负泊松比超材料的研究进展

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提 纲:

一. 介绍负泊松比超材料和超结构

二. 负泊松比超材料与超结构的应用

三. 课题组的相关工作

四. “负泊松比”的研究热度

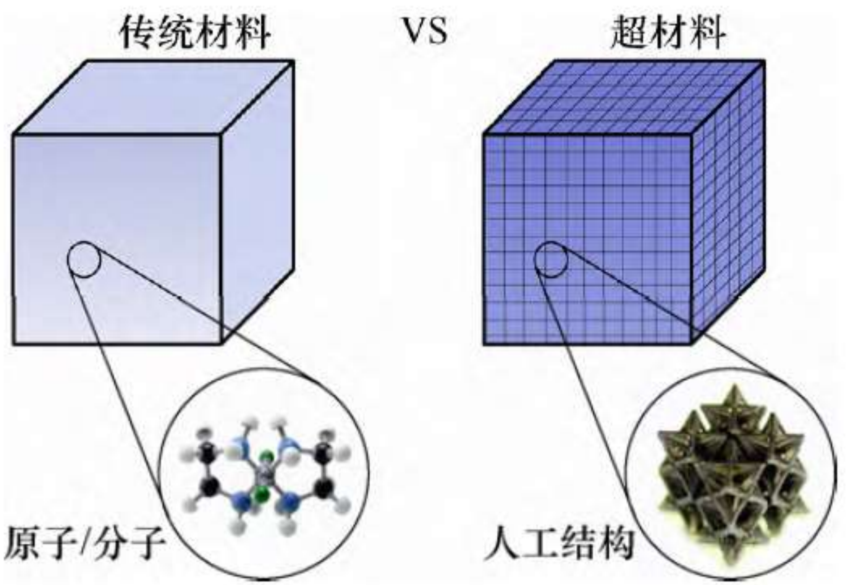
超材料 (Meta-materials)

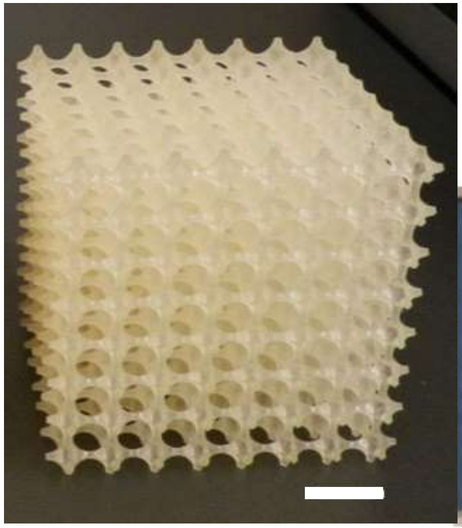
超材料的定义：

由人类创造出来、自然界中不存在、拥有特殊结构、并具有特殊物理特性的材料统称为“超材料”或“超构材料”。

超材料的三个重要特征：

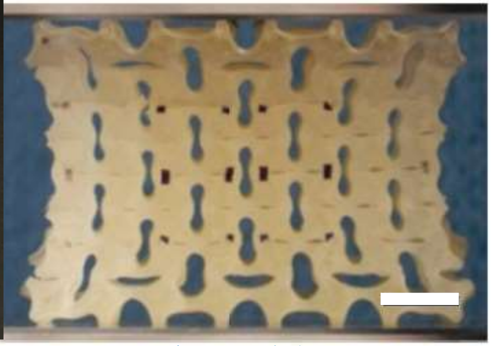
1. 超材料通常是具有新型**人造结构**的材料；
2. 超材料具有**超常的物理性质**（往往是自然界的材料所不具备的）；
3. 超材料**性质**往往不主要取决于构成材料的本征性质，而**取决于其中的人造微结构**。





橡胶

(Scale bar: 20 mm)

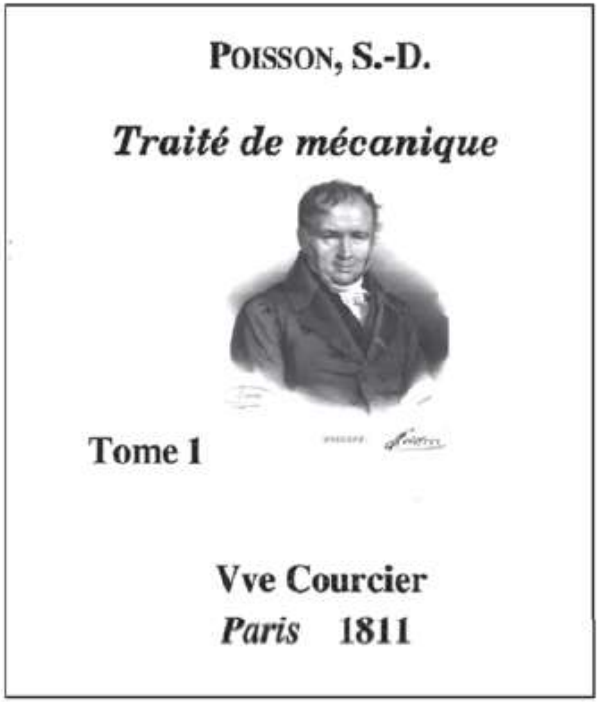


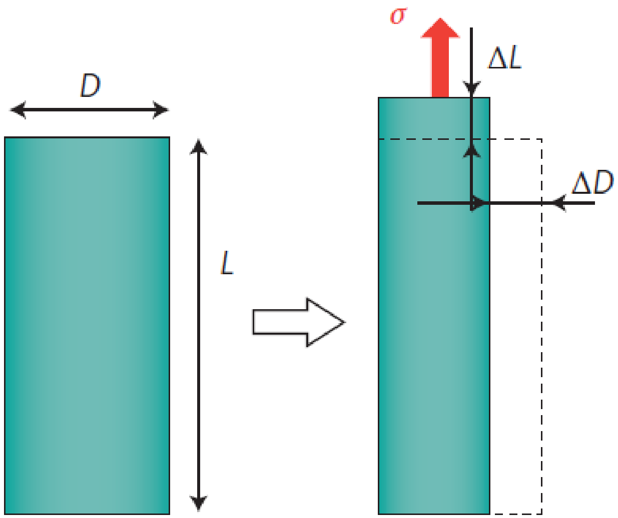
负泊松比

一. 负泊松比超材料和超结构

Introduction

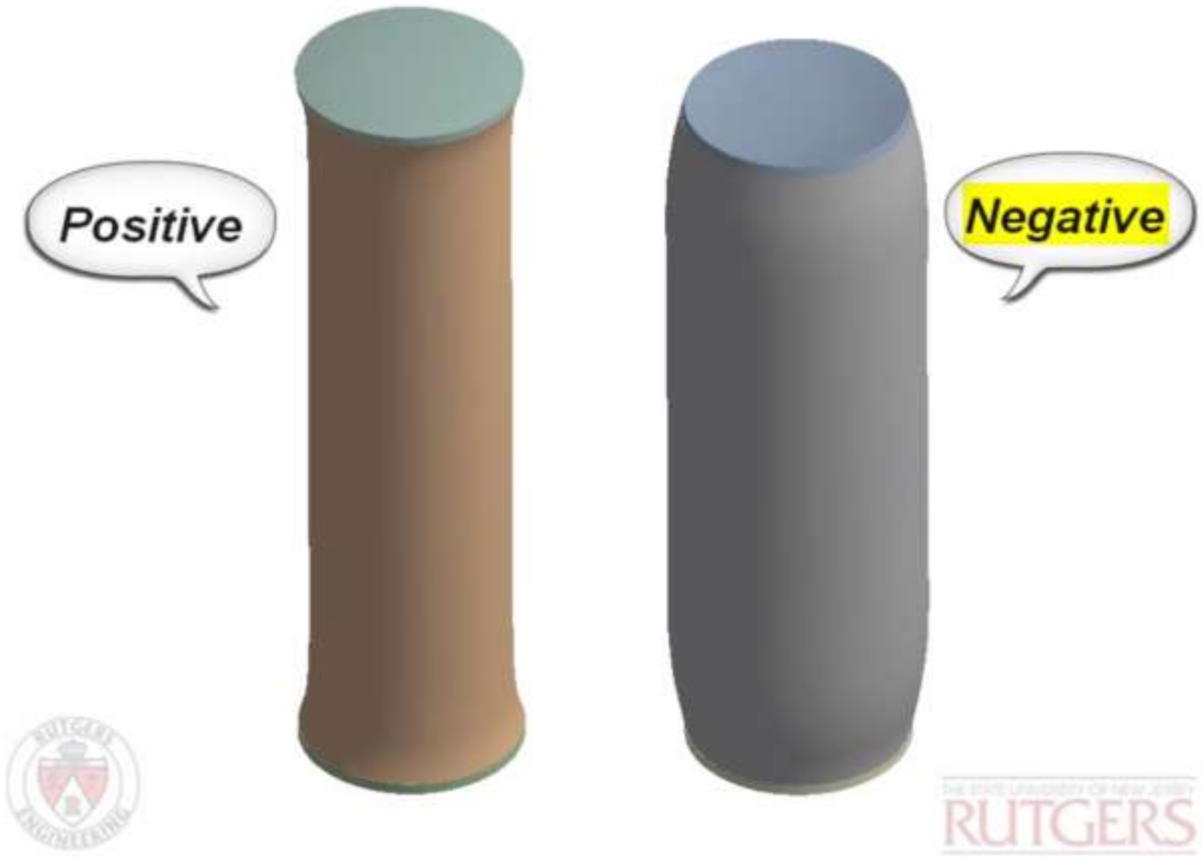
- **Poisson's ratio** **(**v, Siméon Denis Poisson (1787-1840)**)**
- $v = -\frac{e_t}{e_l} = -\left(\frac{\Delta D}{D}\right) / \left(\frac{\Delta L}{L}\right)$
- $v = \left[3\left(\frac{B}{G} - 2\right)\right] / \left[6\left(\frac{B}{G} + 2\right)\right]$
- **(Isotropic material, B 体积模量，G 剪切模量)**
- **For $0 \leq B/G \leq \infty, -1 \leq v \leq 0.5$**





Greaves et al., 2011, *Nature Materials*, Vol. 10, pp. 823-837.

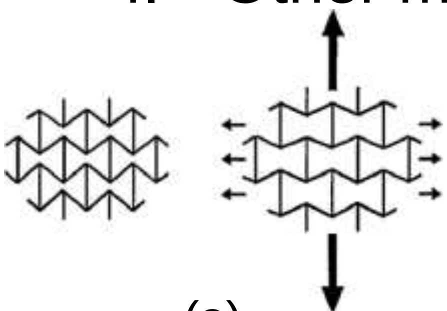
Auxetic (From Greek - auxetikos)



Evans et al., 1991, Molecular Network Design, *Nature*, Vol. 353, pp. 124.

Cellular auxetic materials and structures

a.	Re-entrant models	凹陷状模型
b.	Rotating polygonal models	旋转多边形模型
c.	Chiral models	掌性模型
d.	Crumpled sheets models	褶皱的层状模型
e.	Perforated sheets models	穿孔的板状模型
f.	Other models	其他模型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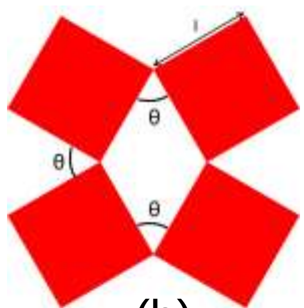

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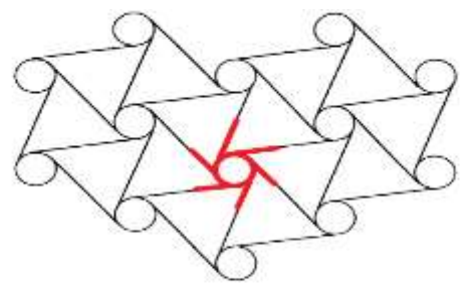
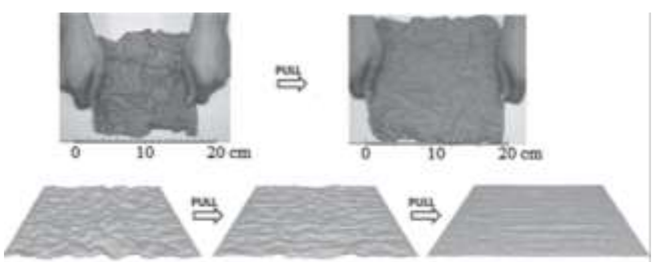
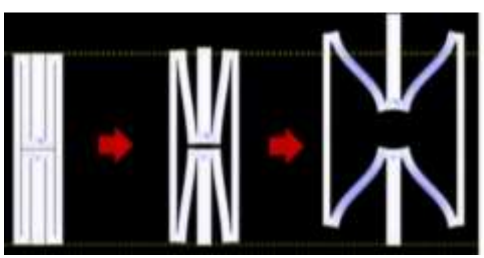

(c)



(d)


(e)

(f)

Xin Ren et al, 2018, *Smart Mater. Struct.* 27, 023001

Properties of auxetics

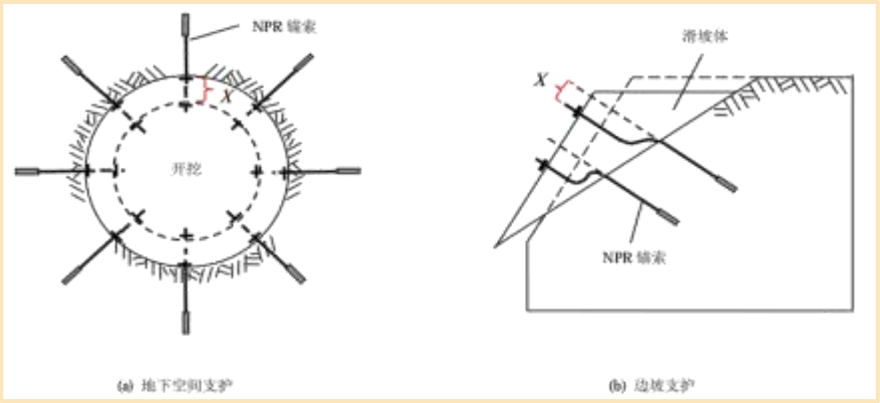
- Shear resistance 抗剪切的性能
- Indentation resistance 抗凹陷的性能
- Fracture resistance 抗断裂的性能
- Synclastic behaviour 曲面同方向的性能
- Variable permeability 多样的渗透性能
- Energy absorption 能量吸收的性能

