جامعة خليفة
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Paper 1484

DAMAGE SENSING CAPABILITIES OF MULTIFUNCTIONAL TRUSS LATTICES ENABLED VIA DLP 3D PRINTING

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Introduction

- **Additive manufacturing (AM)** has enabled the fabrication of lightweight structures with complex geometries, including **lattice structures**.
- Well-designed lattice structures can achieve **excellent weight-specific mechanical and functional properties**. These are **tunable** through the design of the unit cell and adjustment of geometrical parameters.
- **Applications:** heat sinks, heat exchangers, orthopedic implants, sports equipment, rocket engines, etc.
- There is a growing need for real-time **monitoring of the damage state of lattice structures**, particularly for safety-critical applications.

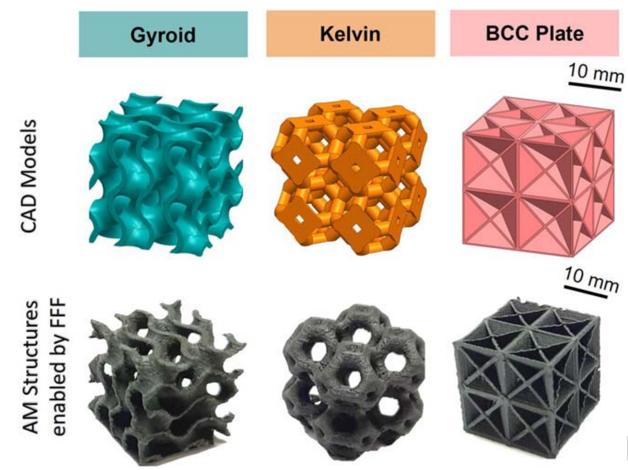
↓

Self-sensing lattice structure

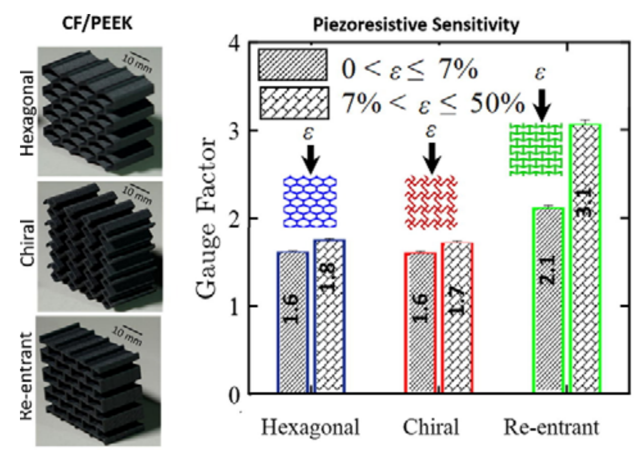
[1] https://all3dp.com/1/3d-printing-lattice-structures-the-ultimate-guide/

Introduction

- **Self-sensing** is the ability of a material to monitor its own condition without the need of additional sensors (the material itself acts as a sensor).
- Self-sensing lattices can be realized by fabricating the structure from a **piezoresistive material**.
- **Polymer-based nanocomposites** are attractive materials for self-sensing lattice structures due to their **pronounced piezoresistivity** and **ability to be 3D printed**.
- This study examines the **mechanical and self-sensing performance of 2D and 3D lattice structures processed via DLP** using an electrically conductive nanocomposite resin.
- The ultimate goal is to unveil **fundamental relations between lattice topology, relative density and sensing performance** in bend- and stretch-dominated lattices.



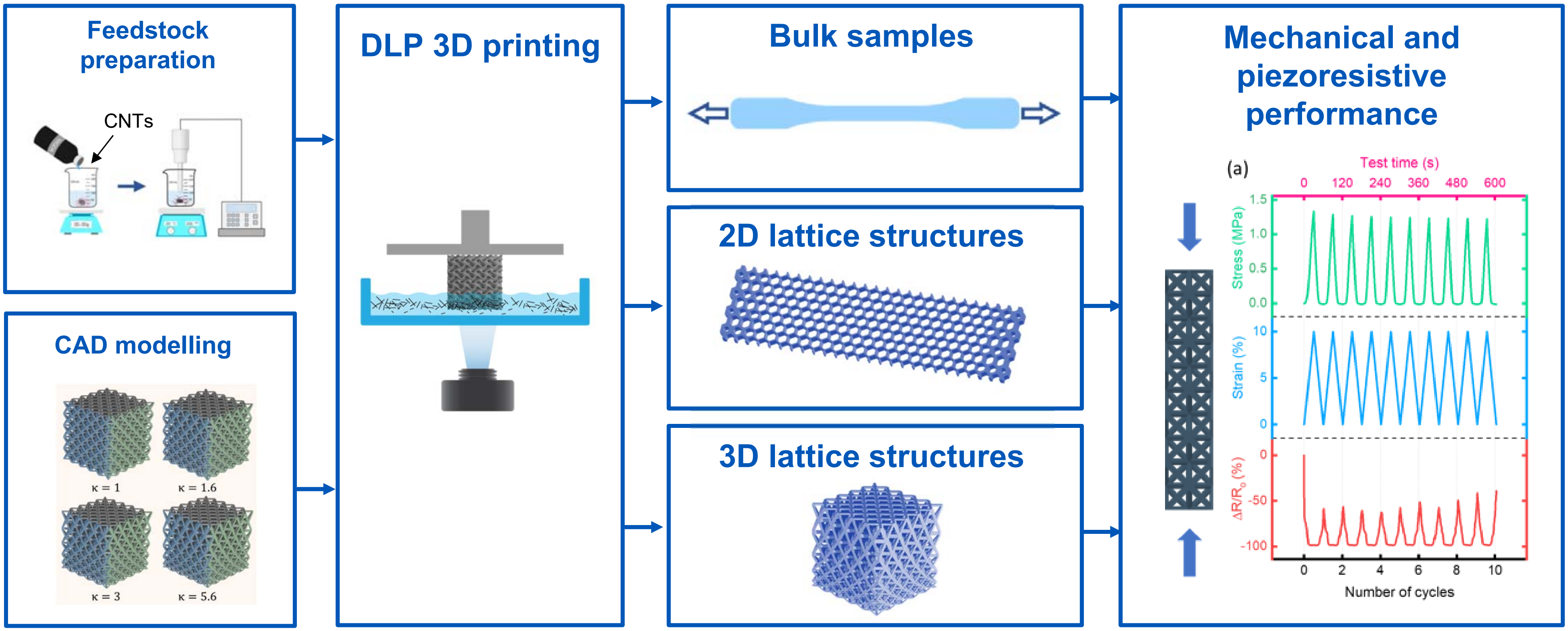
[2]



