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Structural metamaterials

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Sandia National Laboratories

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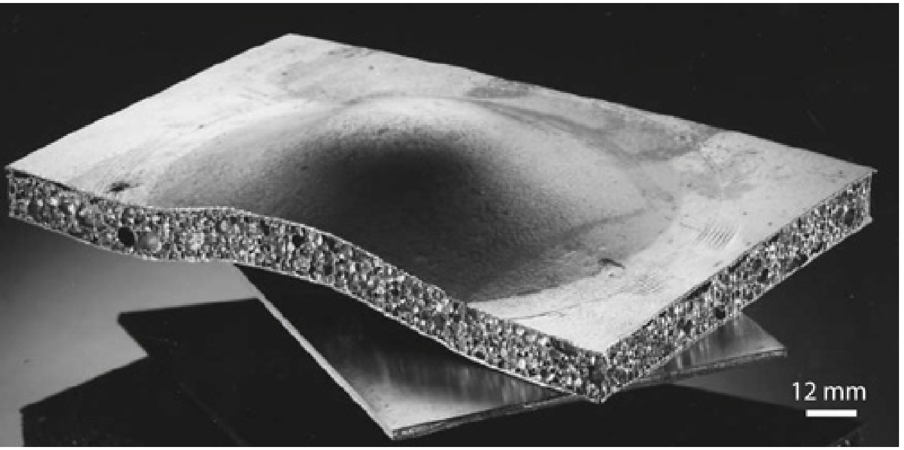
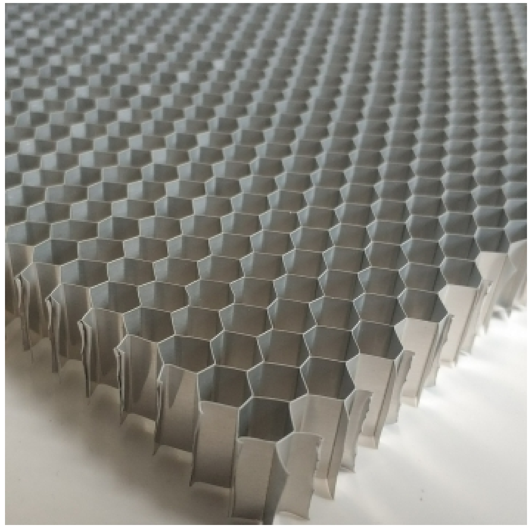
Structural lattices & cellular structures



Aluminum Foam Sandwich (AFS) Panel



Aluminum Honeycomb

Uses of Structural Metamaterials

Quasi-static elastic behavior:
- High strength-to-weight ratio
- High stiffness-to-weight ratio

Dynamic elastic behavior:
- Delayed wave transmission

Plastic behavior:
- Plastic energy absorber (‘crumple zone’)

Dynamic plastic behavior:
- Modification of acceleration-time profile

Vibration behavior:
- Damping of specific frequencies
- Broadband damping

Novel functions:
- Negative poisson’s ratio
- Multifunctional behavior

Other Uses

Particle Filter
Catalyst
Heat Exchanger
Electrolytic reactor
Etc.

Key background references:

Surjadi…Lu, *Adv. Eng. Mater.*, 2019
Bauer…Valdevit, *Adv. Mater.*, 2017
Zadpoor, *Materials Horizons*, 2016

Structural metamaterials outline

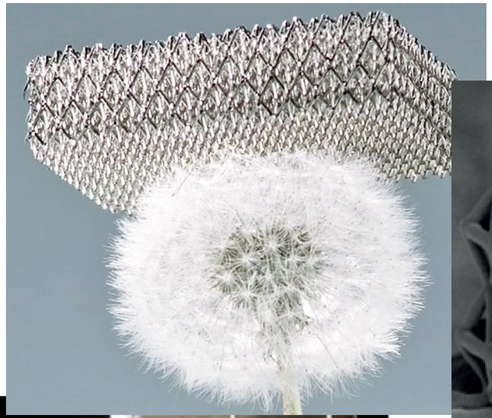
Topic 1: Novel metamaterials for Sandia environments

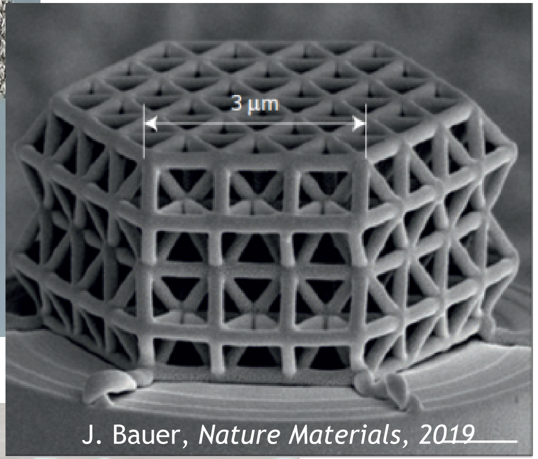
Topic II: Requirements-based optimization of metamaterials

Topic III: Material imperfections & lattice qualification

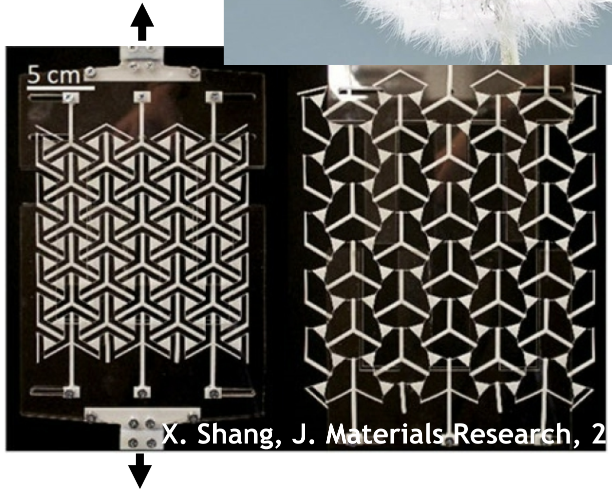
Lattices: unique, tailorable properties

1. Lattices can give you properties not found in bulk materials
2. Lattices expand the range of effective properties available to your printer

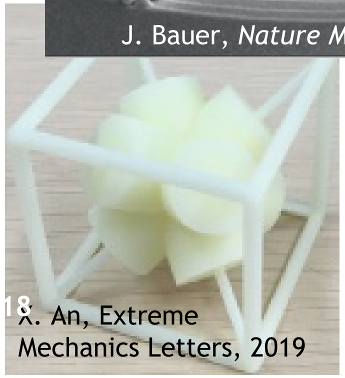




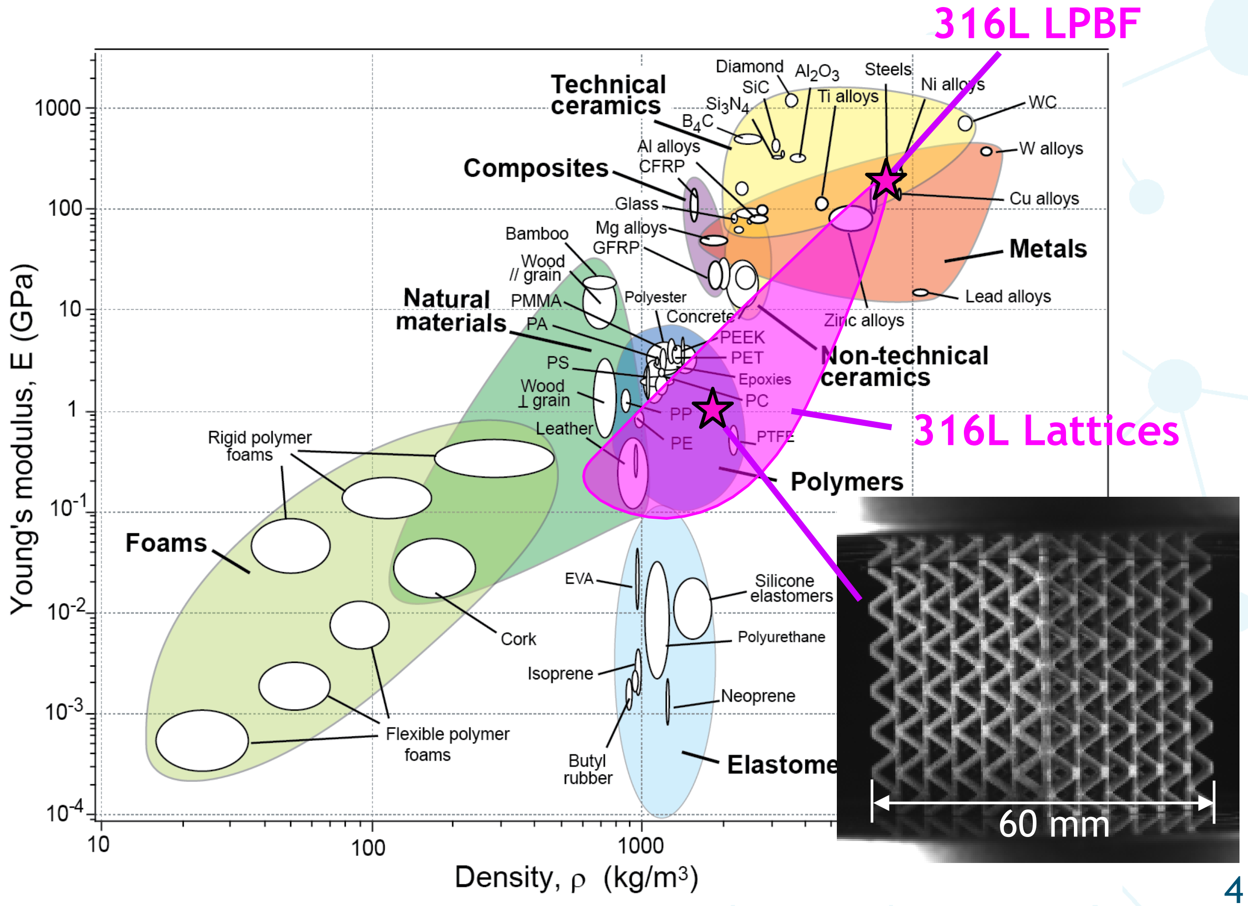
J. Bauer, *Nature Materials*, 2019



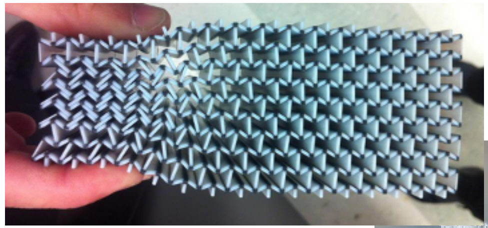
X. Shang, J. Materials Research, 2018

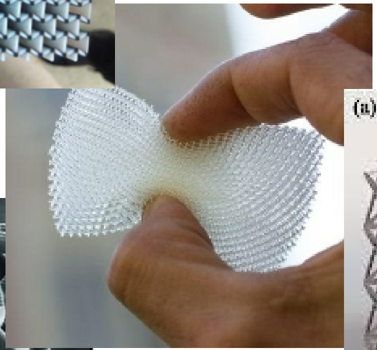


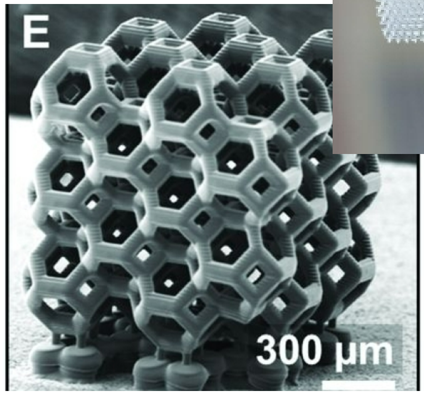
X. An, Extreme Mechanics Letters, 2019

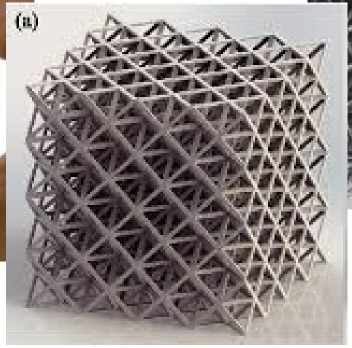


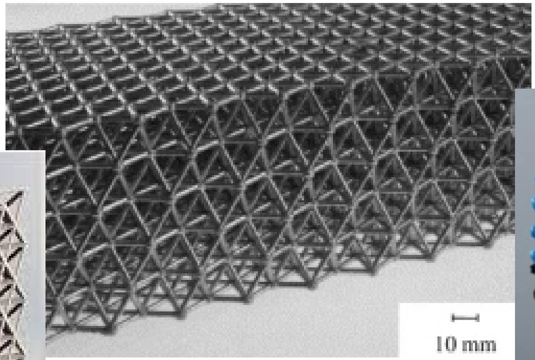
The rubric for developing structural lattices is unnecessarily constrained

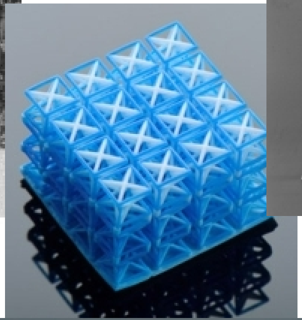


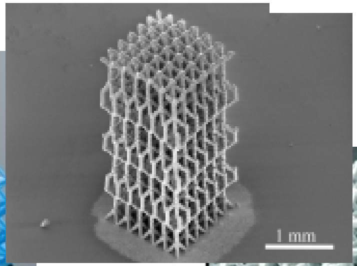


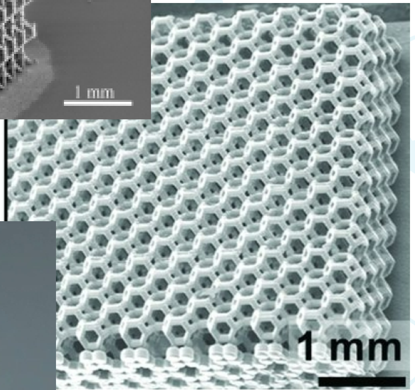


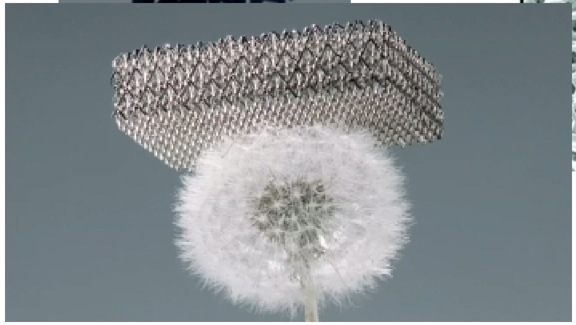












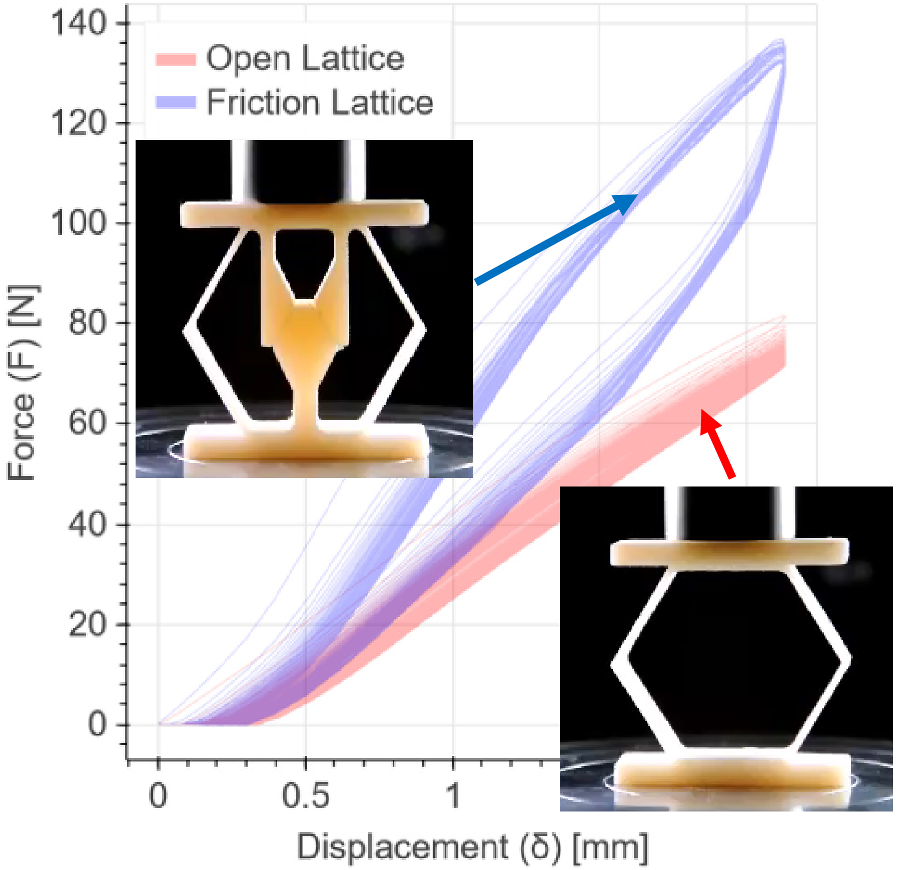
Example publications:
Schaedler…Carter, *Science*, 2011
Jiang…Chen, *Advanced Materials*, 2018

Truss-like strut-and-node architectures are limiting:

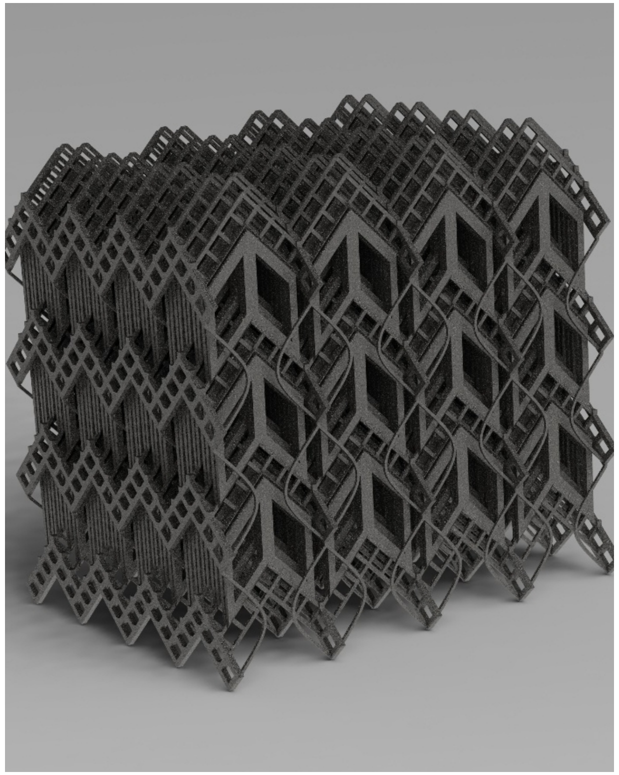
- Bending & torsion
- Tension & Compression
- Buckling

What have others missed?
Can we envision new deformation modes that give more opportunities for control?

