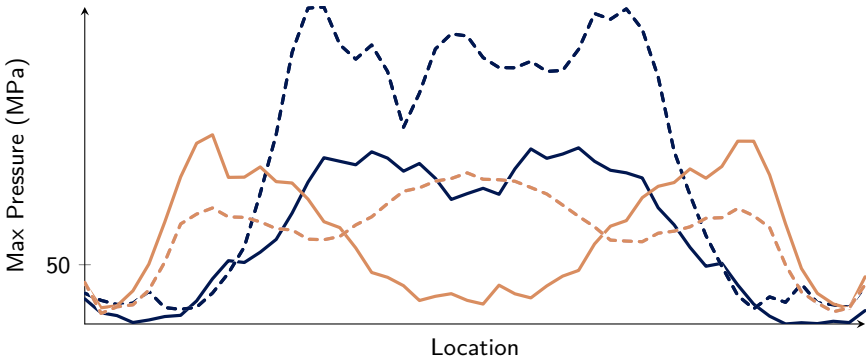
Localization of Forces for Auxetic Structures (Experiments)





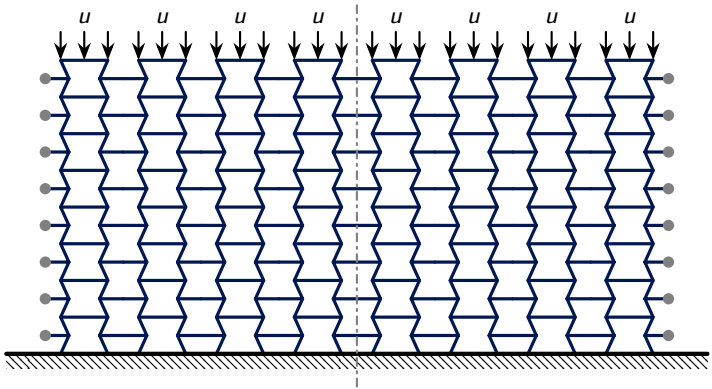
Localization of Forces for Auxetic Structures (Simulations)





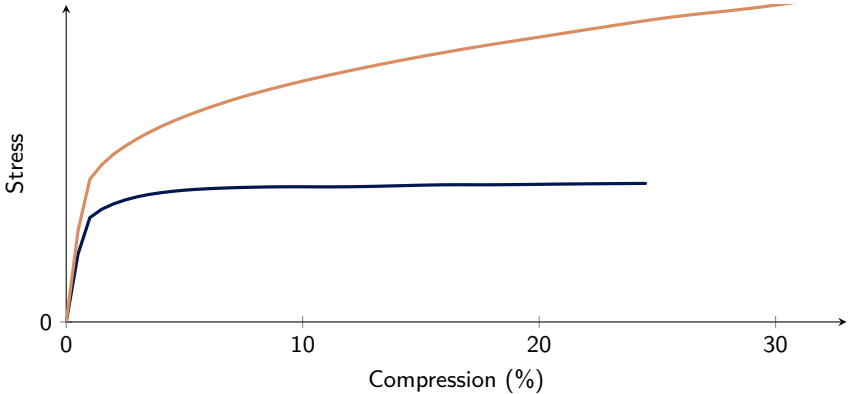
Constant Strain Rate Test Setup

- Constant strain rate test setup mimicked in simulation
- Bottom is fully fixed, and a constant velocity enforced on the top



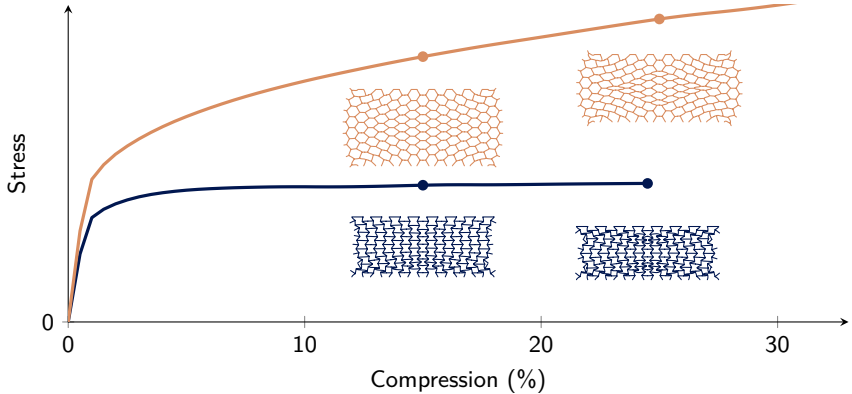
Non-auxetic patches deform homogenous under static compression





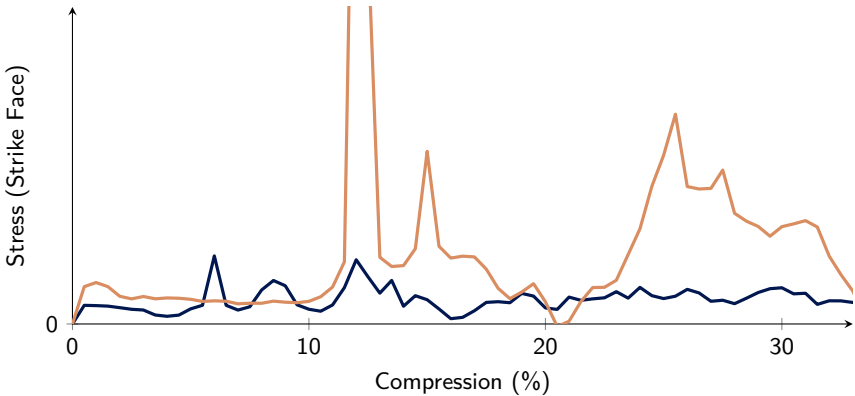
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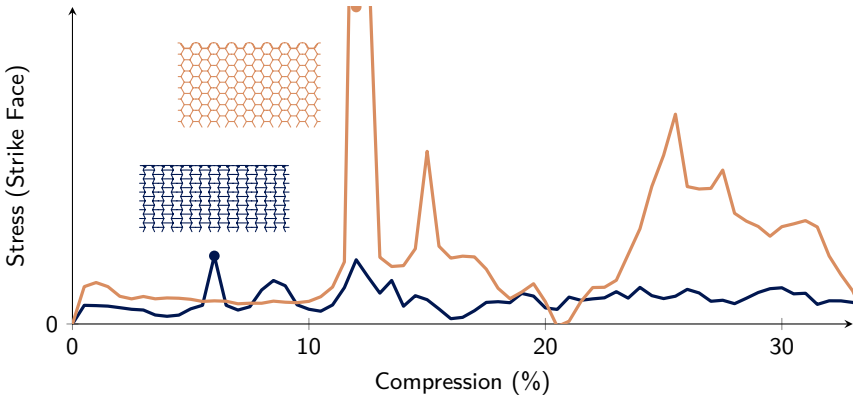
High strain rate response determined by microstructure





