A multi-stage auxetic metamaterial with enhanced stability and energy absorption for transportation protection

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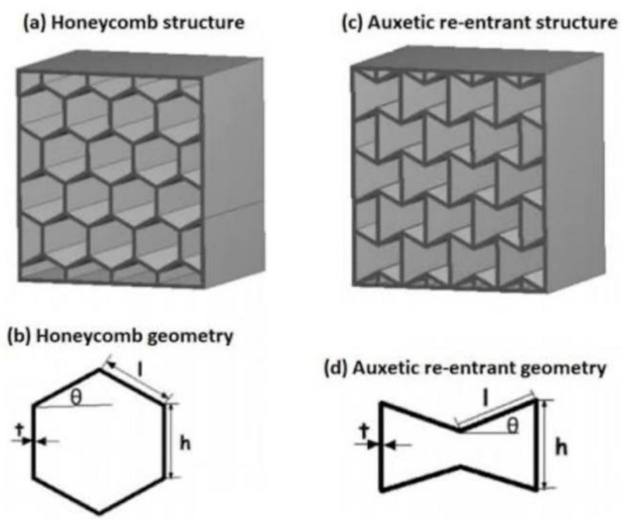
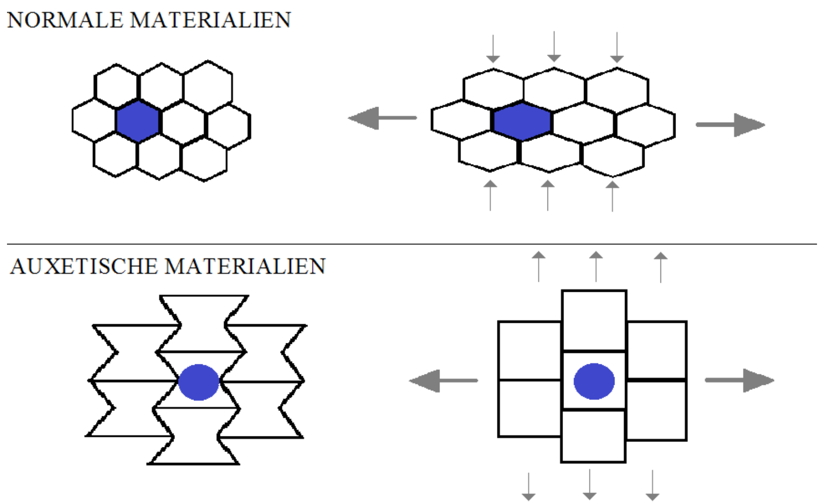
Transportation protection background

- Purpose: Prevent severe highway accidents by absorbing impact energy instead of rigidly stopping vehicles.
- Key Systems:
  - Corrugated beam guardrails – deform to redirect vehicles and dissipate kinetic energy.
  - Honeycomb impact attenuators – crush progressively to reduce collision force and injury.
- Significance: Enhance roadside safety and protect passengers and infrastructure.

Introduction of auxetic metamaterials

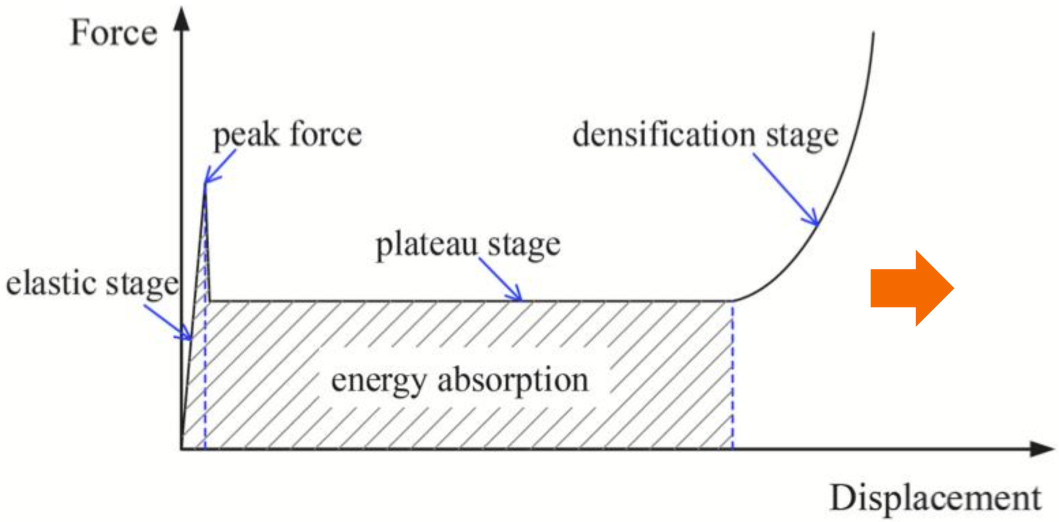
- Derived from re-entrant or modified honeycomb structures that exhibit unusual deformation behavior.
- Negative Poisson's ratio (NPR): when stretched, the material expands laterally instead of contracting.
- Advantages over conventional materials:
    - Enhanced energy absorption and impact resistance
    - Improved shear resistance and indentation toughness
    - Potential for lightweight protective structures





Energy absorption of auxetic materials

- Force-displacement curve of energy absorbing materials in compression.
  - Elastic stage – Elastic and reversible.
  - Plateaus stage – Irreversible plastic deformation.
  - Densification stage – The force rises sharply.
- The energy absorption (EA) is expected to be as large as possible.
- The plateau stage contributes most significantly to the total EA of the structure.



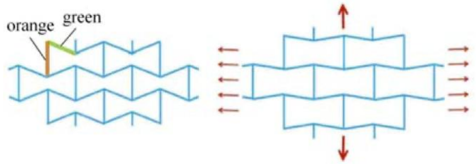
Extend plateau stage

Increase plateau stress / force

Problem 1: low load capacity

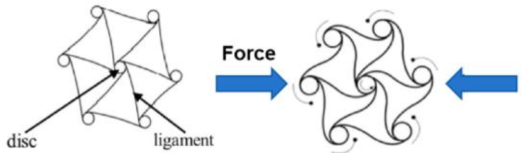
Auxetic materials typically have low load capacity (stiffness/ plateau stress) due to their deformation mechanisms.

Reentrant mechanism



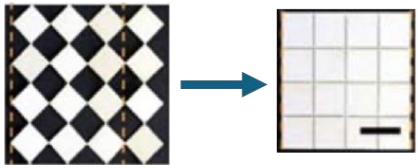
Rotation of inclined struts leads to overall expansion /contraction.

Chiral mechanism



Rotation of rigid discs causes ligaments on the rings to wind or unwind .

Rotating rigid mechanism



Rigid polygons rotate around vertices under load, driving overall expansion/contraction.

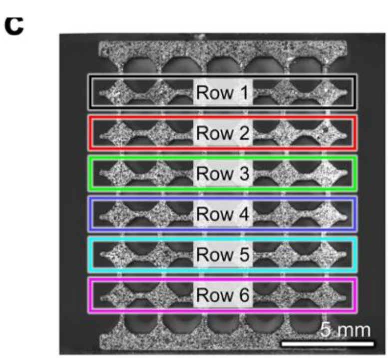
Rely on 'soft' strut bending or joint rotation deformation modes to reach perceptible levels of negative Poisson's ratios (NPR).