Xin Ren et al, 2018, *Smart Mater. Struct.* 27, 023001

二. 负泊松比超材料与超结构的应用

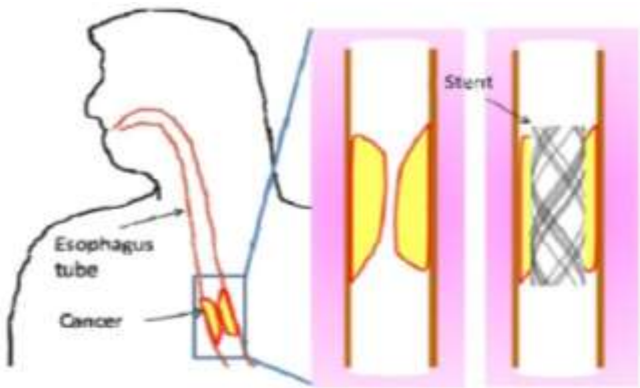
NPR（负泊松比）锚杆

何满潮
中国矿业大学
中国科学院院士



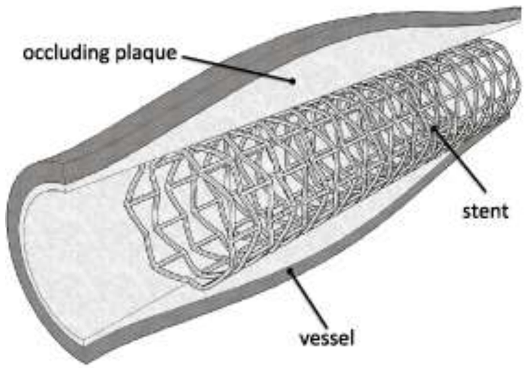
NPR锚杆/索支护原理及大变形控制技术 [J]. *何满潮,李晨,宫伟力,王炯,陶志刚. 岩石力学与工程学报. 2016(08)*

Medical applications 医学上的应用

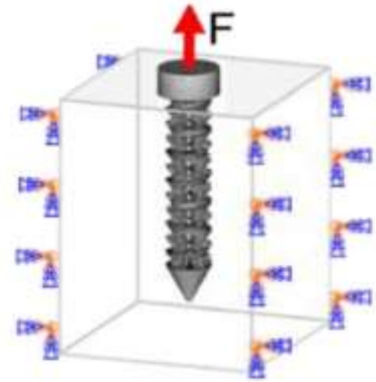


食道支架

Bhullar et al., 2014, *International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering*

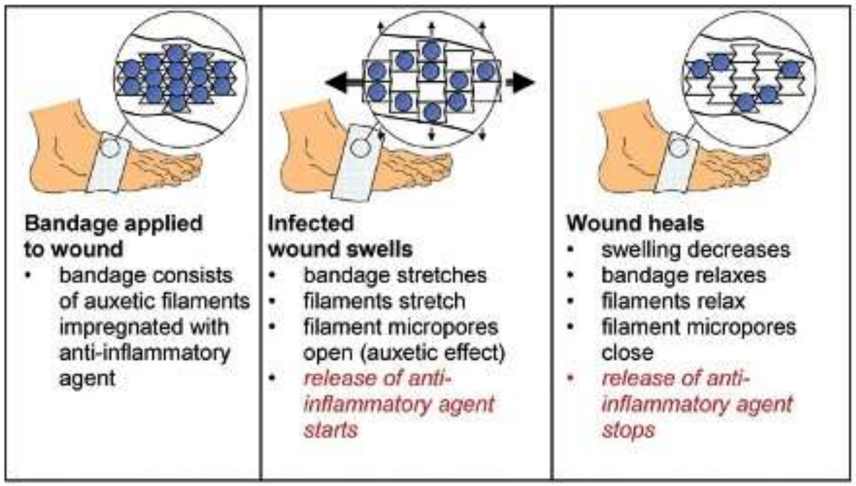


血管支架



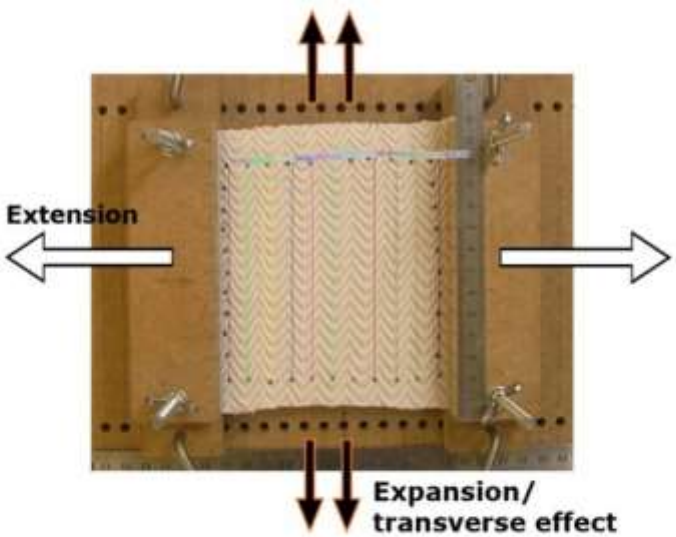
接骨螺钉

Yao et al., 2020, *Mater. Des.*, 188, 108424.

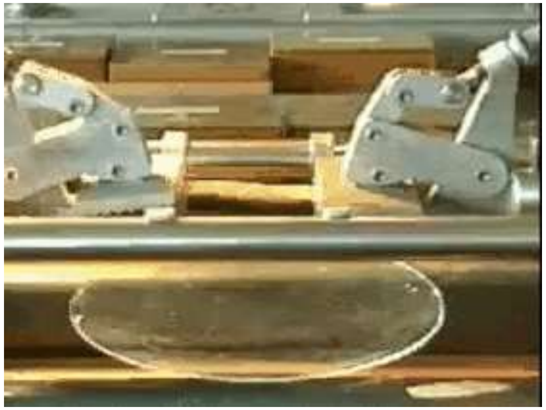


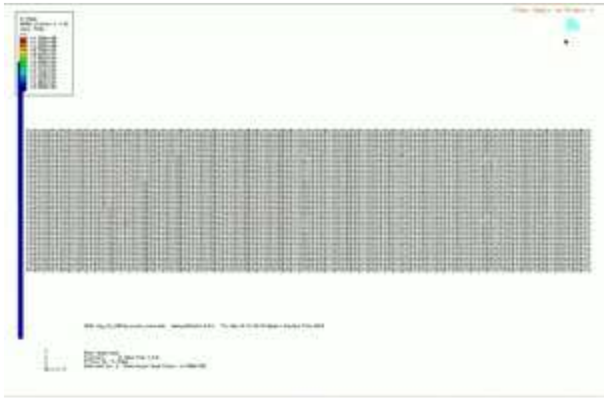
自调节绷带

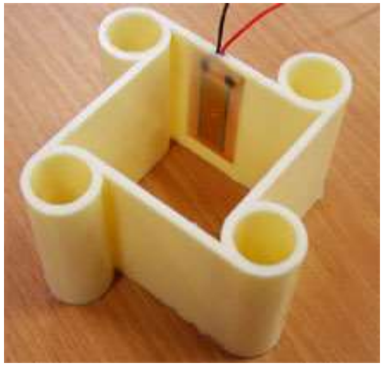
Auxetic textiles 负泊松比织物

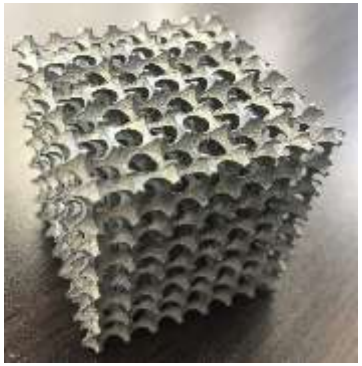


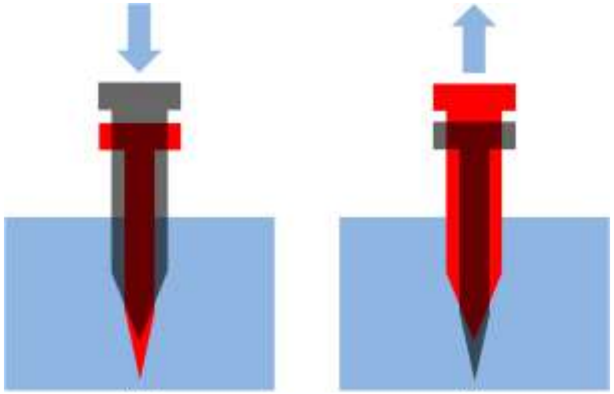
Other applications 其他方面的应用





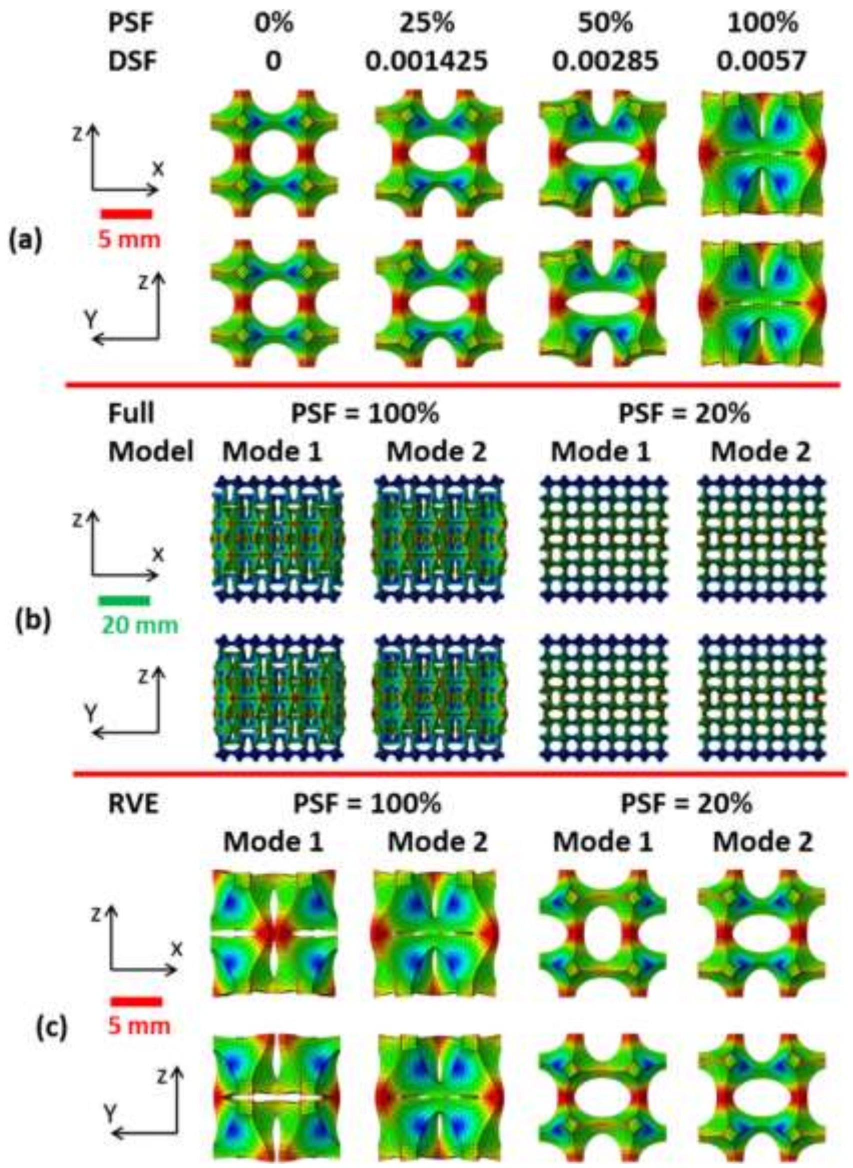


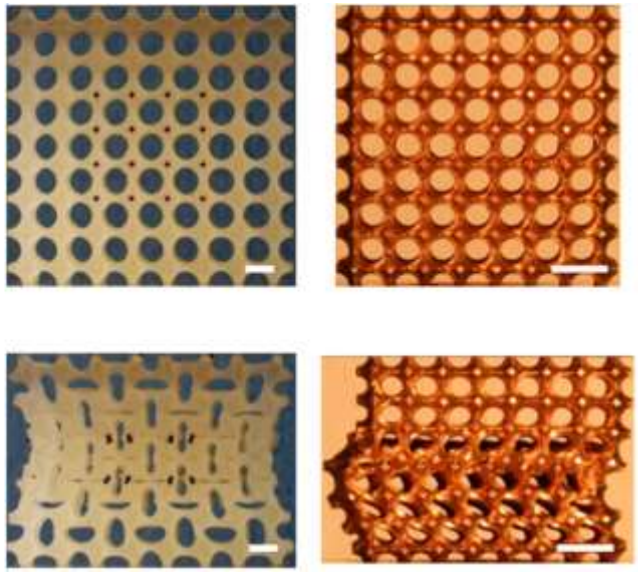




三. 课题组的相关工作

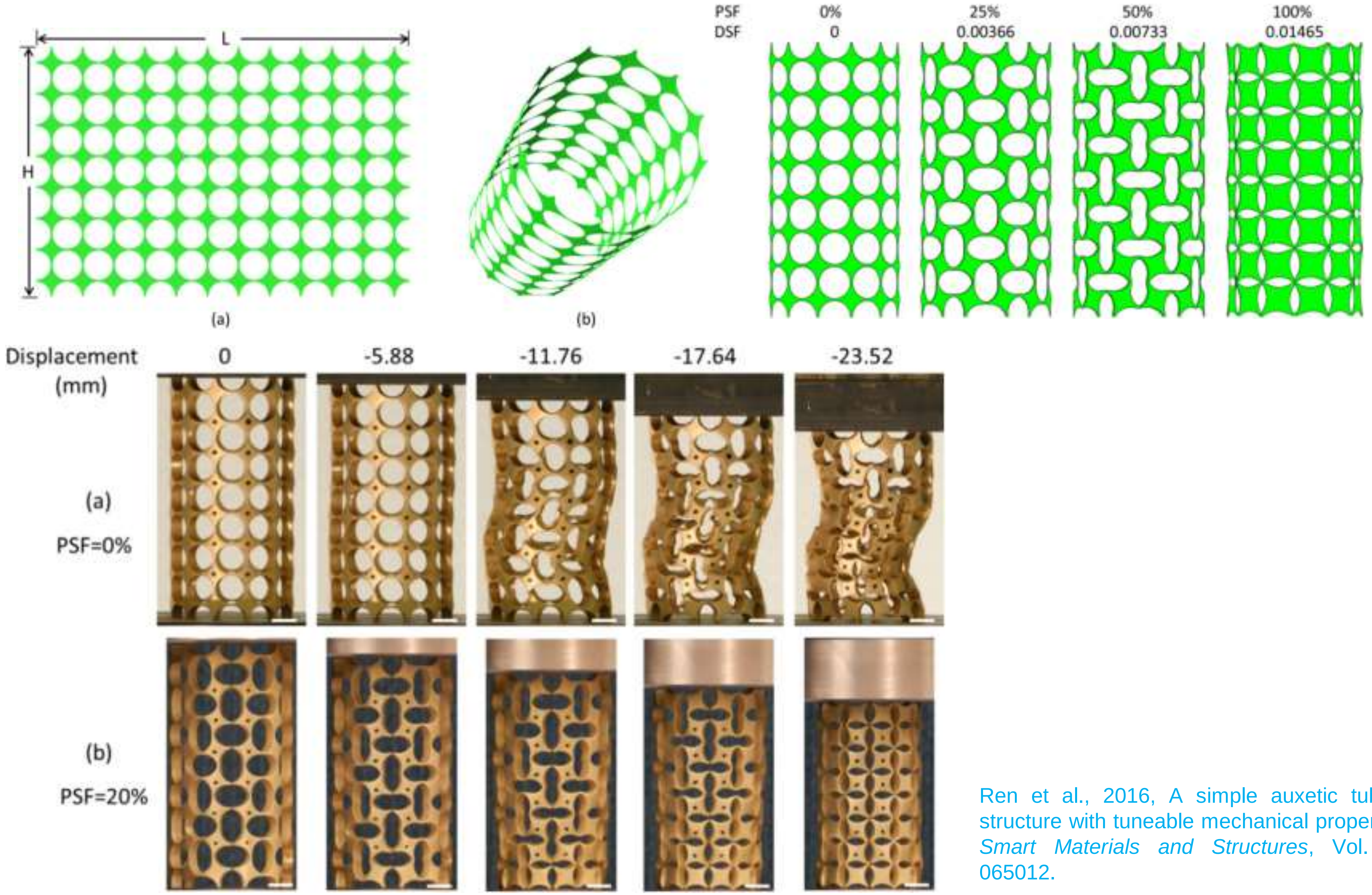
1. 模态比例因子法 Pattern Scale Factor (PSF) Method