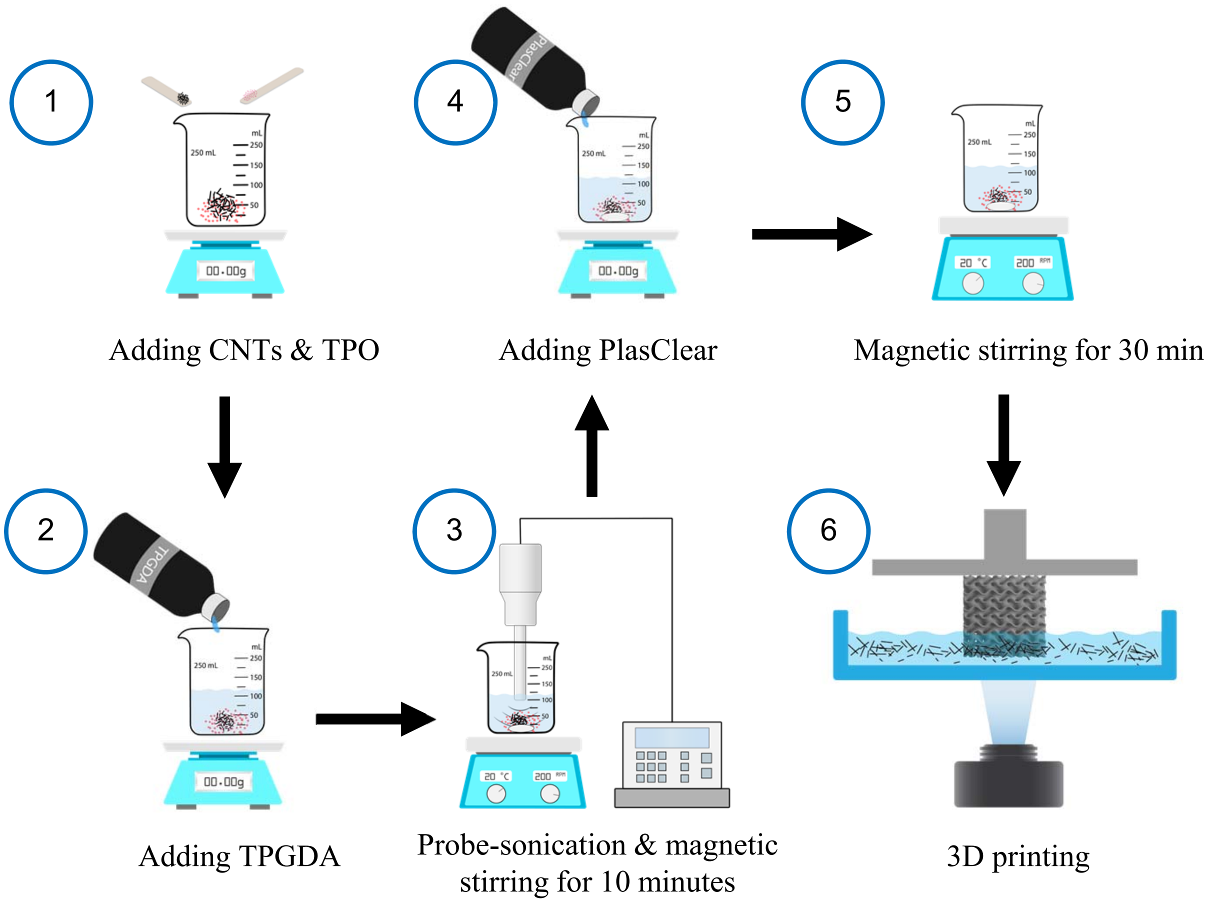
[3]

[2] Ubaid, Jabir, et al. "Multifunctionality of nanoengineered self-sensing lattices enabled by additive manufacturing." *Advanced Engineering Materials* 24.7 (2022): 2200194.
[3] Andrew, J. Jefferson, et al. "Energy absorption and self-sensing performance of 3D printed CF/PEEK cellular composites." *Materials & Design* 208 (2021): 109863.

Methodology



Feedstock preparation and 3D printing



CNT concentration (phr)	Sample Designation
0	PC-0
0.01	PC-0.01
0.025	PC-0.025
0.05	PC-0.05
0.1	PC-0.1
0.2	PC-0.2

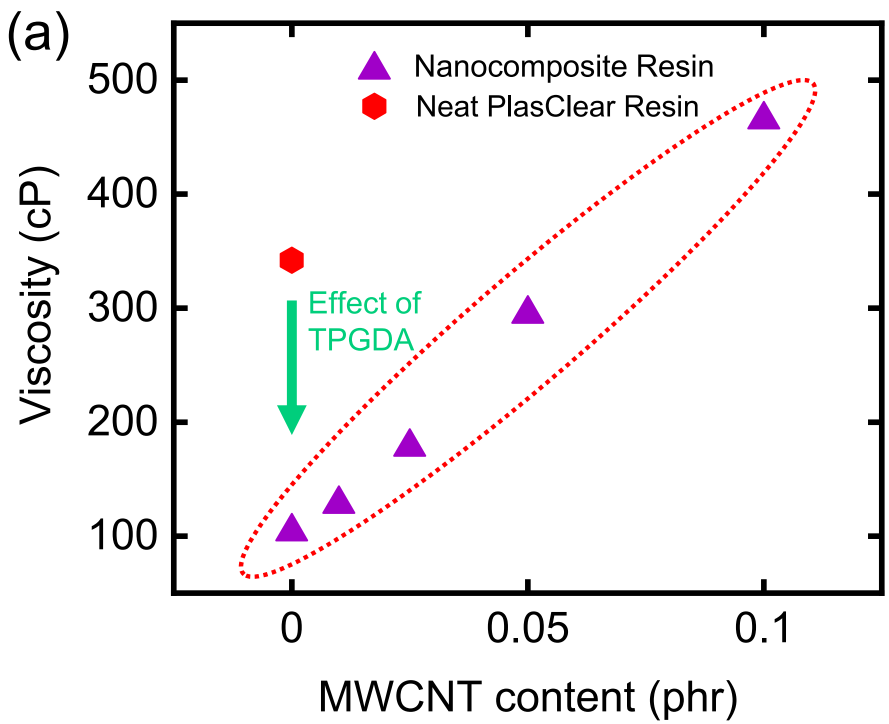
After 3D printing:

- Samples were rinsed in isopropyl alcohol.
- No post-treatments were applied.