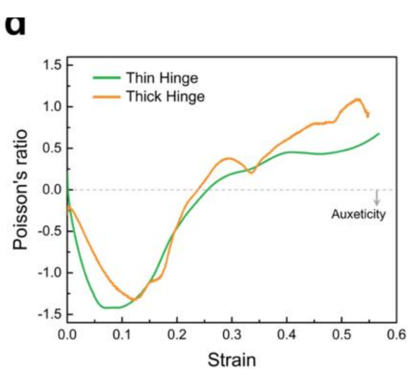
Low specific modulus or poor load bearing capacity, which means low plateau stress /force in the plateau stage.

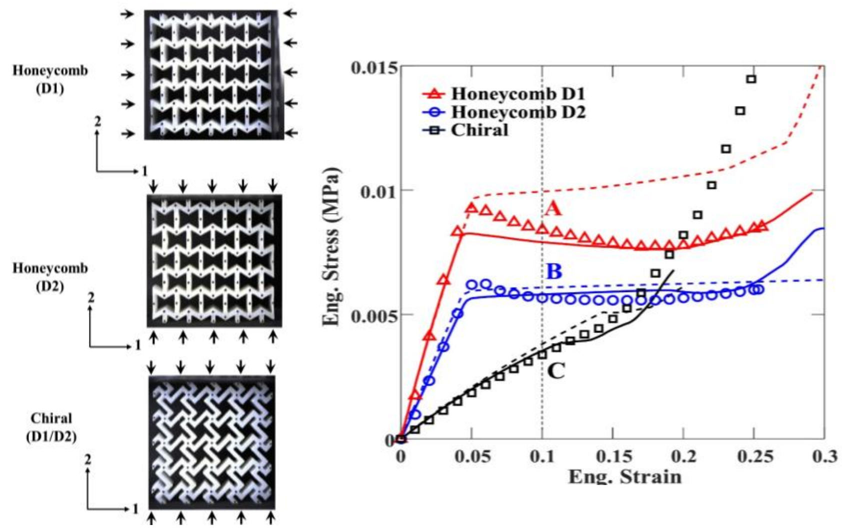
Problem 2: limited effective strain range

Single mechanism auxetic materials usually exhibit limited effective strain range before reaching full densification.

- Single-mechanism auxetic materials can only maintain NPR within a relatively small strain range.
- The strain range of classic single-mechanism model is generally lower than 0.3.
- There remains substantial room for optimization before the design reaches full densification.





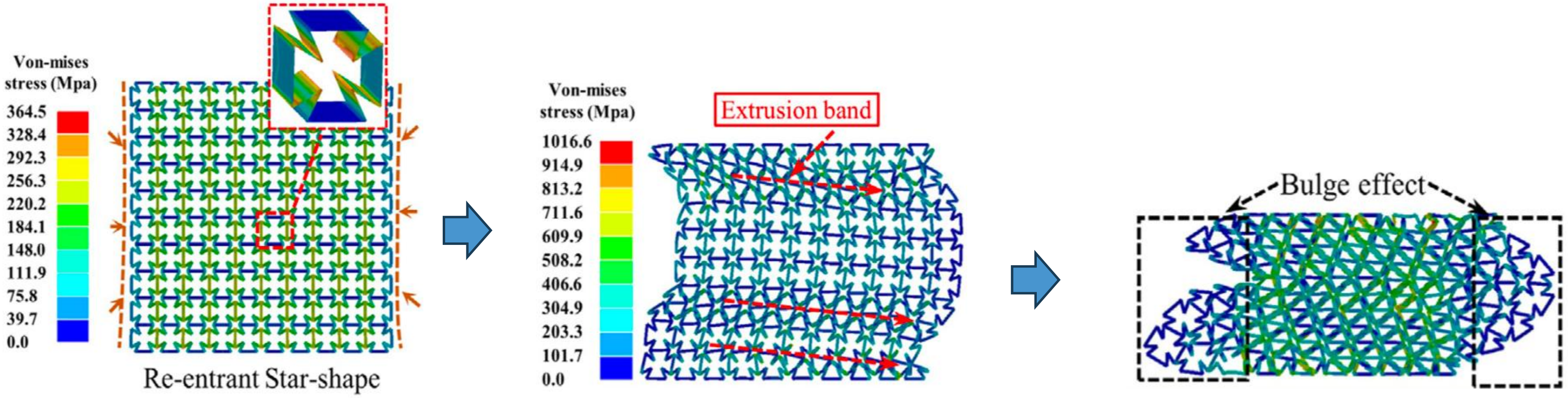


International Journal of Solids and Structures, 162 (2019) 87–95.International Journal of Impact Engineering, 195 (2025) 105128.

Problem 3: stability problem

Auxetic materials, especially reentrant mechanism materials, tend to lose stability in the late deformation stage, causing premature densification and preventing full utilization and participation of all structural components in the materials.

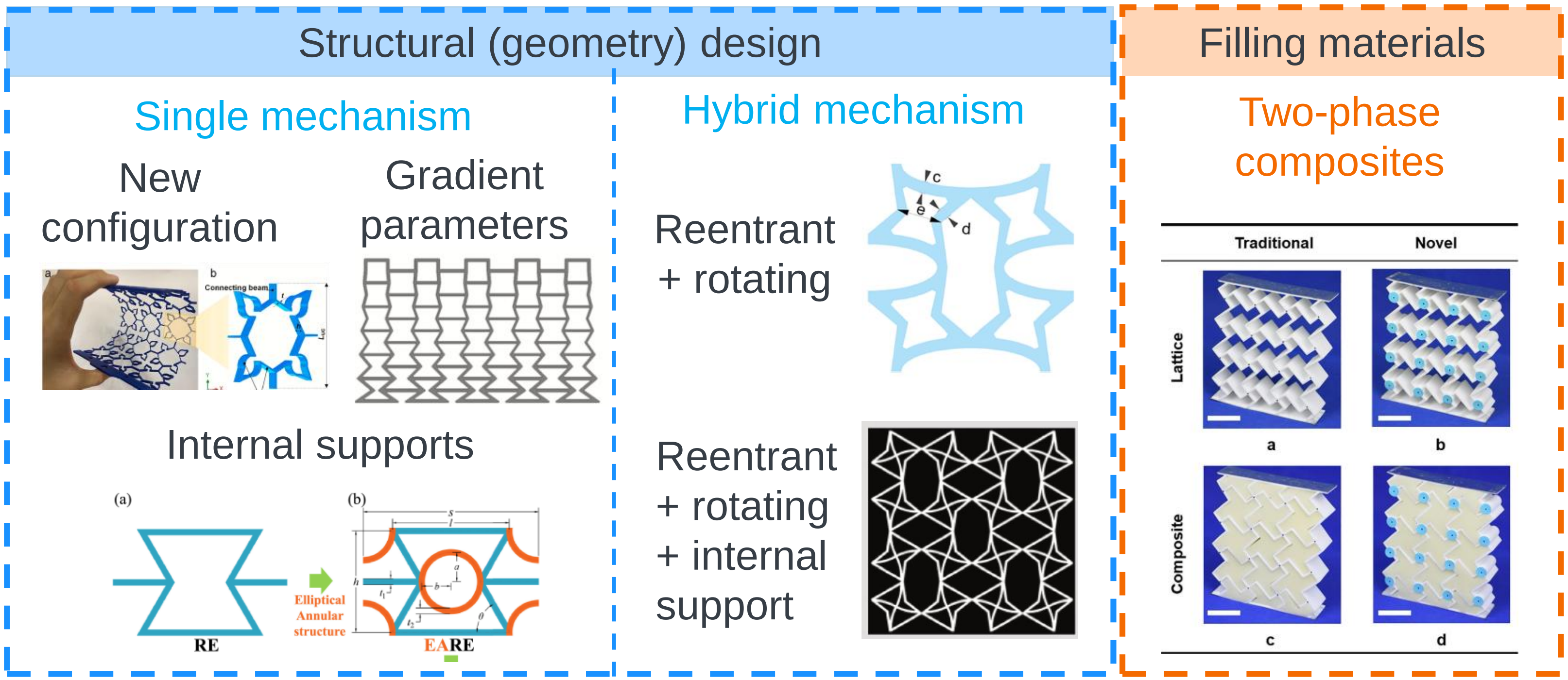
- The design exhibits an overall rightward shift during deformation.
- Deformation process is unstable and uncontrollable.
- In the third image, the “bulge effect” region do not effectively participate in the deformation, resulting in low material utilization.