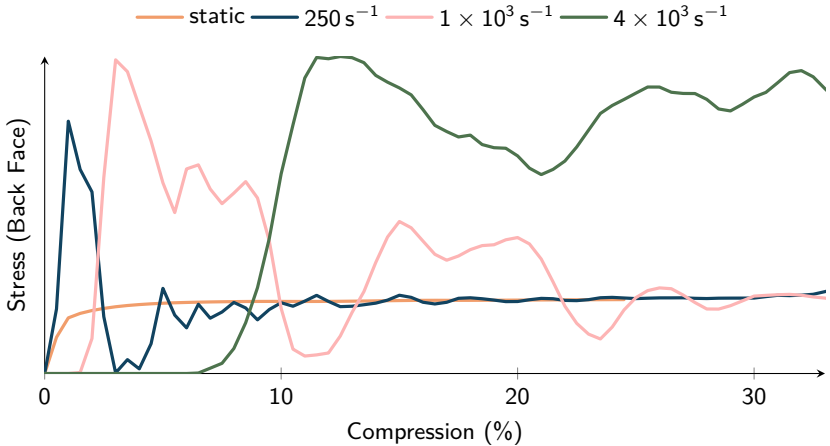
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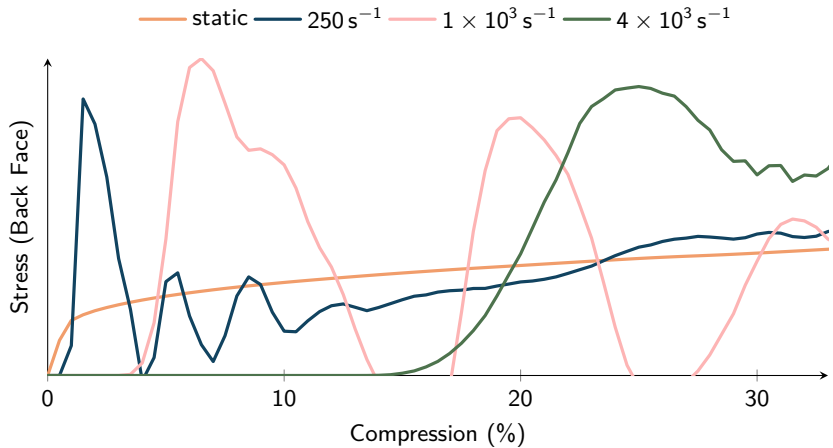
In a first approximation, the static yield limits the transmitted Forces



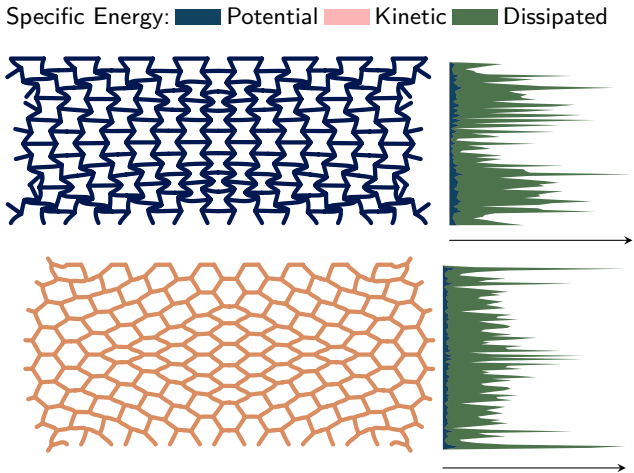


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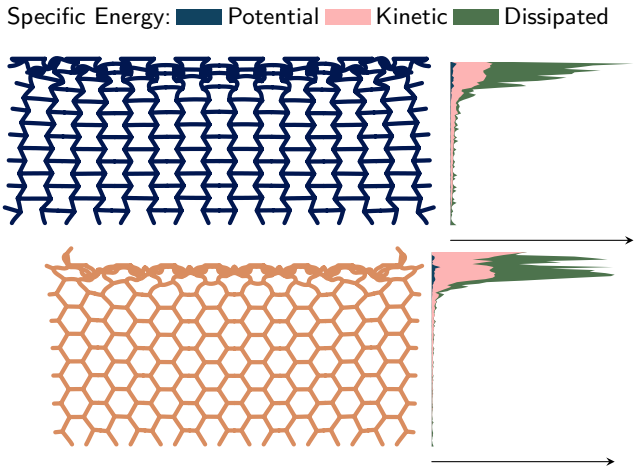




Energy is concentrated at the localization of deformation (Static)

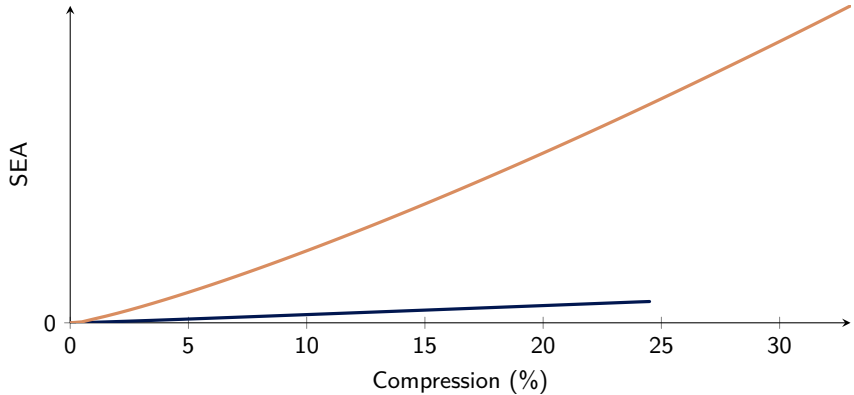


Energy is concentrated at the localization of deformation ($1 \times 10^3\,\mathrm{s}^{-1}$)



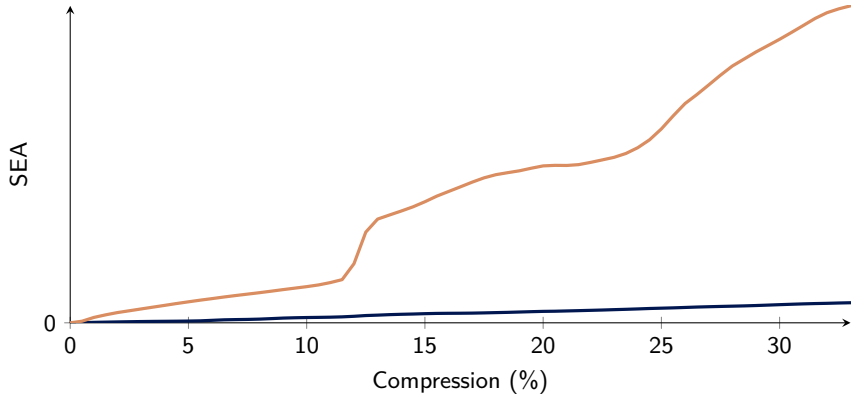
The regular honeycomb absorbs more energy (Static)





The regular honeycomb absorbs more energy ($4 \times 10^3\,\mathrm{s}^{-1}$)





Are Auxetics Better for Protection?