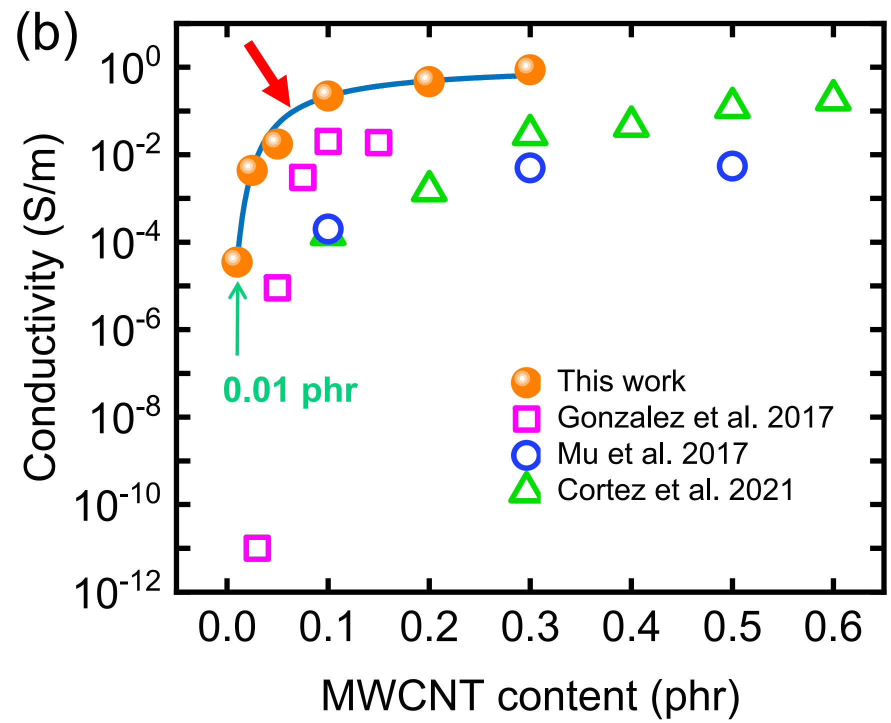
[4] Saadi, O. W., Schiffer, A., & Kumar, S. (2023). Piezoresistive behavior of DLP 3D printed CNT/polymer nanocomposites under monotonic and cyclic loading. *The International Journal of Advanced Manufacturing Technology*, *126*(5-6), 1965-1978.

Resin properties

Dynamic viscosities of the prepared resins

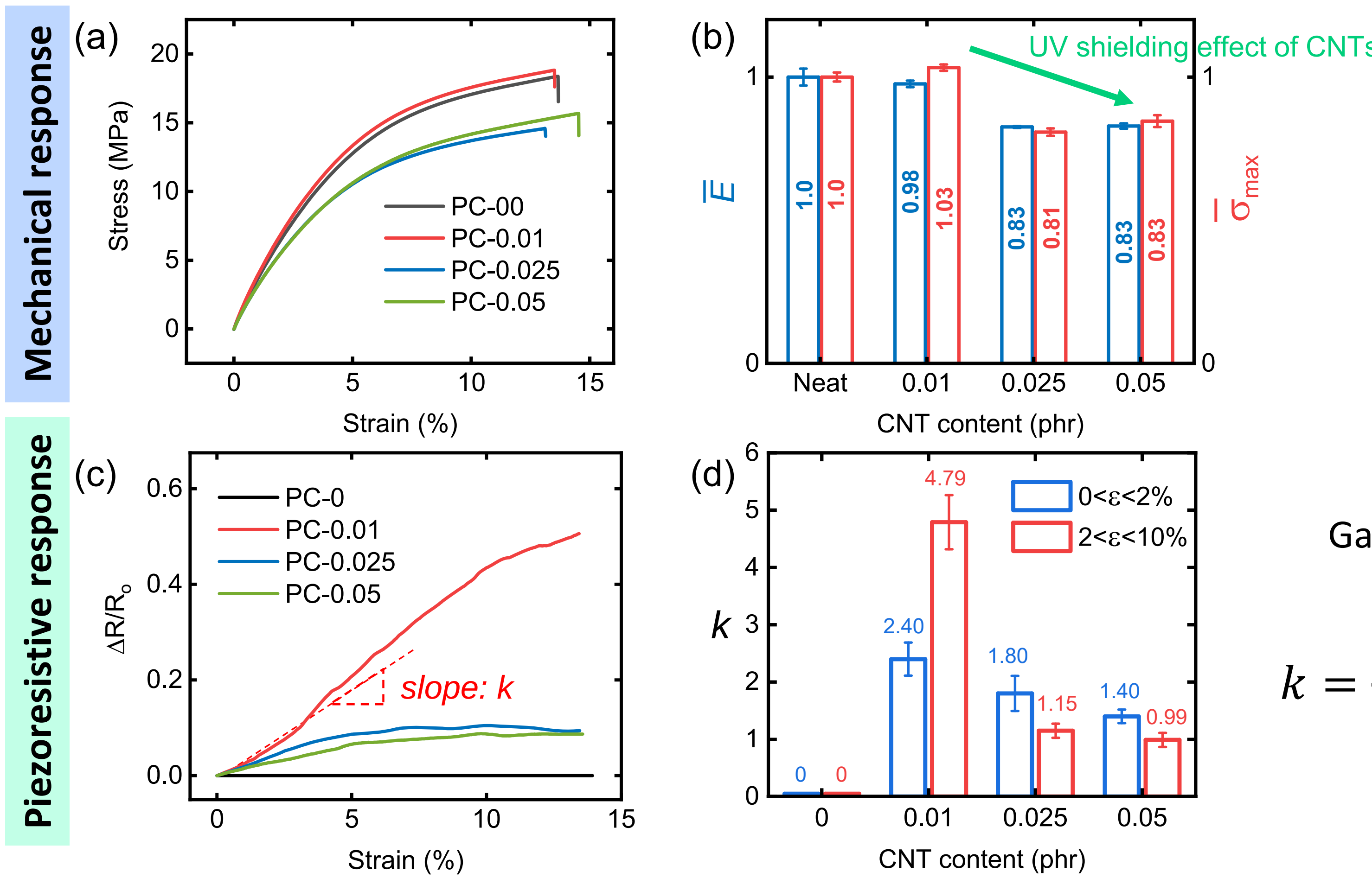


Electrical conductivities of the 3D printed nanocomposites



[4] Saadi, O. W., Schiffer, A., & Kumar, S. (2023). Piezoresistive behavior of DLP 3D printed CNT/polymer nanocomposites under monotonic and cyclic loading. *The International Journal of Advanced Manufacturing Technology*, *126*(5-6), 1965-1978.

Bulk samples: Tensile response



Gauge factor:

$$k = \frac{\Delta\left({\Delta R}/{R_0}\right)}{\Delta \varepsilon}$$

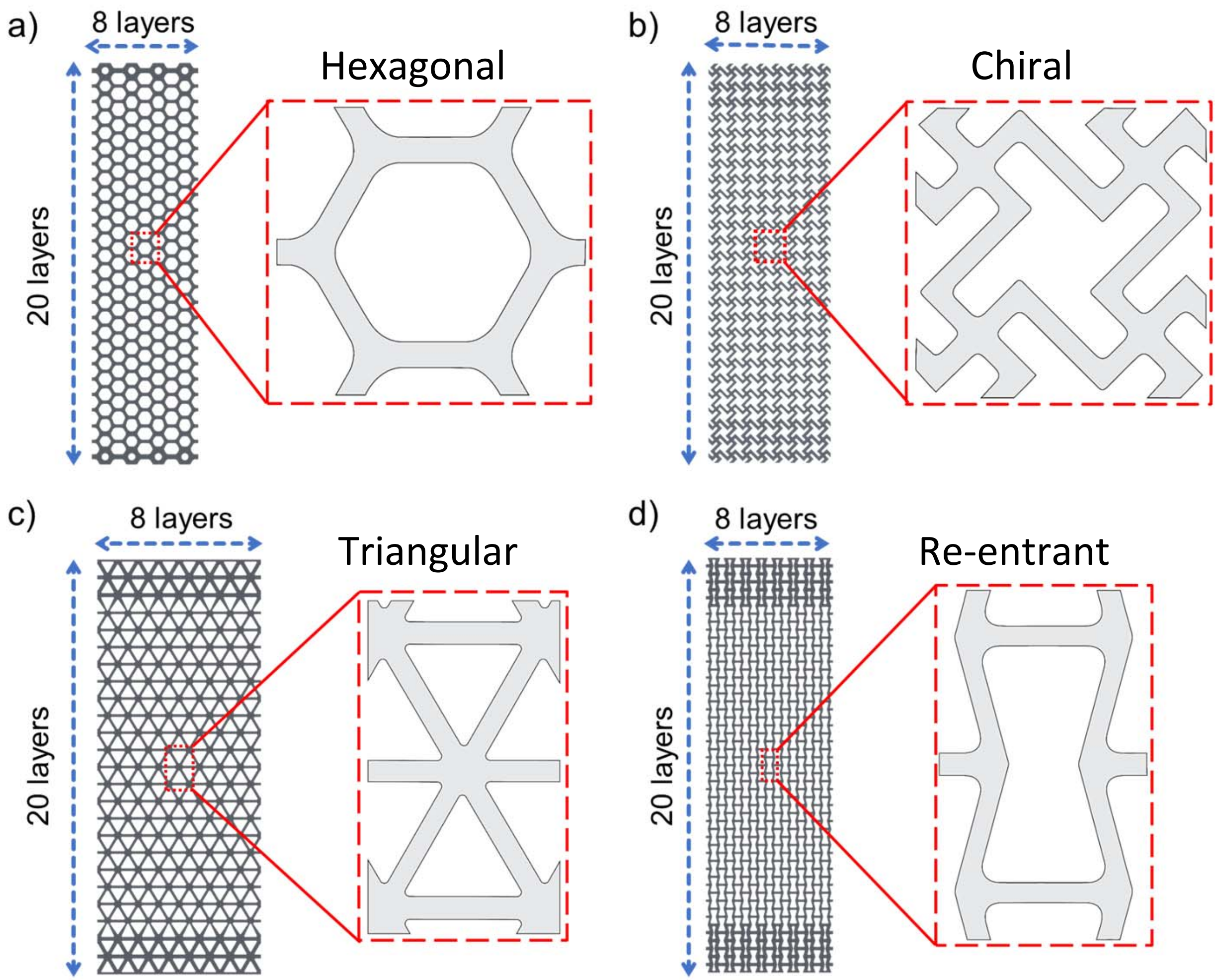
[4] Saadi et al. (2023)

2D lattice structures

- 0.025 phr CNT/polymer
- Four unit cell geometries
  - **Hex**agonal
  - **Ch**iral
  - **Tri**angular
  - **Re**-entrant
- Three relative densities
  - 20%
  - 30%
  - 40%

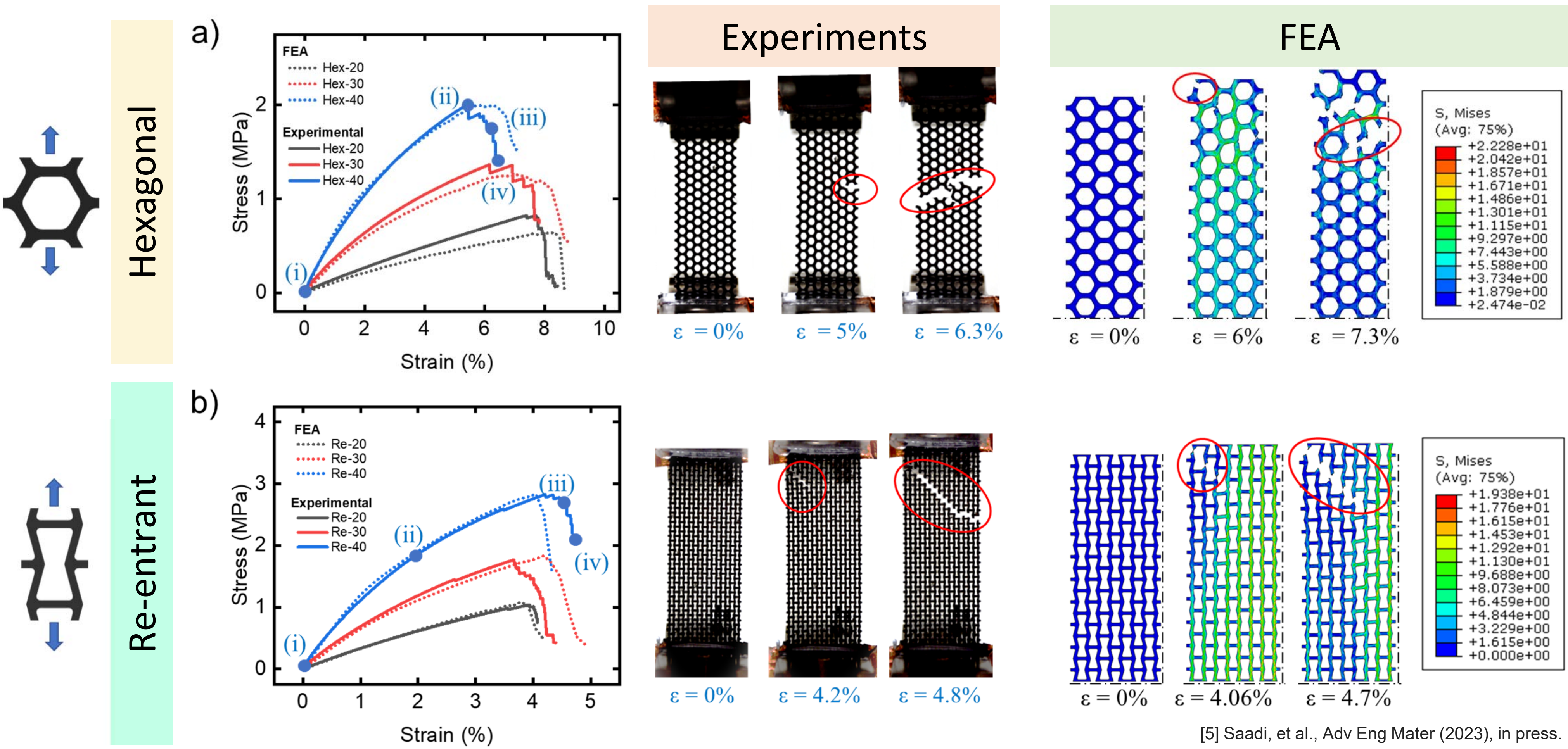
$$\bar{\rho} = \frac{\rho^*}{\rho_s}$$

images correspond to 40% relative density



[5] Saadi, O. W., Uddin, M. A., Schiffer, A., & Kumar, S. (2023). Digital light processing of 2D lattice composites for tunable self-sensing and mechanical performance. *Advanced Engineering Materials*, *in press*.

2D lattice structures: Tensile response



[5] Saadi, et al., Adv Eng Mater (2023), in press.