International Journal of Solids and Structures, 162 (2019) 87–95.International Journal of Impact Engineering, 195 (2025) 105128.

Existing studies for improving auxetic materials performance

- Current efforts to improve the mechanical performance of auxetic materials mainly follow two fundamental approaches: structural-level design and material-level enhancement.

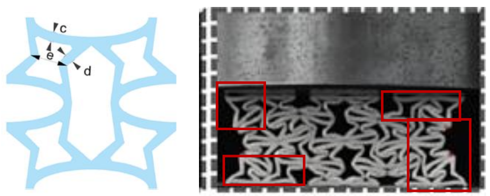


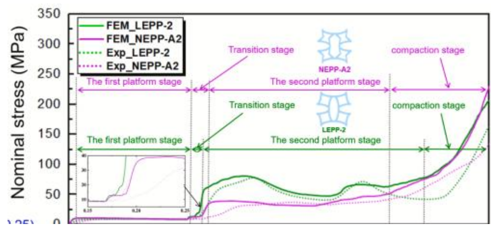
Materials & Design, 241 (2024) 112913.International Journal of Mechanical Sciences, 276 (2024) 109223.International Journal of Mechanical Sciences, 262 (2024) 108732.Composite Structures, 282 (2022) 115043.

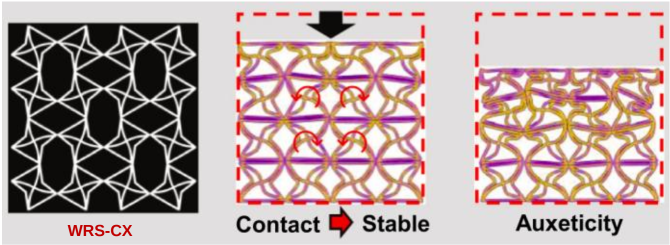
Hybrid mechanism

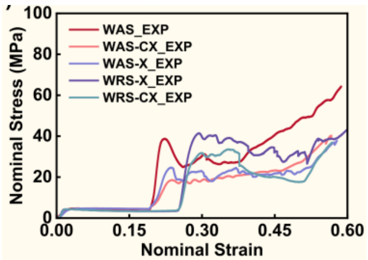
- Hybrid mechanism designs have a significantly higher effective strain range than single designs and have multiple stress platforms.

Reentrant + rotating	Reentrant + rotating + internal support
• Benefit: Two distinct plateau stages are realized, extending the effective deformation range. • Limitation: Instabilities and non-participating regions (**red notes** in the figure)	• Benefit: Stable deformation; extended first plateau (blue). • Limitation: Reduced second plateau stress; lack of parameter specification (e.g., angle, length) for supports design.



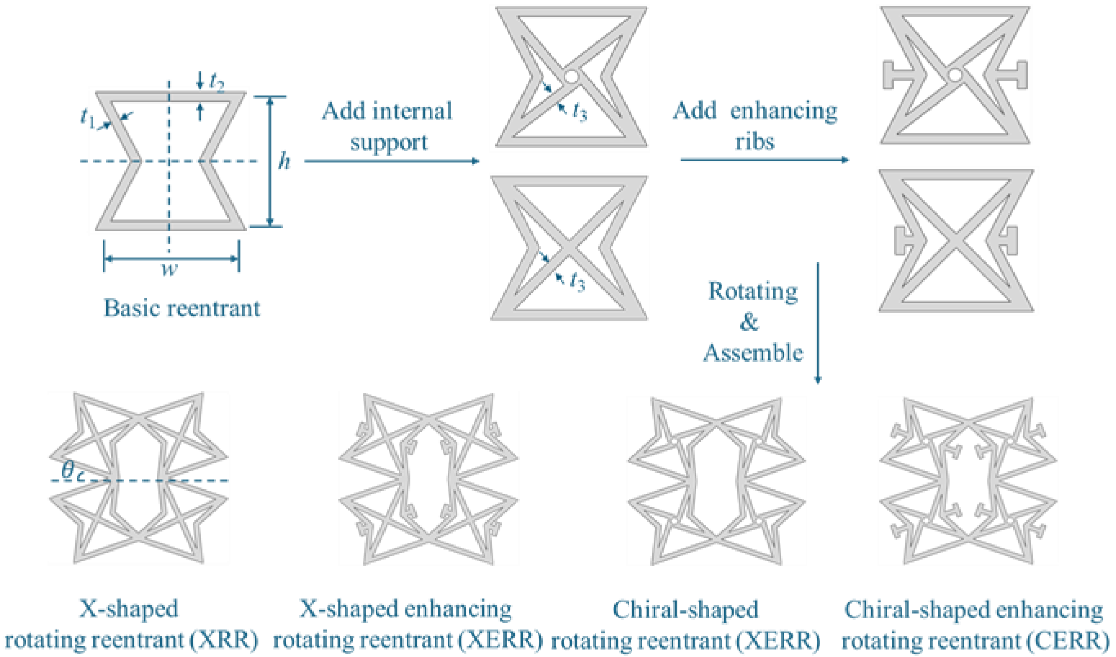






Research objectives

- Designing deformation sequences of auxetic metamaterials through a hybrid mechanism, achieving an extended strain range.
- Strengthening & stabilizing auxetic metamaterials through adding internal and side structs, achieving enhance load bearing capacity and energy absorption ability.



Methods

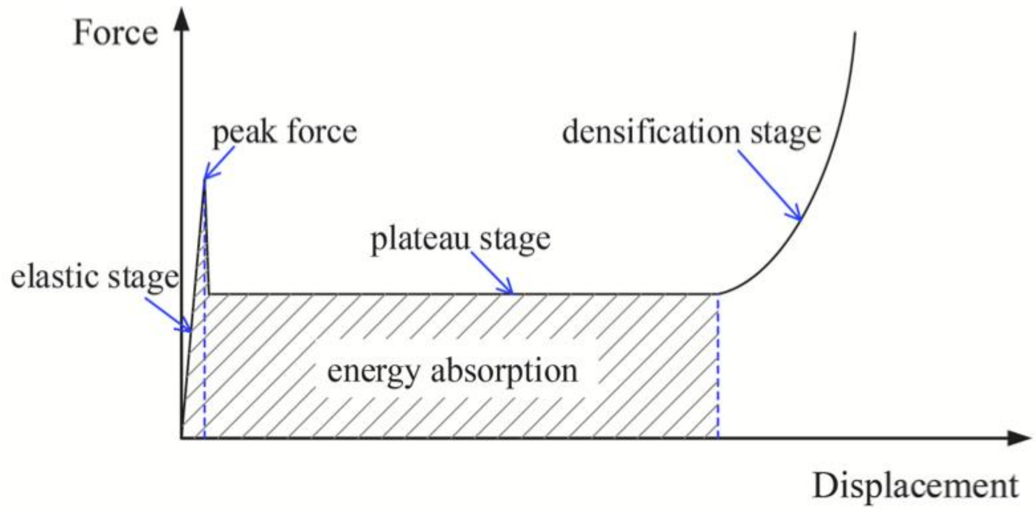
- Finite element analysis: Quasi-static compressive simulations are conducted to obtain the force–displacement relation, damage process, and Poisson's ratio of the auxetic materials.