On the Behaviour of Architected Metamaterials under High-Rate Loading Conditions

Investigation #3

How does the Poisson effect influence
force transmission in architected materials?

A negative Poisson's ratio concentrates the load over a smaller time frame and a narrower zone.

Gärtner, van den Boom, et al. ***Mater. Today Adv.*** **(2025)**

Gärtner, Dekker, et al. ***Int. J. Impact Eng.*** **(2025)**

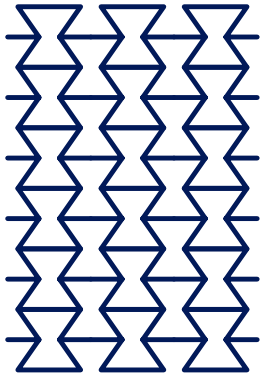
Investigation #4

How to efficiently predict and design
the response of non-uniform lattices?



Vast Plethora of Design Options

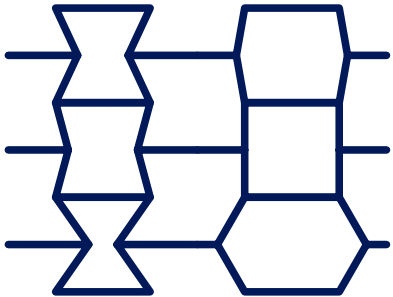
- Changes in single parameters well understood



Vast Plethora of Design Options

- Changes in single parameters well understood
- Combination of different unit cells explodes the design space

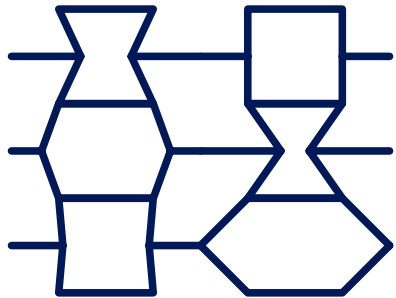
  $\mathbb{R}^3 \rightarrow \mathbb{R}^{3 \cdot N \cdot M}, \quad \text{for } N \cdot M \,\text{RUCs}$
- Different responses for different strain rates



Vast Plethora of Design Options

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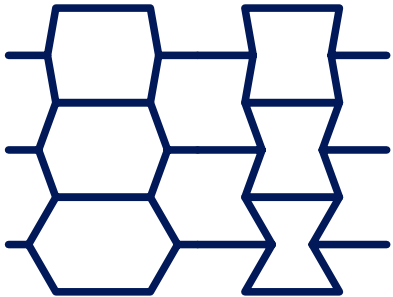
  $\mathbb{R}^3 \to \mathbb{R}^{3 \cdot N \cdot M}, \quad \text{for } N \cdot M \,\text{RUCs}$
- Different responses for different strain rates
- Targeted responses require inverse design



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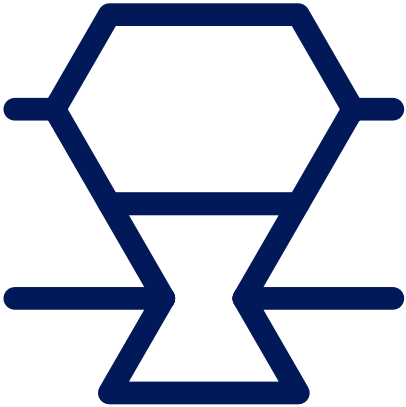
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- Different responses for different strain rates
- Targeted responses require inverse design
- Exploration of design space expensive
- Limitations for initial investigations

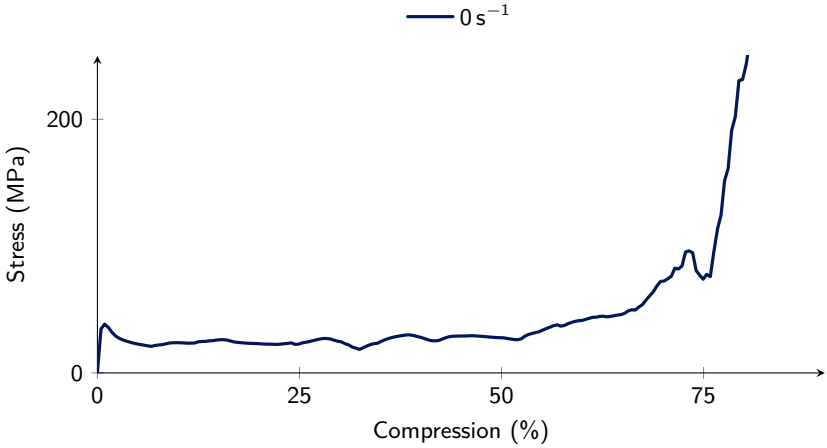


Vast Plethora of Design Options

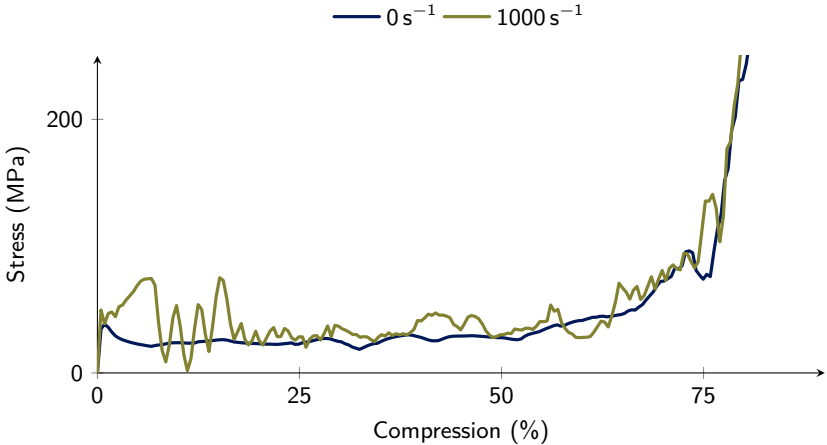
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- Different responses for different strain rates
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- First proxy for large lattice: single column