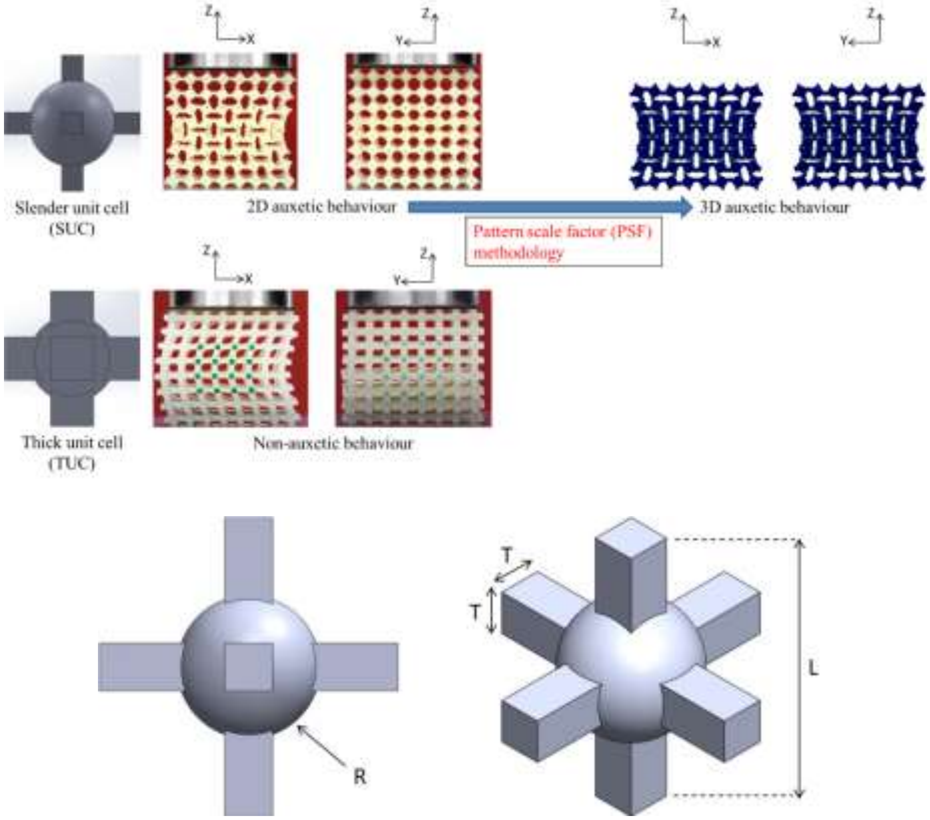
Ren et al., 2015, Experiments and parametric studies on 3D metallic auxetic metamaterials with tuneable mechanical properties. *Smart Materials and Structures*, Vol. 24, 095016.

1. 模态比例因子法 Pattern Scale Factor (PSF) Method

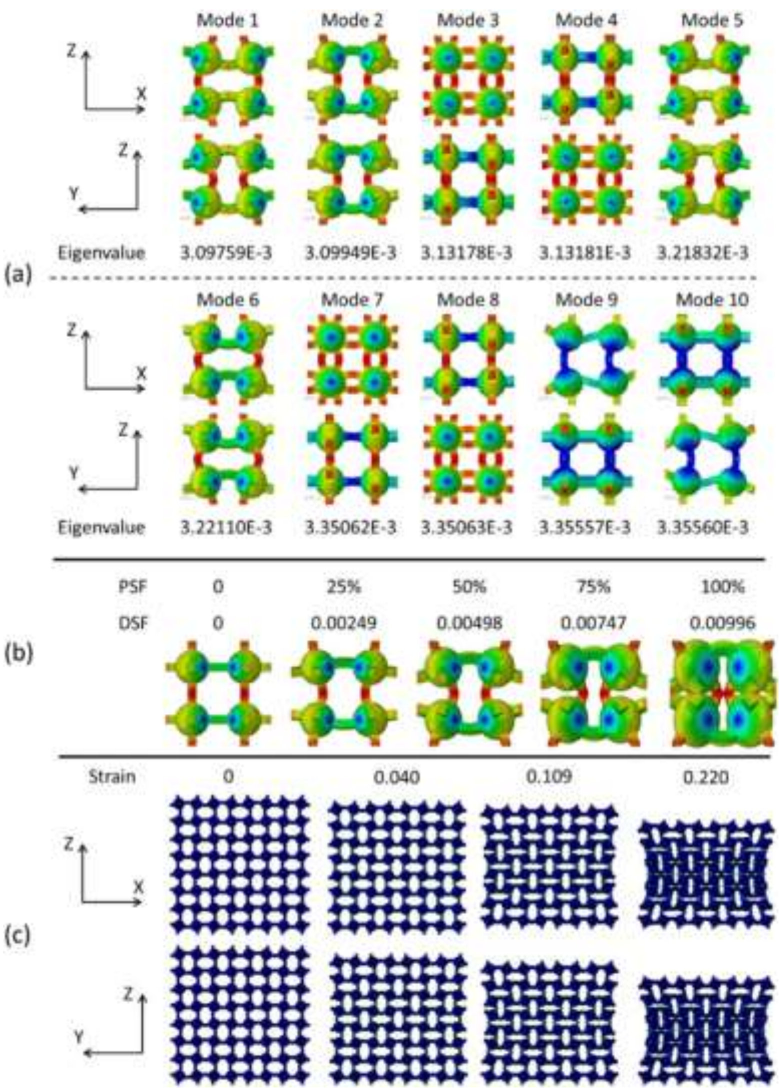


Ren et al., 2016, A simple auxetic tubular structure with tuneable mechanical properties. *Smart Materials and Structures*, Vol. 25, 065012.

模态比例因子法Pattern Scale Factor（PSF）Method的**推广**——将二维负泊松比（拉胀）效应转化为三维

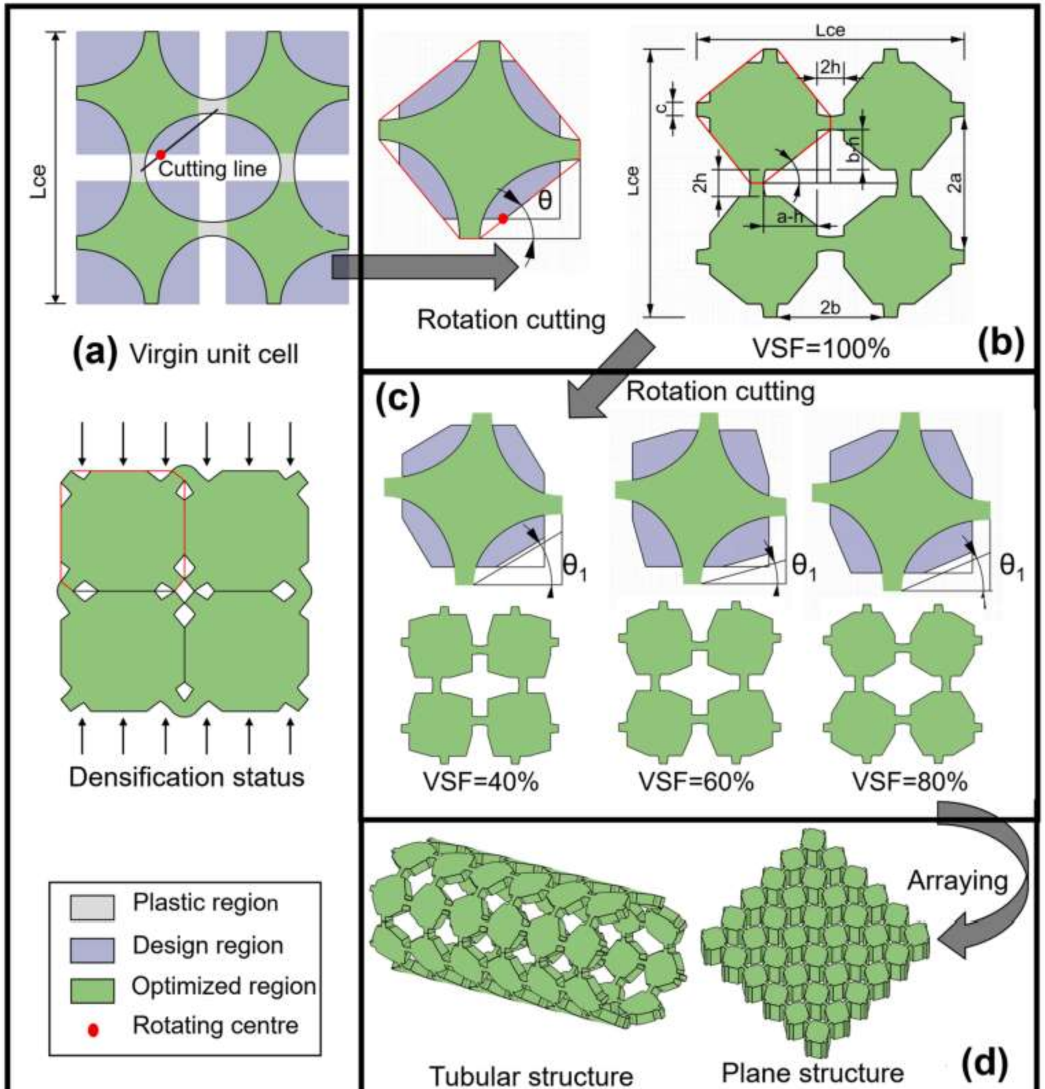


Ren et al., 2018, Design and characterisation of a tuneable 3D buckling-induced auxetic metamaterial. *Materials and Design*, Vol. 139, pp. 336–342



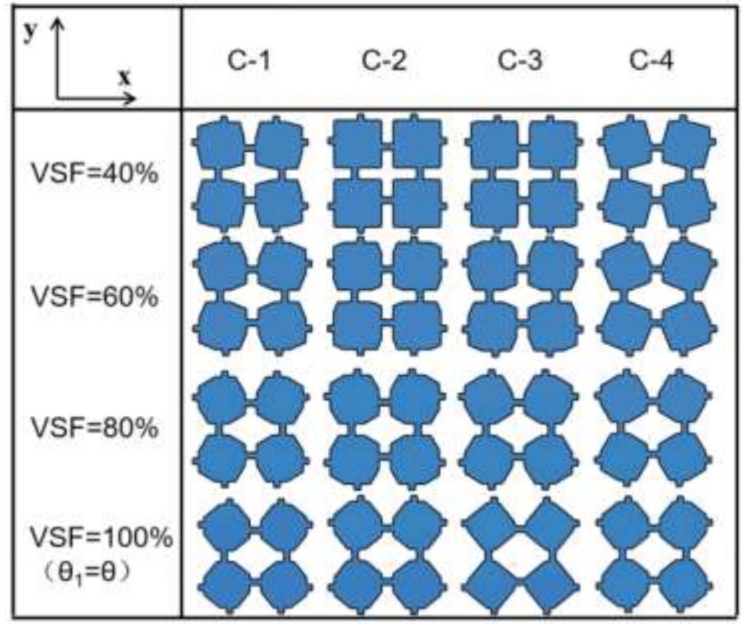
Ren et al., 2018, Design and characterisation of a tuneable 3D buckling-induced auxetic metamaterial. *Materials and Design*, Vol. 139, pp. 336–342.

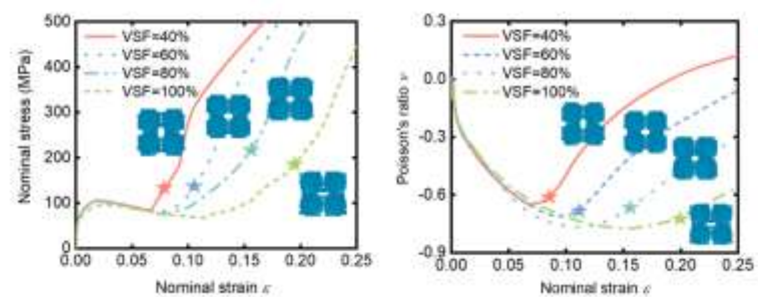
2. 可变刚度比例因子法 Variable Stiffness Factor (VSF) Method



Zhang et al., 2022, Static and dynamic properties of a perforated metallic auxetic metamaterial with tunable stiffness and energy absorption. *International Journal of Impact Engineering* , Vol. 164, 104193.

利用单一参数精准调控超材料在变形过程中的刚度值

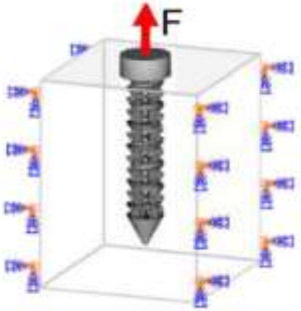




Zhang et al., 2022, Design and analysis of an auxetic metamaterial with tuneable stiffness. *Composite Structures*, Vol. 281, 114997.