- Performance metrics

  - Poisson's ratio

$$\nu = -\frac{\varepsilon_{transverse}}{\varepsilon_{axial}}$$

  - Plateau stress σ_{ps}



  - Specified energy absorption (SEA)

$$SEA = \frac{\int_0^{D_a} FdD}{M}$$

$\int_0^{D_a} FdD$: energy absorption (EA)

F: The compressive force.

D: The displacement during compression.

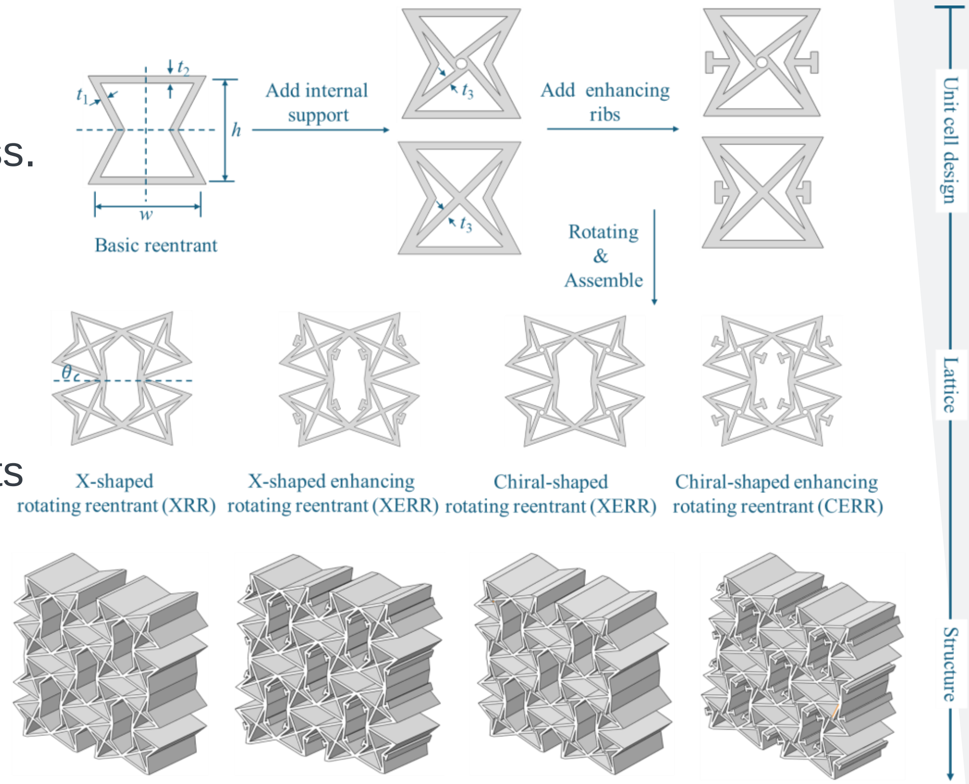
D_a: The maximum displacement at the end of the loading process.

M: The total mass.

Description of the geometrical characteristics

This study proposed a novel chiral + enhancing T-shaped structs auxetic material design (CERR).

- Unit cell design
  - Add internal chiral supports → guide deformation & enhance stiffness.
  - Add side enhancing ribs → suppress uneven deformation & improve load capacity.
- Assemble
  - Unit cells are linked by rotational joints to enable global rotation.
- Comparison models
  - X-shape series XRR & XERR

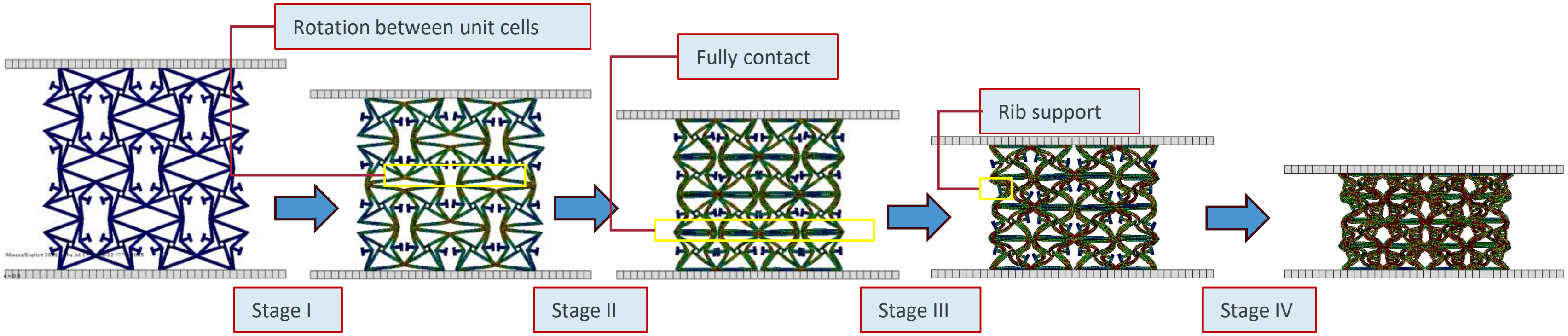


θ	w	h	t_1	t_2	t_3
20°	14 mm	14 mm	1 mm	1 mm	1 mm

Results 1: damage process

A sequential rotation-to-reentrant deformation is successfully realized in the proposed structure .

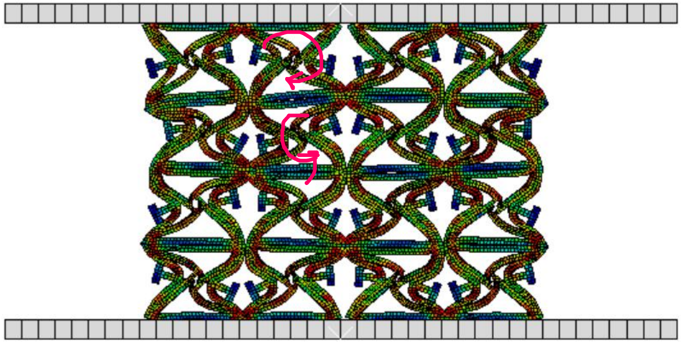
- Stage I – Rotation:
  - Plastic deformation occurs at hinge-like joints between adjacent unit cells.
- Stage II – Coupled rotation & bending:
  - Continued rotation until top and bottom surfaces contact; ligaments start bending.
- Stage III – Reentrant bending & rib support:
  - Ligaments bend while ribs engage to stabilize and resist uneven deformation.
- Stage IV – Densification:
  - Internal voids close; base material dominates the response.



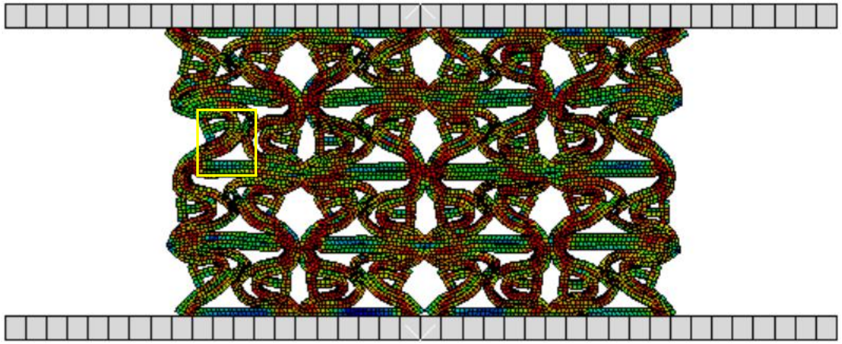
Results 1: damage process

The symmetric and stable deformation of proposed CERR is realized.