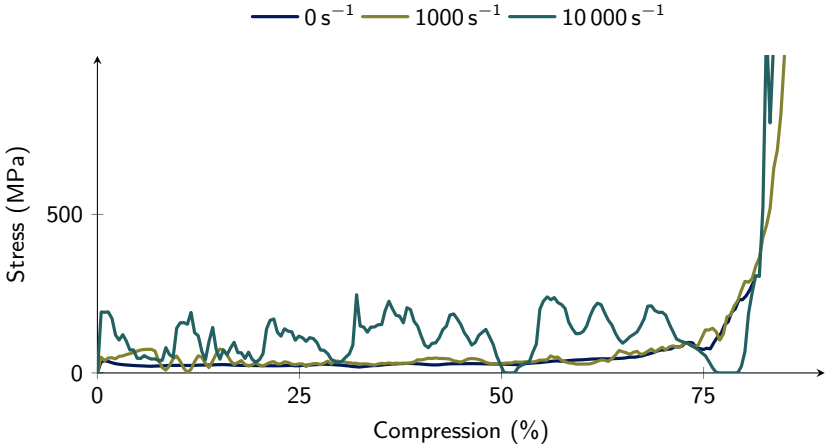

0 s^{-1}
200
0
Stress (MPa)
0
25
50
75
Compression (%)

Nonlinear Response under High Strain-rates

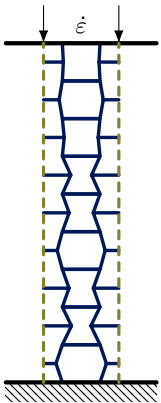


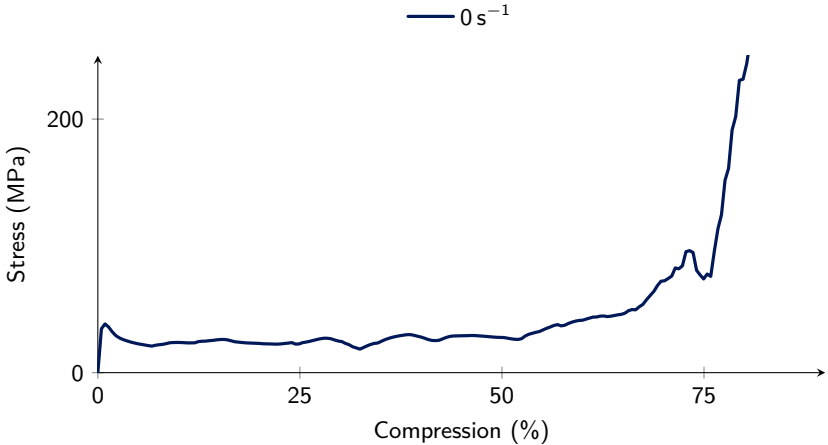


Nonlinear Response under High Strain-rates



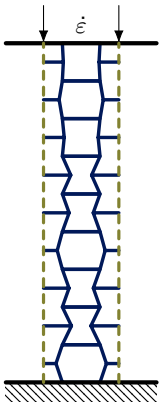
Description by Characteristic Parameters

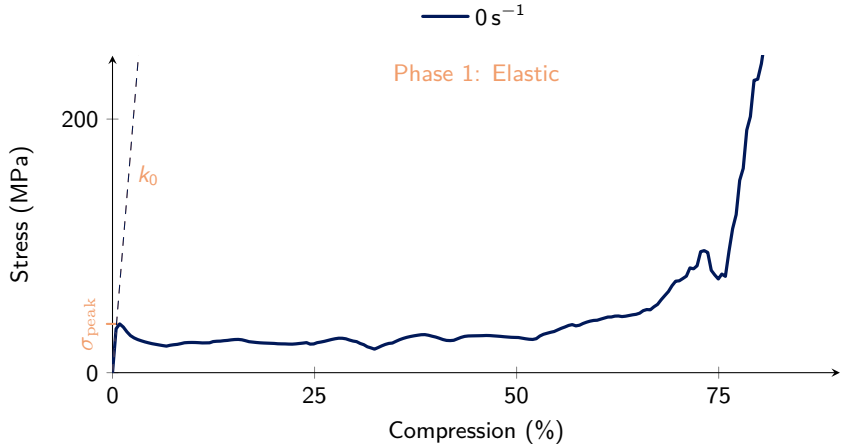




Shinde et al. 2024; *ISO 13314* 2011; Zimmerman et al. 2026

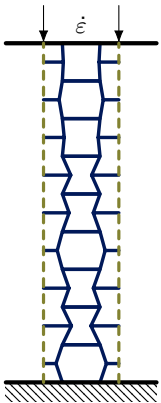
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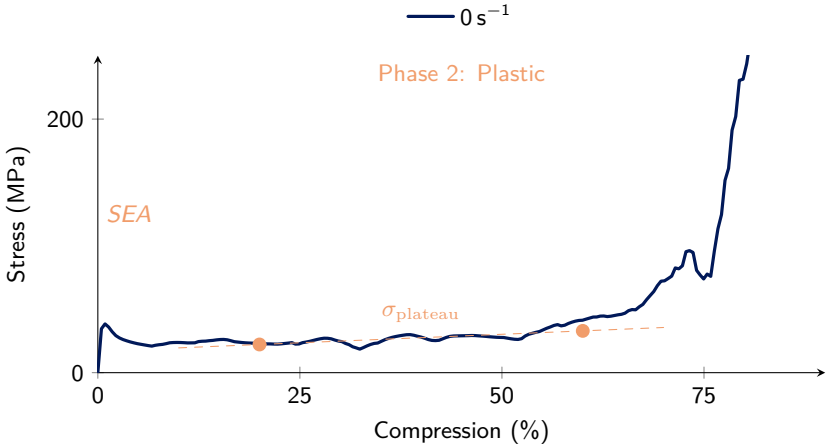




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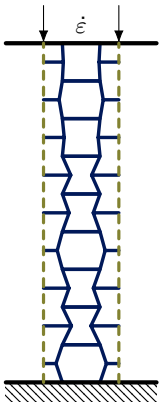
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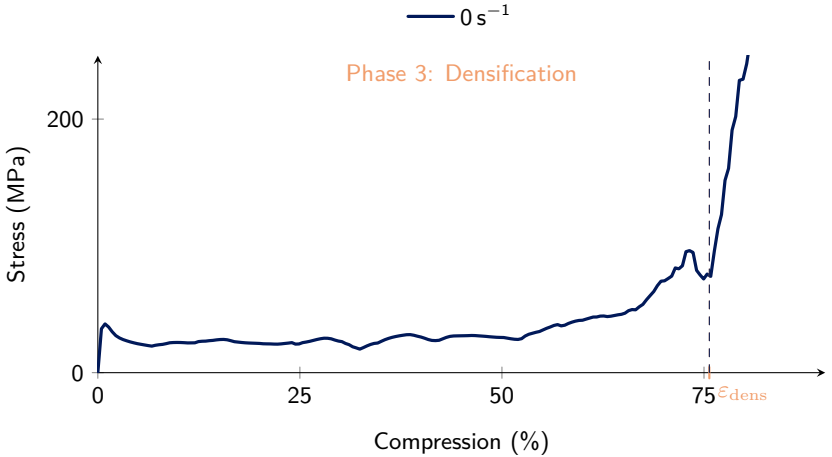