3. Auxetic nails 负泊松比钉子

设计、制造并研究了第一个具有负泊松比效应的钉子

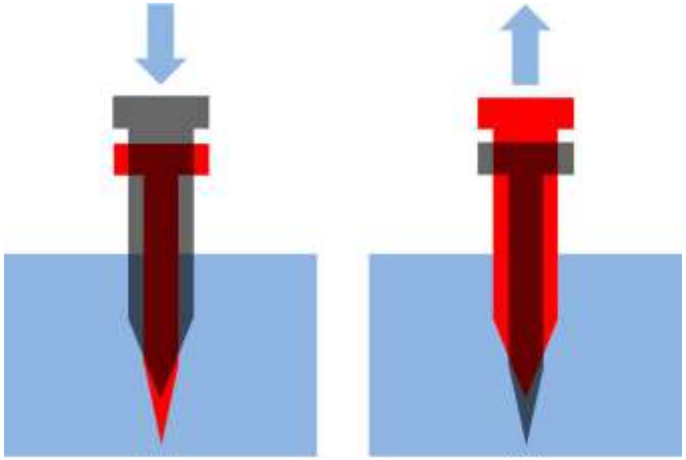


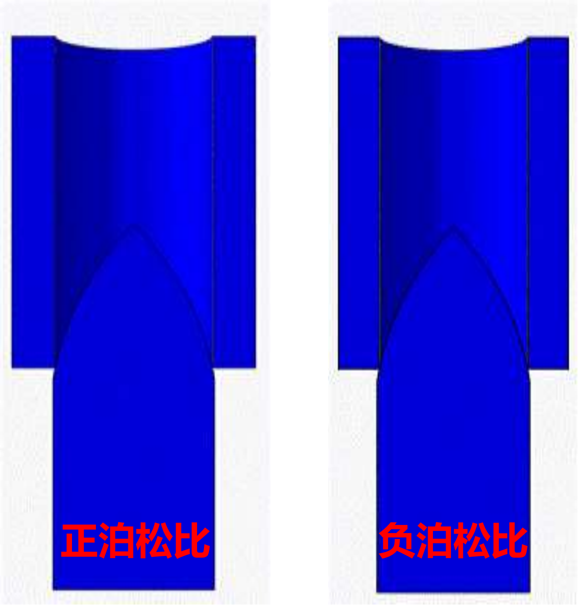
接骨螺钉

北航樊瑜波教授课题组

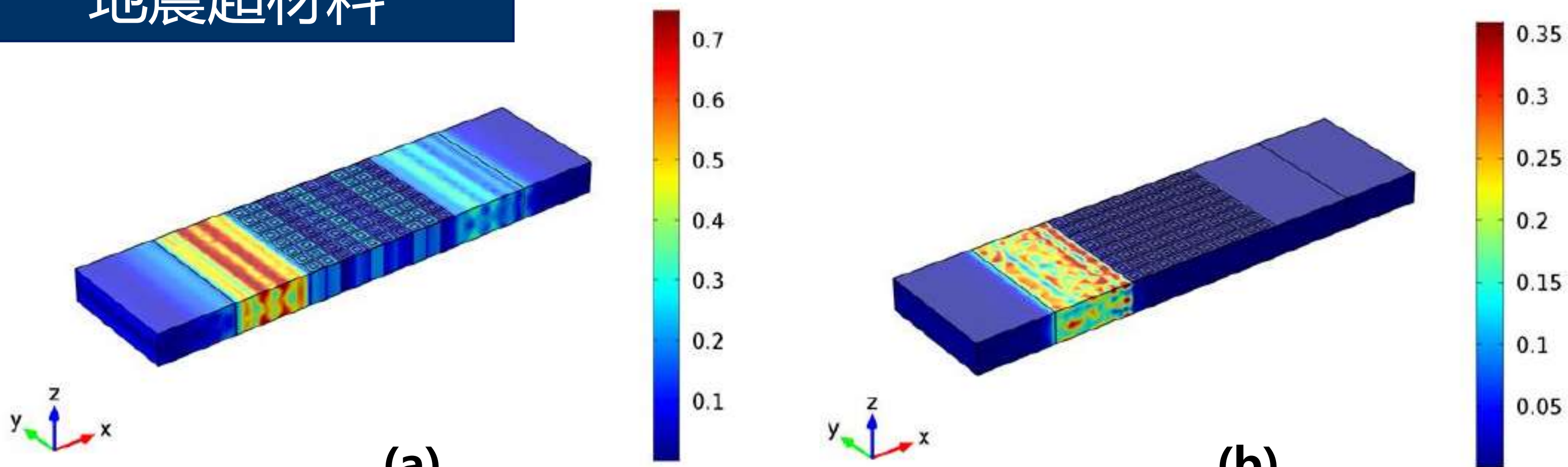
Yao et al., 2020, *Mater. Des.*, 188, 108424.

Ren et al., 2018, Auxetic nail: Design and experimental study. *Composite Structures*, Vol. 184, pp. 288–298.

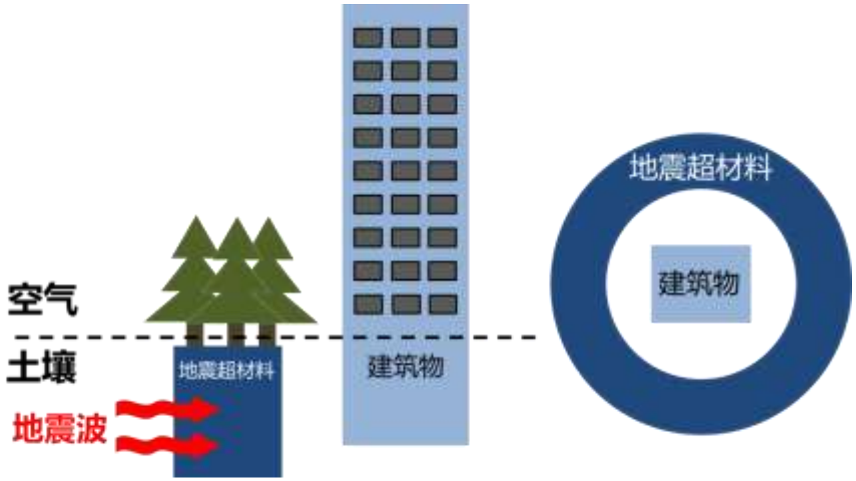




地震超材料



(a) (b)



(c)

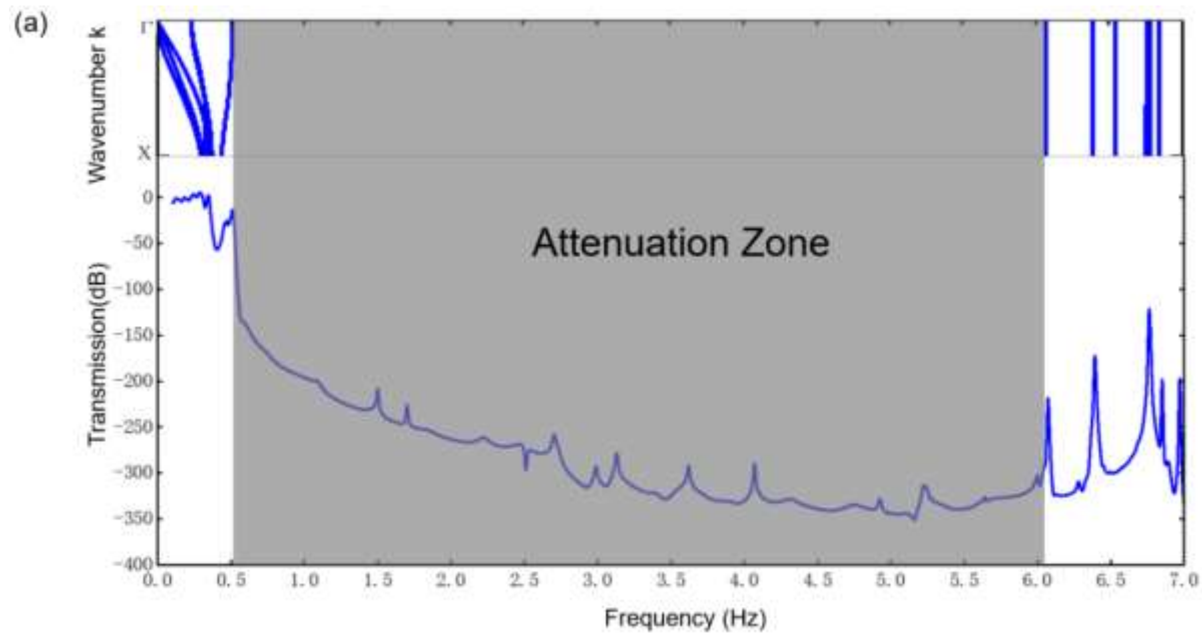
地震超材料是基于**声子晶体**和弹性波超材料的一种衰减地震波的**周期性排列**的人工结构。地震超材料具有**带隙**特性，处在带隙的频率范围内的地震波受到**抑制或者禁止**不能在地震超材料中传播。

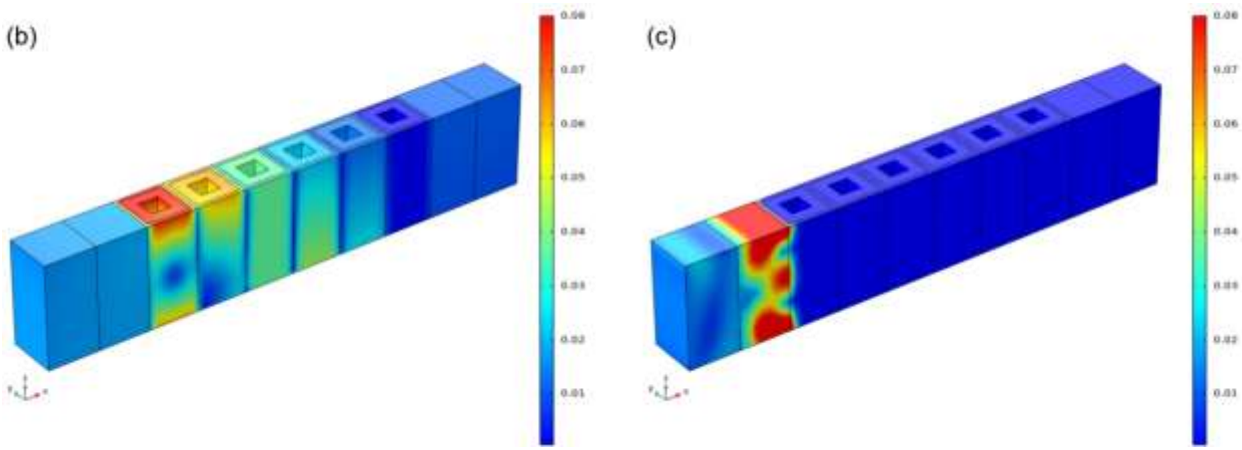
4. Seismic metamaterial 地震超材料

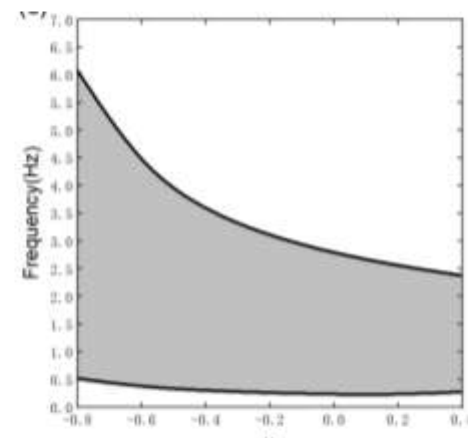
传输损耗分析

1. 衰减区域与能带结构的带隙基本重合

2. 带隙范围内，入射波几乎完全反射且局限于左边土壤中





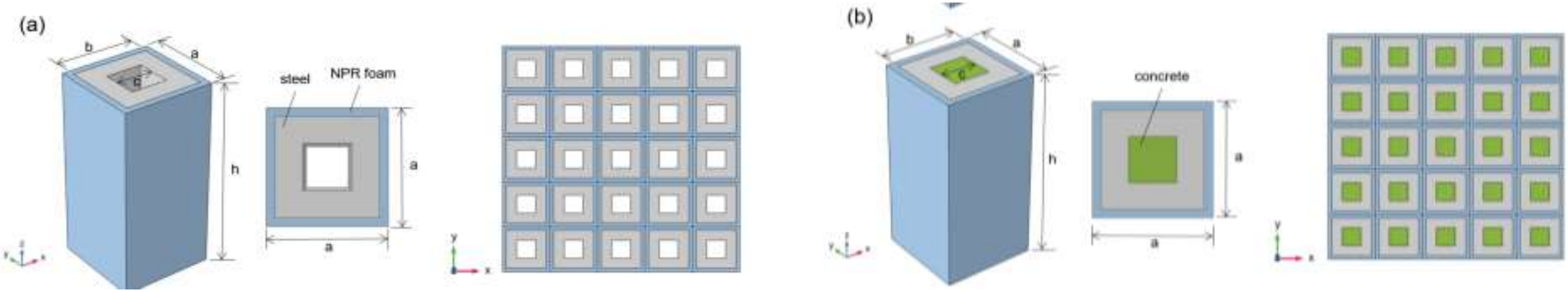


不同频率下的位移：(a)0.36 Hz 和 (b)3.5 Hz

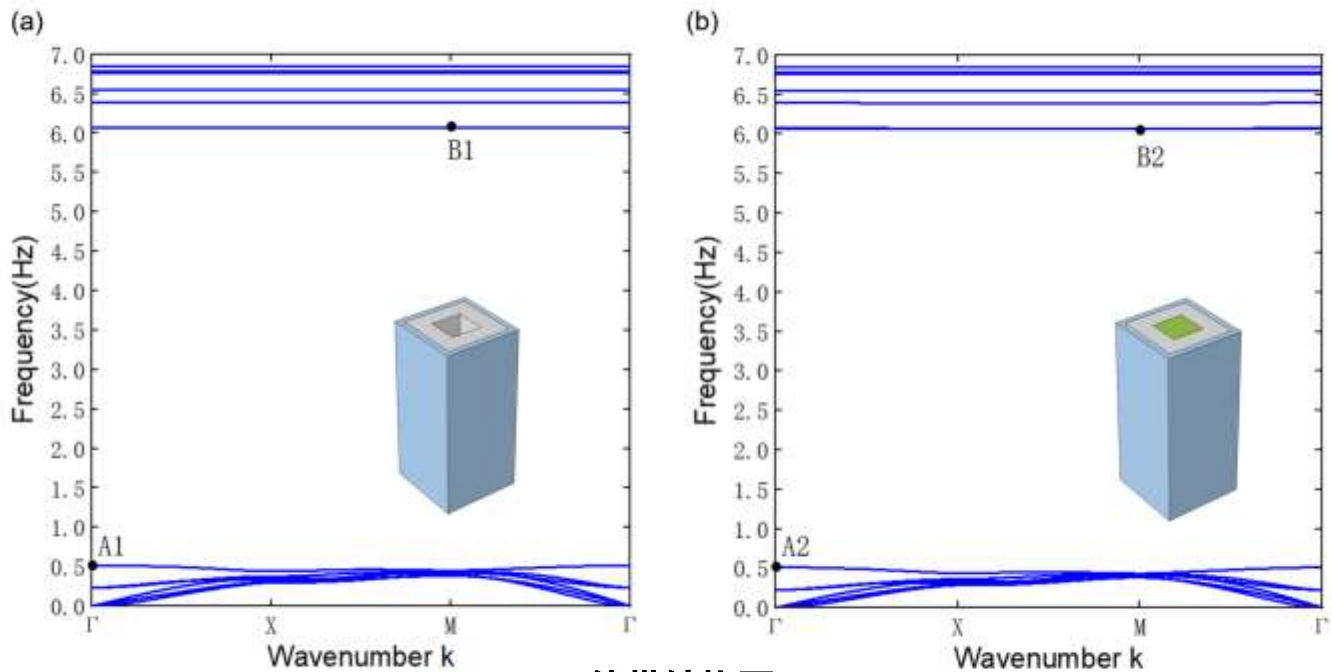
泊松比对于能带的影响

Ting Ting Huang, Xin Ren *et al.*, 2021, Based on auxetic foam: A novel type of seismic metamaterial for Lamb waves. *Engineering Structures*, 246, (112976)