Frictional energy dissipation



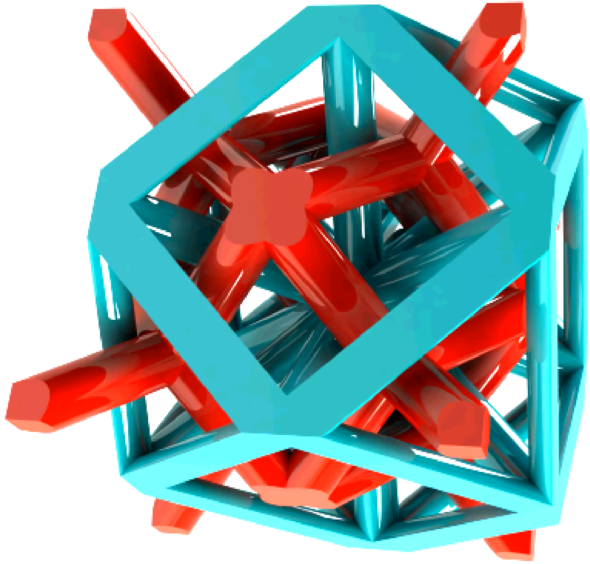
A. Garland, Coulombic friction in metamaterials to dissipate mechanical energy, *Extreme Mechanics Letters*, 2020

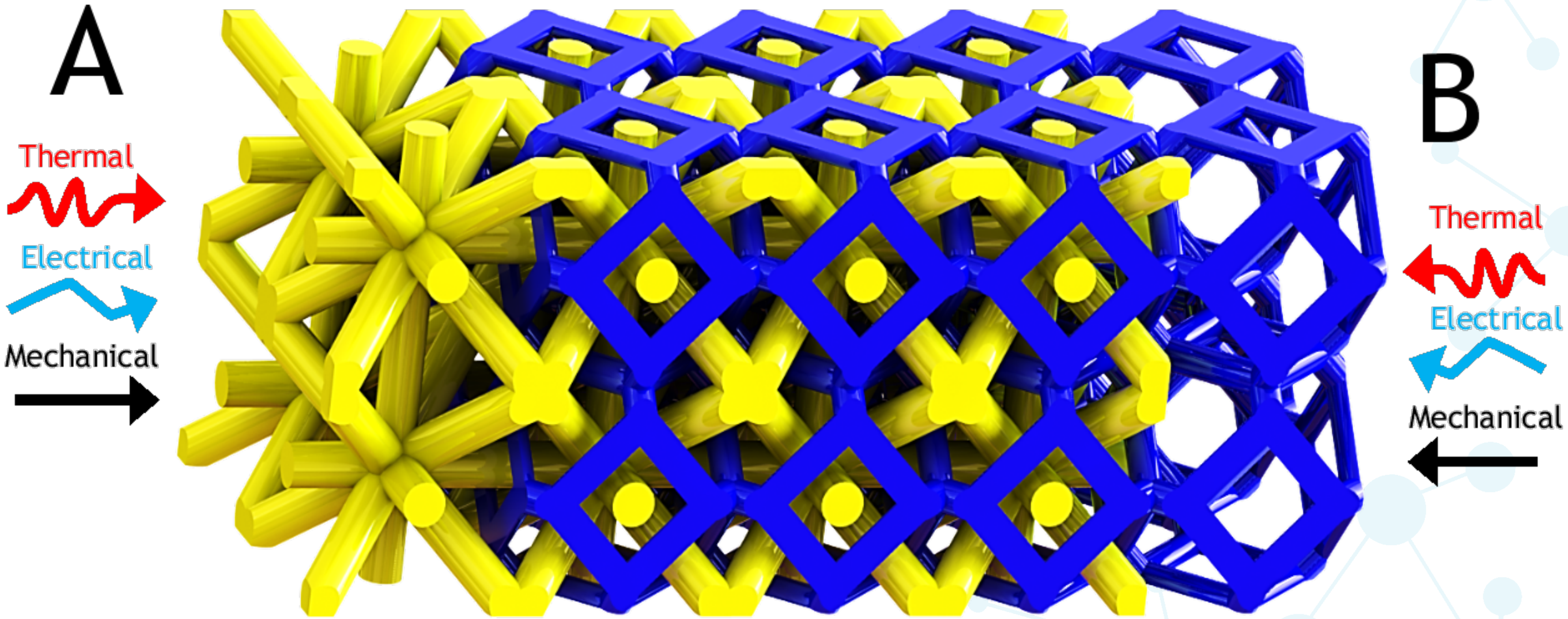


US Patent 10,808,794, “Topological damping materials and methods thereof”, issued 10/20/2020

Interpenetrating Lattices

Two semi-independent sublattices transmit energy via contact or a controllable separation distance

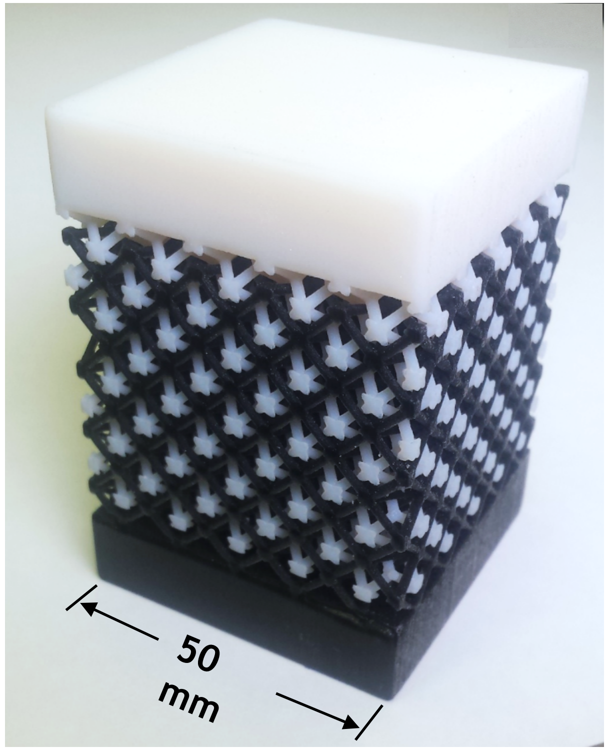




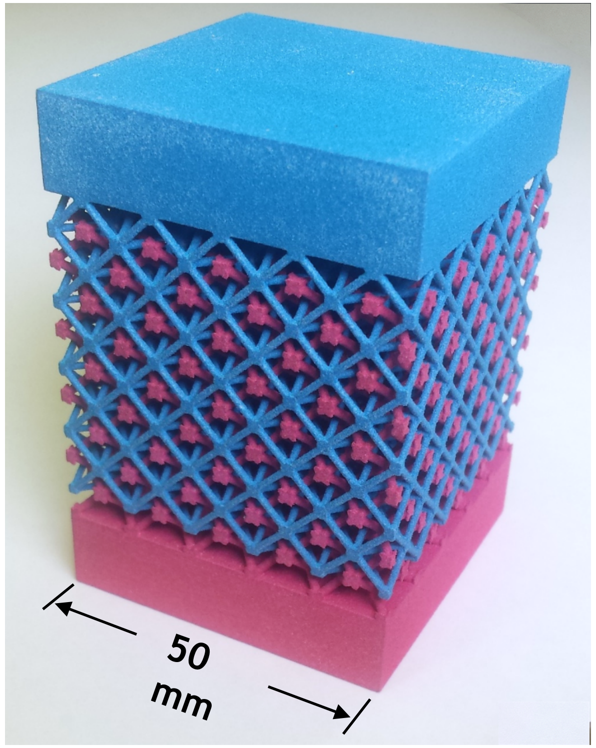
US Patent Filed: “Metamaterials comprising interpenetrating lattices”, March 2021

Interpenetrating lattices can be readily produced from a single material on many printers!

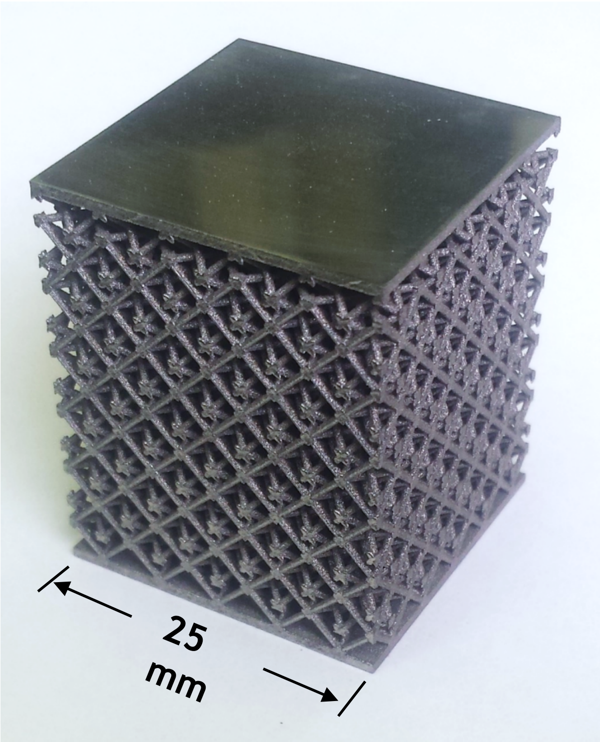
Polyjet
(Objet J826)



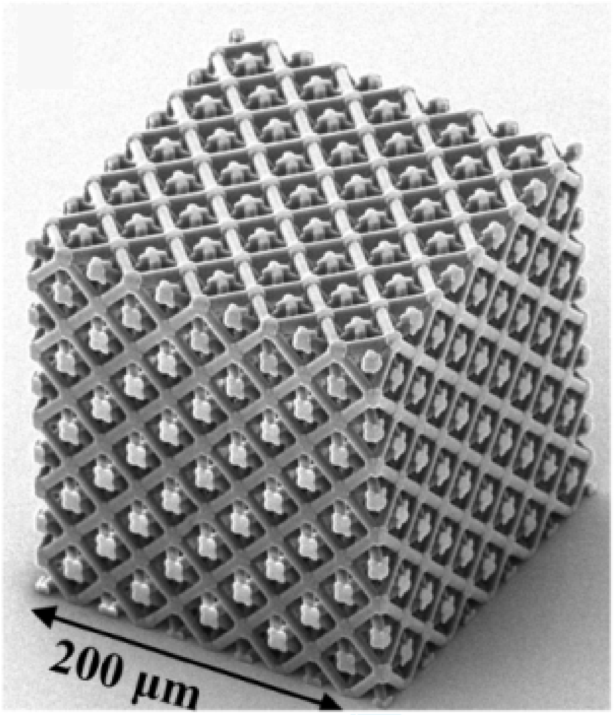
Multi-Jet Fusion
(HP 580)



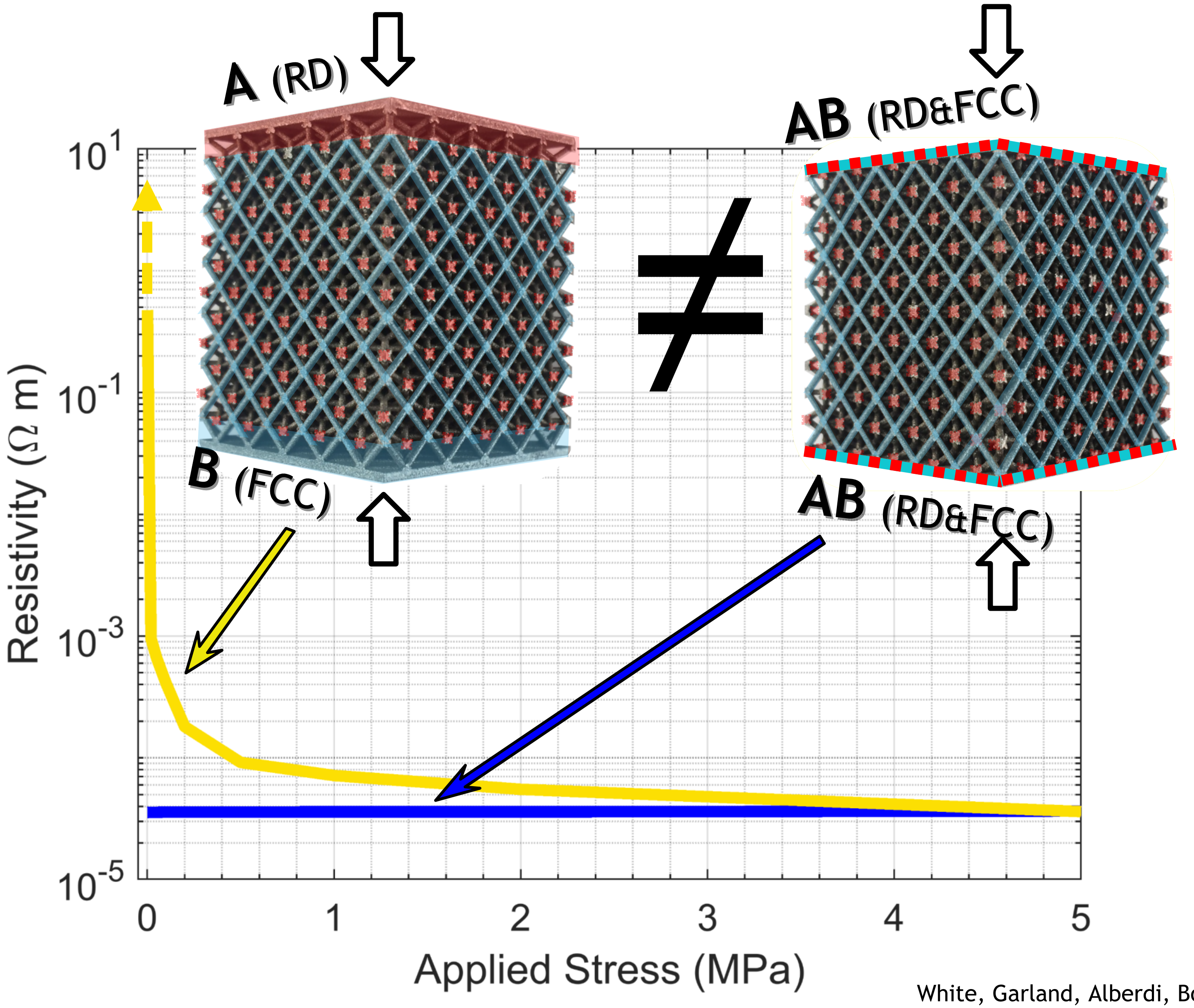
Laser Powder Bed Fusion
(ProX DMP 200)



Multiphoton Lithography
(Nanoscribe GT)



Example: Stress-dependent electrical resistivity



Lattice arraignments controls interface interactions

- Interfaces offer new behaviors

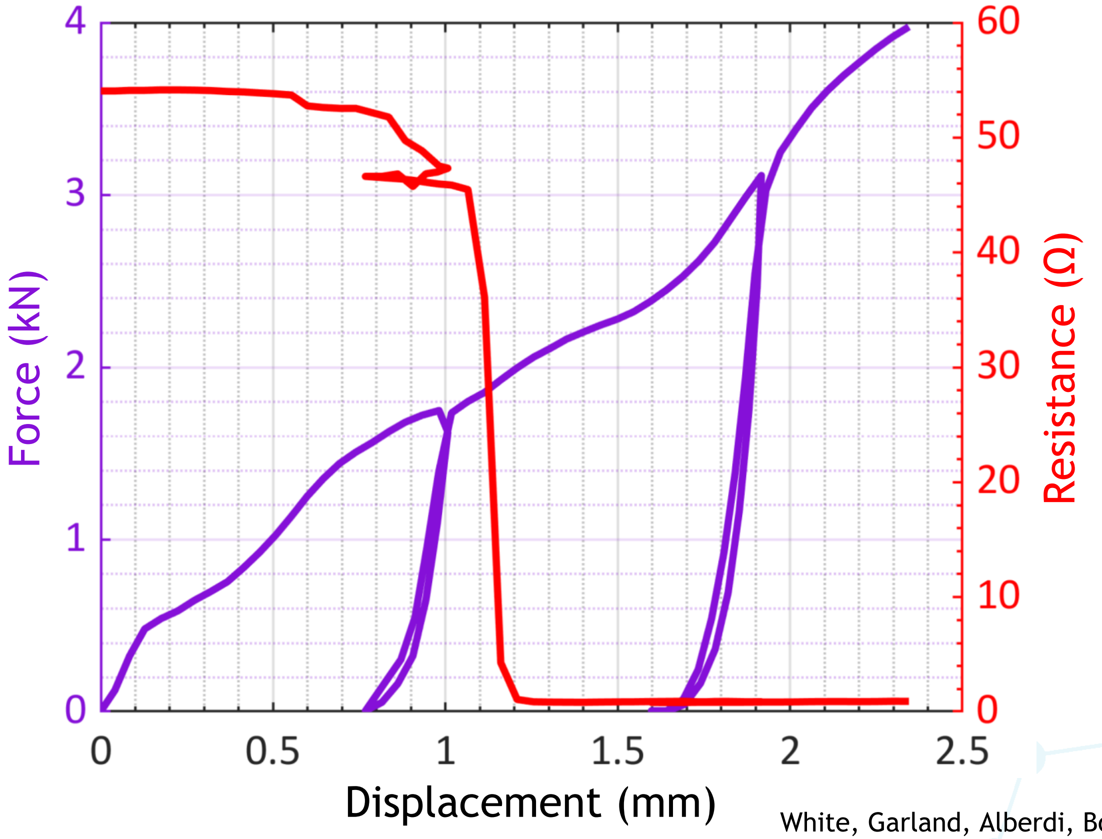
Highly stress sensitive resistivity

White, Garland, Alberdi, Boyce, *Additive Manufacturing*, 2021

Damage Sensing

Plastic damage can be assessed in real time, or passively after the fact

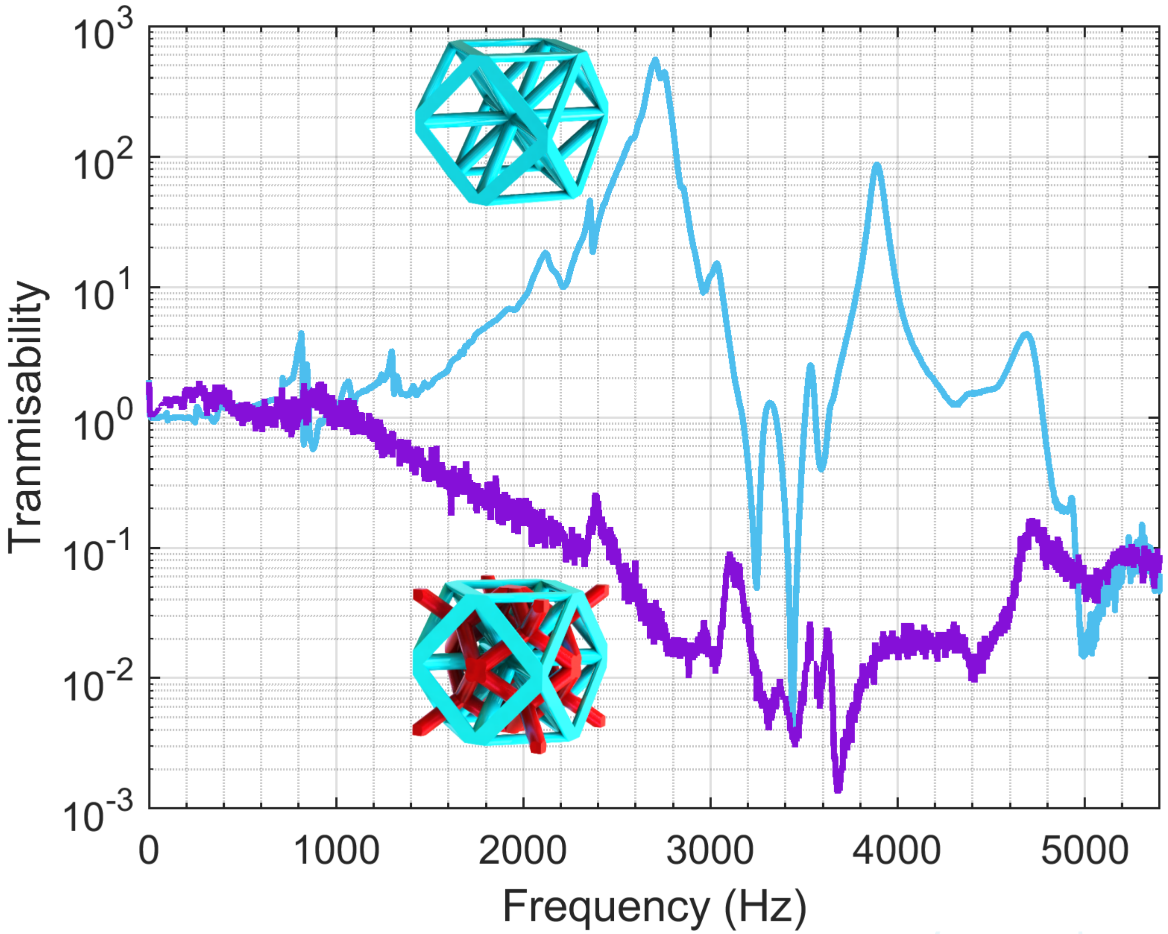
Structural components can double as unpowered sensors