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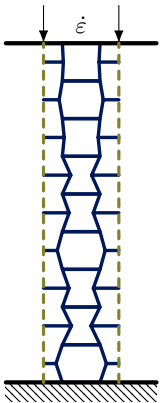
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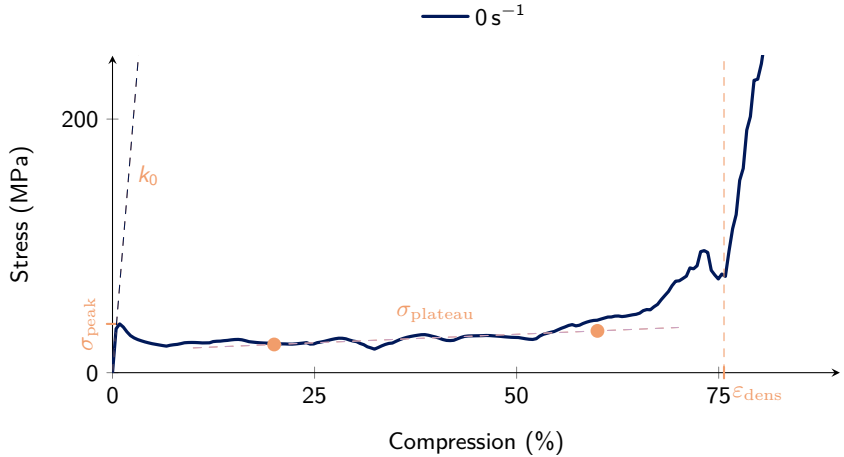




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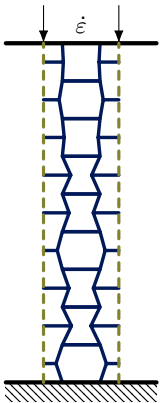
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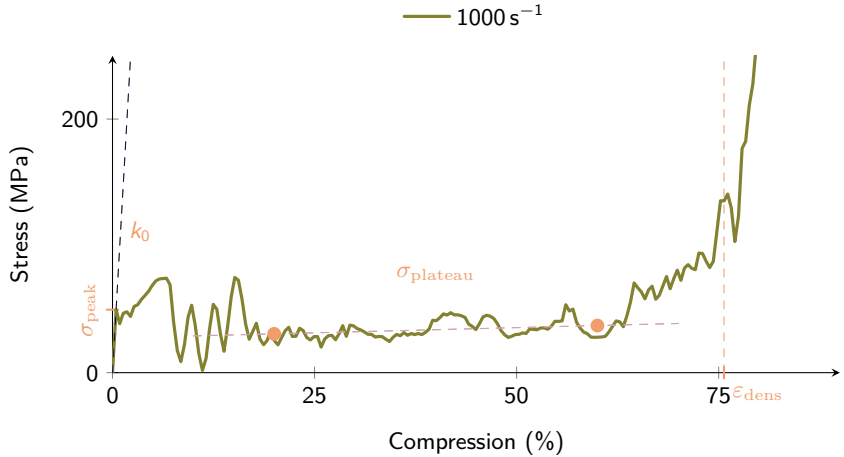




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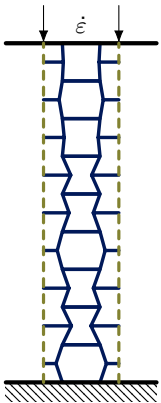
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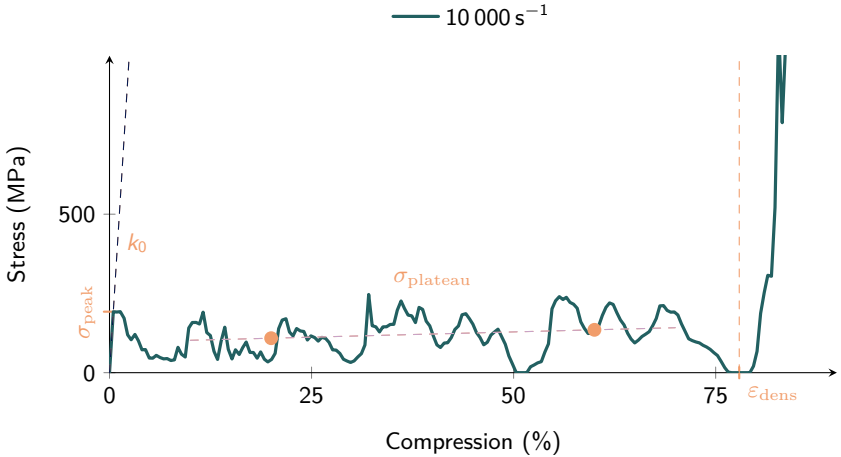




Shinde et al. 2024; *ISO 13314* 2011; Zimmerman et al. 2026

Description by Characteristic Parameters





Shinde et al. 2024; *ISO 13314* 2011; Zimmerman et al. 2026

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Denoising Diffusion:



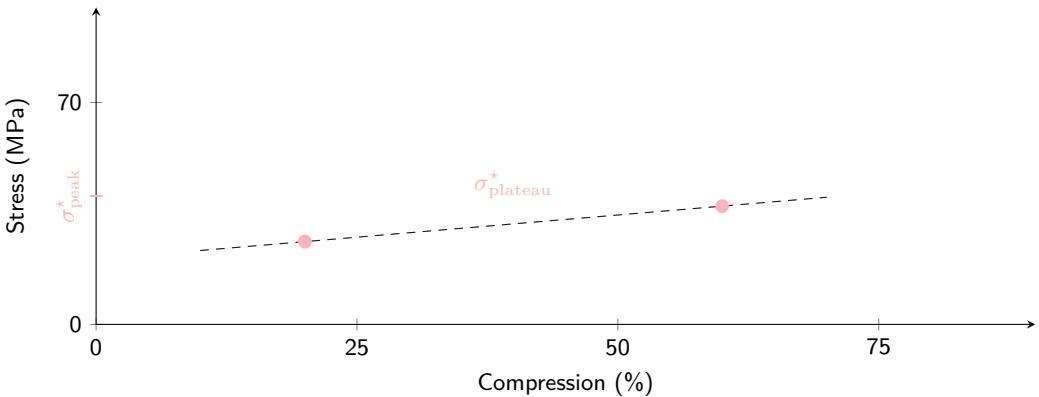
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- Design variables of unit cells as “image”
- Characteristic parameters & strain rate as conditioning