4. Seismic metamaterial 地震超材料



地震超材料模型



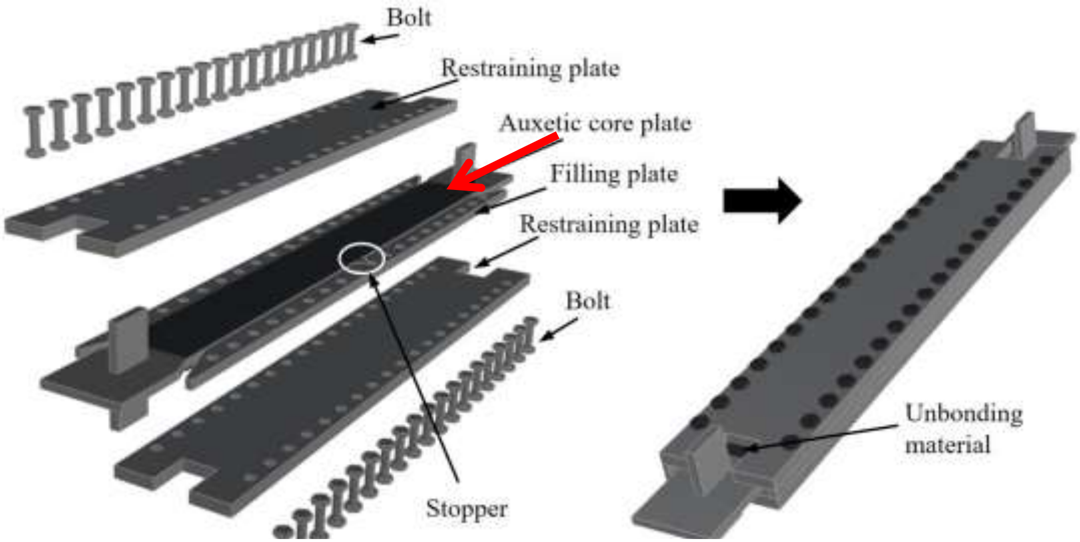
能带结构图

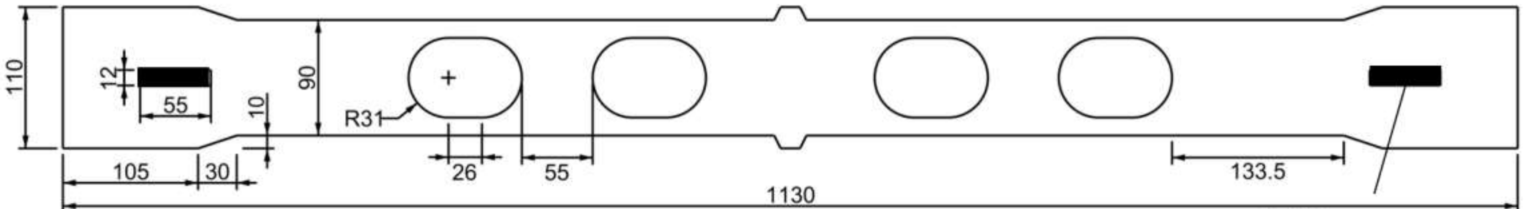
Ting Ting Huang, Xin Ren *et al.*, 2021, Based on auxetic foam: A novel type of seismic metamaterial for Lamb waves. *Engineering Structures*, 246, (112976)

5. Buckling-Restrained Brace (BRB) 屈曲约束支撑

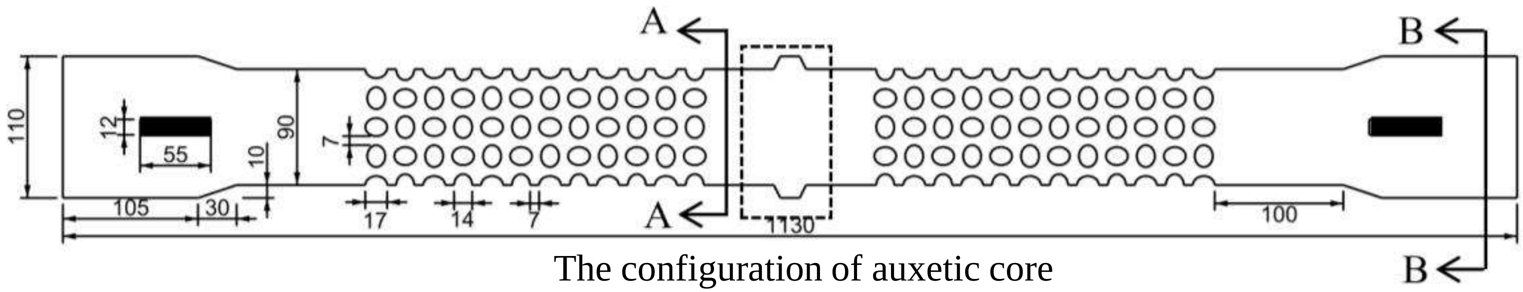
屈曲约束支撑又称防屈曲支撑或BRB(Buckling restrained brace),产品技术最早发展于1973年的日本，当时的一批日本学者成功研发了最早的墙板式防屈曲耗能支撑。

5. Buckling-Restrained Brace (BRB) 屈曲约束支撑





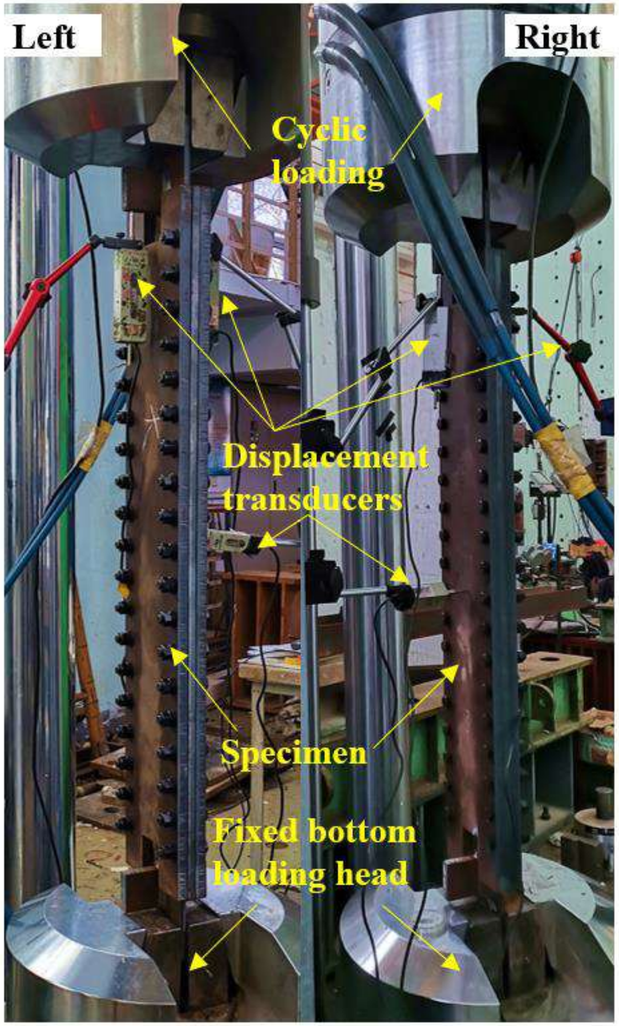
The configuration of traditional perforated core

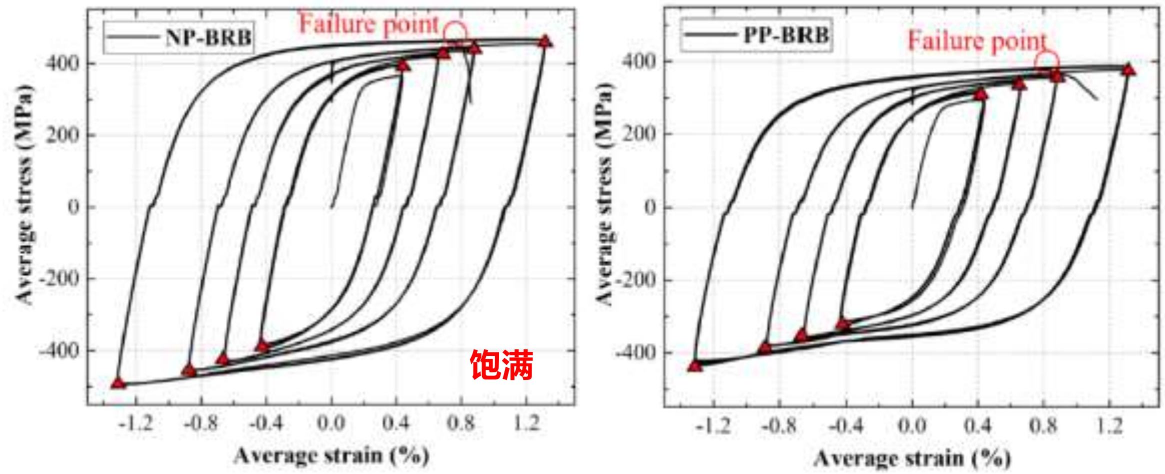


The configuration of auxetic core

Yi Zhang, Xin Ren *et al.*, 2021, A novel buckling-restrained brace with auxetic perforated core: Experimental and numerical studies. *Engineering Structures* (Accepted)

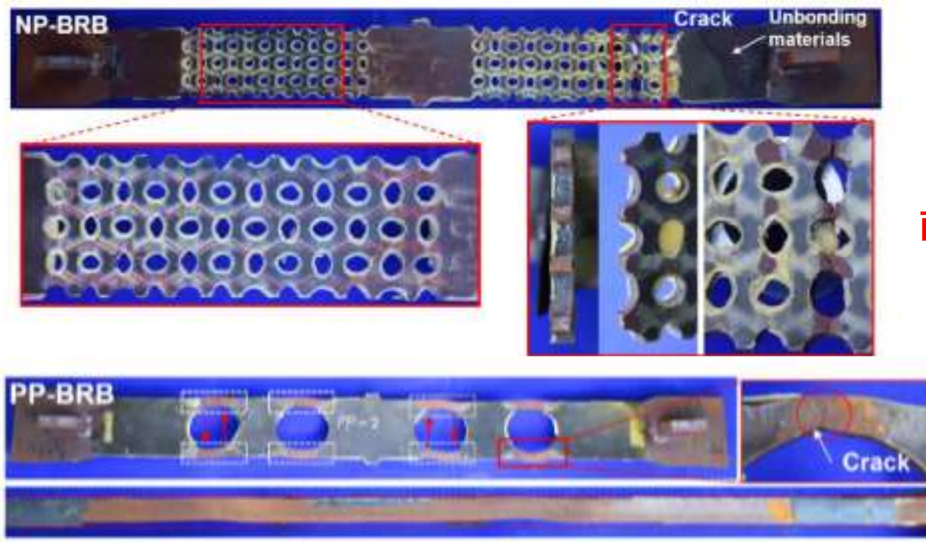
5. Buckling-Restrained Brace (BRB) 屈曲约束支撑





(a) NP-BRB (b) PP-BRB

滞回曲线：(a)负泊松比 和 (b)正泊松比



面内变形

面外变形

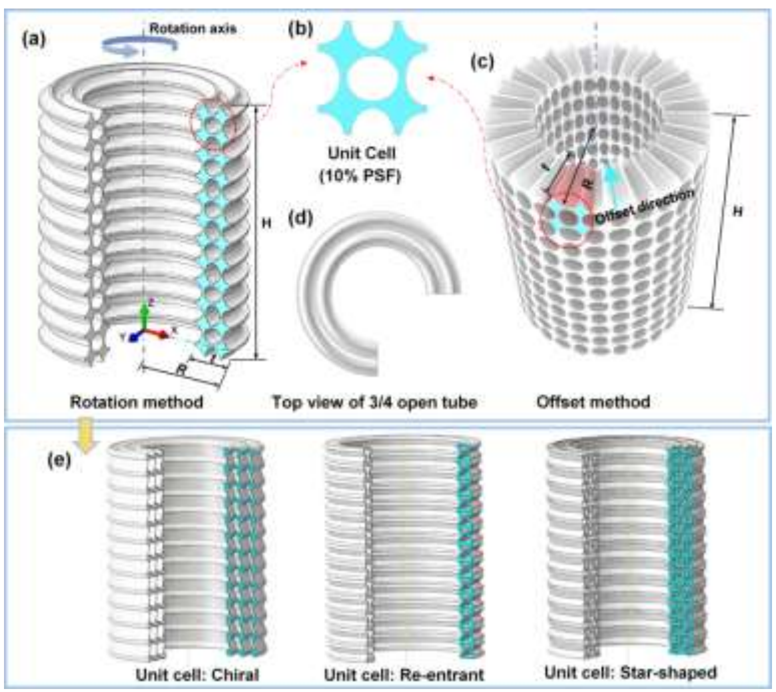
失效模式

Yi Zhang, Xin Ren *et al.*, 2021, A novel buckling-restrained brace with auxetic perforated core: Experimental and numerical studies. *Engineering Structures* (Accepted)

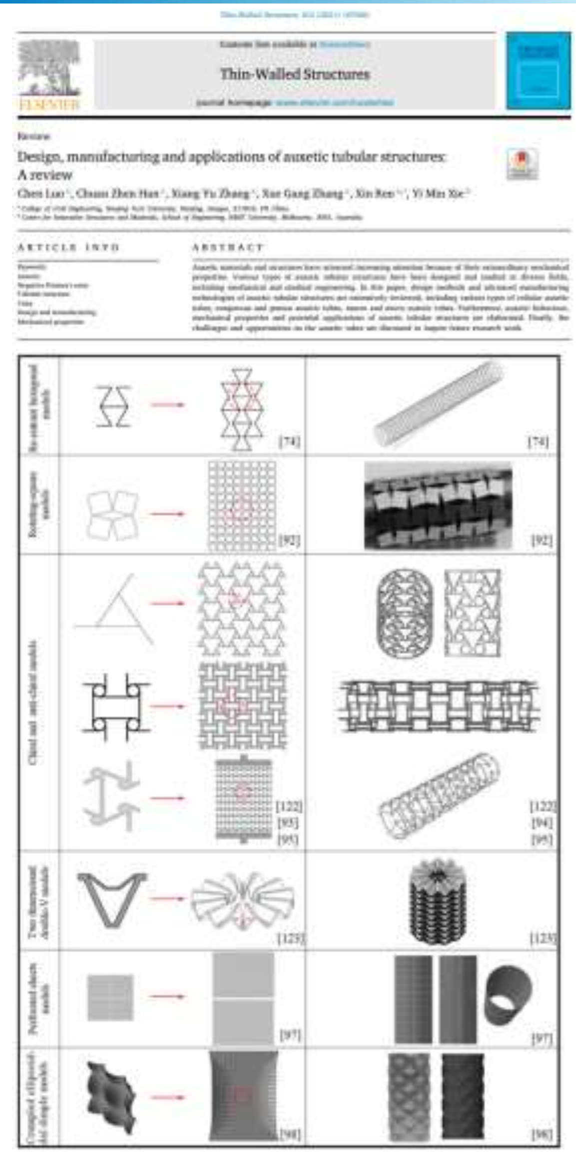
6. Auxetic tubular structure 负泊松比管状结构

Ren et al., 2016, *Smart Materials and Structures*, Vol. 25, 065012.