- During the large-strain stage, the deformation remains highly symmetric.
- All structural components are uniformly engaged in the deformation process, ensuring an even distribution of internal forces throughout the structure.
- Explanations:
  - Symmetric chiral supports control unit cell deformation by opposing rotation.
  - Ribs engage at large strain to support vertical compression and suppress local asymmetry.



Internal chiral supports symmetric rotation

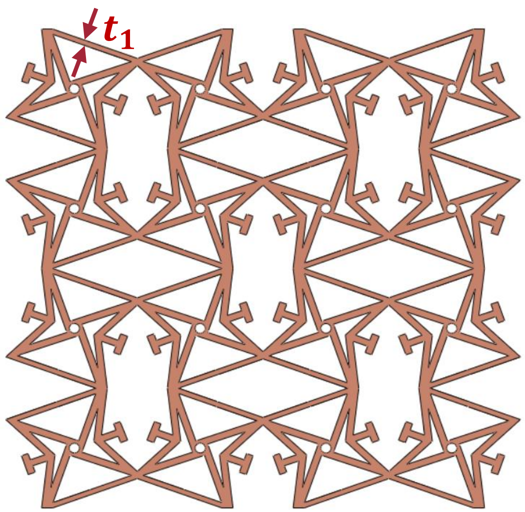


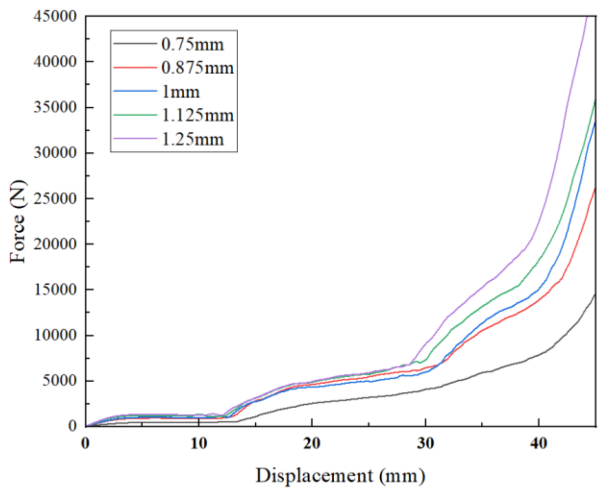
Ribs resist ligaments deformation

Parameter analysis

Thickness: Effect of cell wall thickness at different locations on deformation stages.

- Top/bottom cell wall thickness (t_1)
  - Increasing t_1 enhances the overall stiffness and load-bearing capacity.
  - Increasing t_1 causes the model to enter the next deformation stage earlier.
  - A larger t_1 results in a steeper slope during later second plateau stage, indicating higher late-stage stiffness.

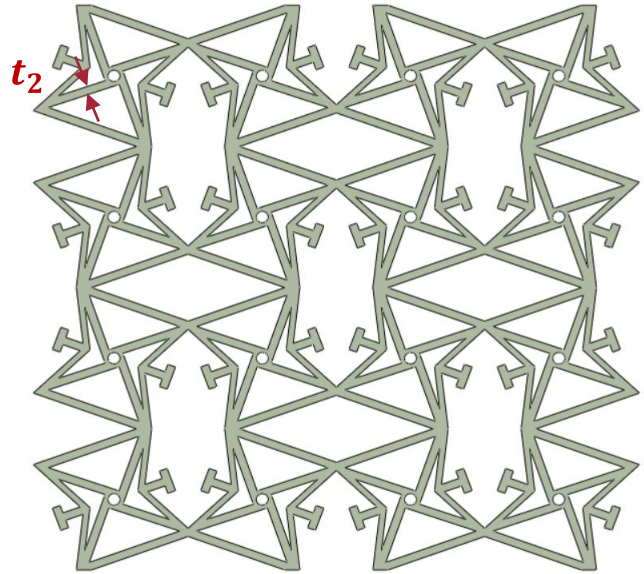


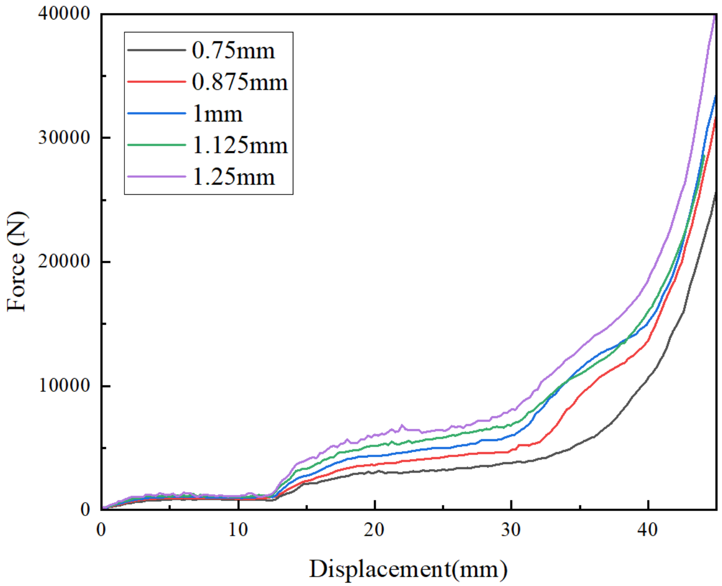


Parameter analysis

Thickness: Effect of cell wall thickness at different locations on deformation stages.

- Internal support wall thickness (t_2)
  - t_2 mainly affects the second deformation stage, with little influence on the first plateau stage.
  - Increasing t_2 enhances the load-bearing capacity in Stage II but causes earlier densification.

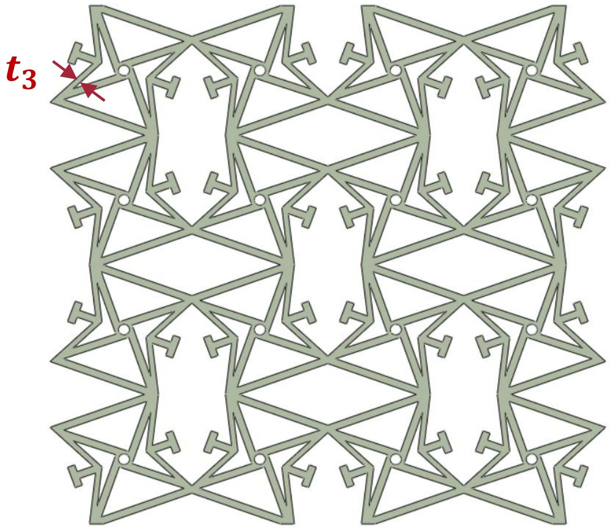


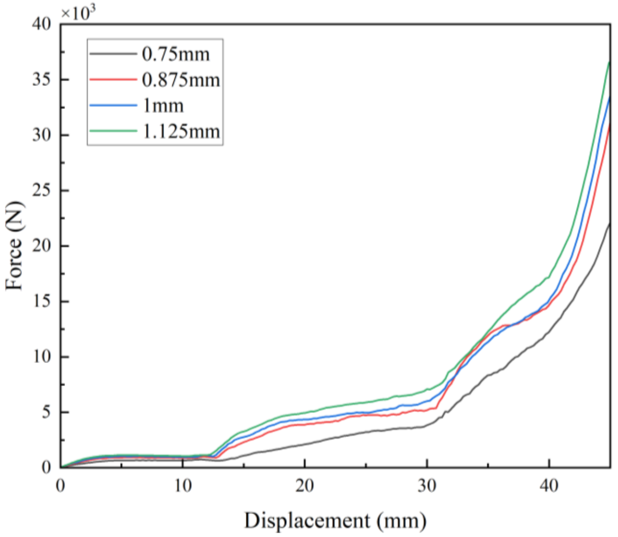


Parameter analysis

Thickness: Effect of cell wall thickness at different locations on deformation stages.