White, Garland, Alberdi, Boyce, *Additive Manufacturing*, 2021

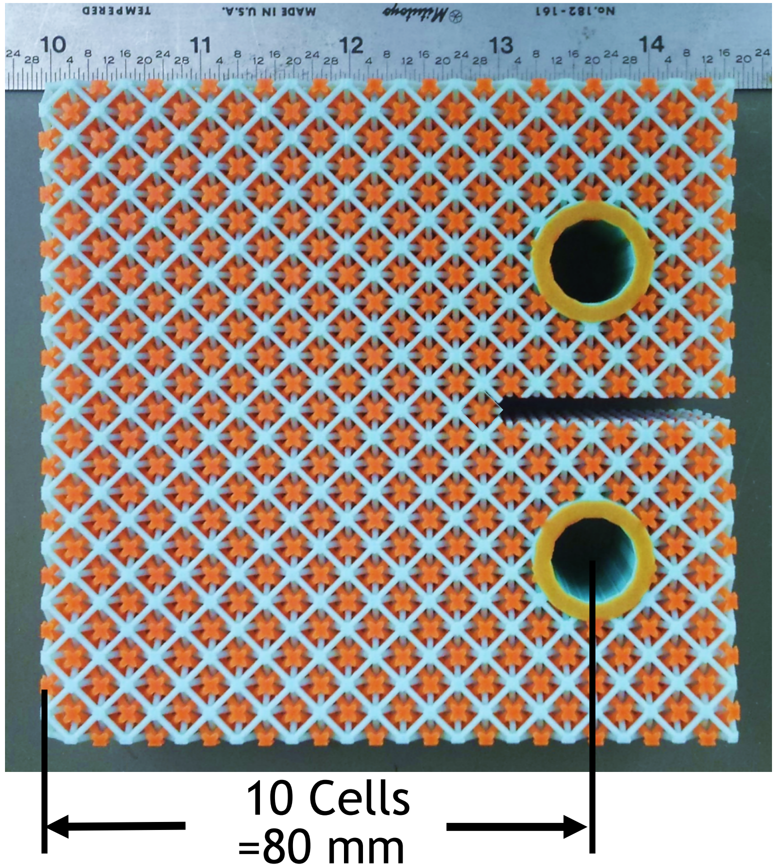
Vibration Isolation

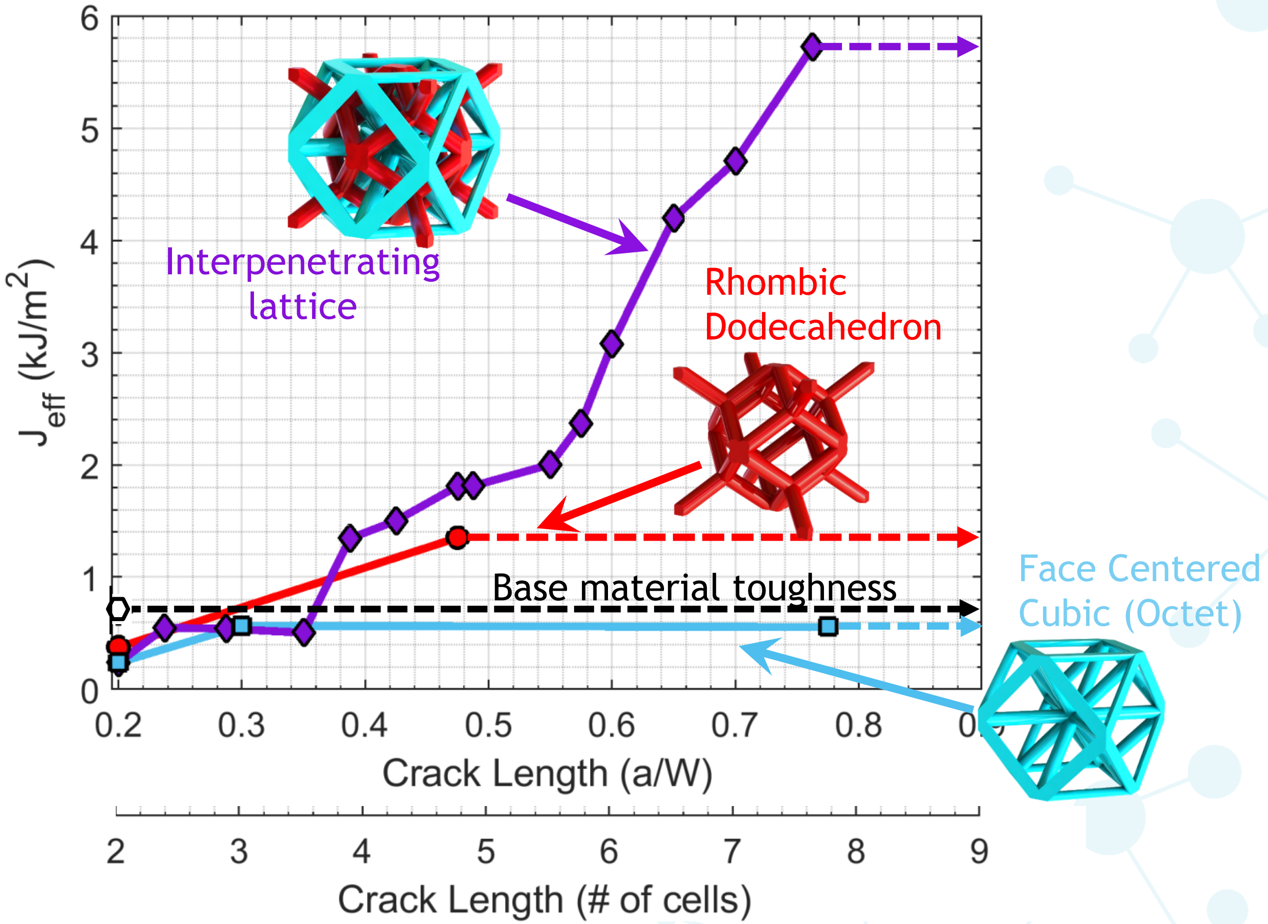
Vibrations are isolated by interfaces and damped by friction