Ren et al., 2018, *Composite Structures*, Vol. 184, pp. 288–298.



Zhang et al., 2021, *Thin-Walled Structures*, Vol. 163, 107758.


Thin-Walled Structures

Review

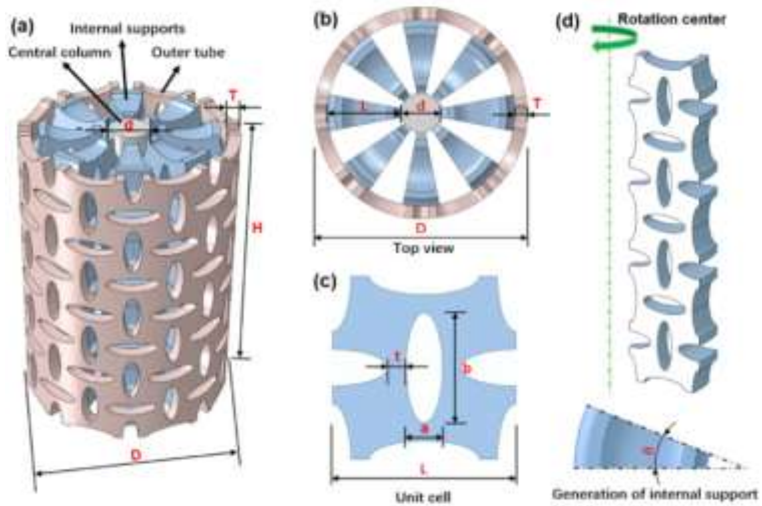
Design, manufacturing and applications of auxetic tubular structures: A review

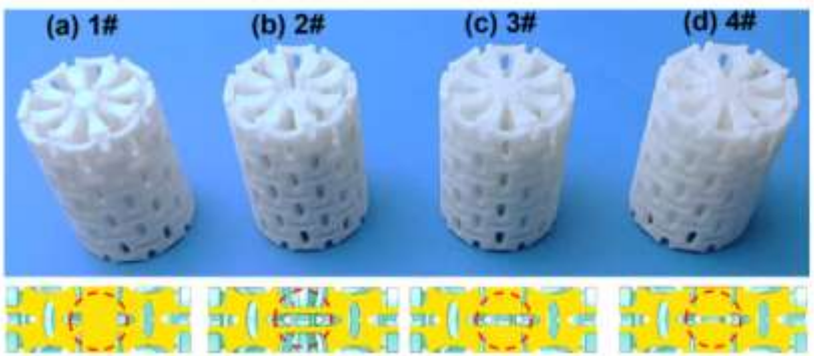
ARTICLE INFO

ABSTRACT

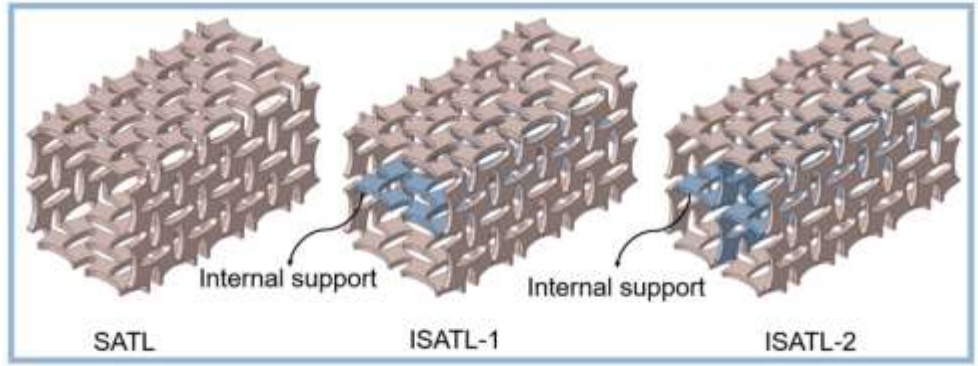
Luo et al., 2021, Design, manufacturing and applications of auxetic tubular structures: A review. *Thin-Walled Structures*, Vol. 163, 107682.

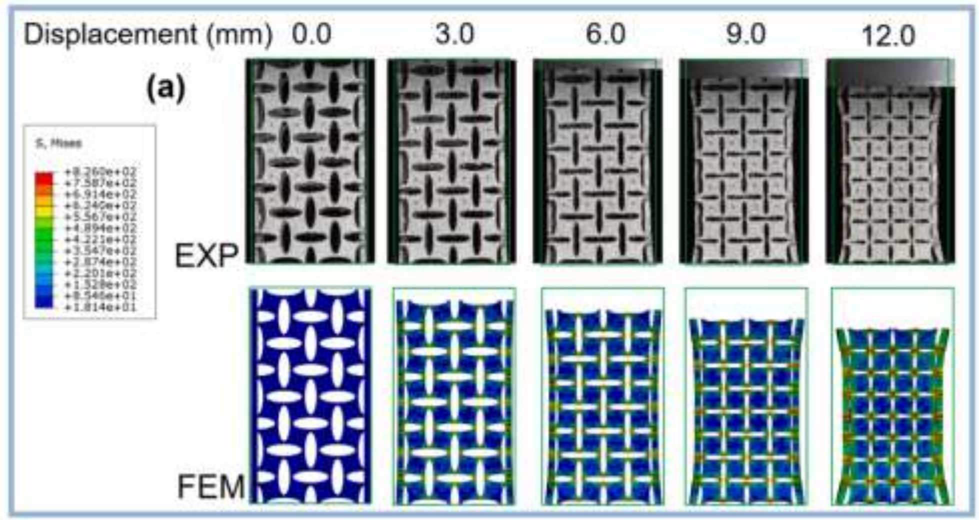
6. Auxetic tubular structure 负泊松比管状结构





Zhang et al., 2021, A novel combined auxetic tubular structure with enhanced tunable stiffness. *Composites Part B: Engineering*, 109303.





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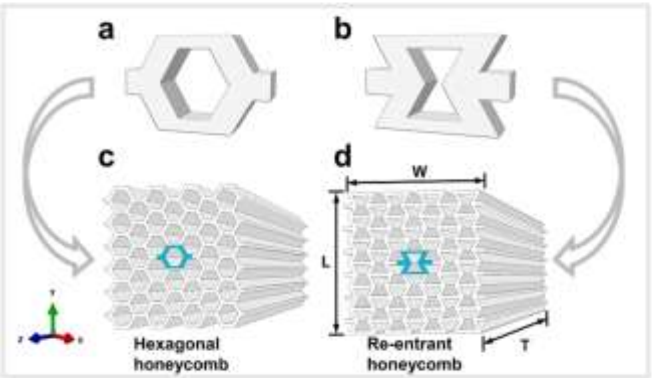
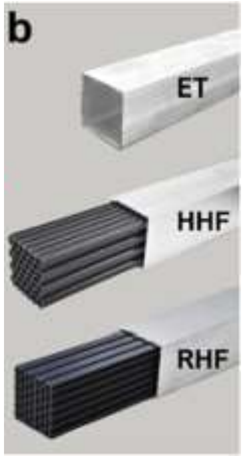
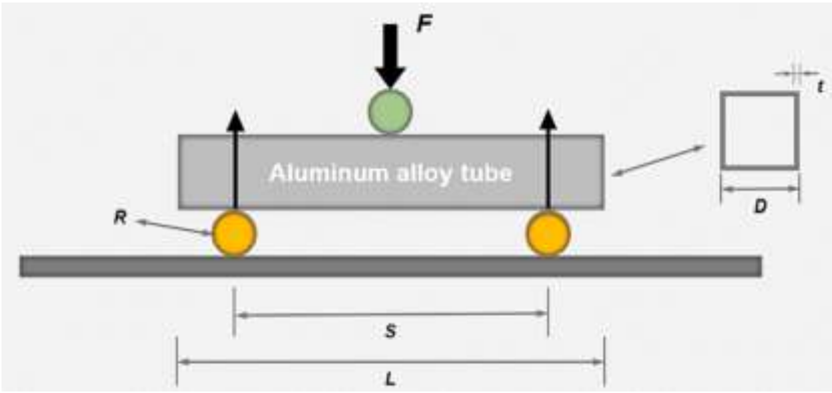
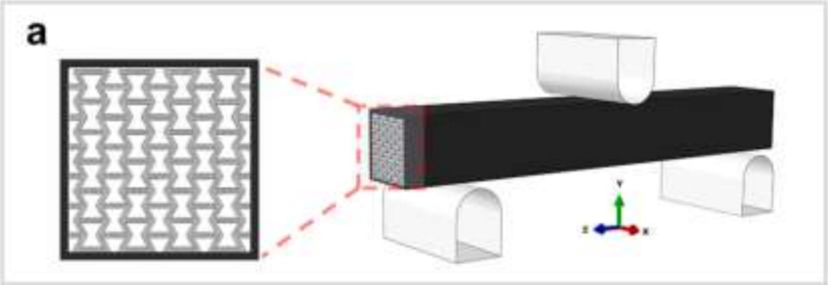
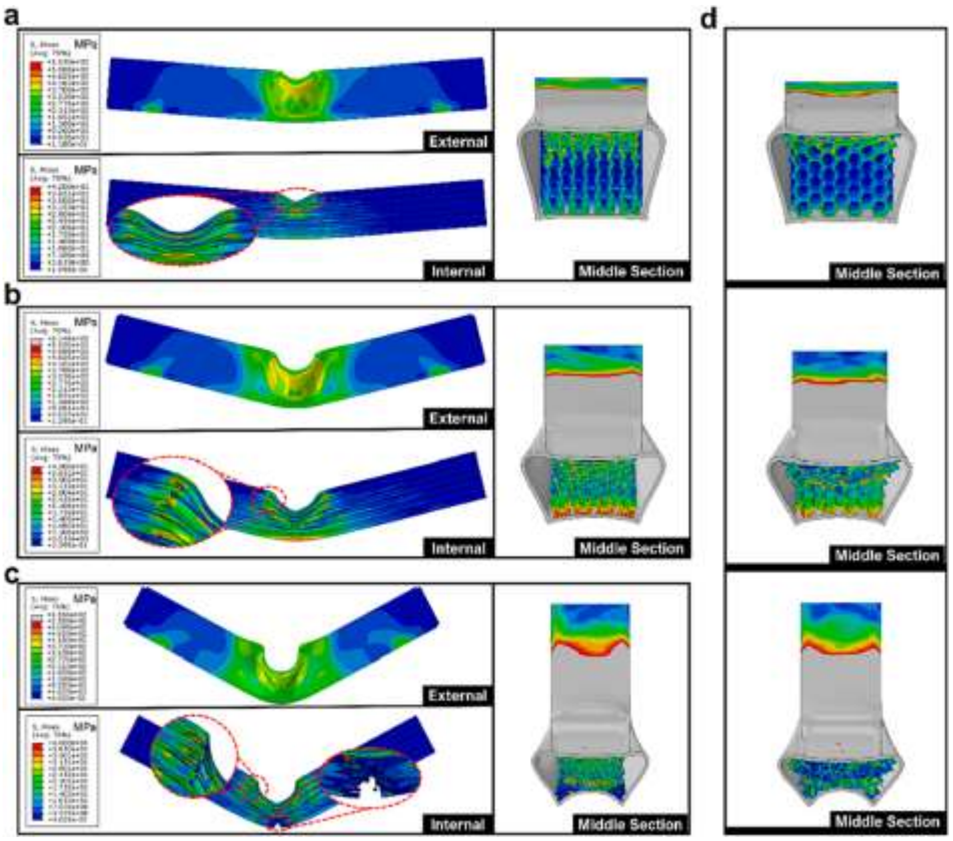




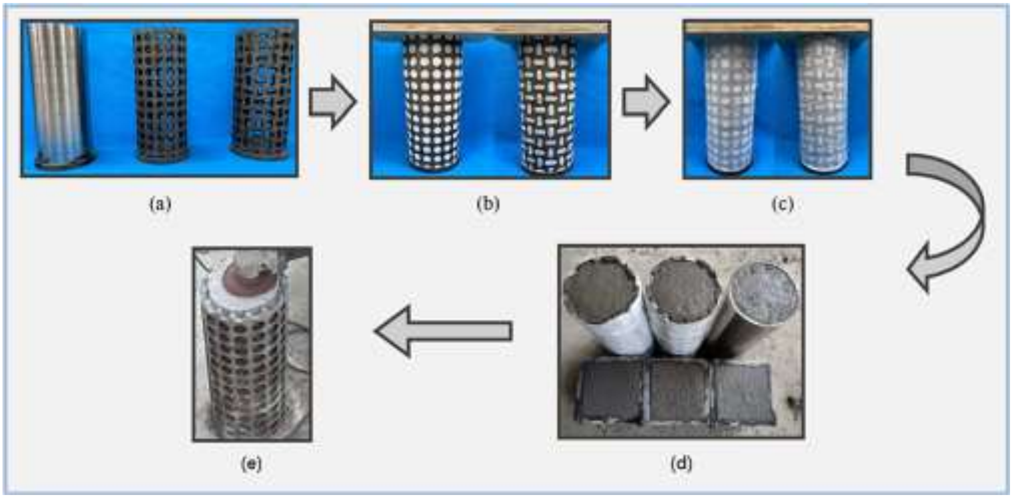


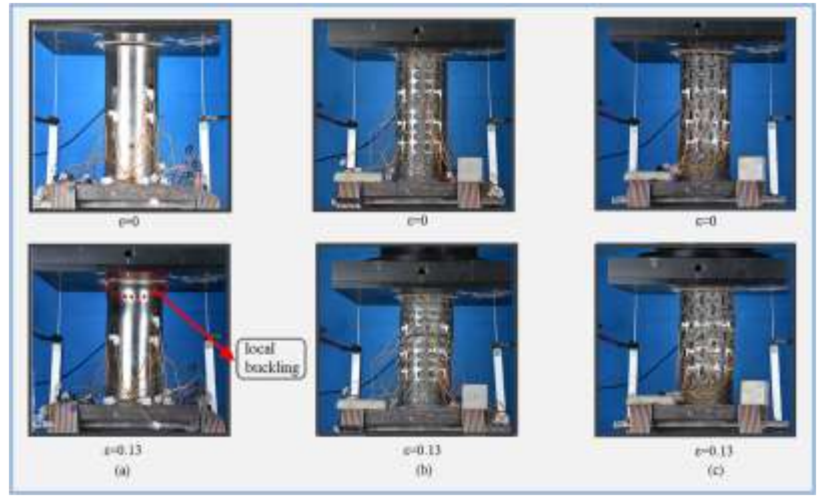


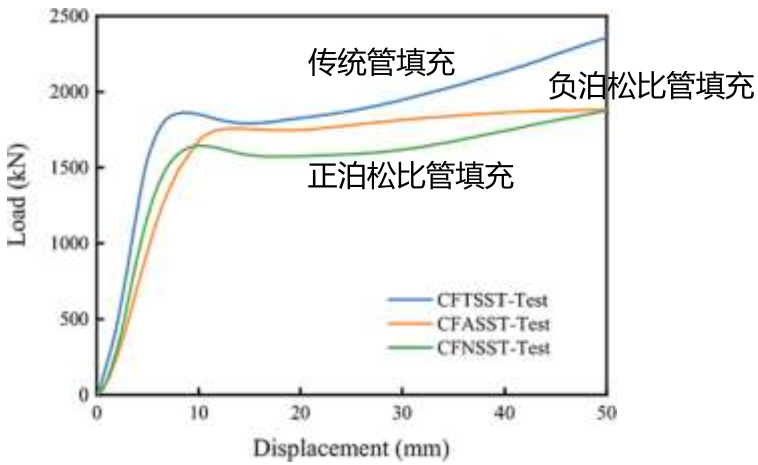


Zhang et al., 2022, Energy absorption properties of composite tubes with hexagonal and re-entrant honeycomb fillers. *Construction and Building Materials*, Vol. 356, 109303.