2D lattice structures: Gibson-Ashby power law fitting

Gibson-Ashby scaling relations:

Modulus: $\bar{E} = \frac{E}{E_s} \propto \bar{\rho}^m,$

Tensile strength: $\bar{\sigma} = \frac{\sigma_y}{\sigma_{ys}} \propto \bar{\rho}^n$

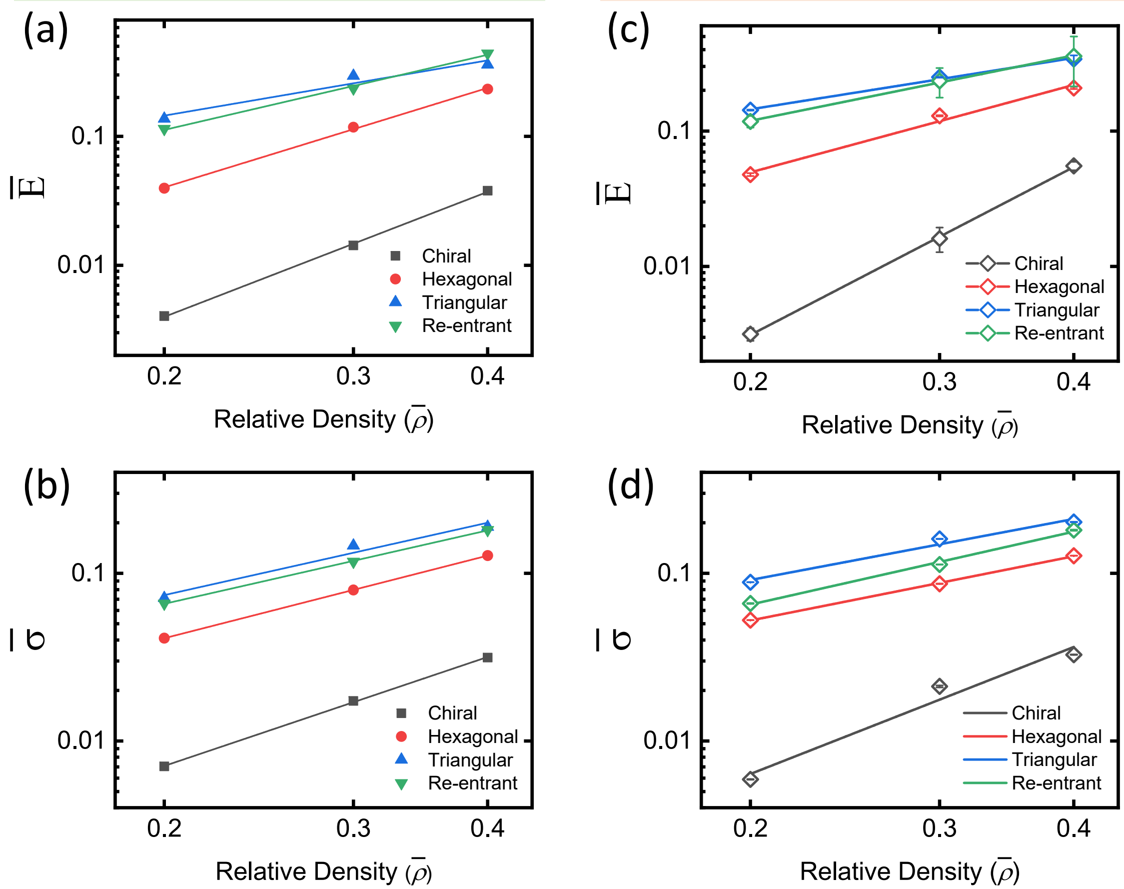
Bend-dominated behavior: $m \approx 2$ and $n \approx 3$

Stretch-dominated behavior: $m = n \approx 1.0$

	{*n*,*m*}
Chiral	{3.2,2.2}
Hexagonal	{2.6,1.6}
Triangular	{1.4,1.4}
Re-entrant	{1.9,1.5}

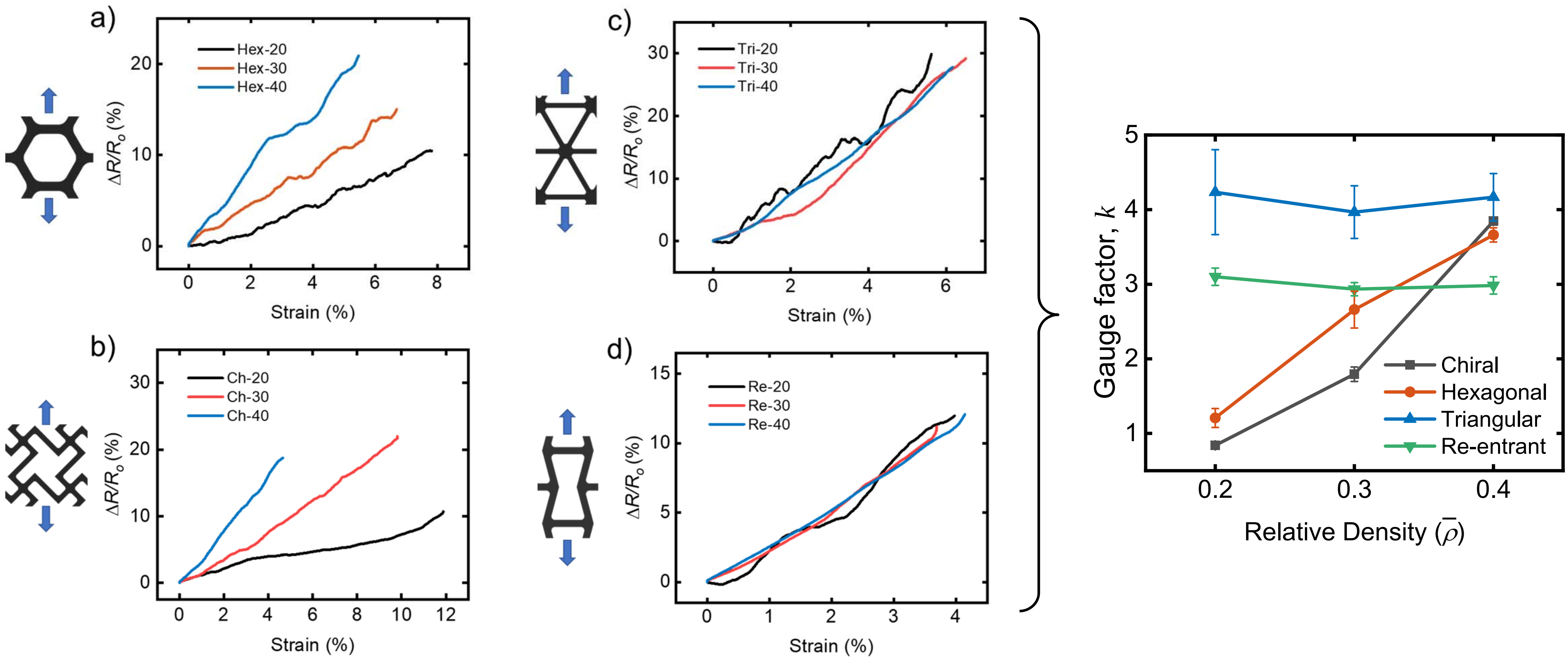
FEA

Experiments



[5] Saadi, et al., Adv Eng Mater (2023), in press.