White, et al., *In preparation*

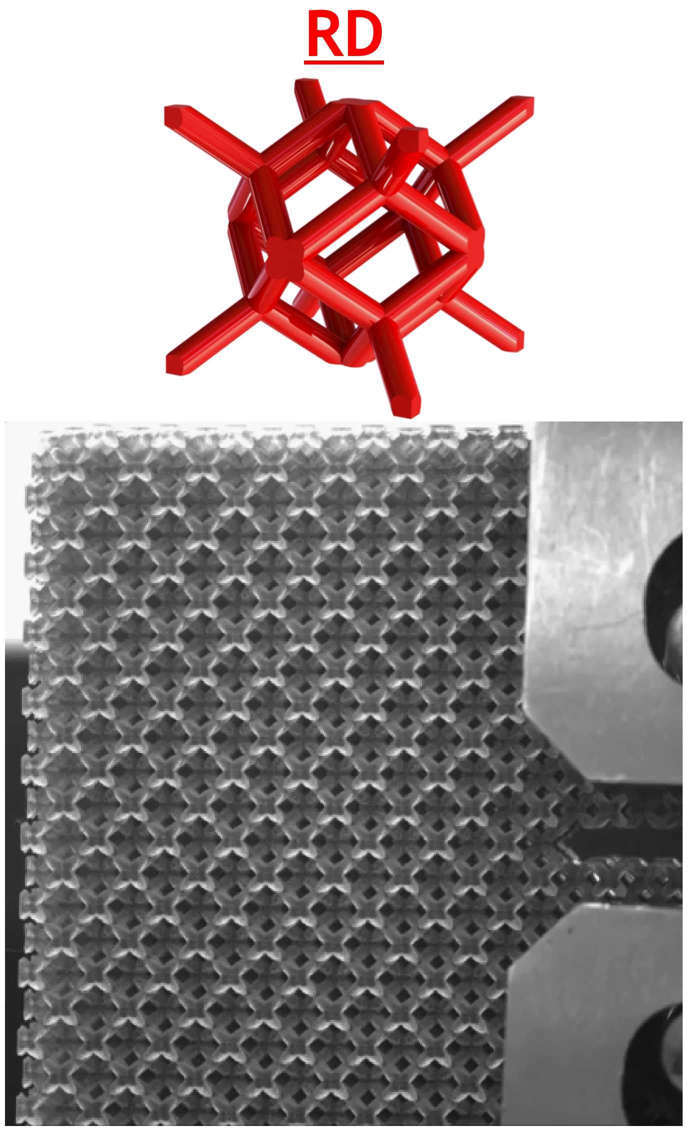
Toughening

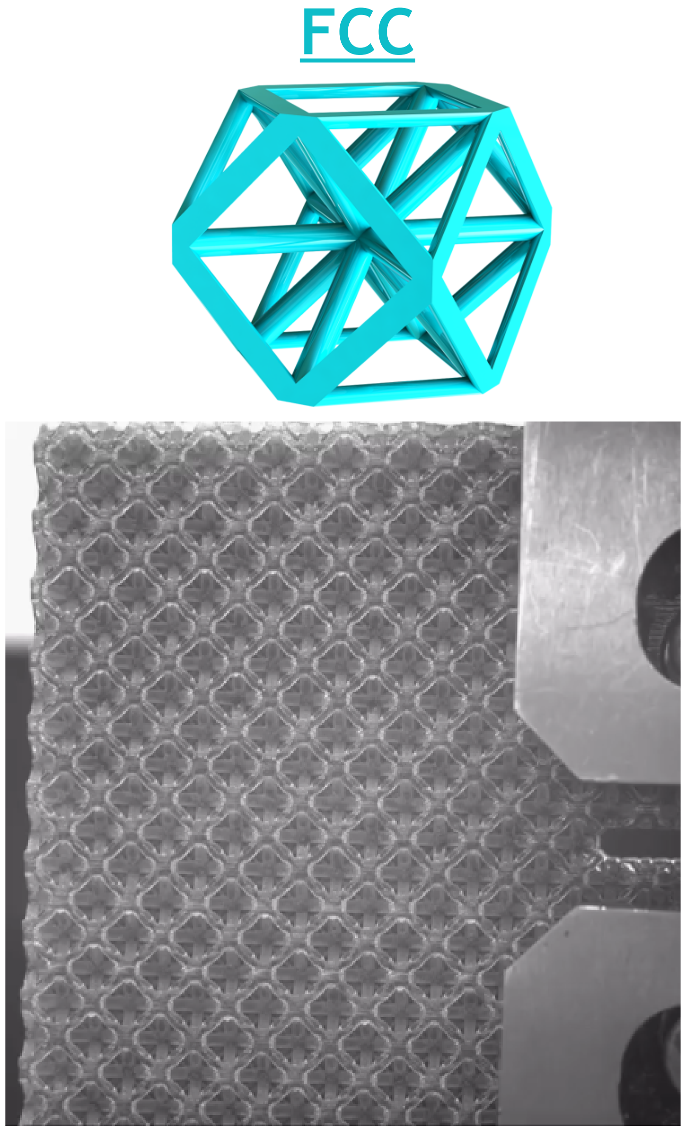


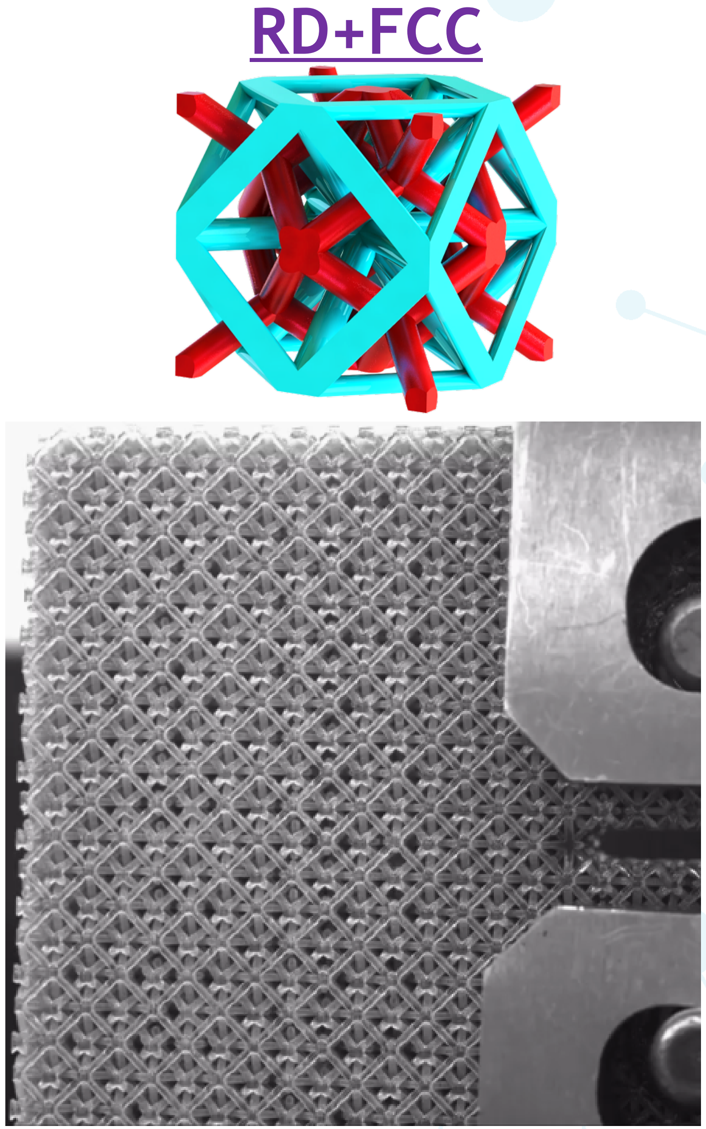


White, et al., *In preparation*

Damage Progression

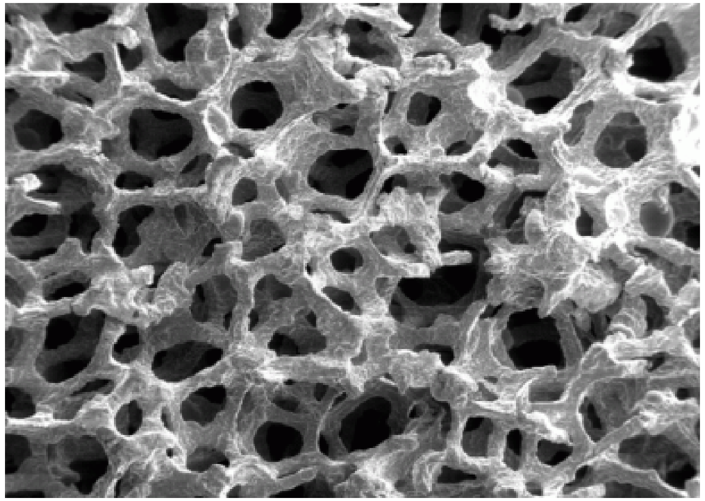


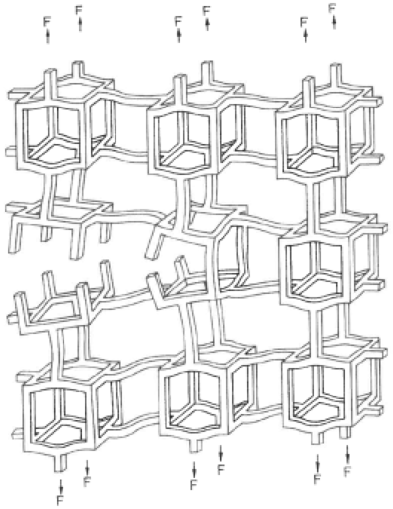


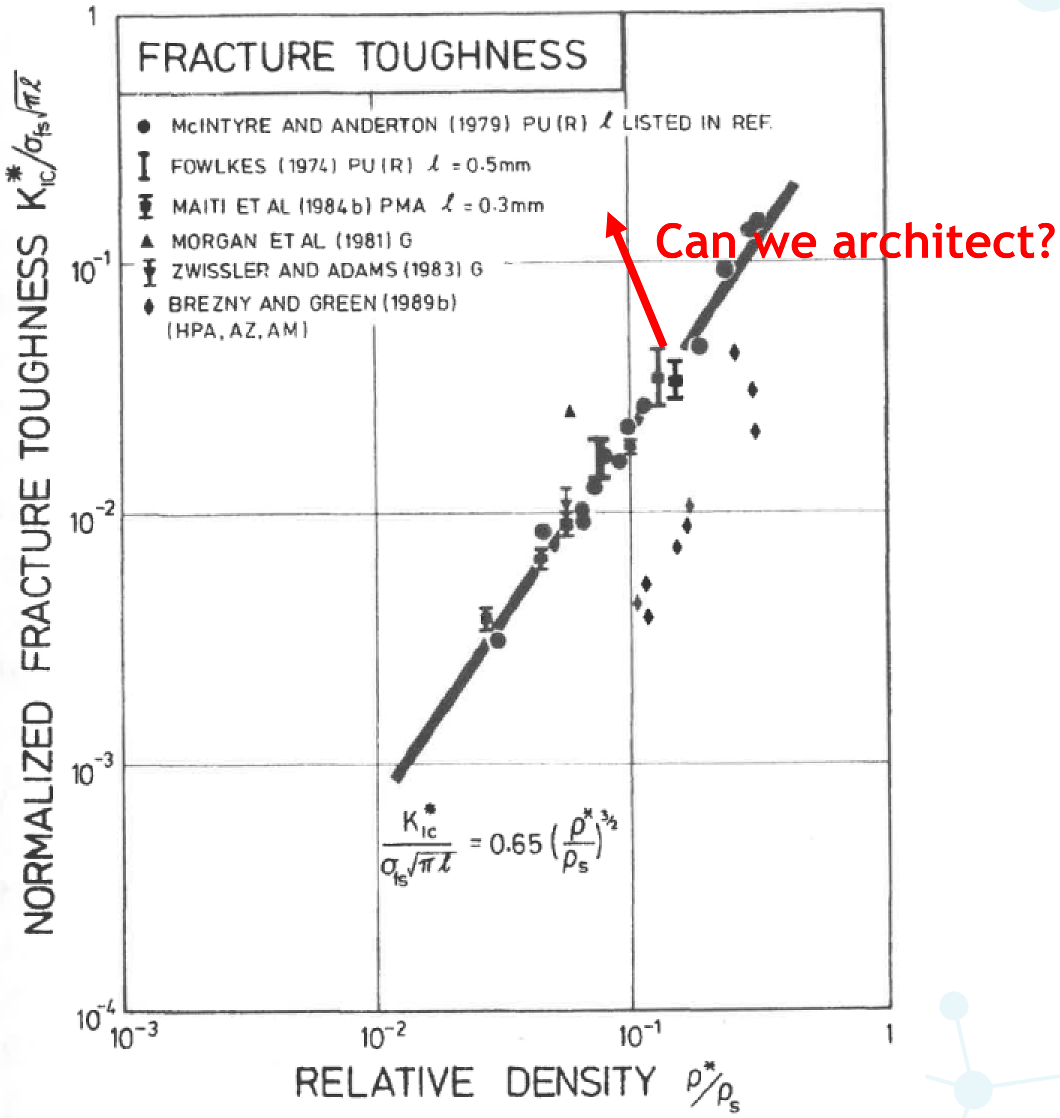


Video speeds are equal: 1 sec =1.75 mm displacement

Cellular structures lose toughness as density decreases

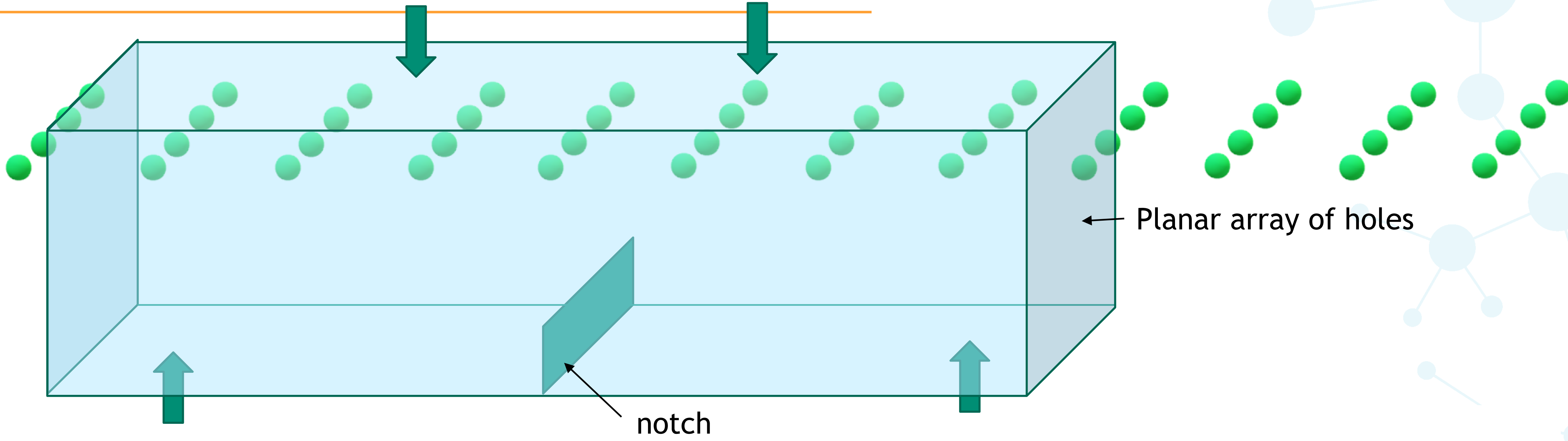


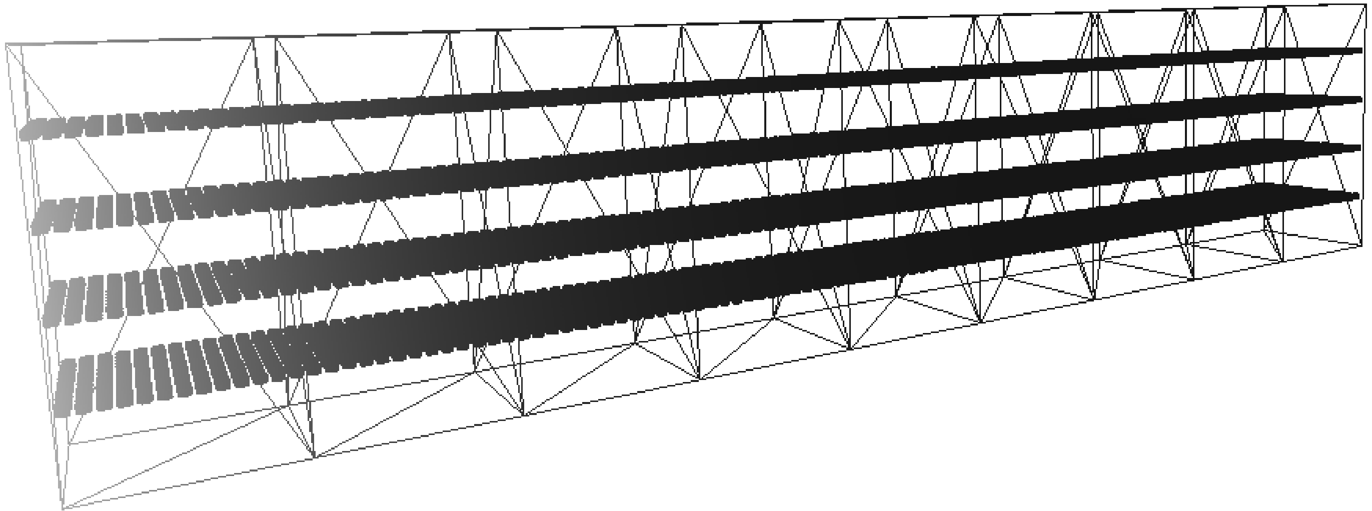




Gibson and Ashby, Cellular Solids, 1997

A simple proof of concept topology: Planar array of holes in an "arrestor" orientation



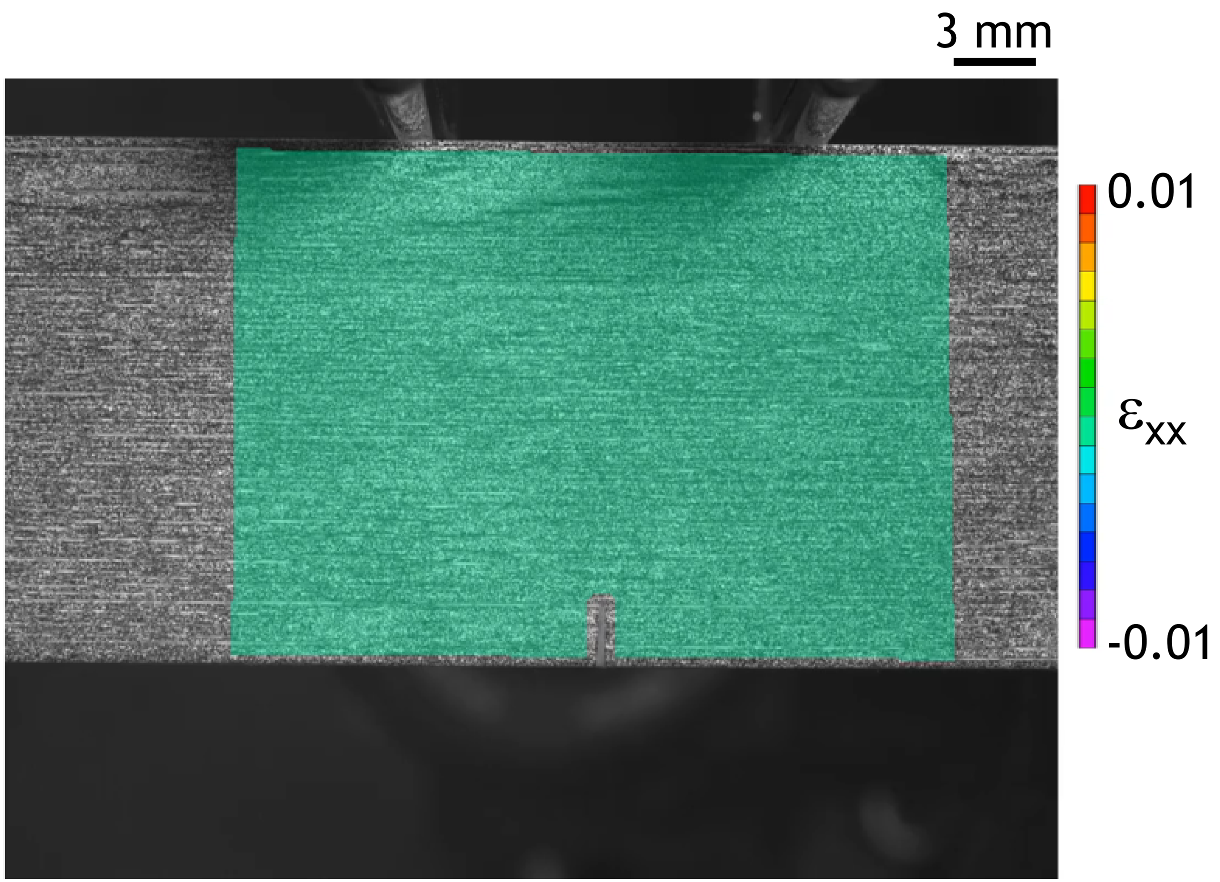


3.4% air
96.6% material

Conway…Boyce, *Materials & Design*, 2021

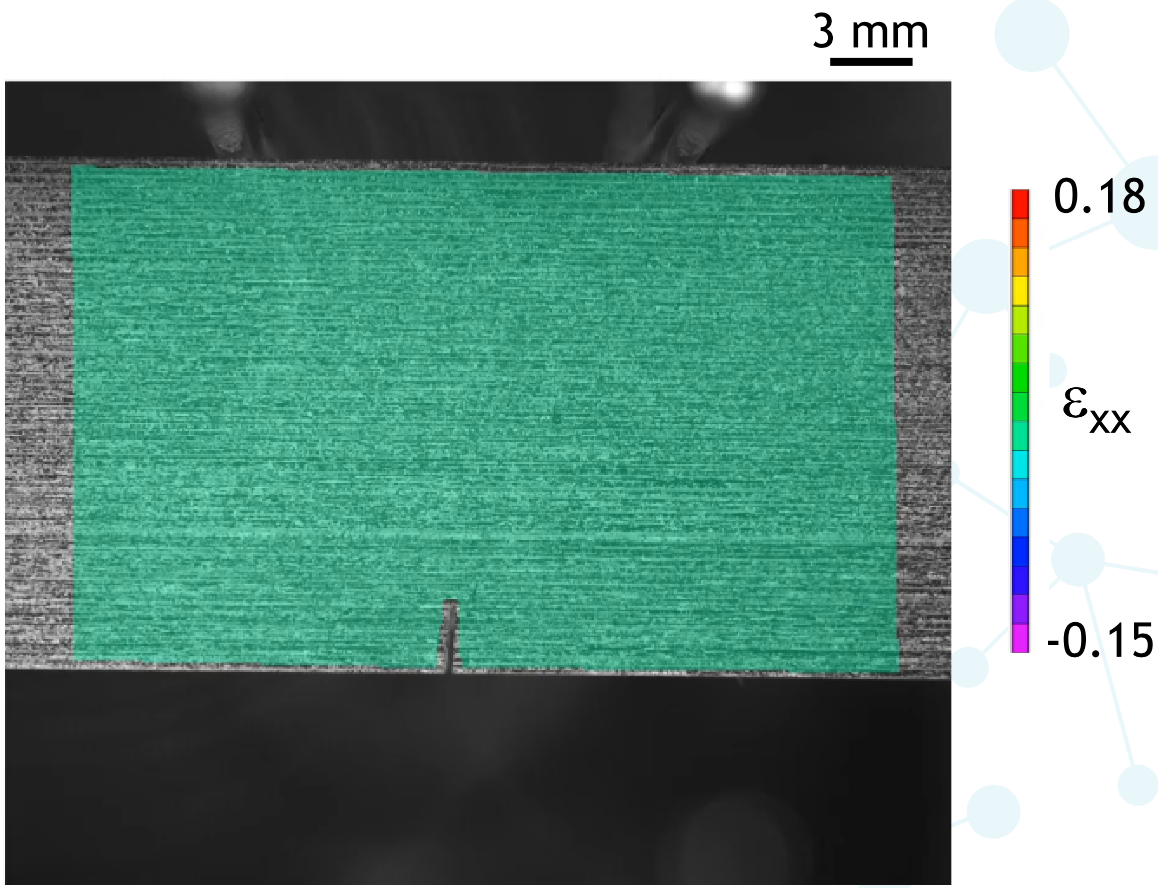
Architected pore-toughening

Unmodified



$G_c \sim 0.6\ kJ/m^2$

96.6% Dense… Four rows of cylindrical holes



$G_c > 3.6\ kJ/m^2$

Material: Stratsys Durus, Polypropylene-like UV-Cured **Glassy Polymer**

Conway…Boyce, *Materials & Design*, 2021

Meso-scale toughening of a Metamaterial

Unmodified Gyroid

Charpy toughness: 34 N-m

Gyroid with additional pores

Charpy toughness: 42 N-m

24% tougher by adding 3% air

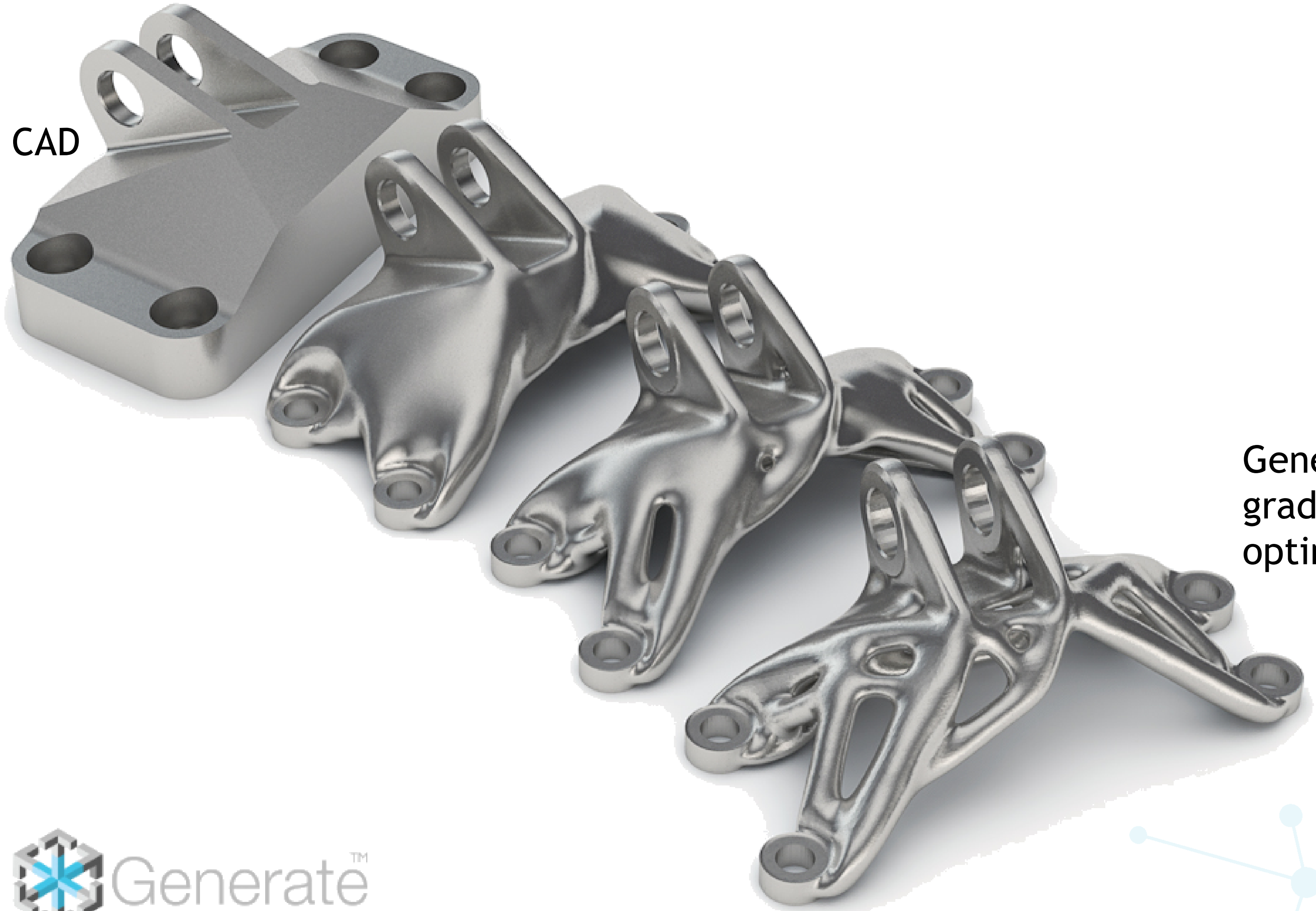
Bar stays in one piece!

Conway…Boyce, *Materials & Design*, 2021

Topic II: Requirements-based optimization of metamaterials

Additive manufacturing enables generative design…

Envisioned by
an engineer in CAD



Generated by an iterative
gradient-based
optimization

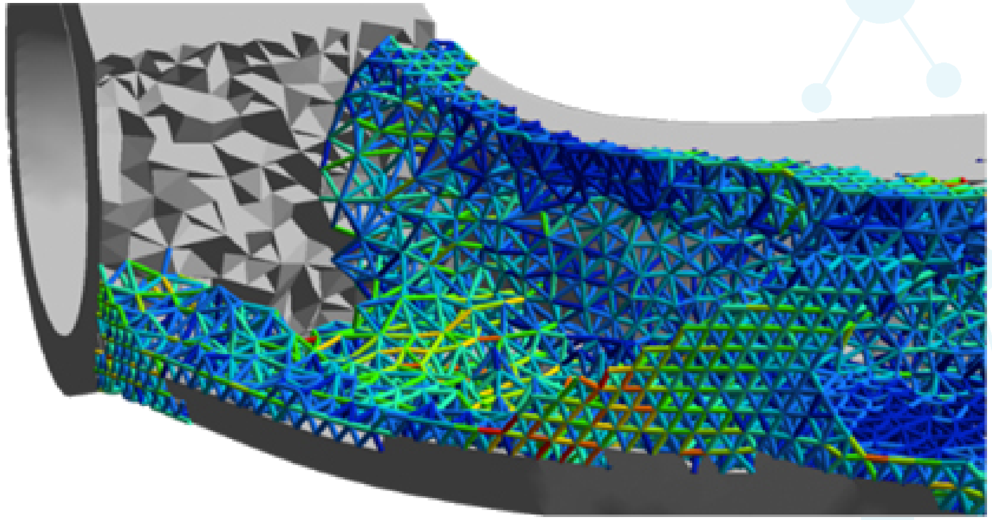
3Dprint.com

Lattices are computationally very expensive …
Optimization is generally confined to elastic problems

Renishaw’s titanium optimized spider support

Even a CAD “STL” file of a simple lattice
Can require many gigabytes.

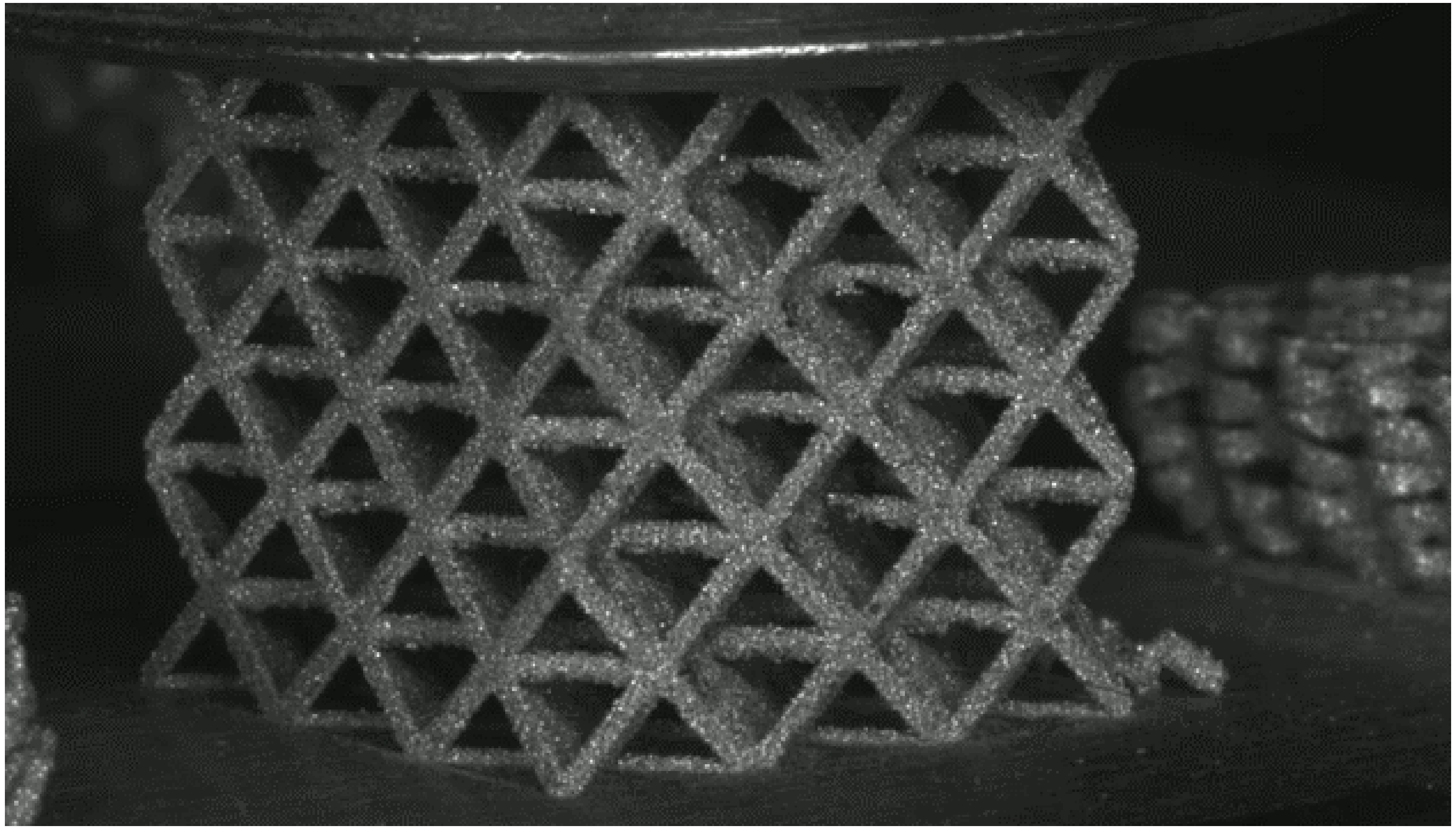
10,000 struts x 100 elements = 1 million elements