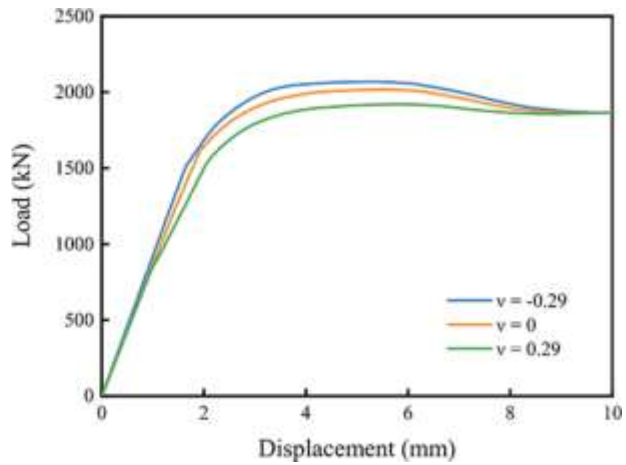
6. Auxetic tubular structure 负泊松比管状结构







外管具有不同负泊松比值对承载力的影响



外管具有不同负泊松比值对承载力的影响

轴向强度增强因子：

$$C = \frac{N_{cfs}}{N_c + N_s}$$

Specimen label	C
CFTSST	1.32
CFNSST	1.62
CFASST	2.32

Luo et al., 2022, A novel concrete-filled auxetic tube composite structure: Design and compressive characteristic study. *Engineering Structures*, Vol. 268, 114759.

7. Enhanced auxetic structure 负泊松比结构的增强优化


Thin-Walled Structures 174 (2022) 109162

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Full length article

A novel auxetic metamaterial with enhanced mechanical properties and tunable auxeticity

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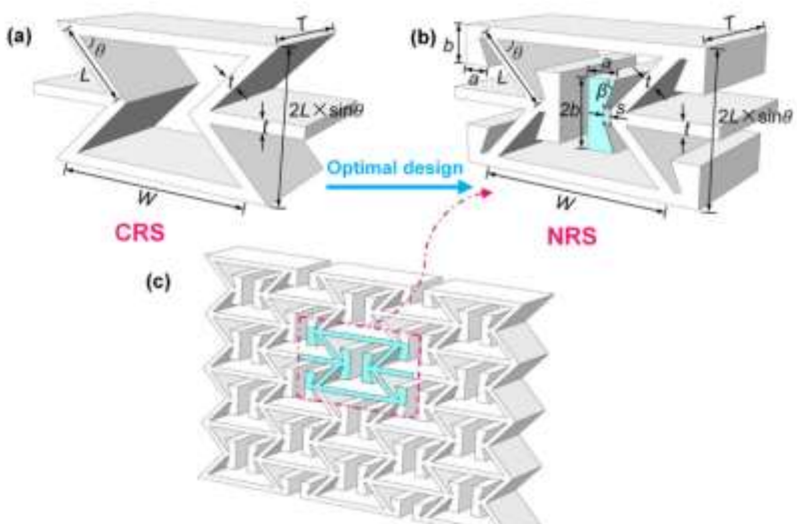
Negative Poisson's ratio
Auxetic
Re-entrant structure
Tunable stiffness

ABSTRACT

An auxetic metamaterial composed of novel re-entrant unit cells was proposed. The new re-entrant structure was constructed by adding wedge-shaped parts to the conventional re-entrant structure. Not only can the additional part regulate the structural stiffness during compression but it can also increase the stability of the structure by hindering lateral buckling of the structure, endowing the metamaterial with more significant and stable auxetic behavior in compression. The mechanical and deformation characteristics of the proposed metamaterial were investigated experimentally and numerically. A parametric study was carried out using the validated finite element model to analyze the influence of the size, angle and stiffness of the wedge-shaped part. Due to its improved stiffness and tunability, the proposed auxetic metamaterial has huge potential to be utilized in civil engineering and protection engineering in the form of two-dimensional, three-dimensional and tubular structures. Furthermore, the self-adjusting stiffness property, better stability and enhanced auxeticity make this metamaterial useful for smart materials and intelligent sensors.



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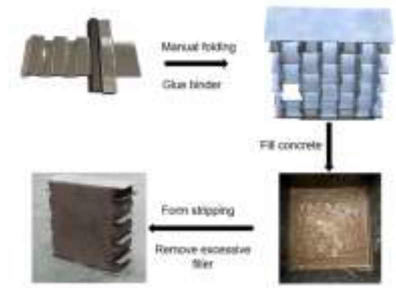

Zhang et al., 2022, A novel auxetic chiral lattice composite: Experimental and numerical study. *Composite Structures* , Vol. 282, 115043.

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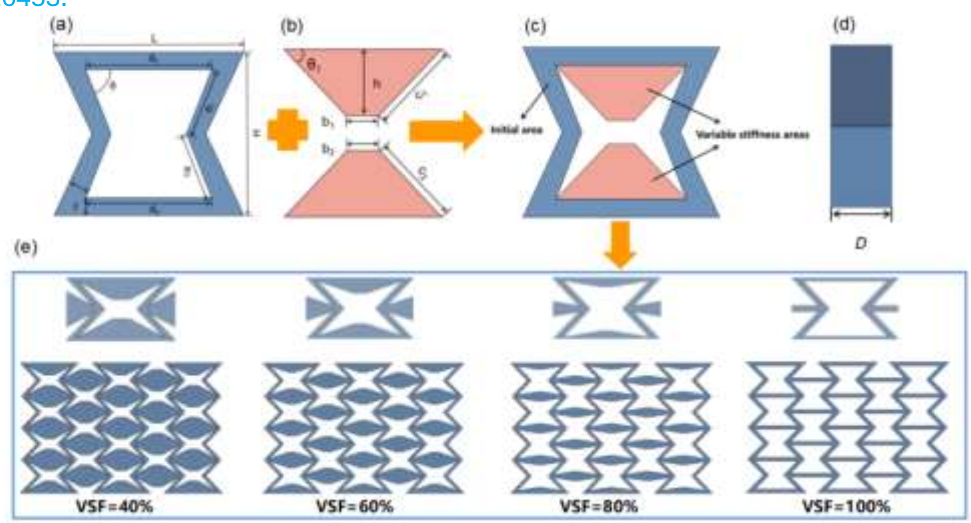
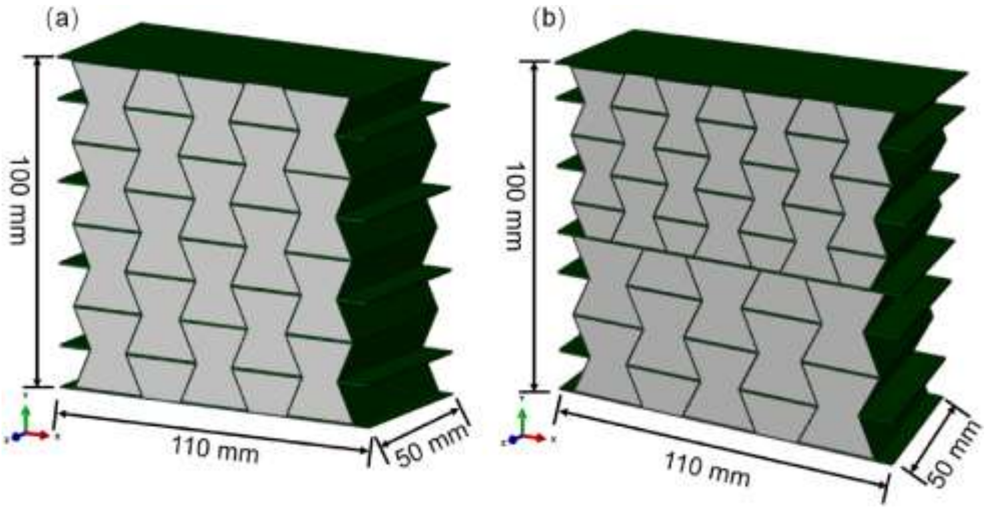
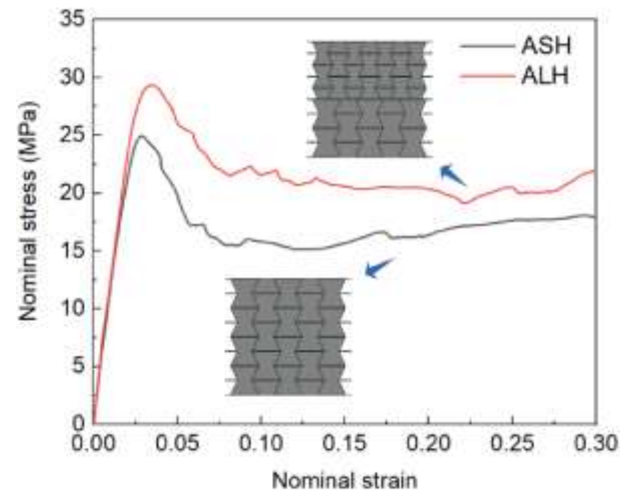
Zhong et al., 2022, Mechanical properties of concrete composites with auxetic single and layered honeycomb structures . *Construction and Building Materials*, Vol. 322, 126453.

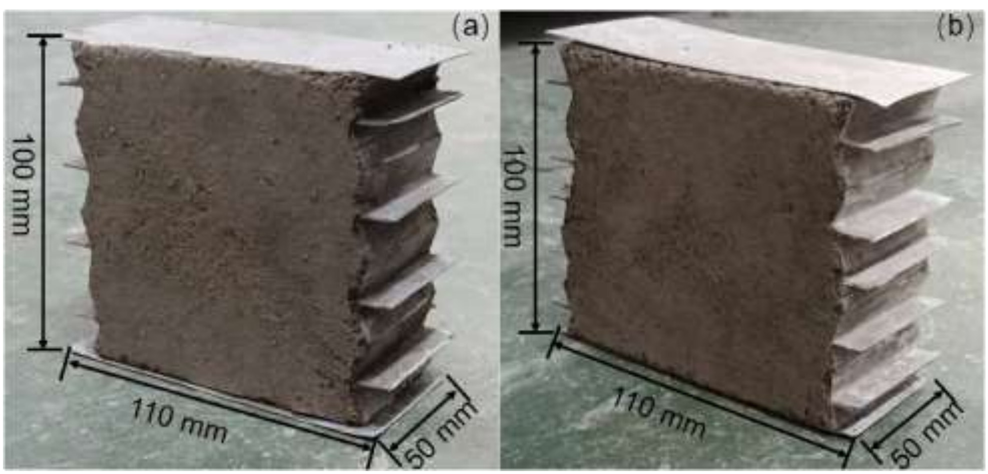


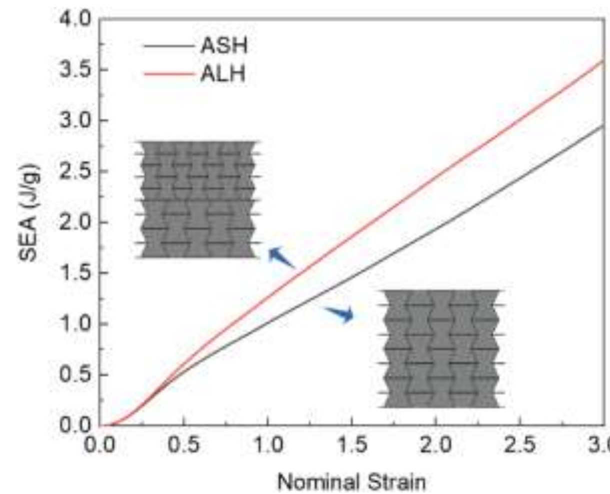
Cheng et al., 2022, Design and mechanical characteristics of auxetic metamaterial with tunable stiffness . *International Journal of Mechanical Sciences*, Vol. 223, 107286.