2D lattice structures: Piezoresistive response



[5] Saadi, et al., Adv Eng Mater (2023), in press.

3D lattice structures

0.025 phr CNT/polymer

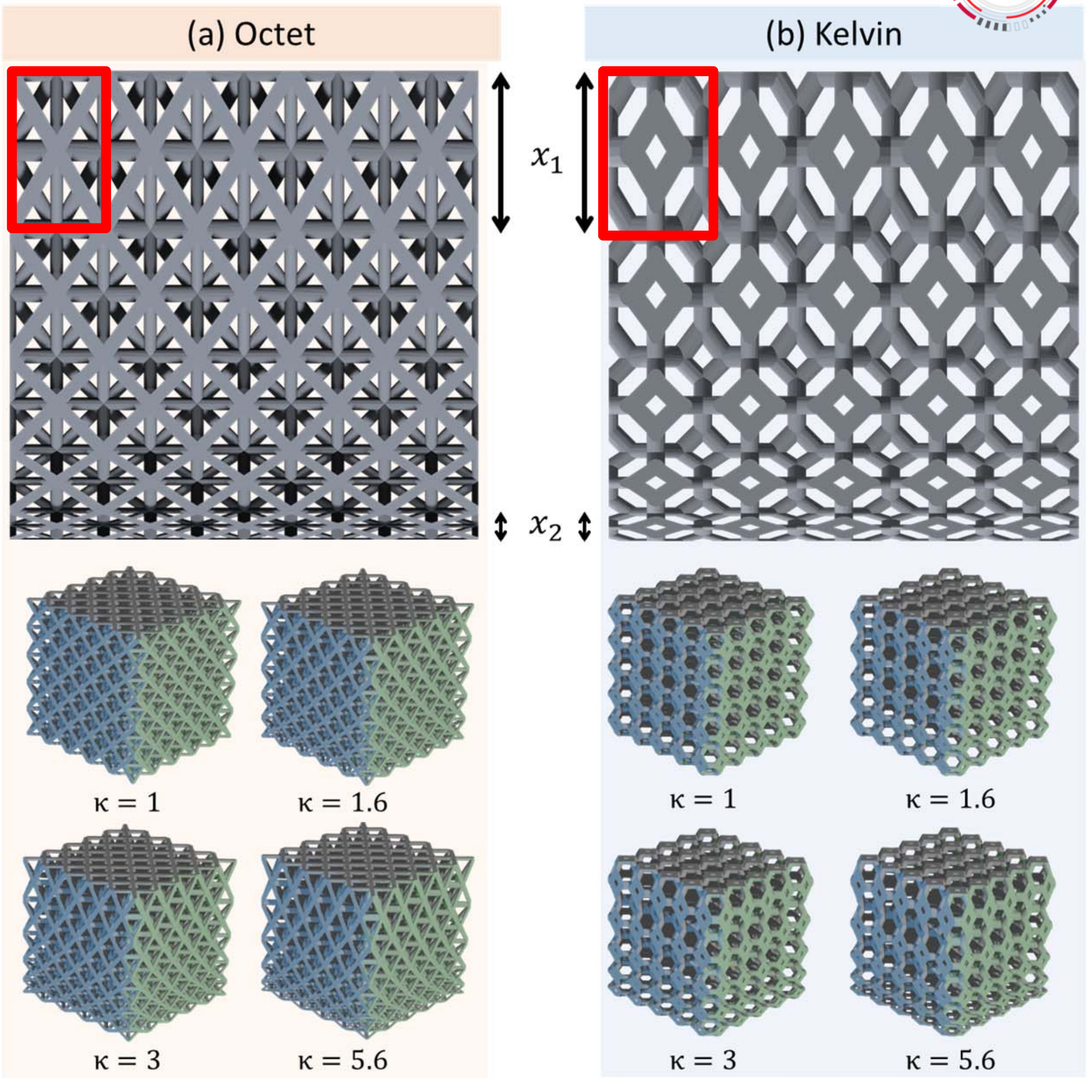
Two unit cell geometries
- Octet lattice
- Kelvin lattice

Three relative densities
- 10%
- 20%
- 30%

Three geometric gradations
- $\kappa = 1.6$
- $\kappa = 3.0$
- $\kappa = 5.6$

$$\kappa = x_1/x_2$$

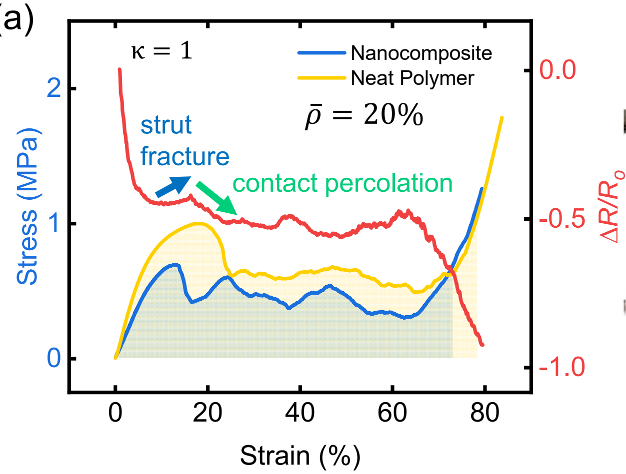
where x_1 and x_2 are the heights of the longest and shortest layers, respectively.

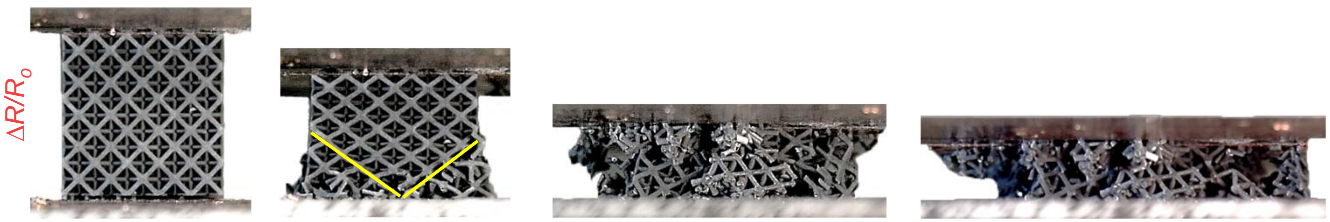


3D lattice structures: Compressive response (Octet)

(a)