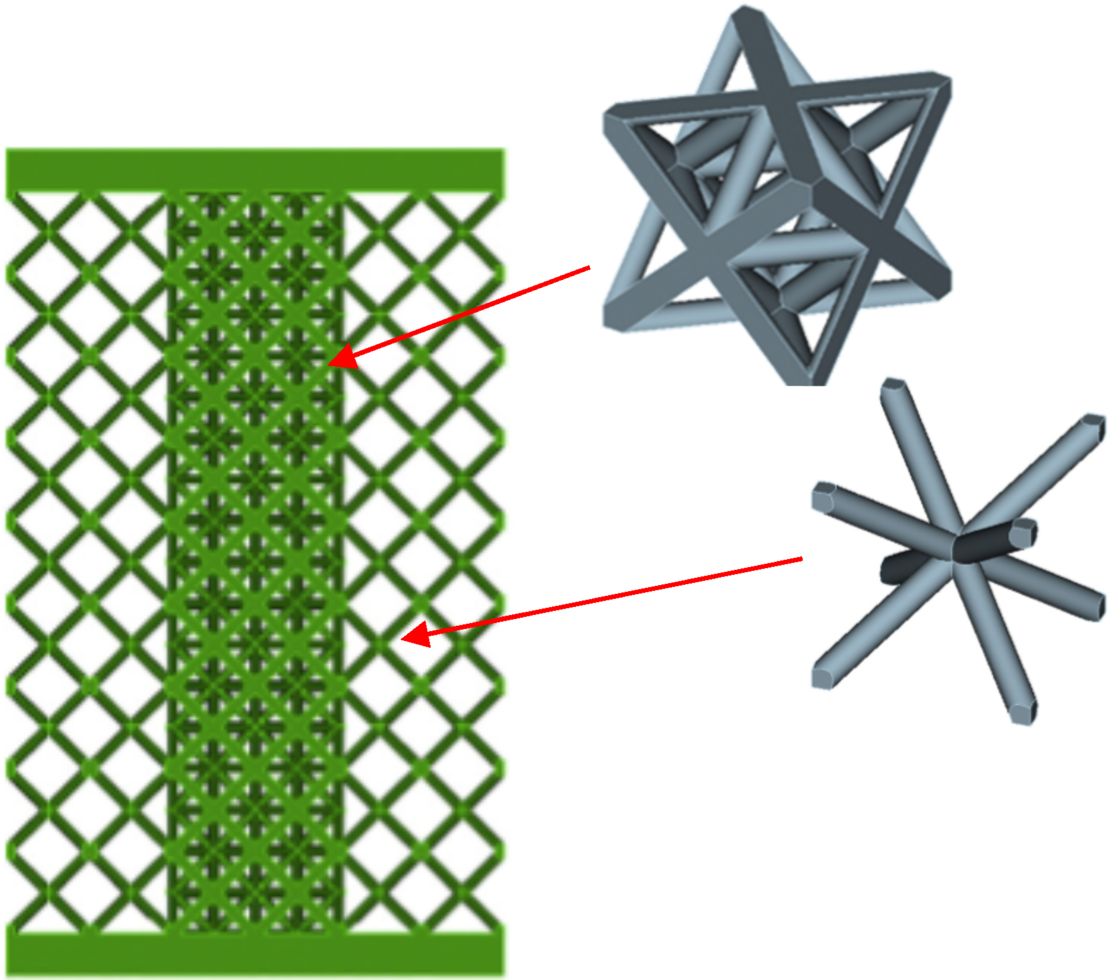
Examples: nTopology; Altair hyperworks; Materialise Magics

Design objective: crush energy absorption

Nonlocality: Shear localization limits crush energy absorption



Can FCC and BCC unit cells be intelligently combined to improve compressive energy absorption?



Homogenization techniques for periodic structures

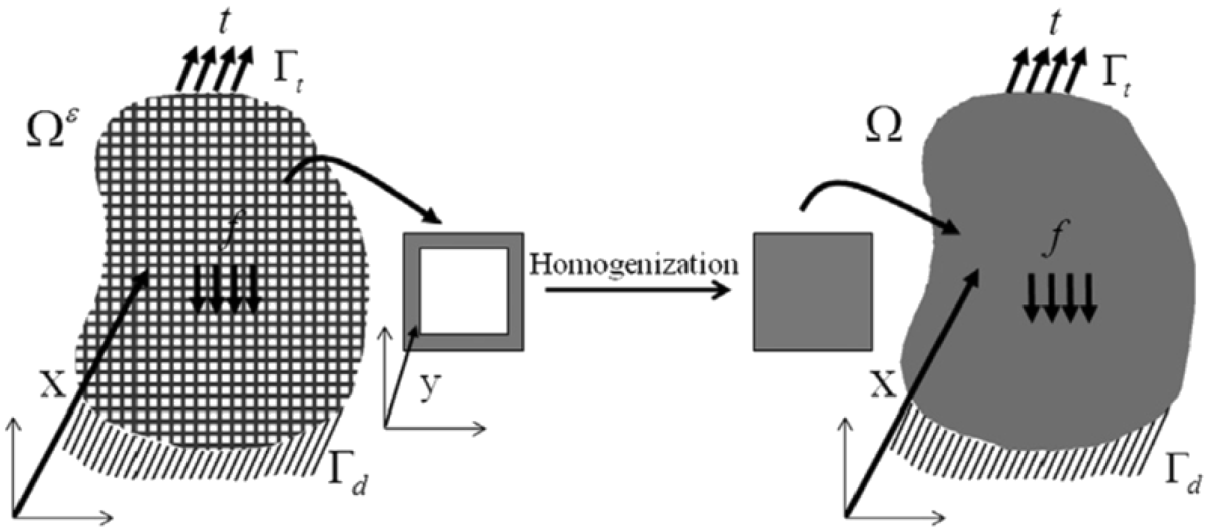
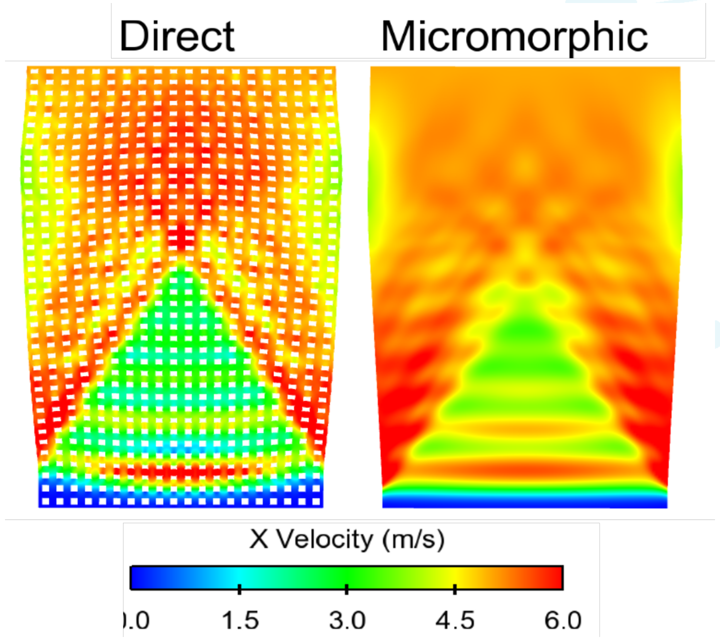


Fig. 2. Homogenization concept of a cellular structure.

Arabnejad and Pasini, *Int. J. Mech. Sci.*, 2013

Review: Hassani and Hinton, Computers & Structures, 1998

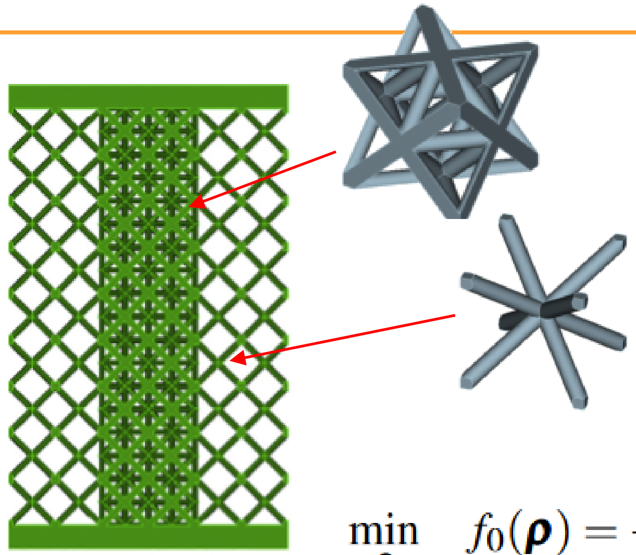


Dingreville, Robbins, Voth, *JOM*, 2013

<u>Micromorphic continuum:</u>

- Developed by Eringen and Mindlin in 1960’s
- Used for size-effects (e.g. strain-gradient theory)
- Captures localization phenomena
- Requires a regularization length scale
- See review by Forest and Sievert (2006)

Two-unit cell Nonlinear optimization problem



$$\min_{\boldsymbol{\rho}} \quad f_0(\boldsymbol{\rho}) = -W^p,$$

Objective: Maximize the plastic work for a given density

$$\text{s.t.} \quad f_1(\boldsymbol{\rho}) = \frac{1}{V}\sum_{e=1}^{n_{ele}} \rho_e v_e - V_f \leq 0,$$

Constrain the volume fraction

$$f_2(\boldsymbol{\rho}) = \frac{\hat{F}^{max}}{F^{end}} - c_0 \leq 0,$$

Prevent softening

$$\boldsymbol{R}^k(\hat{\boldsymbol{u}}^k, \hat{\boldsymbol{u}}^{k-1}, \boldsymbol{c}^k, \boldsymbol{c}^{k-1}, \boldsymbol{\rho}) = \boldsymbol{0}, \quad k = 1, 2, \ldots, n,$$

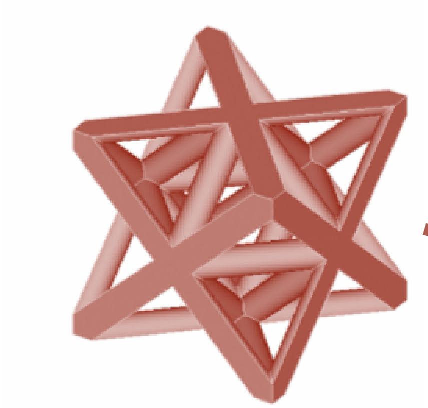
$$\boldsymbol{H}^k(\hat{\boldsymbol{u}}^k, \hat{\boldsymbol{u}}^{k-1}, \boldsymbol{c}^k, \boldsymbol{c}^{k-1}, \boldsymbol{\rho}) = \boldsymbol{0}, \quad k = 1, 2, \ldots, n,$$

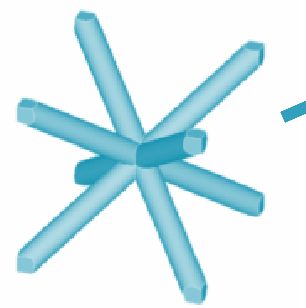
Implicit global and local PDE constraints from enforcing equilibrium

$$\boldsymbol{0} \leq \boldsymbol{\rho} \leq \boldsymbol{1}.$$

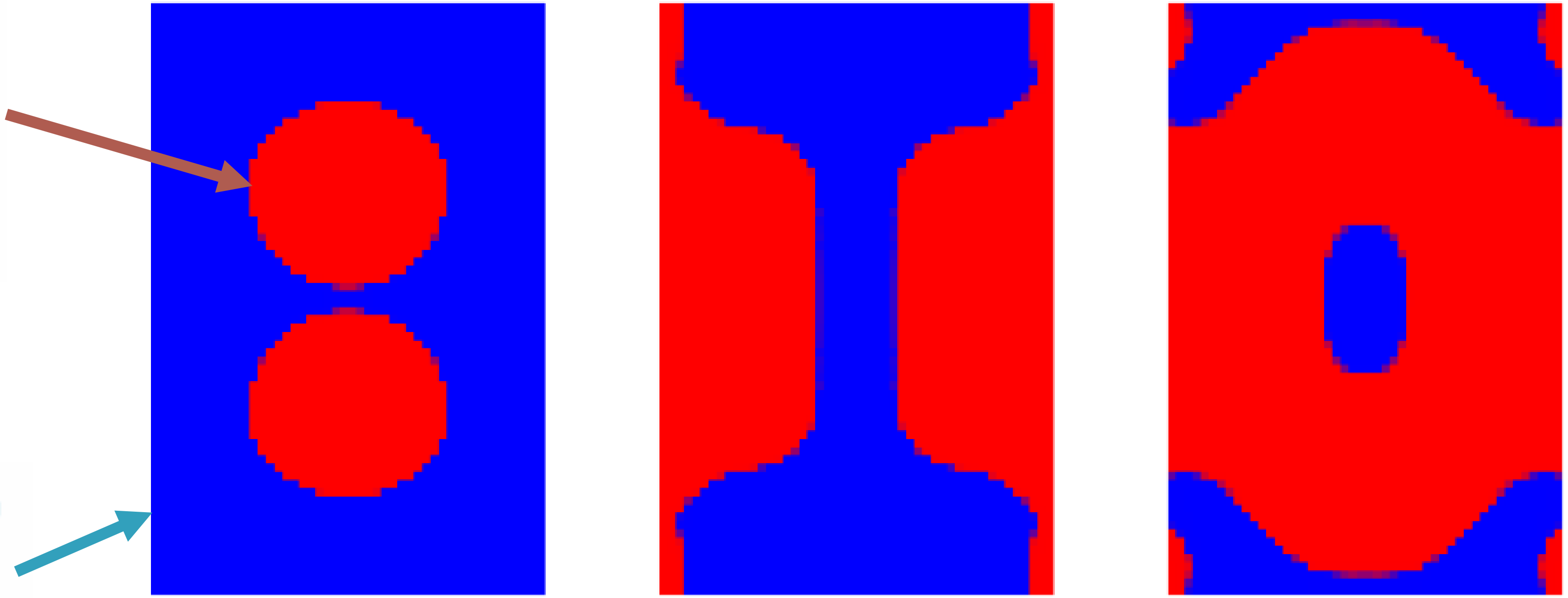
Constrain density

Result: optimal tiling for different volume fractions





25% dense | 50% dense | 75% dense

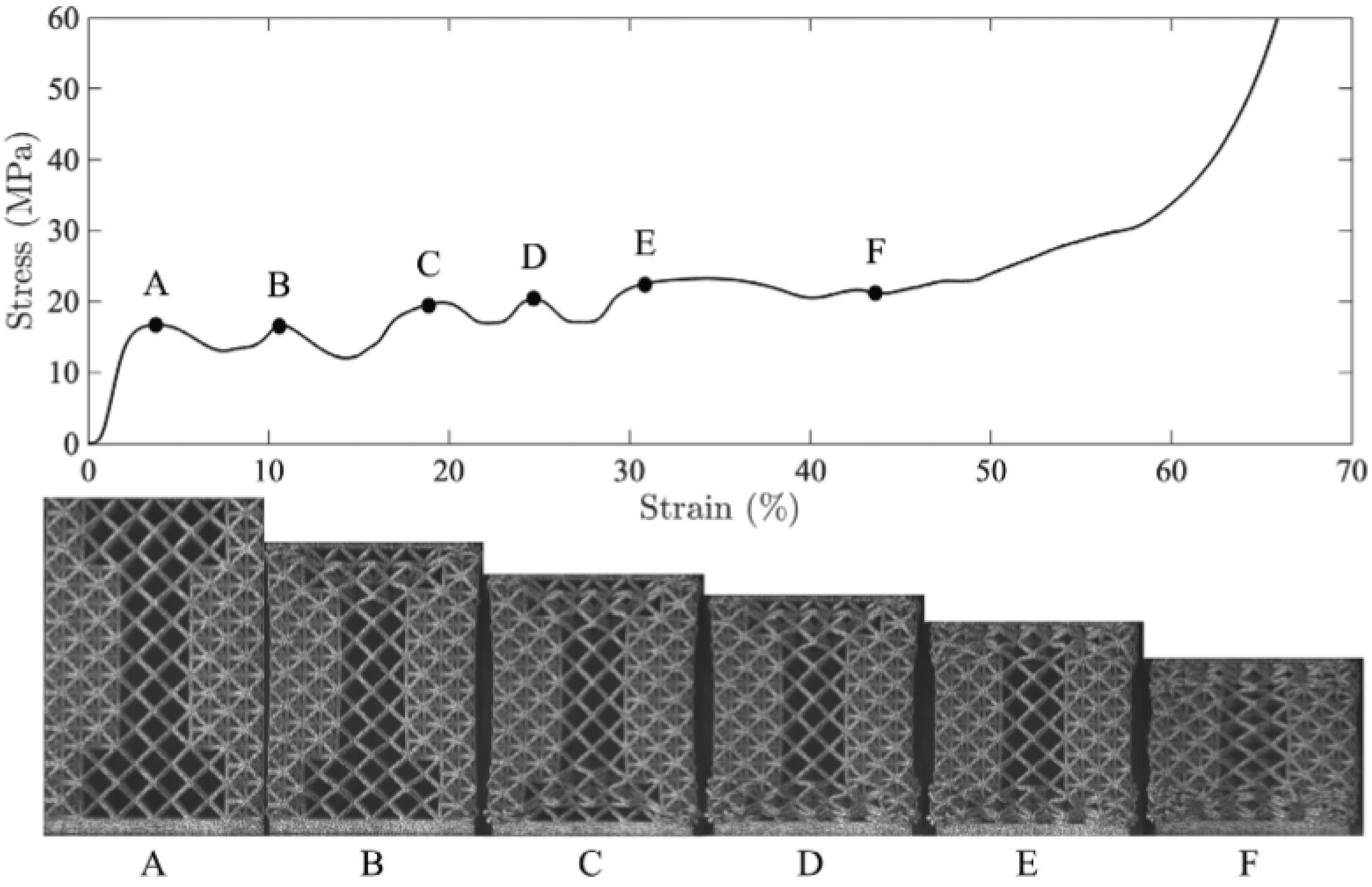


(a) $V_f = 0.25$ | (b) $V_f = 0.5$ | (c) $V_f = 0.75$

“meso-I”

Alberdi, et al., *Materials & Design*, 2020

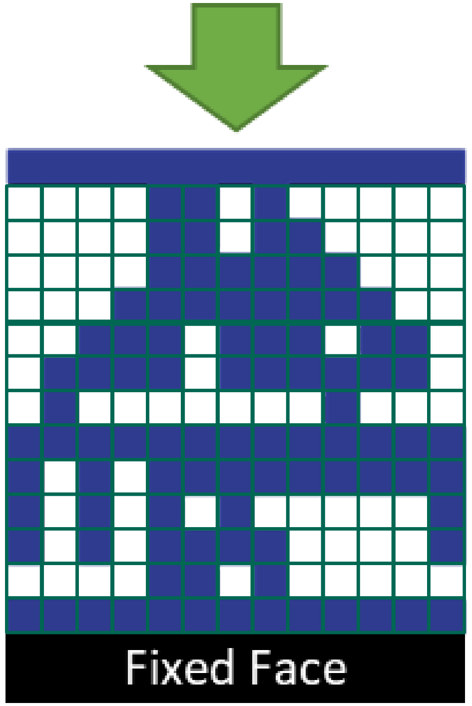
Experimental validation of the “meso-I” structure