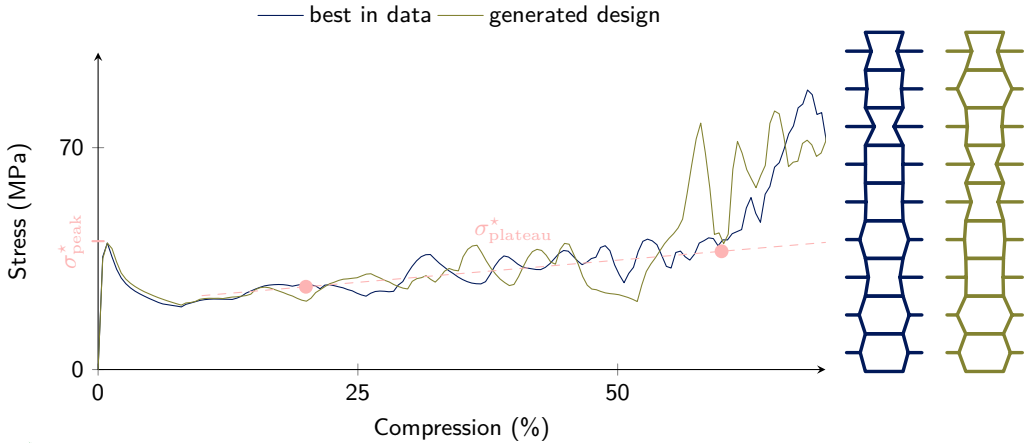
Inverse Design Fits the Given Target

Target: mean values of the data distribution (at $\dot{\varepsilon} = 0\,\mathrm{s}^{-1}$)



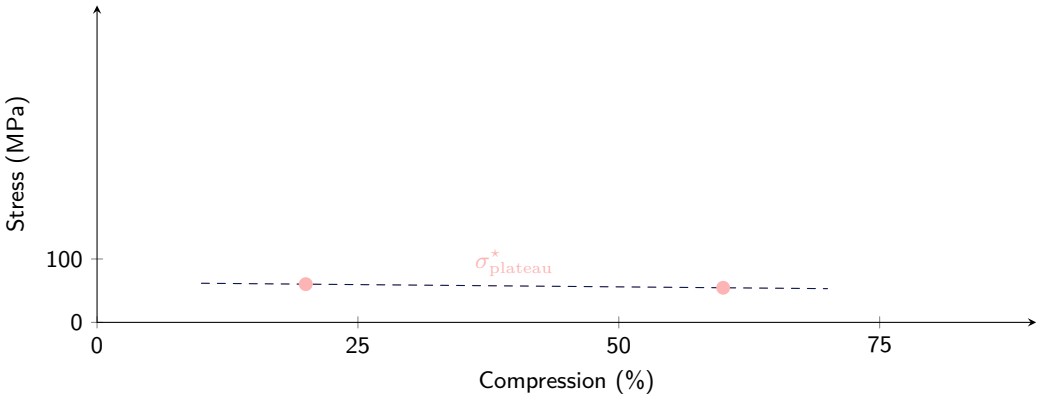
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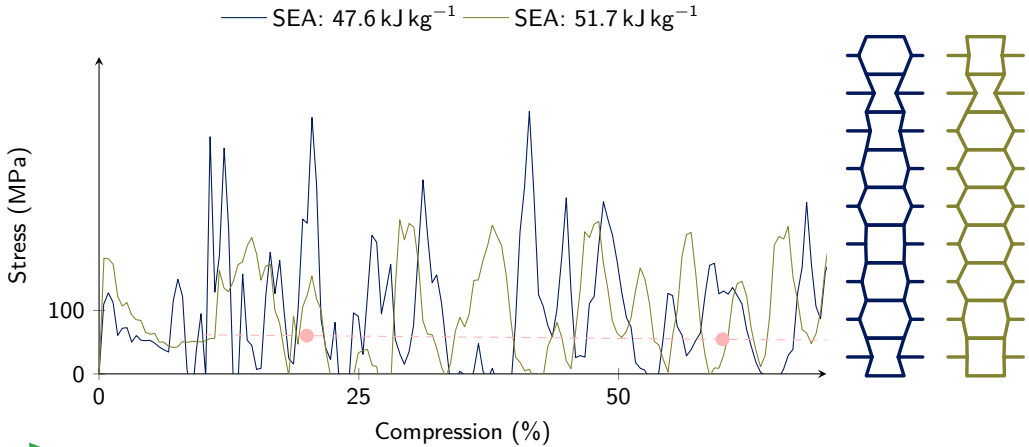
Inverse Design For Better Characteristics

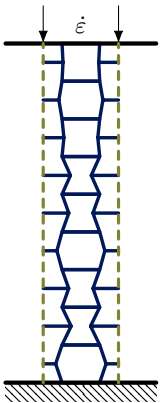
Target: low σ_{plateau}; high SEA (at $\dot{\varepsilon} = 10\,000\,\text{s}^{-1}$)



Inverse Design For Better Characteristics

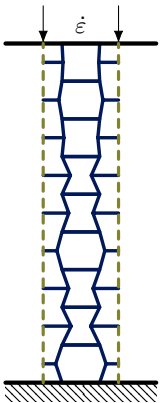
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!! Need for more data to better calibrate the inverse model

– Direct numerical simulation prohibitively expensive

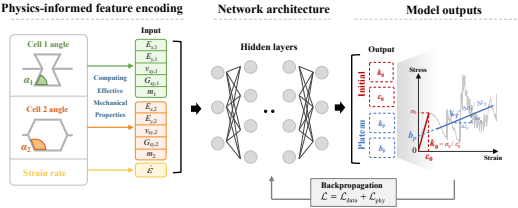


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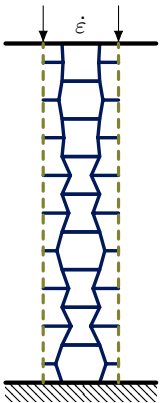
■ Solution:

Surrogate mapping for design variables to characteristic parameters



Wang, Gärtner, Aldakheel *under review*

Design Variables to Characteristic Parameters



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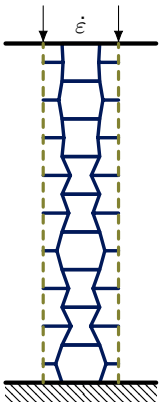
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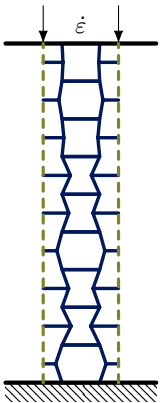
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⇒ Need for more capable models

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⇒ Need for more capable models

- *Enter the attention model*

  everything on the following slides is still work in progress

Capturing of Features by cross-linking all Cells in the Patch

- Inspired by modern transformer architectures:

Capturing of Features by cross-linking all Cells in the Patch

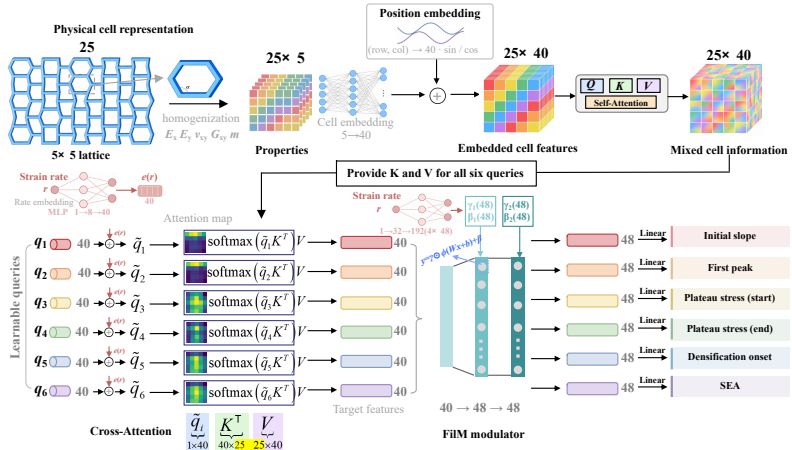
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  - Self-attention between the unit cells inside a patch
  - Positional encoding to regulate the exchanges

Capturing of Features by cross-linking all Cells in the Patch

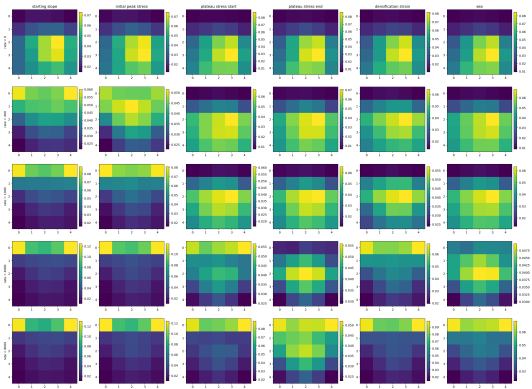
- Inspired by modern transformer architectures:
  - Self-attention between the unit cells inside a patch
  - Positional encoding to regulate the exchanges
  - ‘Cross’-attention between the “geometry”- and “target”-embeddings
- Readout of the attention-maps allows for insight into the behavior of the model

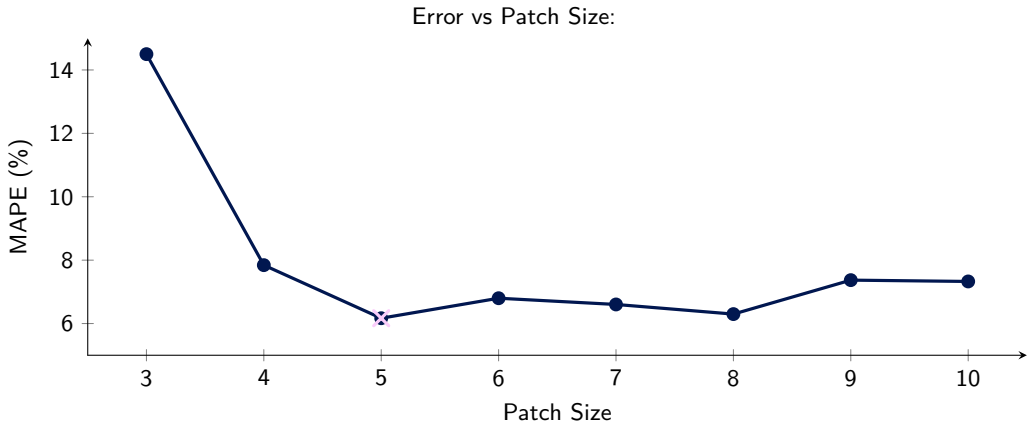
Capturing of Features by cross-linking all Cells in the Patch

- Inspired by modern transformer architectures:
  - Self-attention between the unit cells inside a patch
  - Positional encoding to regulate the exchanges
  - 'Cross'-attention between the "geometry"- and "target"-embeddings
- Readout of the attention-maps allows for insight into the behavior of the model
- Positional encoding allows for training on one 'resolution' and inference on another
- Embedding of physics still work in progress

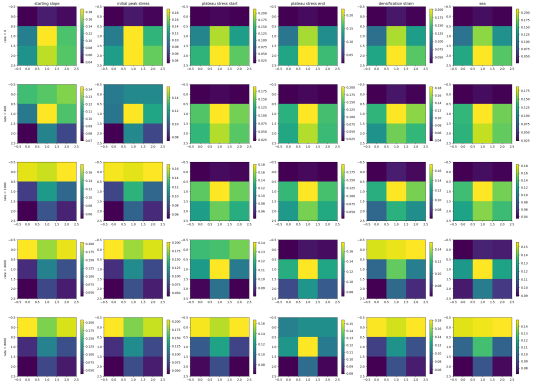

Physical cell representation
25
5× 5 lattice
homogenization
$E_x, E_y, \nu_{xy}, G_{xy}$ m
25× 5
Properties
Position embedding
(row, col) → 40 · sin / cos
Cell embedding
5⟶40
25× 40
Embedded cell features
Q K V
Self-Attention
25× 40
Mixed cell information
Provide K and V for all six queries
Strain rate
r
Rate embedding
MLP 1⟶8⟶40
e(r)
40
Attention map
Learnable queries
q_1 q_2 q_3 q_4 q_5 q_6
softmax $(\tilde{q}_i K^T)V$
Cross-Attention
Strain rate
r
1⟶32⟶192(4× 48)
$\gamma_1(48)$ $\beta_1(48)$
$\gamma_2(48)$ $\beta_2(48)$
$x' = \gamma \odot (Wx + b) + \beta$
40 → 48 → 48
FiLM modulator
Target features
Linear
Initial slope
First peak
Plateau stress (start)
Plateau stress (end)
Densification onset
SEA

5-by-5 unit cells (training):