κ = 1

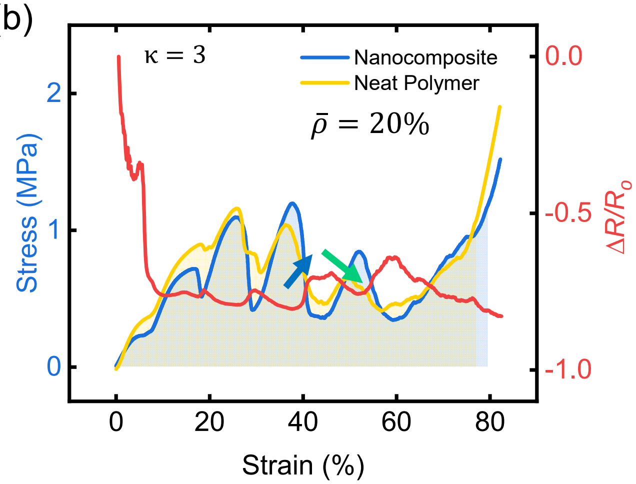




ε = 0% ε = 22% ε = 50% ε = 60%

(b)

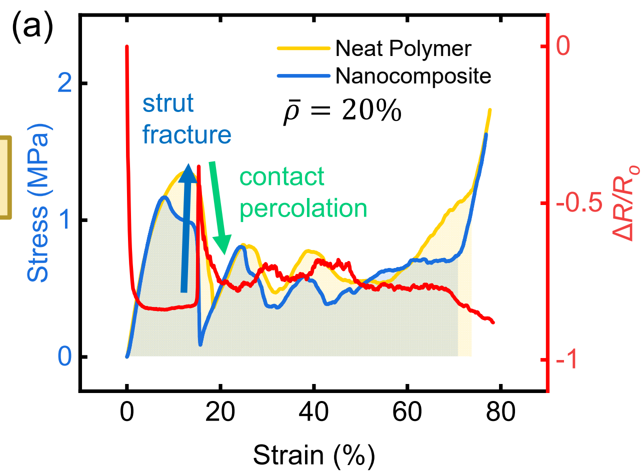
κ = 3

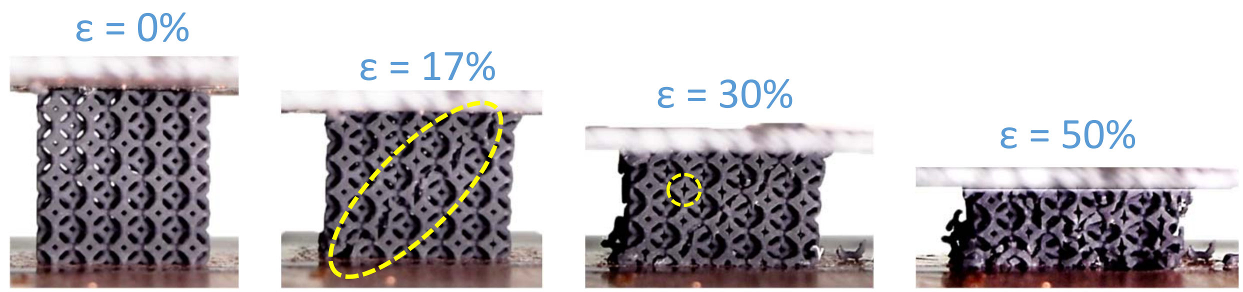


ε = 0% ε = 7% ε = 17% ε = 40%

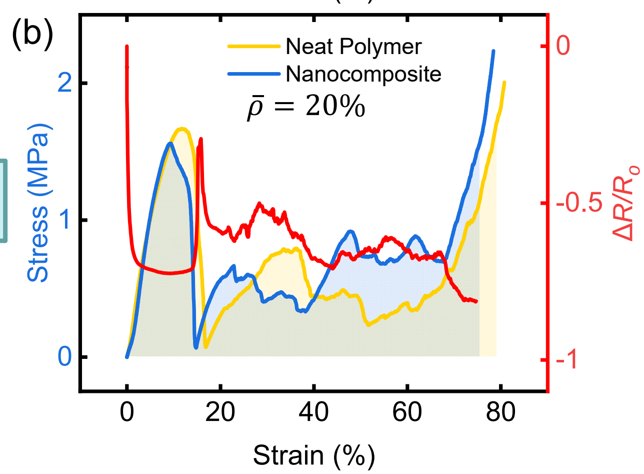
3D lattice structures: Compressive response (Kelvin)