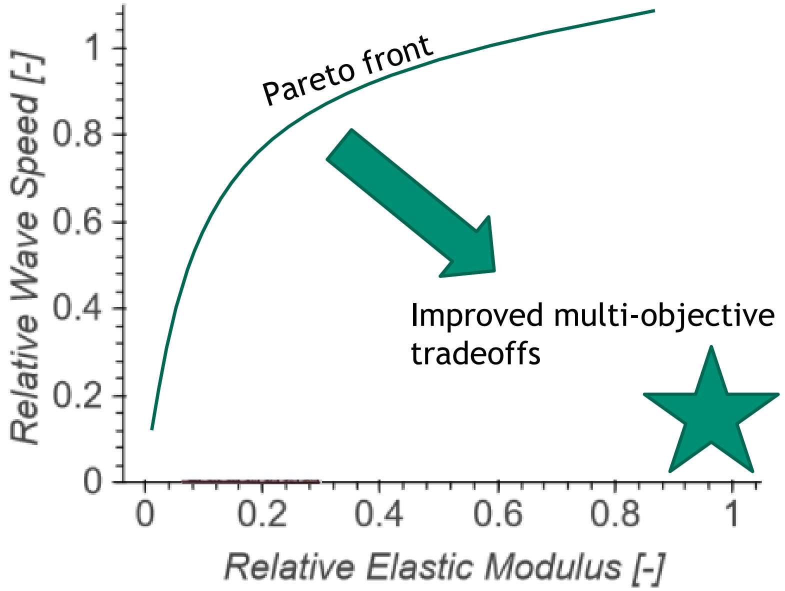


Alberdi, et al., *Materials & Design*, 2020

Second example: two objectives & manufacturing constraints

Two-objective optimization of a unit cell shape





For a 13x13 pixel discretized unit cell, maximize:

1) stiffness

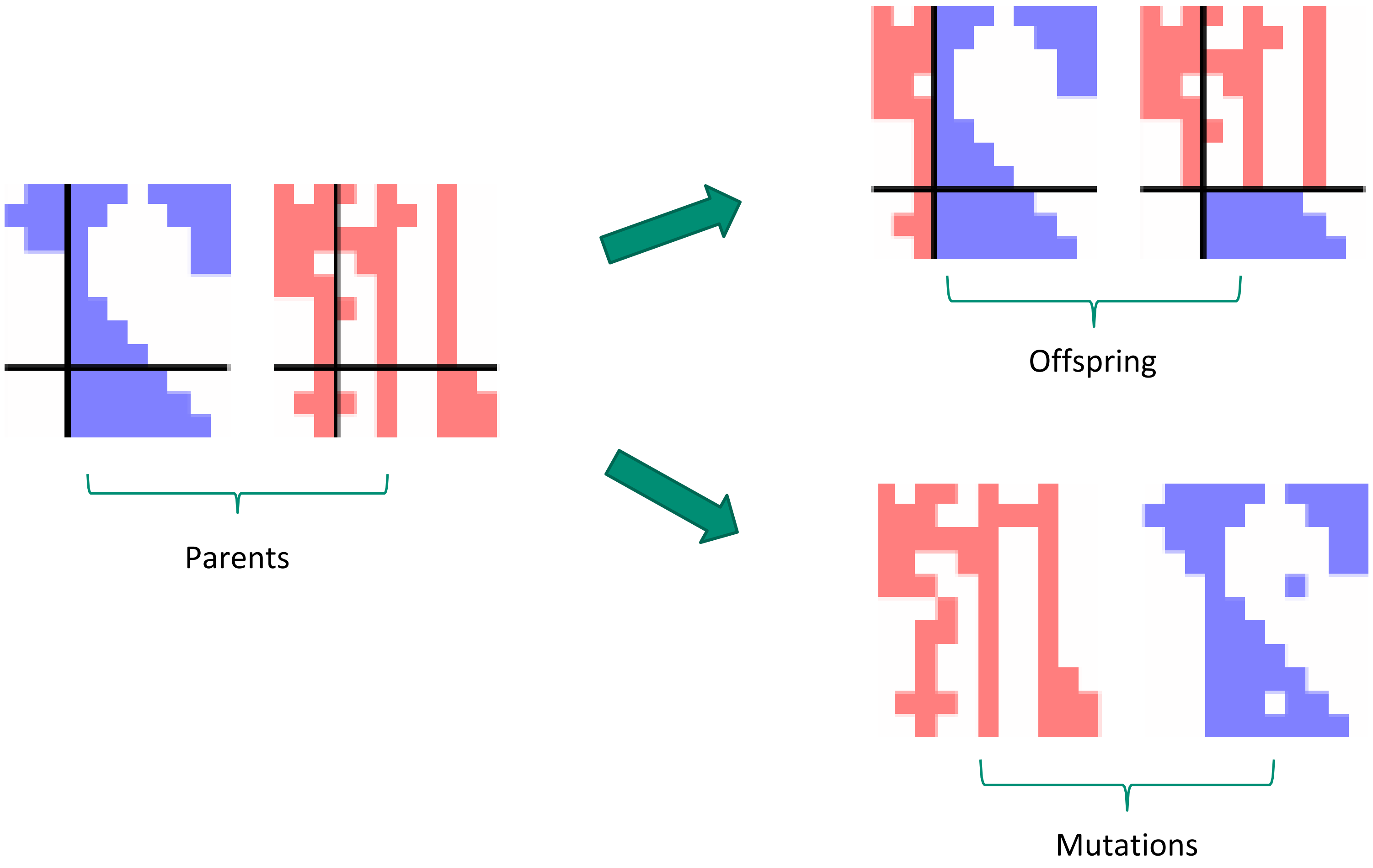
2) transmission time for an elastic wave (shock)

Employ manufacturability constraints:

1) minimum feature size = 1 pixel

2) no unsupported overhangs

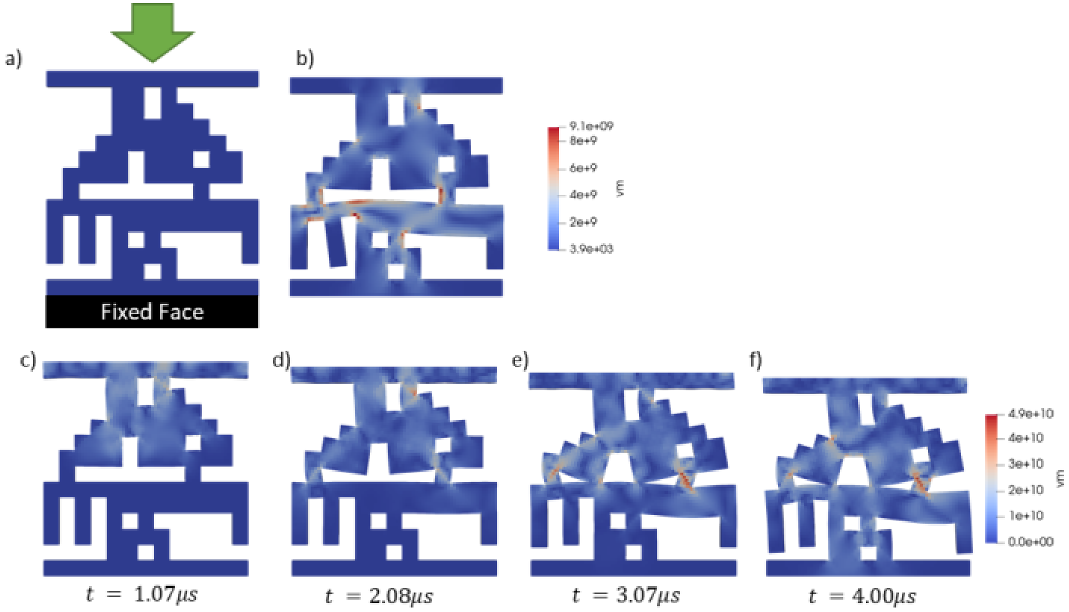
A genetic algorithm…



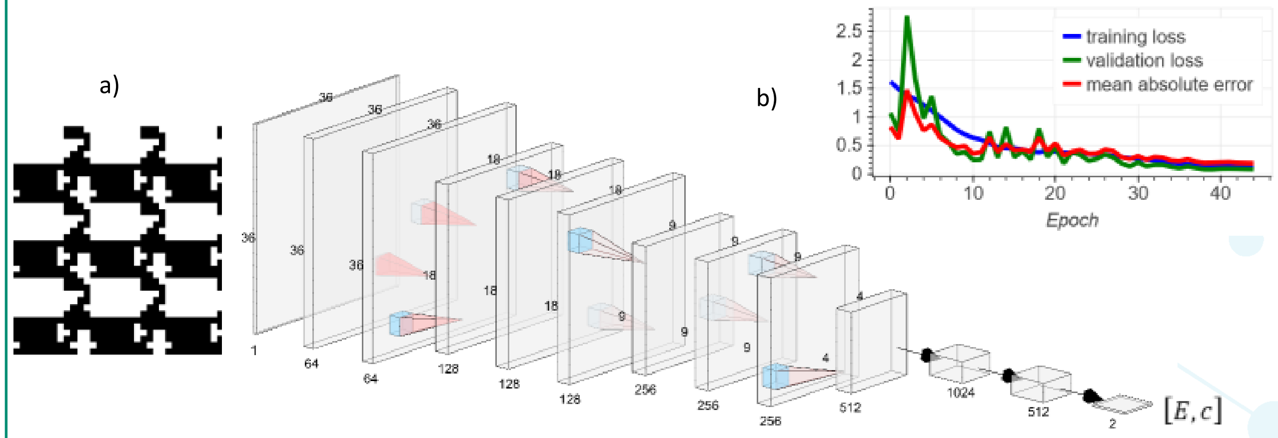
Garland, et al., *Materials & Design*, 2021

Replace costly explicit FEA with a CNN

Explicit FEA

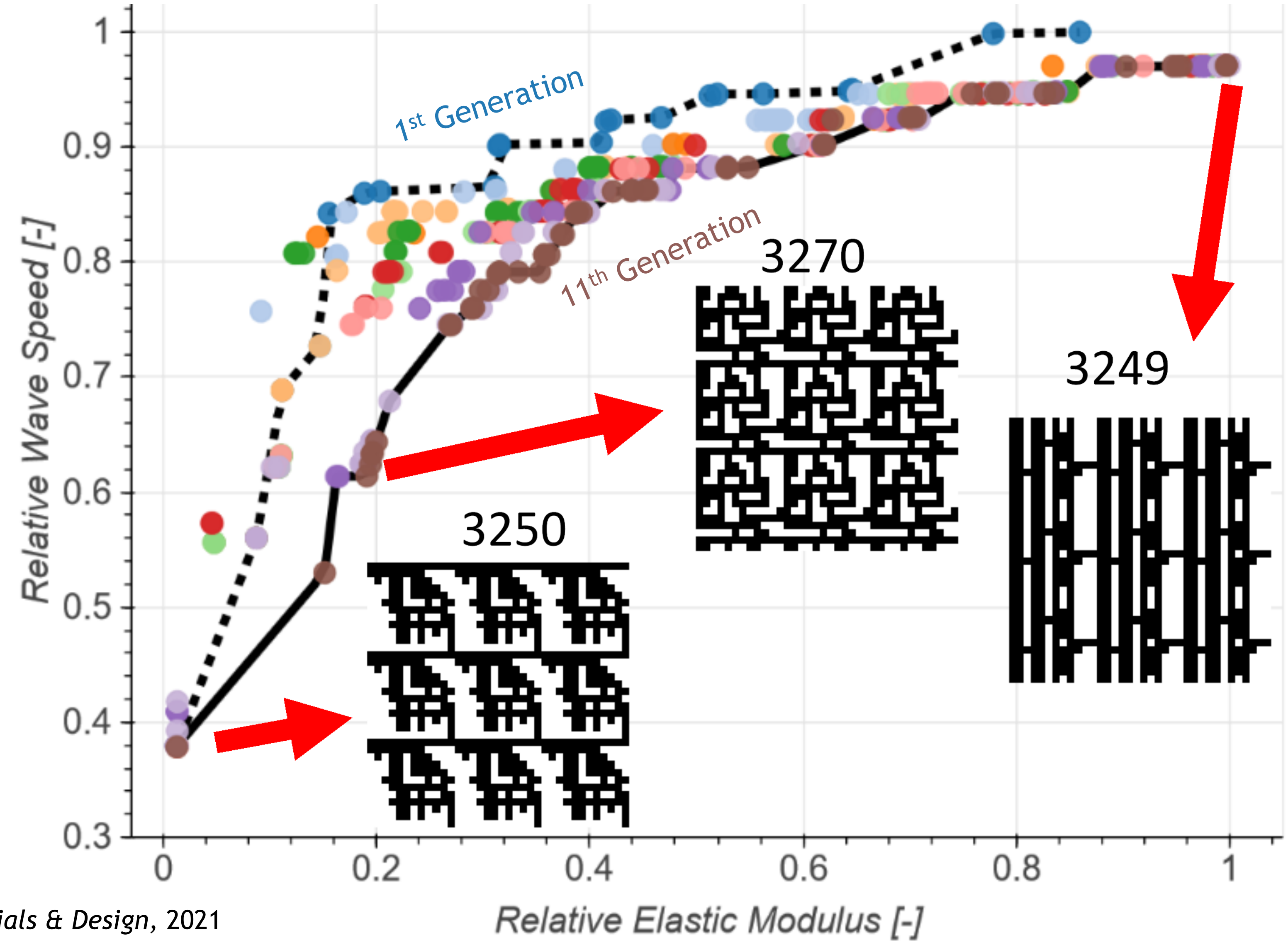


Convolutional Neural Network



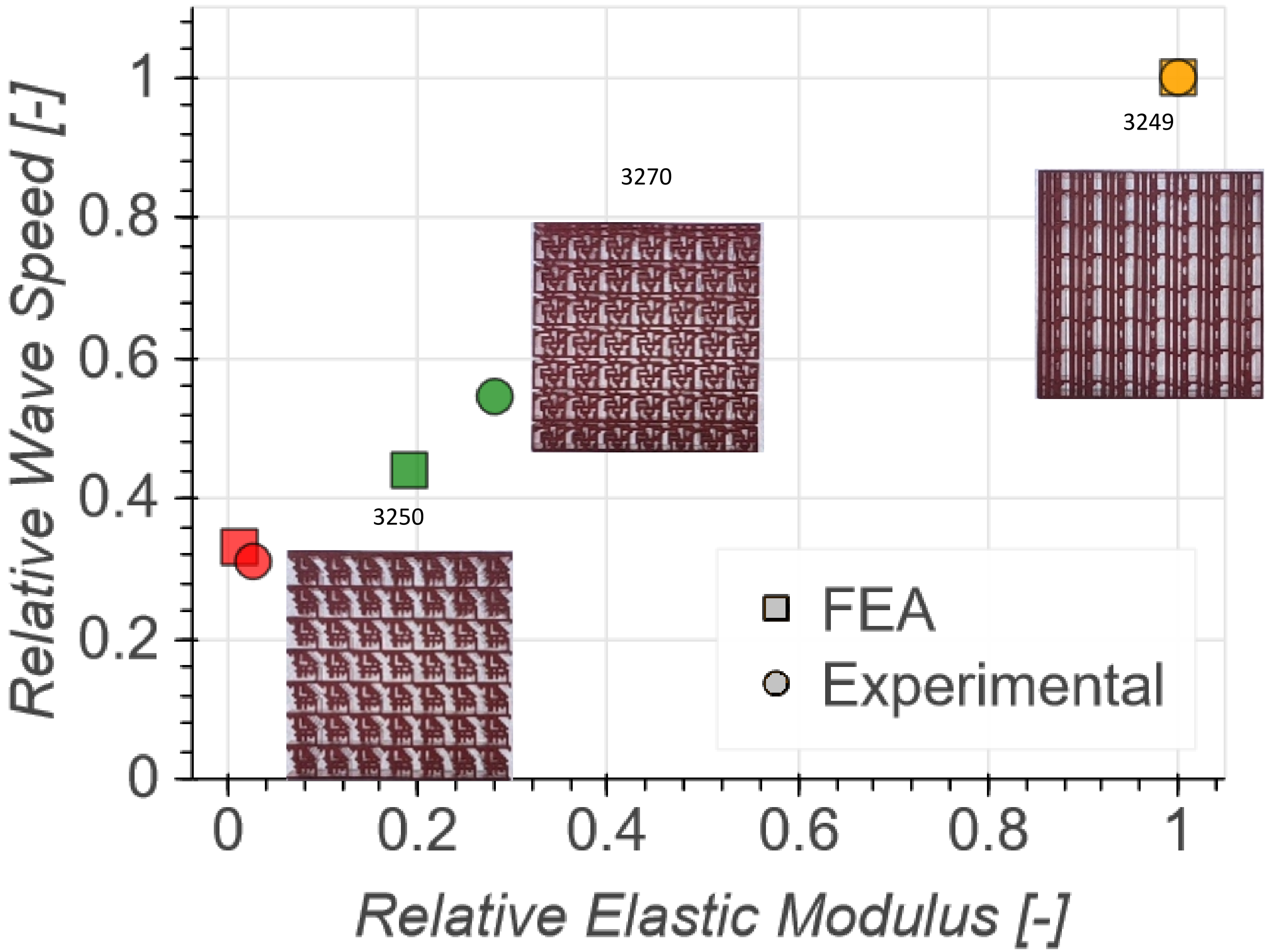
Garland, et al., *Materials & Design*, 2021

Active-learning based lattice design:
two objectives: stiffness and elastic wave delay



Garland, et al., *Materials & Design*, 2021

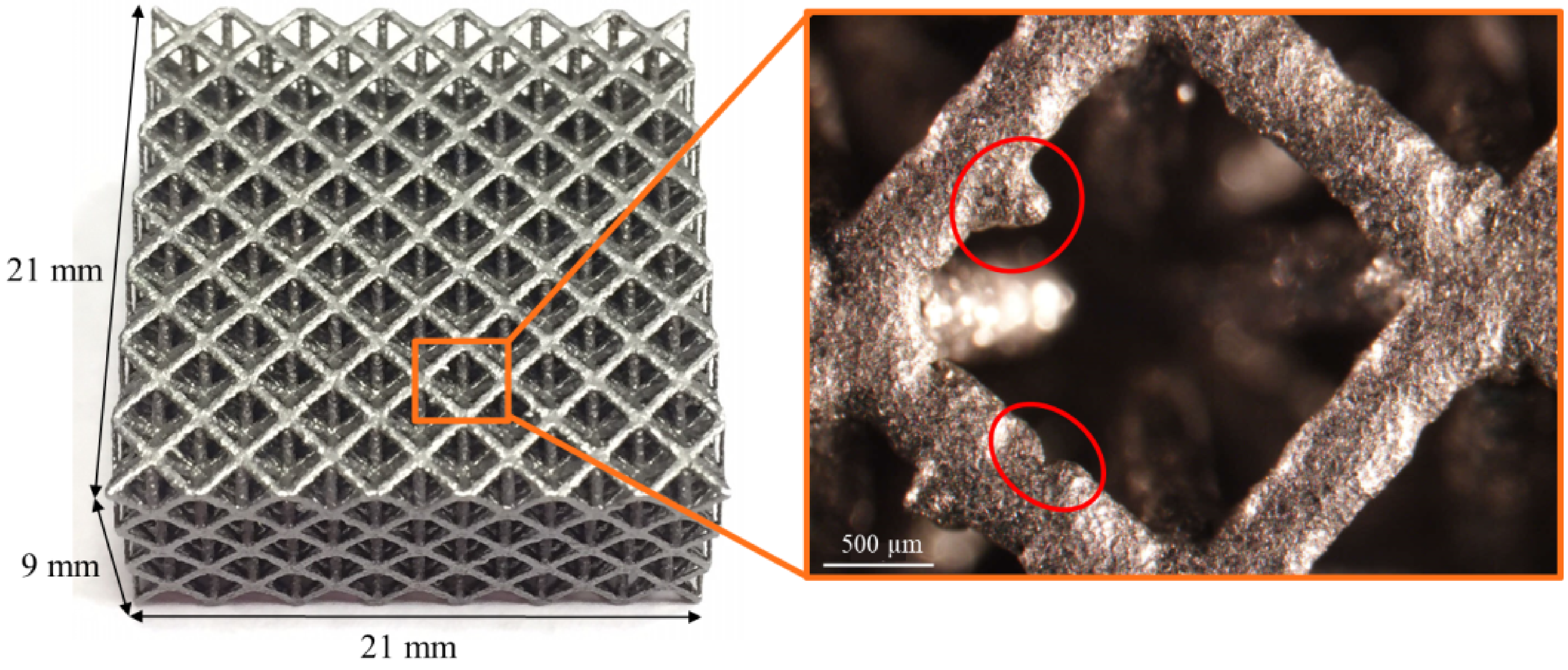
Experimental validation



Garland, et al., *Materials & Design*, 2021

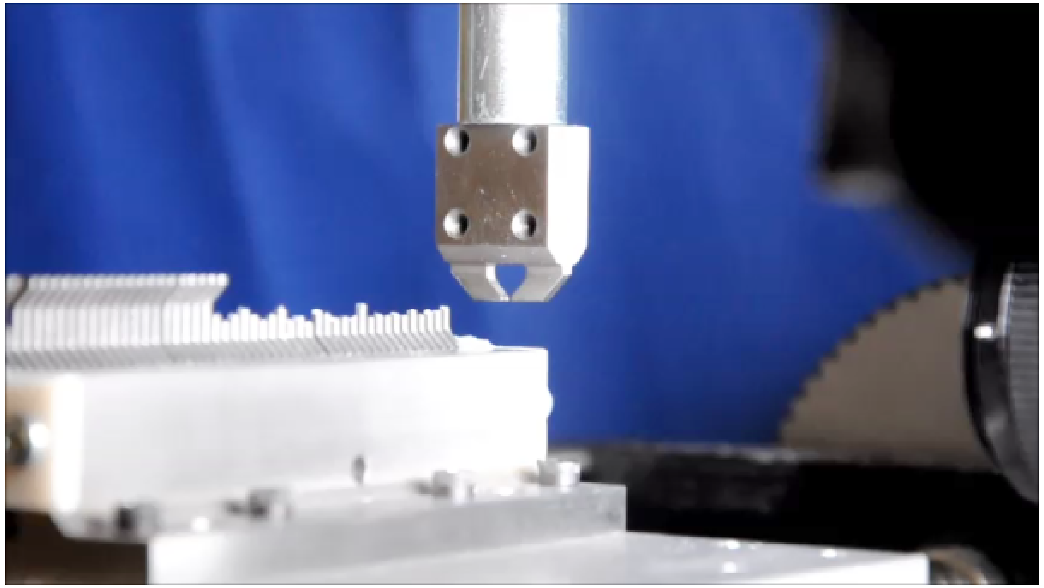
Topic III: Material imperfections & lattice qualification