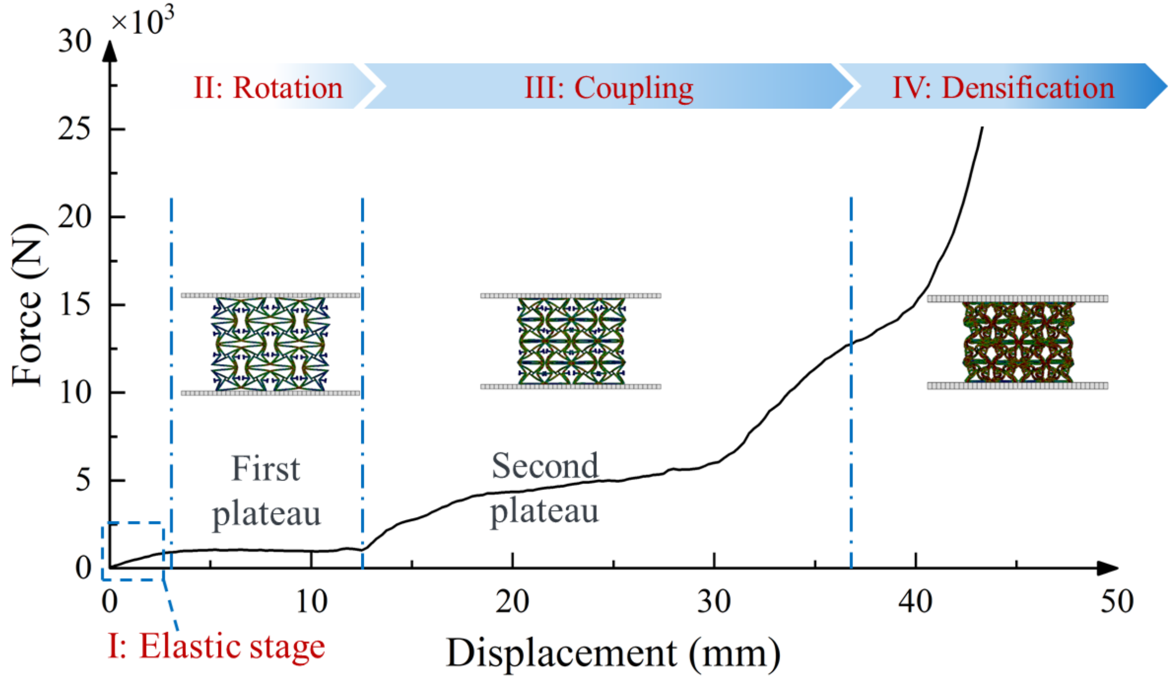
- Side cell wall thickness (t_3)
  - Increasing t_3 enhances the overall load-bearing capacity.
  - The initial deformation stage (before ~10 mm) is almost unaffected by thickness.
  - Thicker side walls lead to a steeper late-stage slope, indicating higher stiffness.
  - Early rotation stage remains nearly unaffected by t_3.





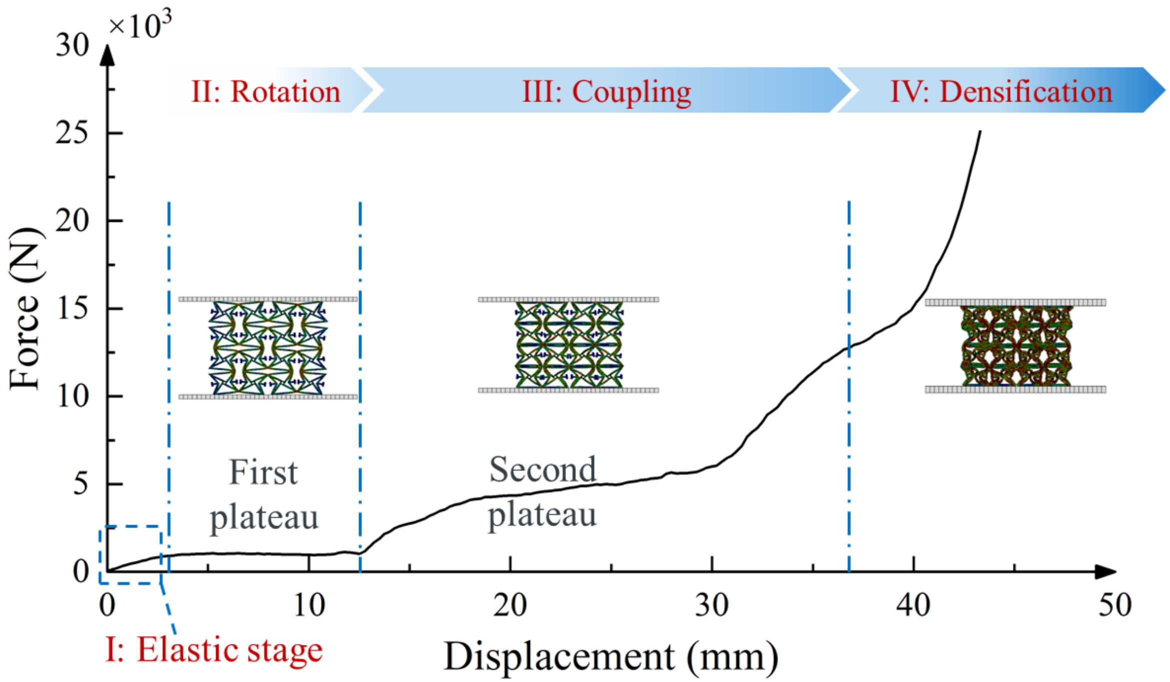
Results 2: force- displacement results

- Double force(stress) plateaus have been achieved due to the hybrid mechanisms.
  - First plateau: Stage Rotation, around 1000N.
  - Second plateau: Stage Coupling, around 5000N.
- In the 30–35 mm range, CERR shows a force increase while maintaining a stable slope, indicating constant stiffness.



Effects of symmetry deformation in Stage III

- Double force(stress) plateaus have been achieved due to the hybrid mechanisms.
  - First plateau: Stage II, around 1000N.
  - Second plateau: Stage III, around 5000N.
- In the late Stage III (30–35 mm range), CERR shows a force increase while maintaining a stable slope, indicating constant stiffness.