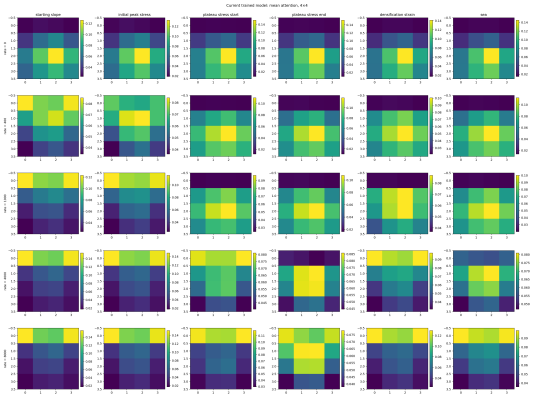



Error vs Patch Size:
MAPE (%)
14
12
10
8
6
3
4
5
6
7
8
9
10
Patch Size

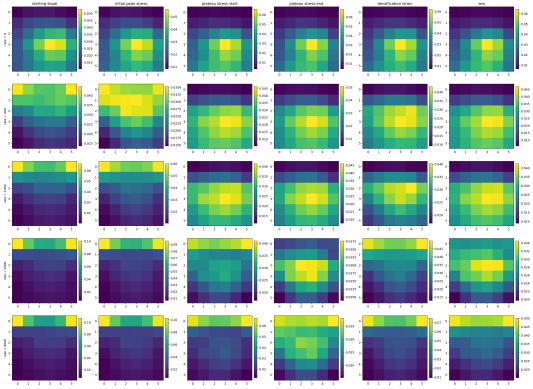
3-by-3 unit cells:



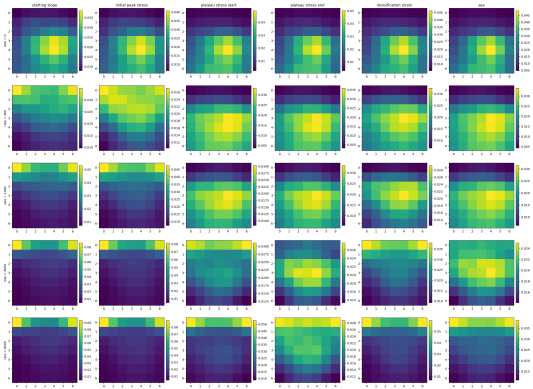
4-by-4 unit cells:



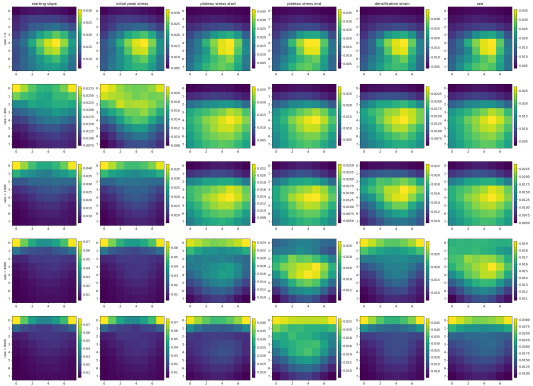
6-by-6 unit cells:



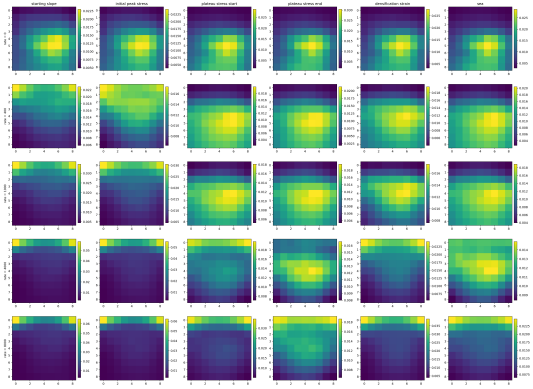
7-by-7 unit cells:



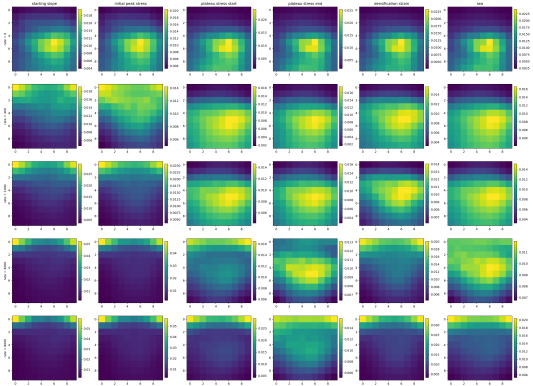
8-by-8 unit cells:



9-by-9 unit cells:



10-by-10 unit cells:



Investigation #4

How to efficiently predict and design
the response of non-uniform lattices?

Modern machine learning methods, enhanced by physical knowledge, enable the quick assessment and targeted design of larger patches consisting of different unit-cells.

Wang, Gärtner, Aldakheel *under review* Wang, Gärtner, Aldakheel *in preparation*

Are Auxetics Better for Protection?

TU Delft

On the Behaviour of Architected Metamaterials under High-Rate Loading Conditions

TNO

Auxetics are *not* Better for Protection.

Are Auxetics Better for Protection?

TU Delft

On the Behaviour of Architected Metamaterials under High-Rate Loading Conditions

TNO

Investigation #1	Investigation #2	Investigation #3
Simulation?	Energy Absorption?	Force Transmission?

Auxetics are *not* Better for Protection.

Are Auxetics Better for Protection?

TUDelft

On the Behaviour of Architected Metamaterials under High-Rate Loading Conditions

TNO

Investigation #1	Investigation #2	Investigation #3
Simulation?	Energy Absorption?	Force Transmission?
Nonlinear beams enable efficient, accurate modeling of architected materials.	**The Poisson effect in itself does not influence the energy absorption capacity of an architected material.**	**A negative Poisson's ratio concentrates the load over a smaller time frame and a narrower zone.**

Auxetics are *not* Better for Protection.

Are Auxetics Better for Protection?

TUDelft

On the Behaviour of Architected Metamaterials under High-Rate Loading Conditions

TNO

Investigation #1

Simulation?

Nonlinear beams enable efficient, accurate modeling of architected materials.

Investigation #2

Energy Absorption?

The Poisson effect in itself does not influence the energy absorption capacity of an architected material.

Investigation #3

Force Transmission?

A negative Poisson's ratio concentrates the load over a smaller time frame and a narrower zone.

Investigation #4

Non-uniform lattice?

Modern machine learning methods for targeted design of larger, heterogenous patches.

Auxetics are *not* Better for Protection.

Force Transmission and the (In)efficacy of Auxetic Metamaterials for Impact Mitigation

SHAPE Seminar Series

10 November 2026

Thank you!

Questions?

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