Real lattices are far from perfect… unlike their CAD/FEA models

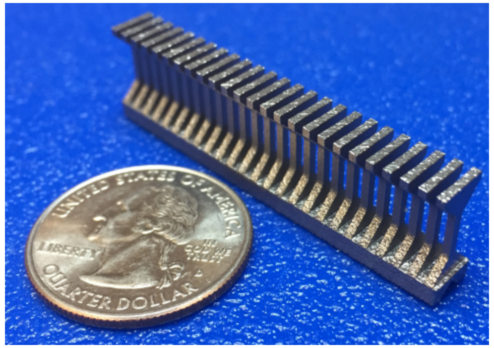


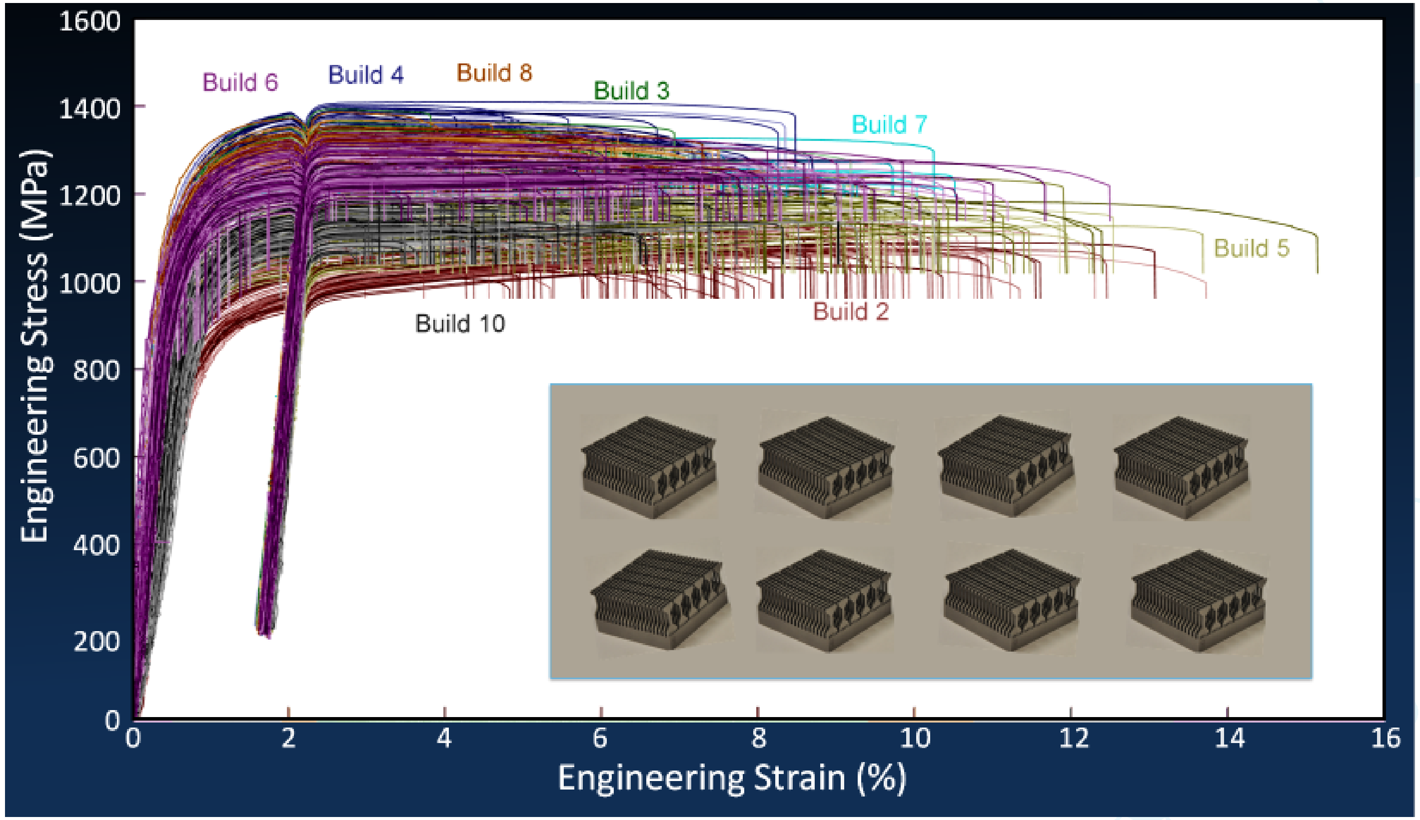
A. Dressler, et al., Additive Manufacturing, 2019

We use high-throughput testing to evaluate stochastic response



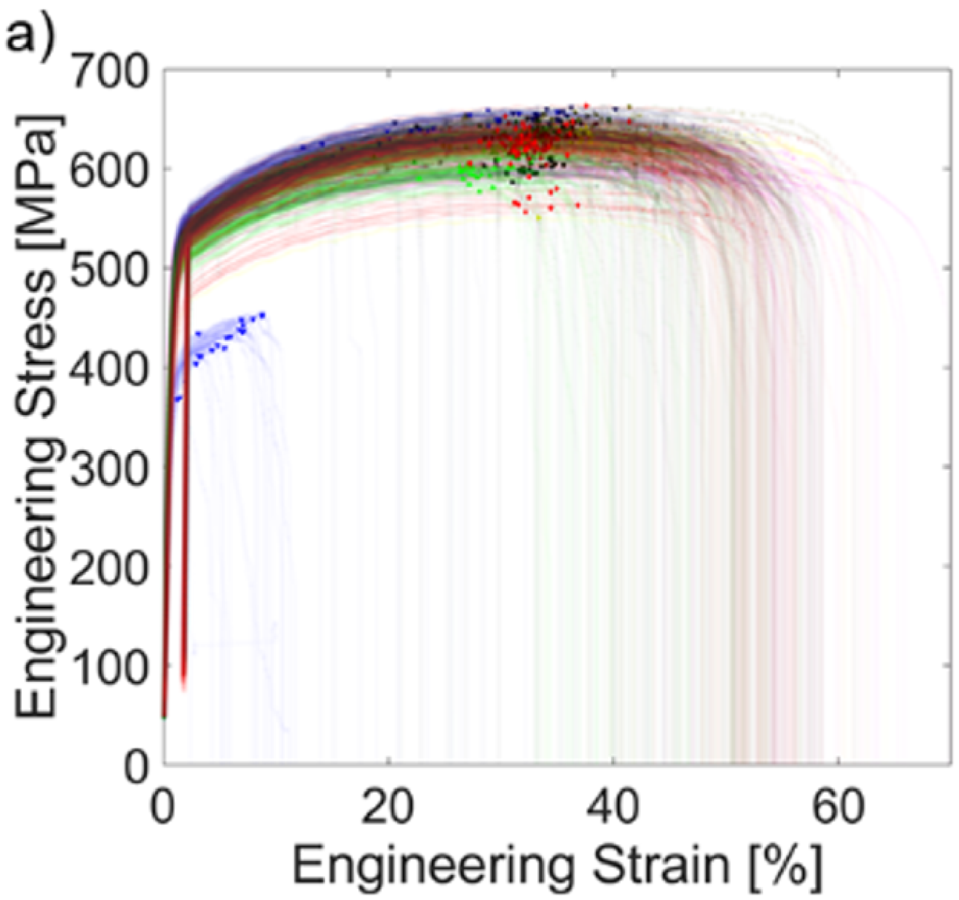
US Patent 11,002,649

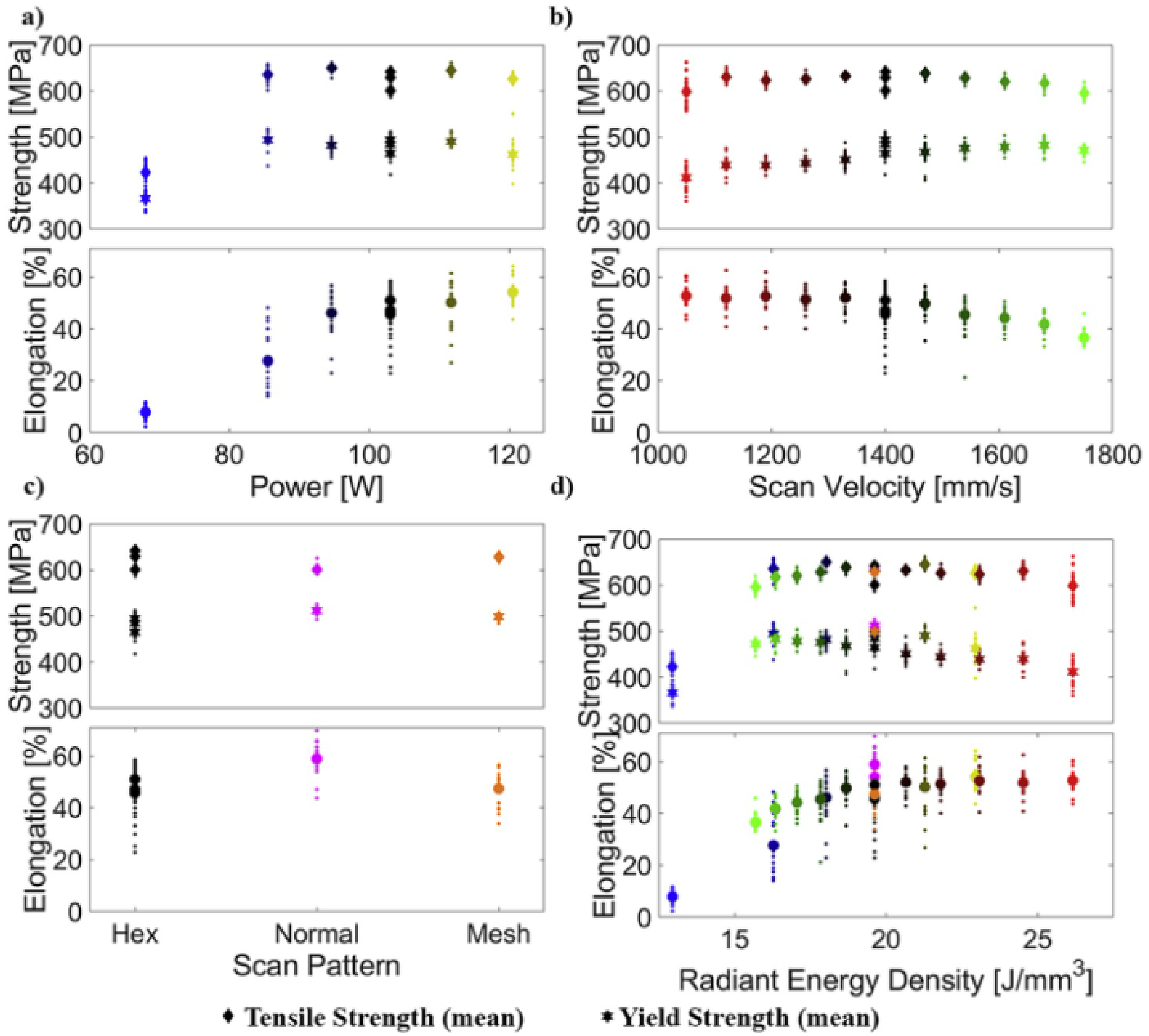




Boyce, Salzbrenner, Rodelas, Swiler, Madison, Jared, Shen, *Adv. Eng. Mater.*, 201

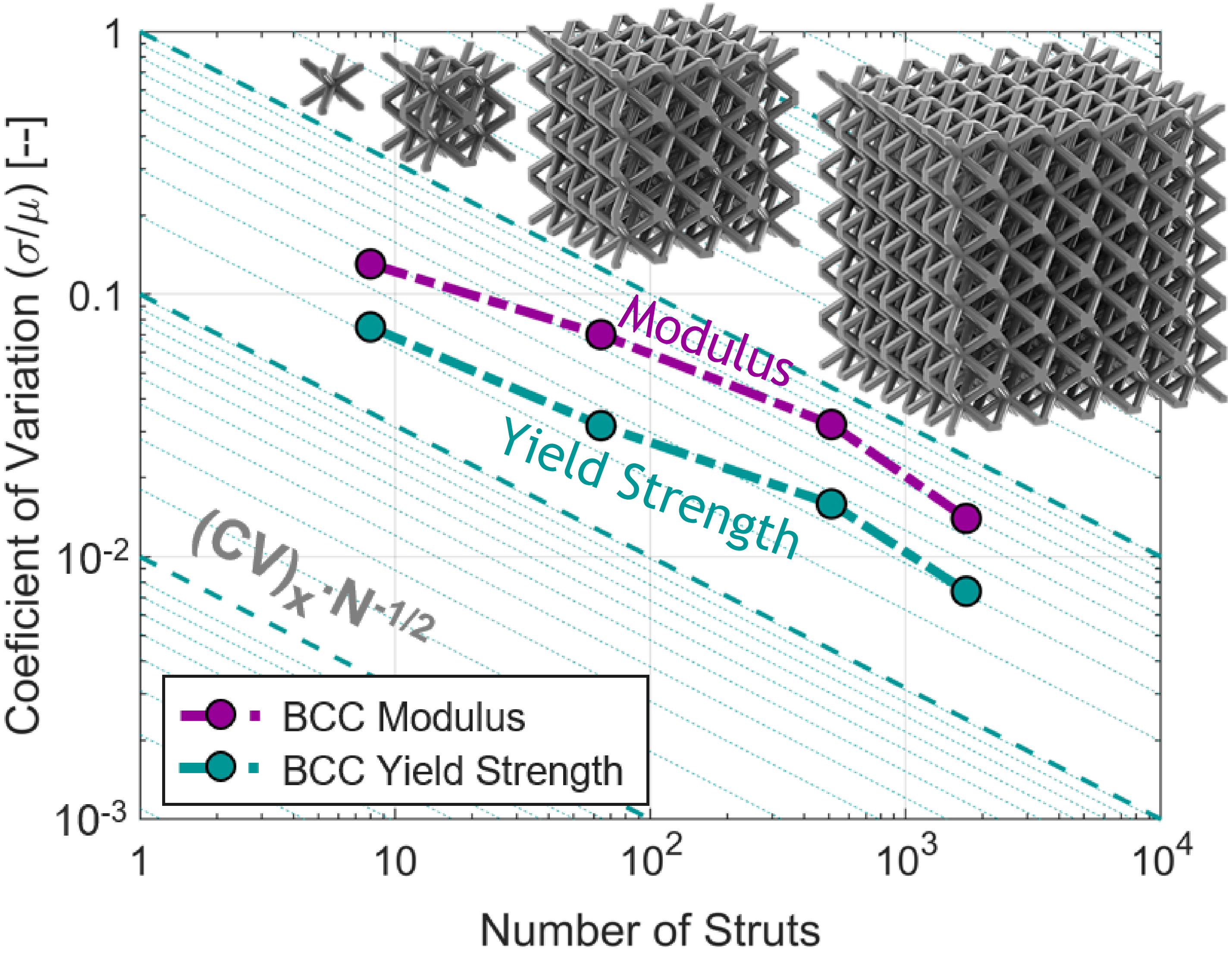
Rapid stochastic-aware process optimization