Results 3: Poisson's ratio (PR)

Calculating process

$$U_{xi} = (B_i' - A_i') - (B_i - A_i)$$

$$\nu = -\frac{\varepsilon_x}{\varepsilon_y}$$

$$\varepsilon_{xi} = U_{xi}/U_{x0}$$

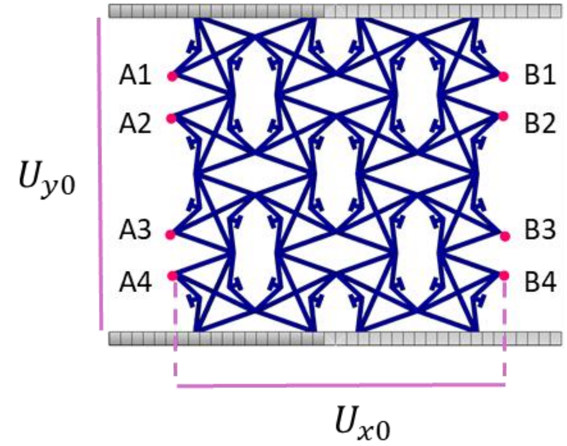
U_{y0}=71.3 mm

$$\varepsilon_x = (\varepsilon_{x1} + \varepsilon_{x2} + \varepsilon_{x3} + \varepsilon_{x4})/4$$

U_{x0}=73.64 mm

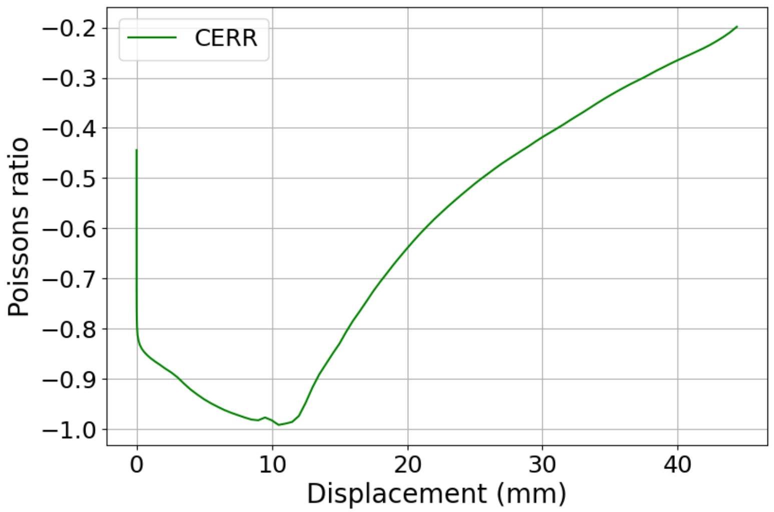
$$\varepsilon_y = displacement/U_{y0}$$

B_i': position after deformation



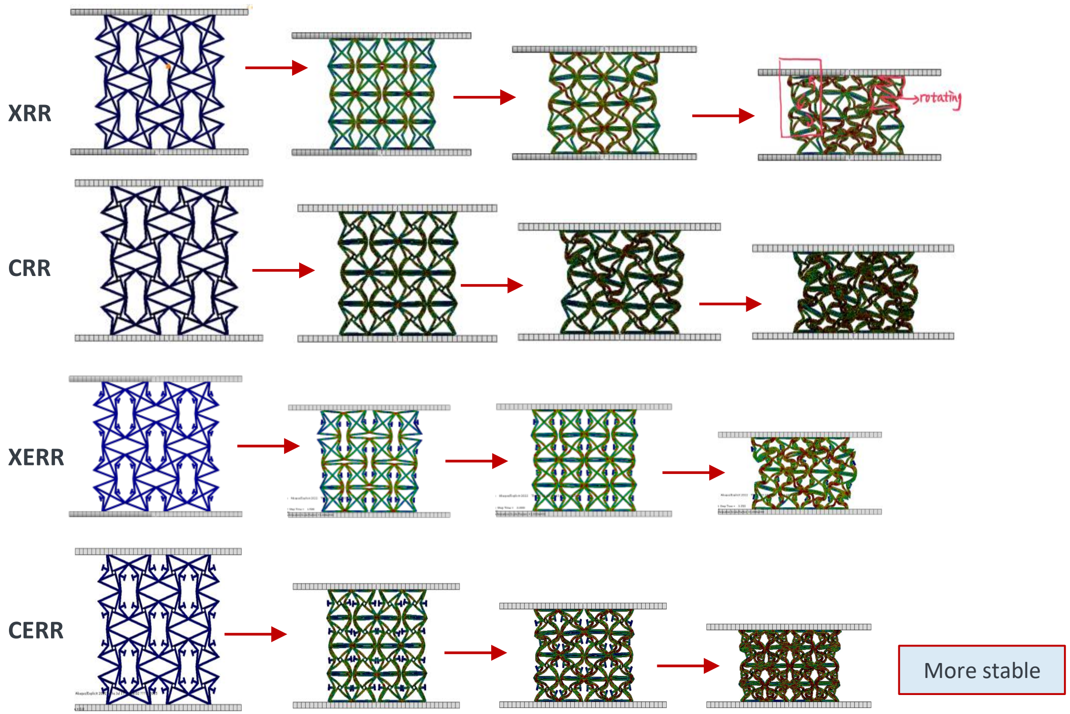
PR – displacement relation

- PR drops to -1 during Rotation stage.
  - Due to the rotation mechanism. Proving AM has obvious NPR effect during rotation mechanism.
- PR begins increase afterwards.
  - Due to the contact of ligaments and ribs limit the deformation.
- NPR effect can be maintained until the densification.



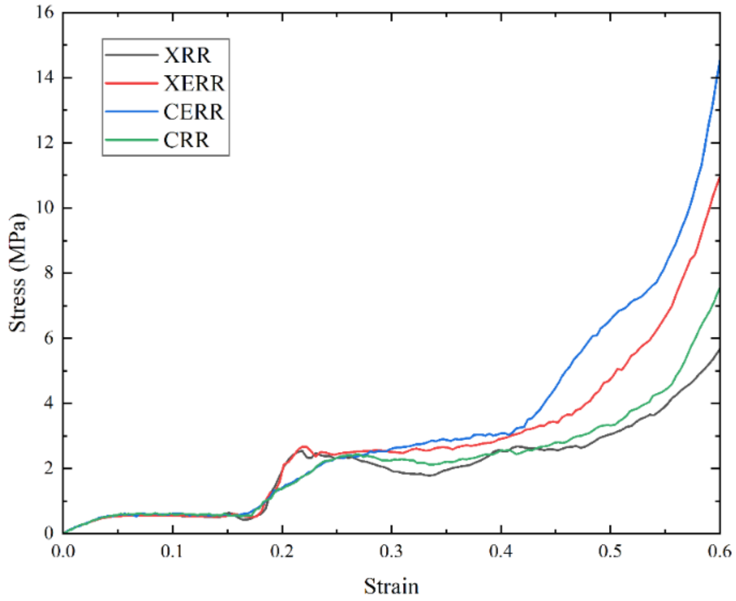
Comparison 1: damage process of four designs

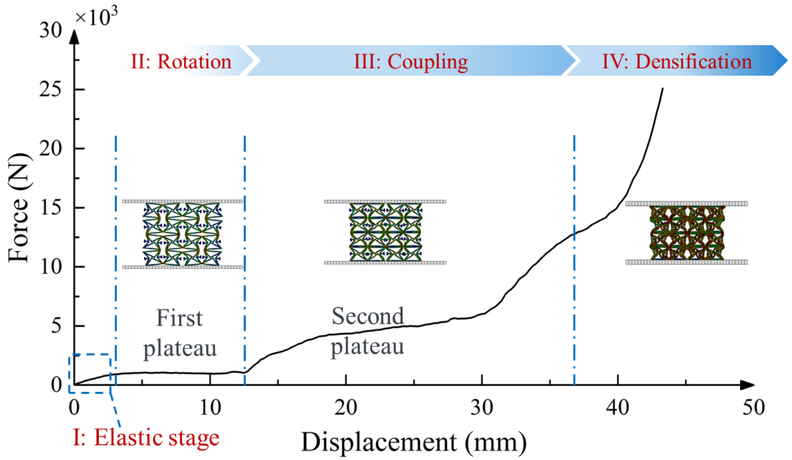
- Internal supports and ribs have little effect on the rotation stage.
  - At Stage I and II (before unit cells fully contact), the deformation process of four models are similar.
- Only CERR can maintain symmetric deformation until large strain stage.
  - Chiral + ribs synergy → stable deformation.