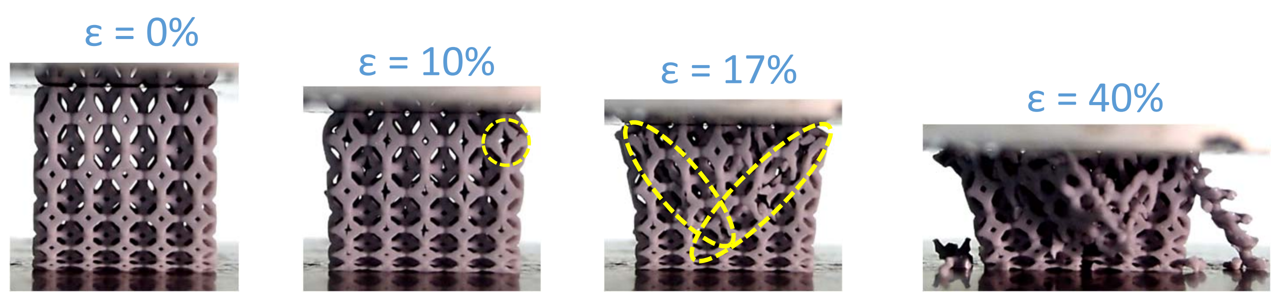
$\kappa = 1$





$\kappa = 3$

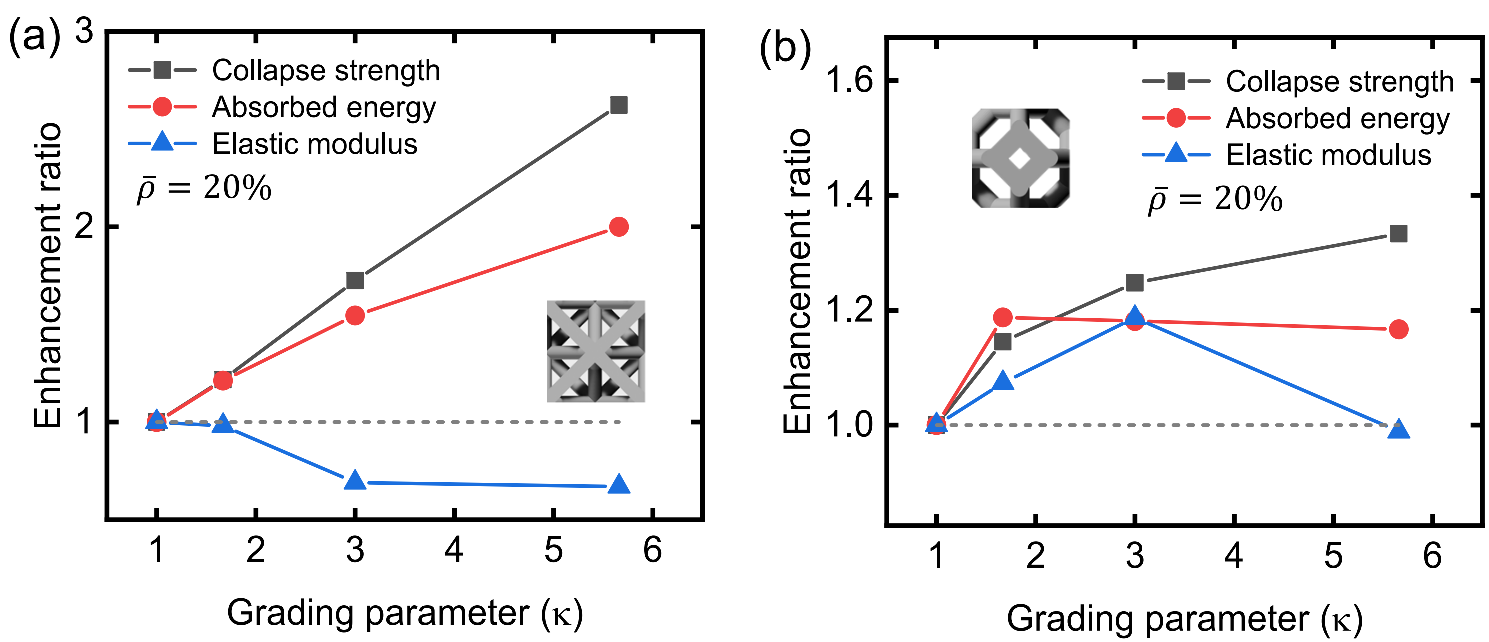




3D lattice structures: Performance comparison

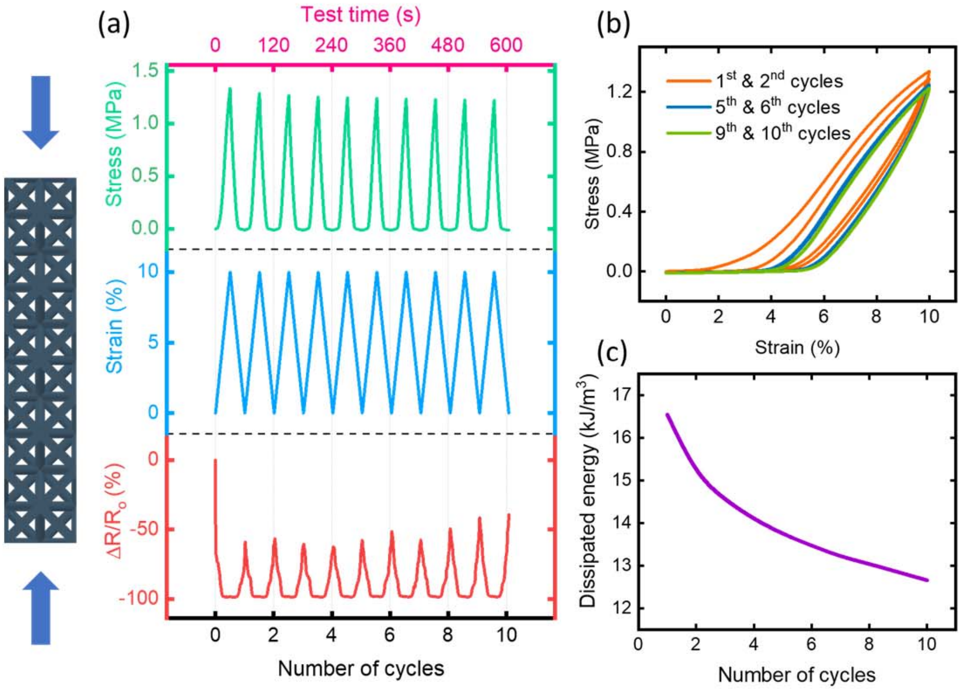
Enhancement ratios:

Strength: $R_{\sigma} = {}^{\sigma_g}/_{\sigma_{ng}}$ Modulus: $R_E = {}^{E_g}/_{E_{ng}}$ Energy absorption: $R_w = {}^{W_g}/_{W_{ng}}$

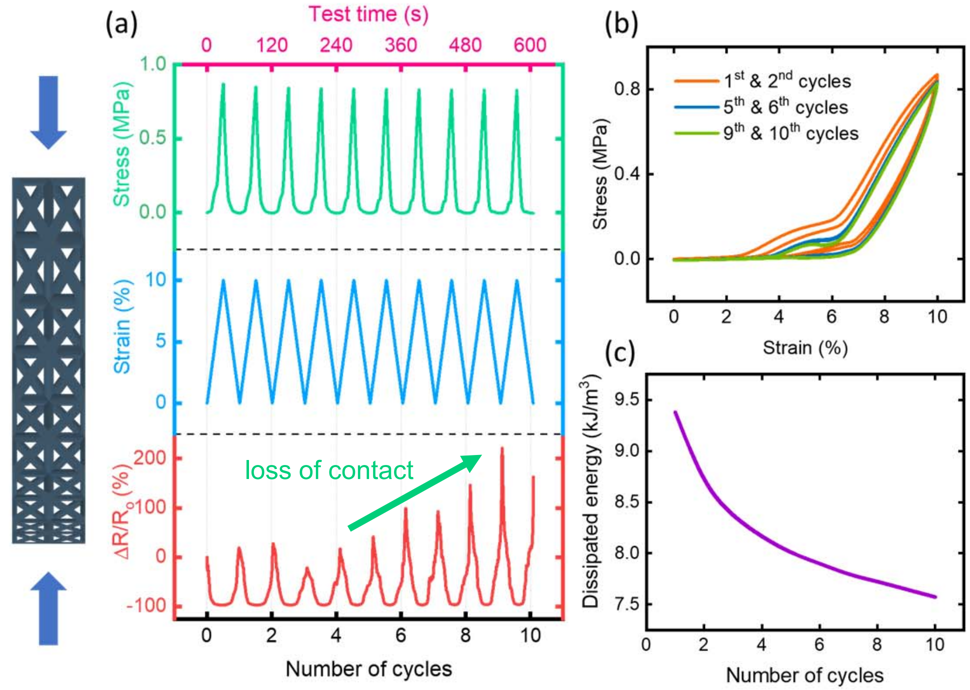


3D lattice structures: Cyclic compressive loading (Octet)

Non-graded



Graded (κ = 5.6)



Conclusions

- The backbone of this work was the **development of a UV curable nanocomposite resin** with dispersed MWCNTs suitable for DLP 3D printing.
- **Electrical percolation** in the 3D printed samples was achieved at an **ultra-low nanofiller loading of 0.01 phr.**

2D lattice structures:

- The **piezoresistive response** of the primarily **stretch dominated structures** (re-entrant and triangular) was insensitive to the relative densities**.**
- The **gauge factors** of the **bend dominated structures** (hexagonal and chiral) increased with increasing relative density.

3D lattice structures:

- The integration of a **gradient in the unit cell length** had a **strong effect on the compressive response of the Octet lattice**, and a relatively **weak effect on the Kelvin lattice**.
- Under compressive loading, the piezoresistive response of was controlled by two competing factors: (i) **the loss of percolation across fractured struts**, causing the electrical resistance to increase, and (ii) **the percolation of contacts across densified cell layers**, causing the resistance to decrease.

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Thanks