8. 混凝土填充蜂窝结构



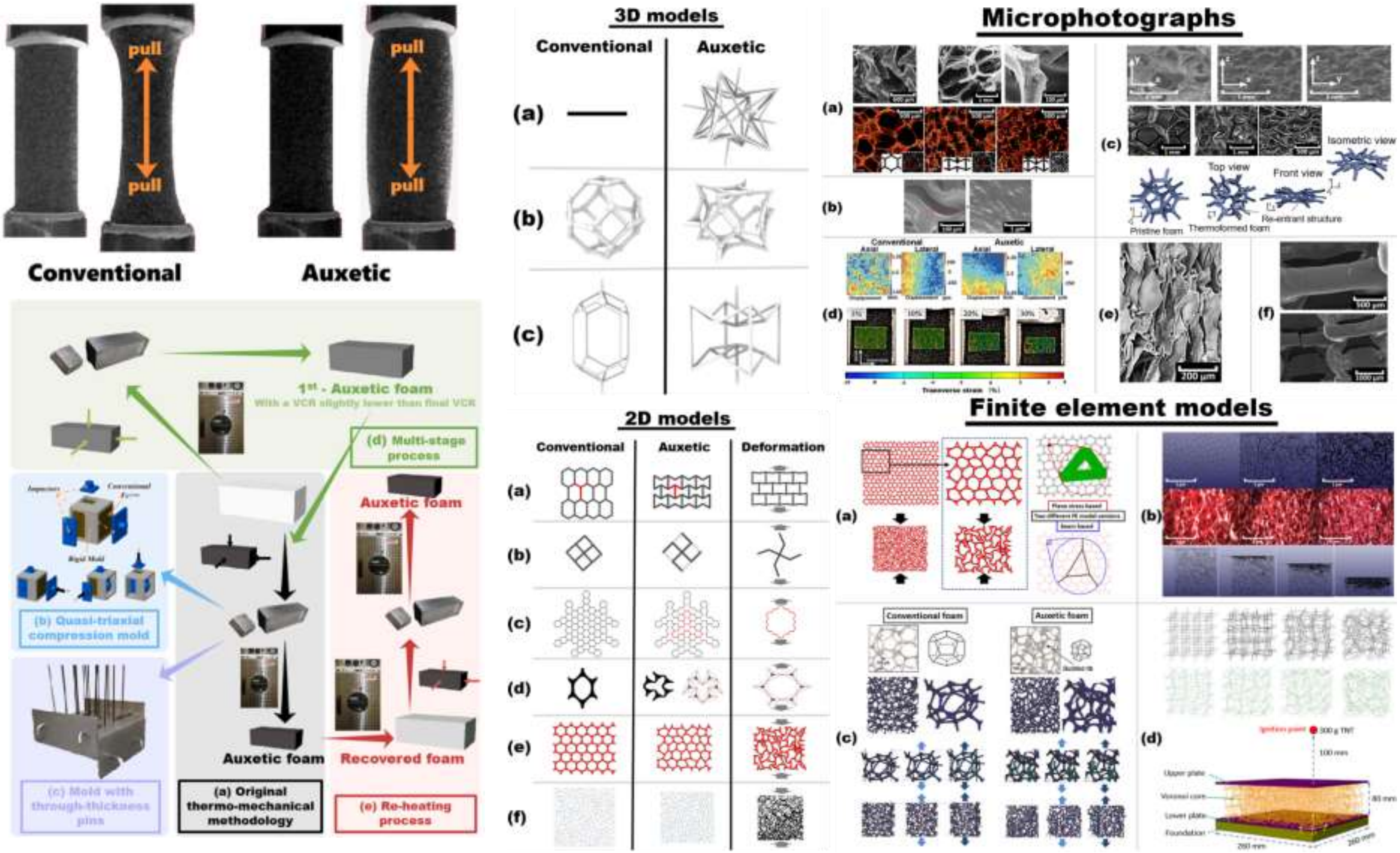






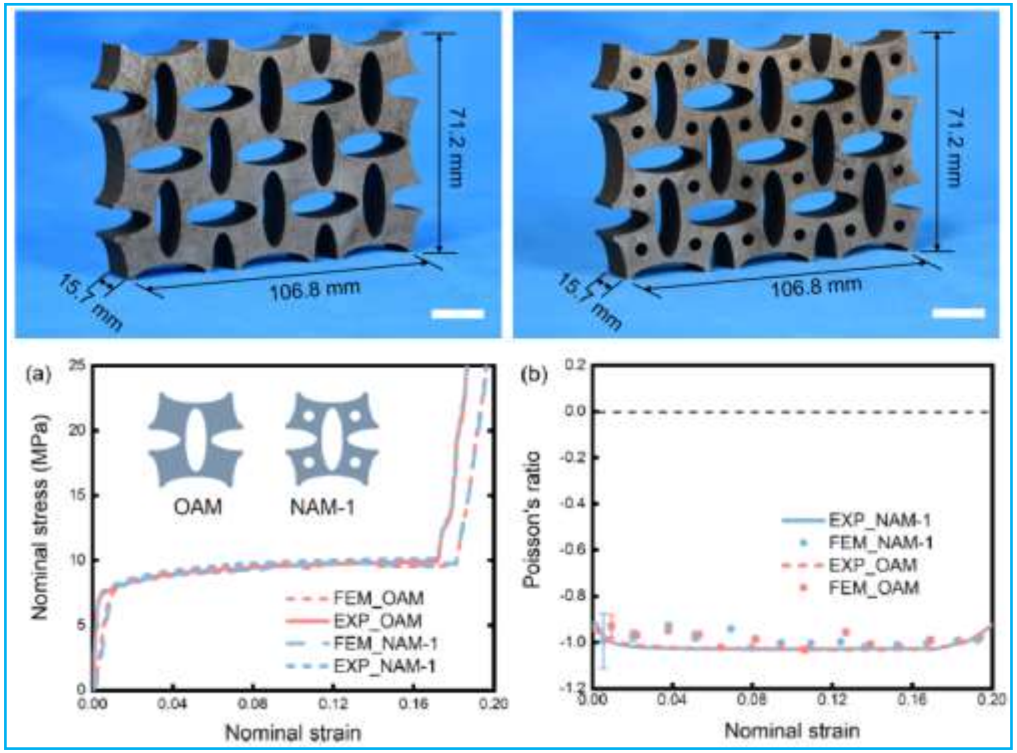
Zhong and Ren et al., 2022, Mechanical properties of concrete composites with auxetic single and layered honeycomb structures. *Construction and Building Materials*, Vol. 322, 126453.

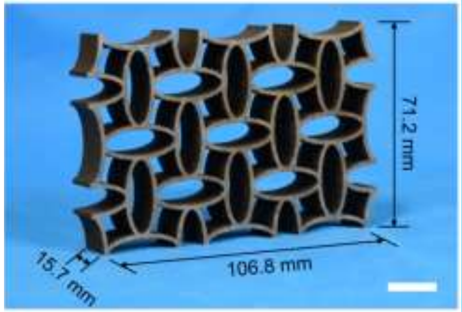
9. Auxetic foam materials 负泊松比泡沫材料



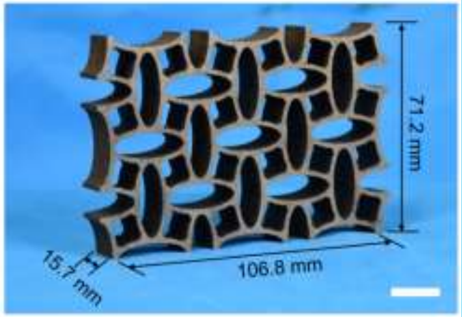
Jiang et al., 2022, Manufacturing, characteristics and applications of auxetic foams: A state-of-the-art review. *Composites Part B: Engineering*, 109733.

10. Lightweight Auxetics 轻量化负泊松比超材料

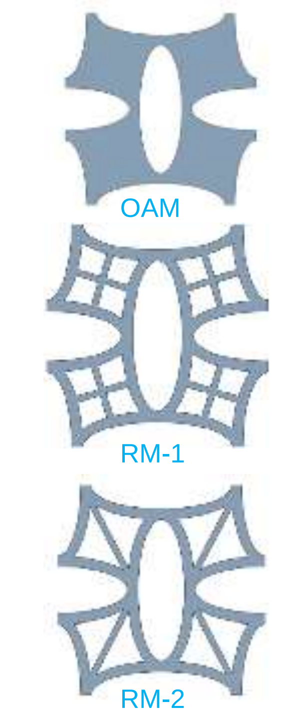


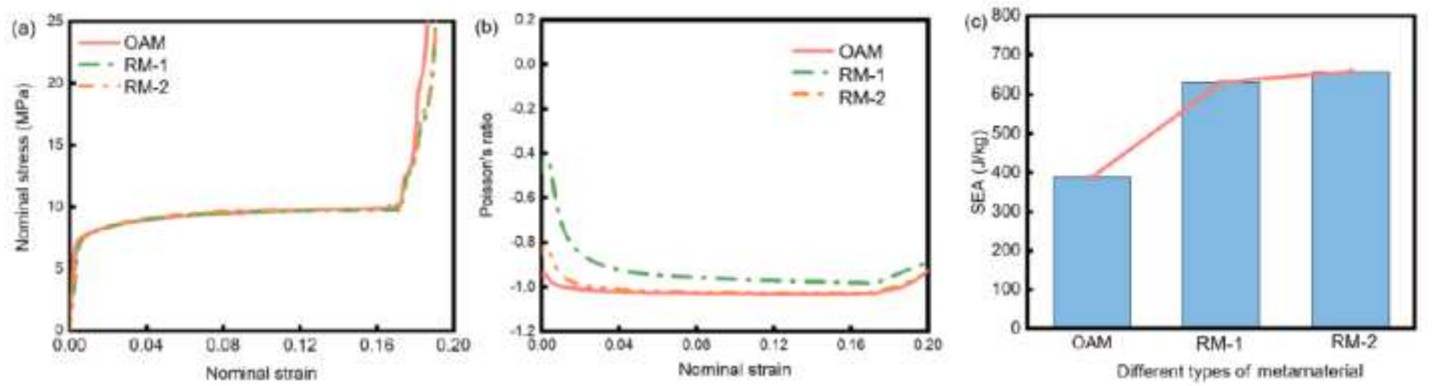


(c) Novel auxetic material-2 (NAM-2)



(d) Novel auxetic material-3 (NAM-3)





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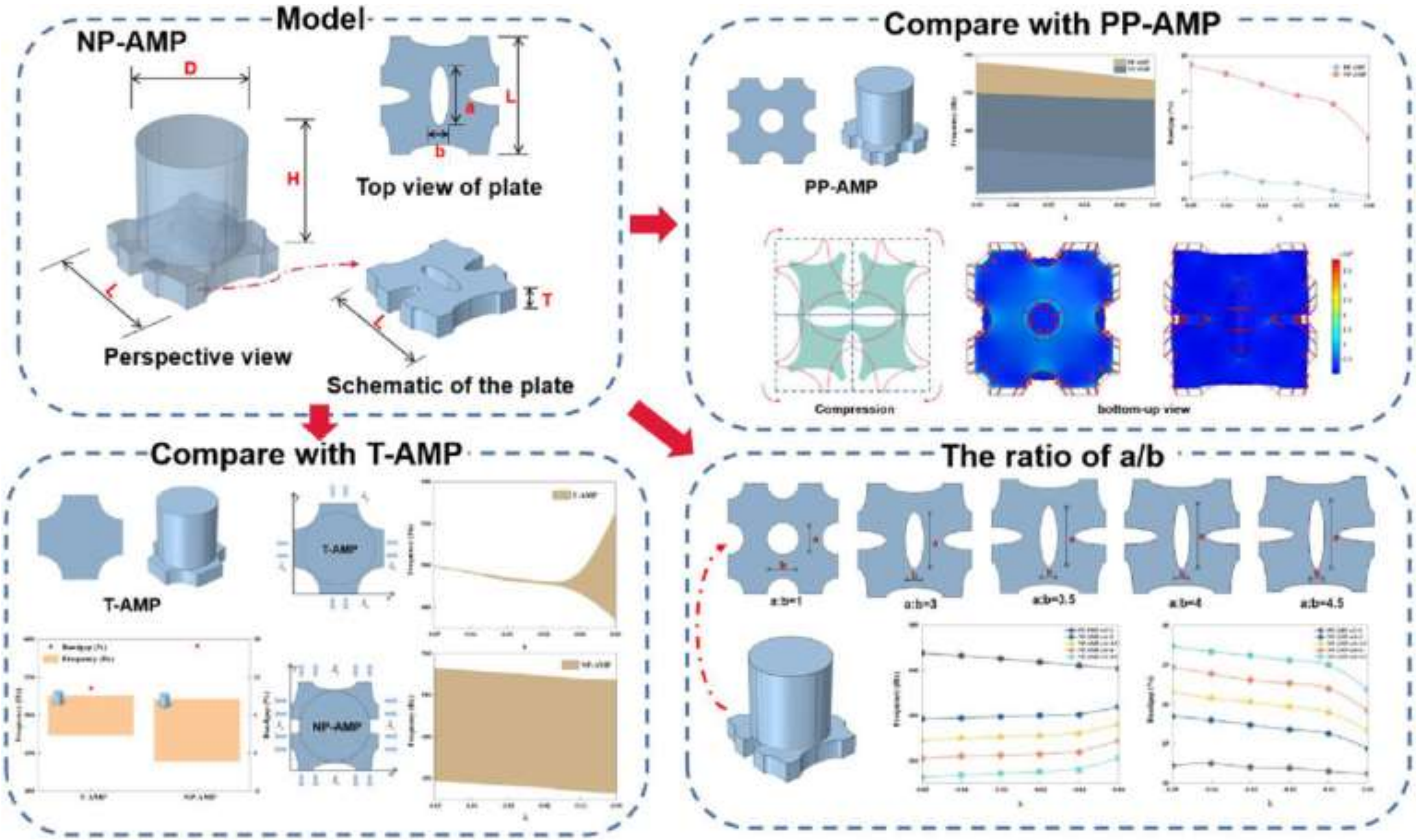
11. Auxetic acoustic metamaterial 负泊松比声学超材料



1. 与T-AMP相比，NP-AMP的带隙具有频率较低、带隙较宽的特点，而带隙的初始频率从474.05 Hz降低到439.72 Hz，相对宽度带隙增加了 65%。
2. NP-AMP带隙的起始频率比PP-AMP降低了7.7%，带宽增加了15.1%。
3. NP-AMP带隙的起始频率随着压缩应变的增加而降低，这与PP-AMP相反。

Tao and Ren et al., 2022, A novel auxetic acoustic metamaterial plate with tunable bandgap. *International Journal of Mechanical Sciences*, Vol. 226, 107414

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Xin Ren[1], Raj Das[2], Phuong Tran[3], Tuan Duc Ngo[3] and Yi Min Xie[2,4]

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Smart Materials and Structures, Volume 27, Number 2

Citation Xin Ren *et al* 2018 *Smart Mater. Struct.* **27** 023001

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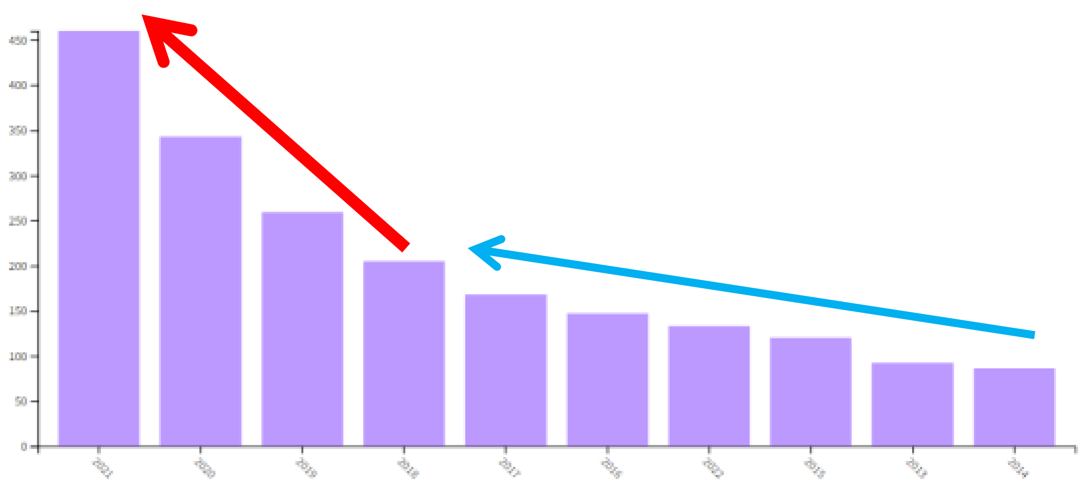

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任 鑫　博士、教授

电子信箱：xin.ren@njtech.edu.cn

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