Comparison 2: mechanical properties

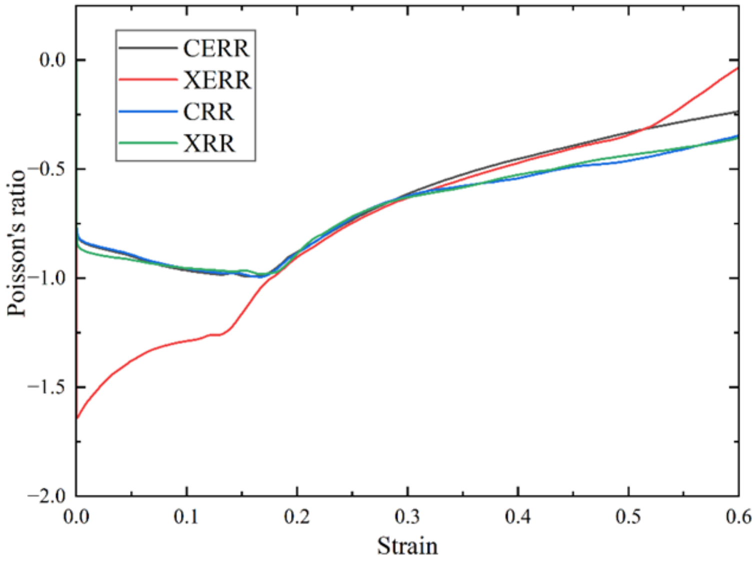
- Stage II- The curves nearly overlap .
  - As the rotation progress is similar (consistent with the deformation patterns shown on the previous page).
- Stage III - The chiral materials (CRR, CERR) exhibits a longer range.
  - Due to its internal support having lower stiffness compared to the X-shaped reinforcement.
- Stage III - The engagement of ribs contributes to an increase in plateau stress.
- Stage III – Only CERR has the effective strength improvement because of the stable deformation.

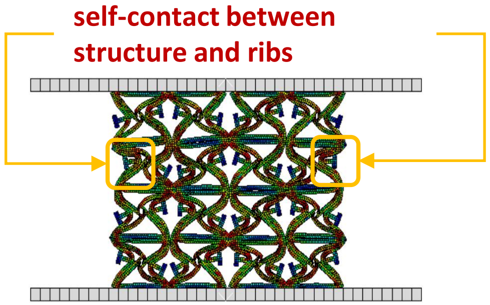




Comparison 3: NPR effect

- The overall trends of NPR are essentially consistent
  - Different deformation mechanisms are the most critical factors affecting the variation in NPR.
- Sharper increases of the NPR curves of both CERR and XERR are observed
  - Indicating that the presence of ribs negatively impacts the NPR effect.

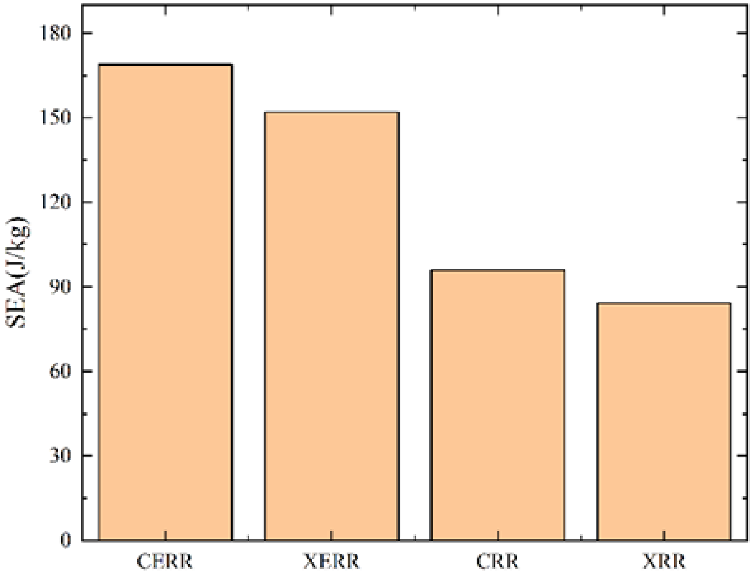




The ribs restrict the bending of the reentrant struts, which negatively affects the NPR performance.

Comparison 4: SEA

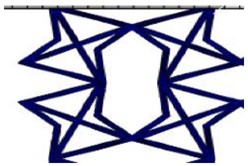
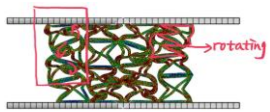
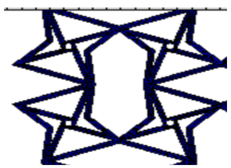
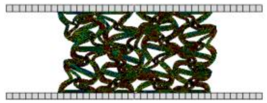
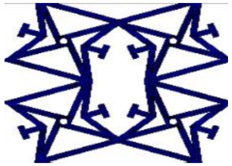
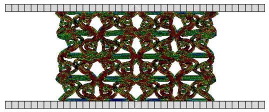
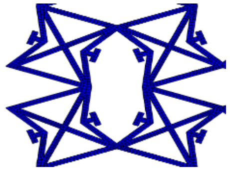
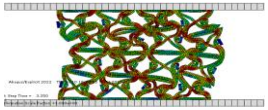
- CERR exhibits the highest SEA among all four designs.
- Compared with the baseline XRR,
  - CERR achieves a 100% improvement,
  - XERR shows an 80% enhancement.
- Under similar configurations,
  - CERR has a 10.5% higher SEA than XERR,
  - CRR shows a 14% increase over XRR.



- Both the T-shaped ribs and chiral features substantially enhance late-stage load-bearing capacity and overall energy absorption efficiency.

Summary comparison

The stable deformation of CERR allows the deign to fully function in the later stage, leading to improved load-bearing performance, structural reliability, and a higher SEA.

	Deformation behavior	First plateau force (max) / N	Second plateau force (max) / N	NPR min value	EA/ J (D_a= 38 mm)	SEA/ (J/g) (D_a= 38 mm)
 XRR		1123.04	4485.45	---	116.23	M=34.11g 3.41
 CRR		1119.92	4519.65	-0.99368	116.01	M=33.7g 3.44
 CERR		1098.49	5637.48	-0.9923	157.11	M=37.73g 4.16
 XERR		1116.4	5637.48	-1.00	140.85	M=37.03g 3.80

Conclusion

- The multi-stage coupled deformation mechanism combining rotating, reentrant, and chiral features can effectively maintain the NPR effect over a strain range of 0-0.56 (40mm/71.3mm=0.56).
- Adding internal supports (X-shape and Chiral-shape) increases stiffness of unit cells and guides the structure to deform in a rotating–reentrant sequence.
- The engagement of enhancing ribs in the later stage of deformation can improve the load-bearing capacity of the structure while suppressing uneven deformation.
- CERR models can greatly enhance the stability of the structure during the later stages of deformation, effectively preventing premature local buckling.

Thank you for your attention!

Questions?

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