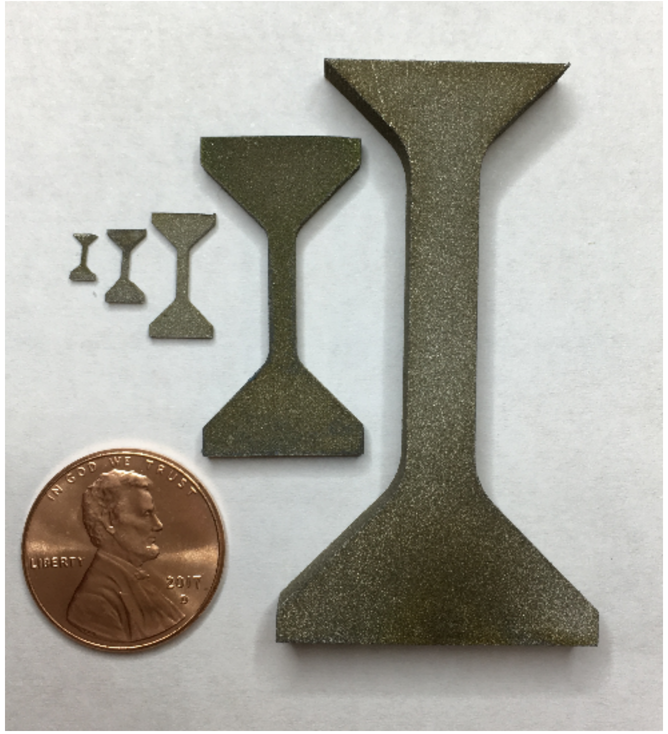


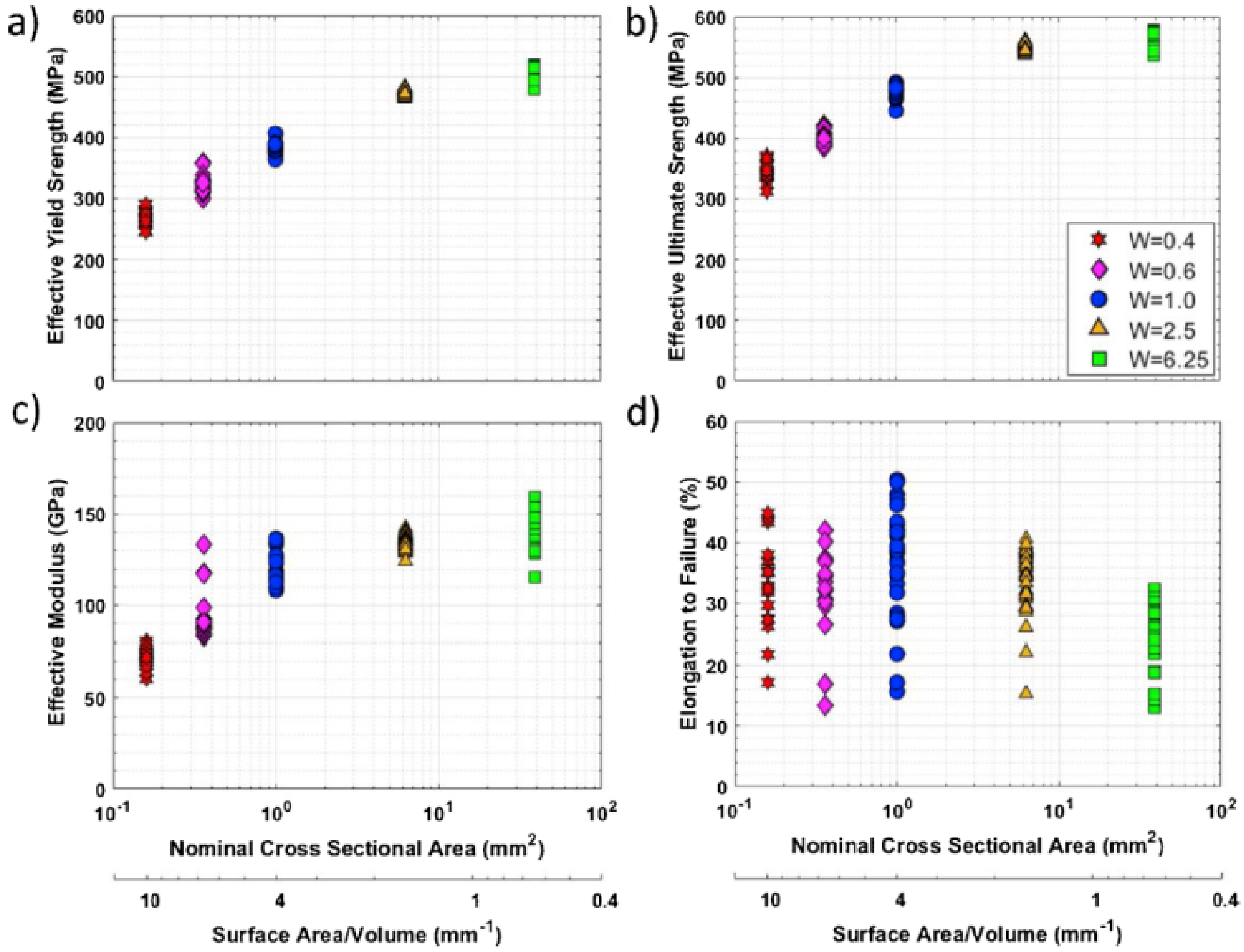
Heckman…Boyce, *Mater. Sci. Eng. A*, 2020

Lattices naturally homogenize heterogeneous material response



Effective mechanical properties of AM are strongly size-dependent

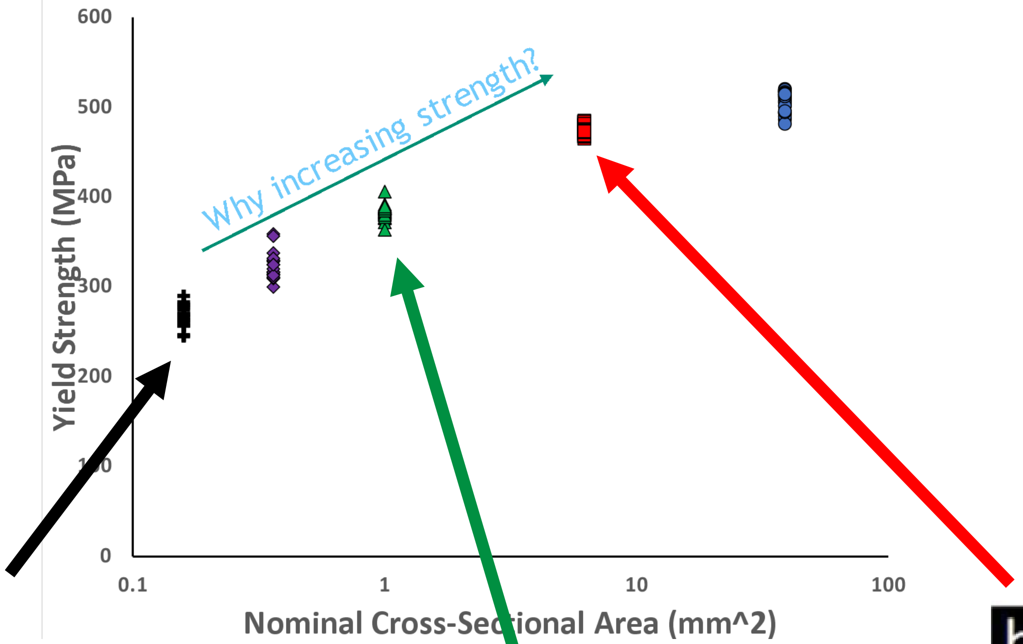


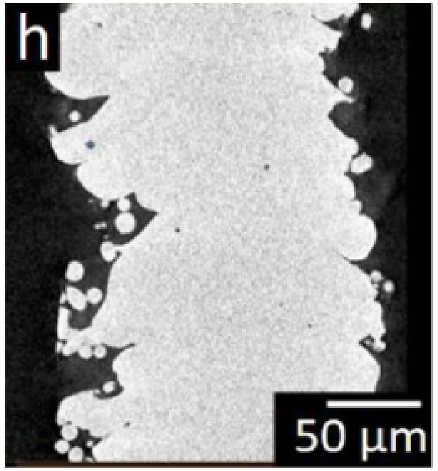


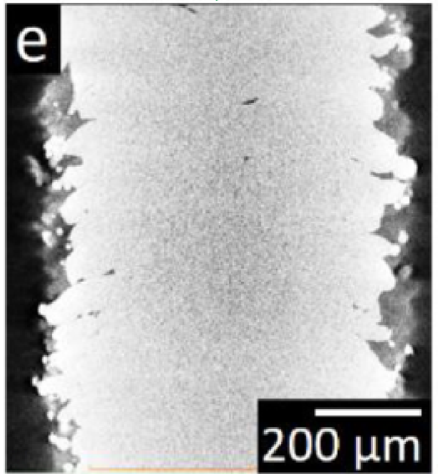
A. Roach, et al., Additive Manufacturing, 2020

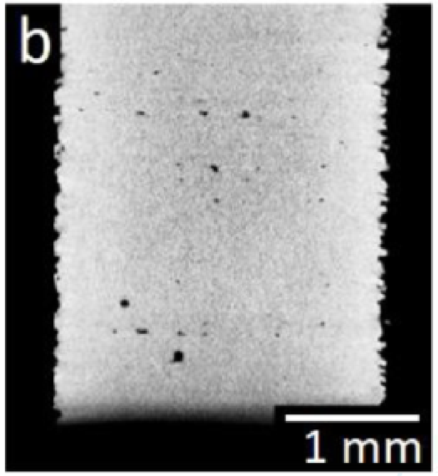
It's the surface roughness

- Reduces the effective cross-sectional area
- Adds a stress concentrating effect



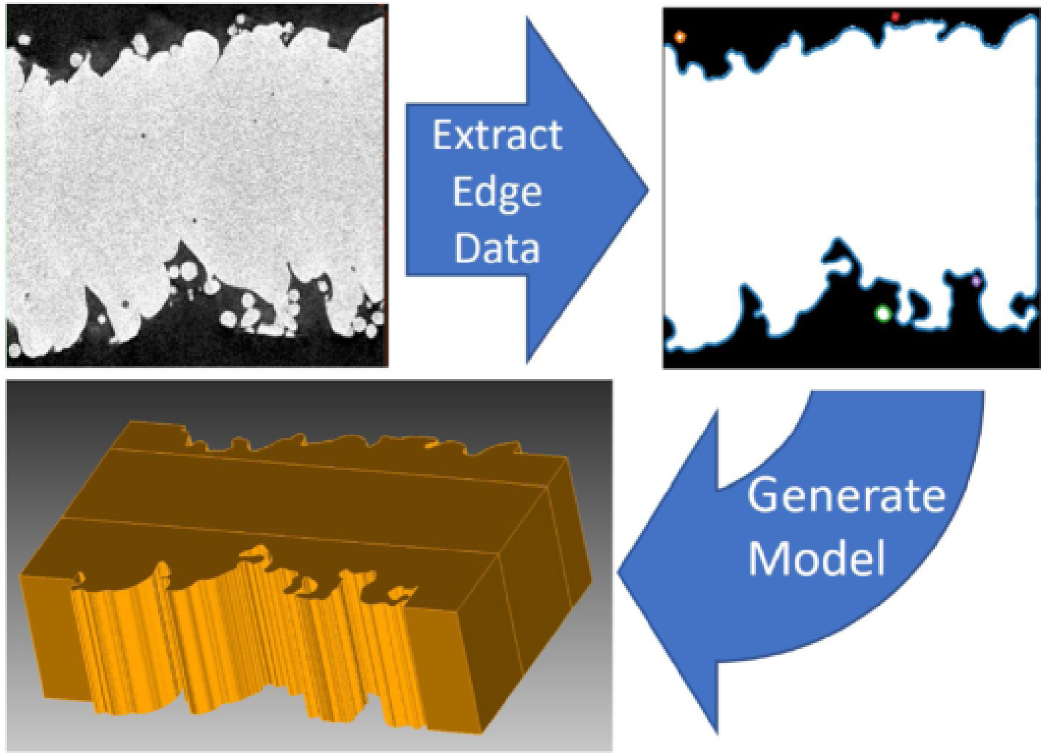


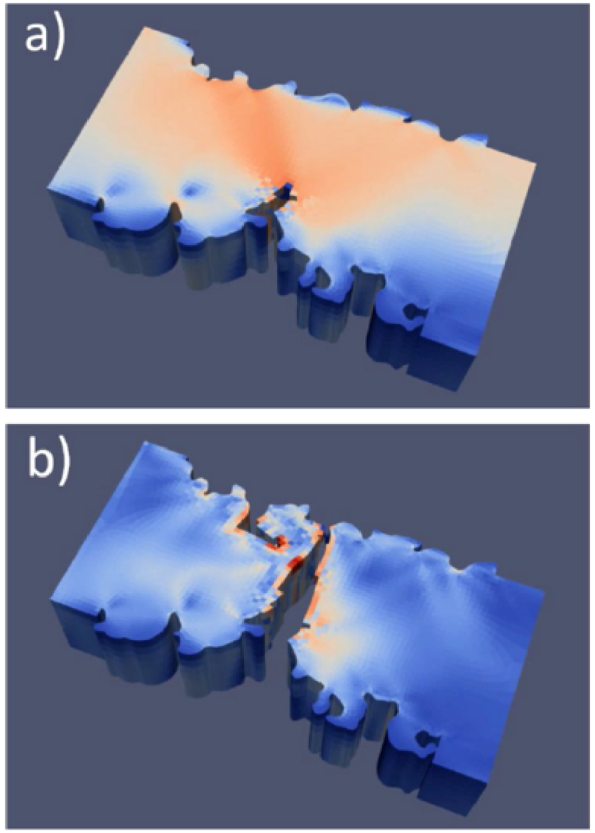


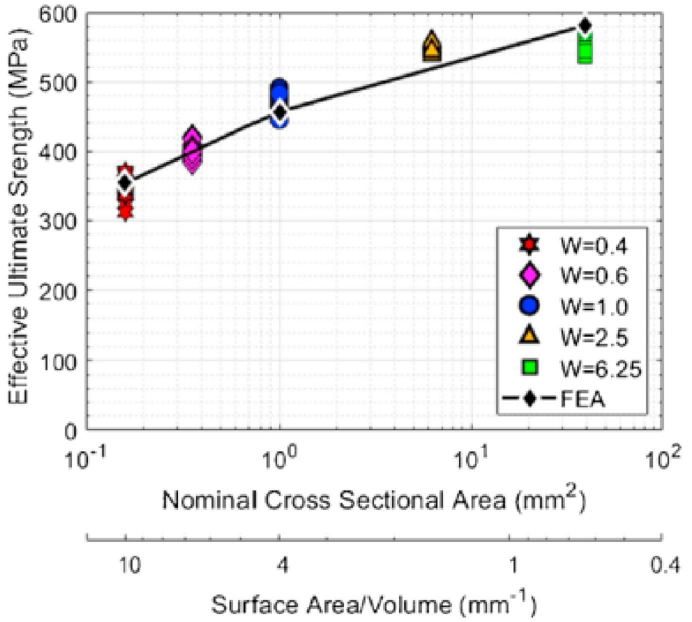


A. Roach, et al., Additive Manufacturing, 2020

FEA validates roughness effect

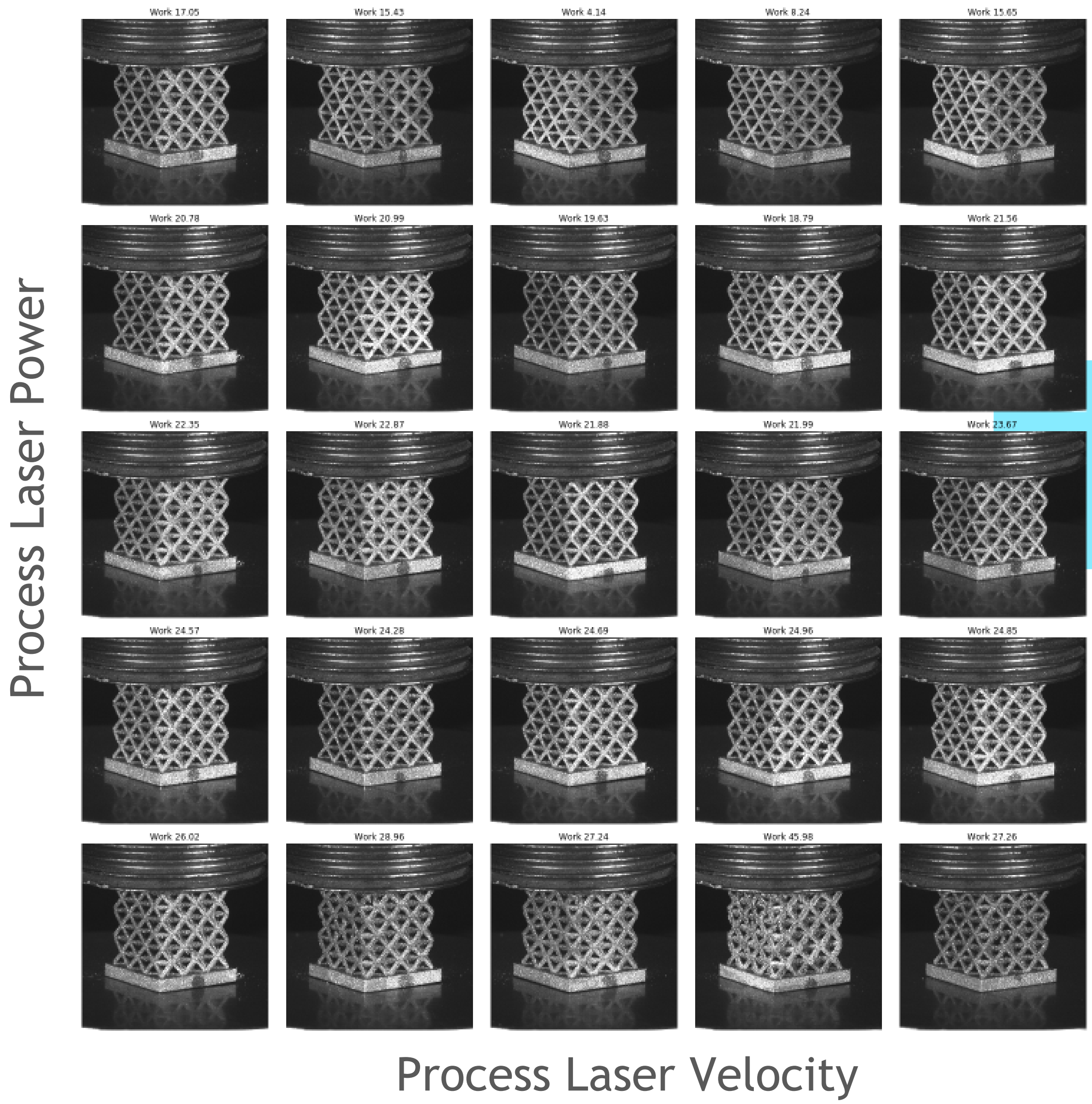


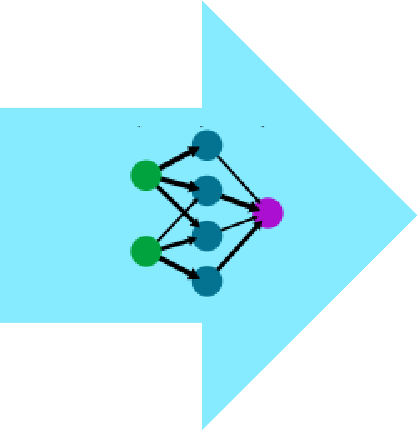


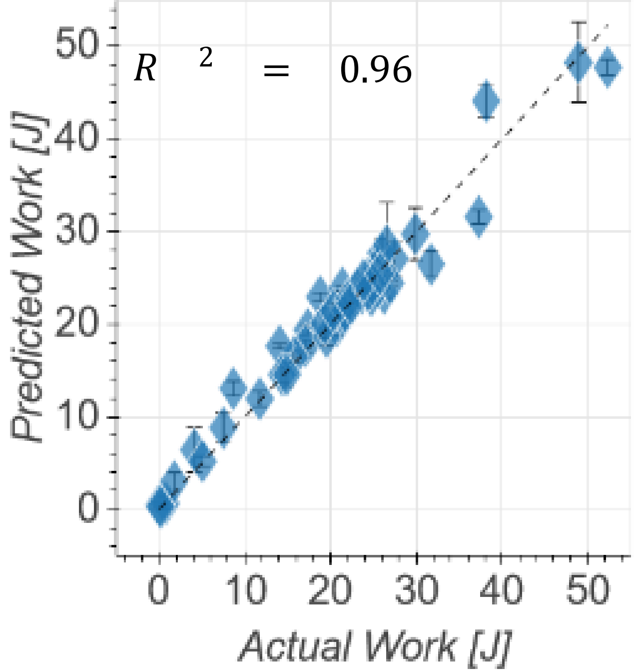


A. Roach, et al., Additive Manufacturing, 2020

Overcoming the Inspection/QC burden?

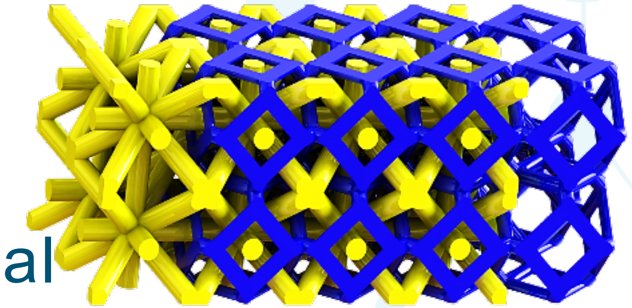




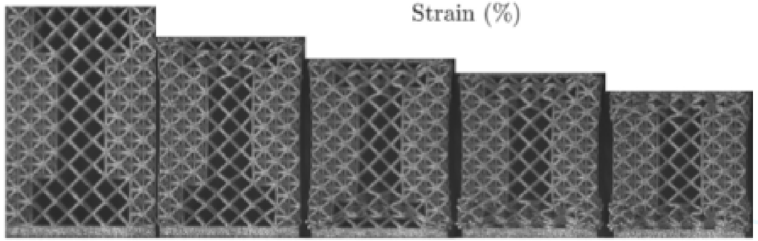


Garland…Boyce, *Additive Manufacturing*, 2020

Summary
Many creative metamaterials are waiting to be discovered



Optimization requires innovation to manage computational expense



As-manufactured lattices are far from perfect, but can qualified