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Challenges in optimized structural metamaterials

PRESENTED BY

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Center for Integrated Nanotechnologies (CINT)

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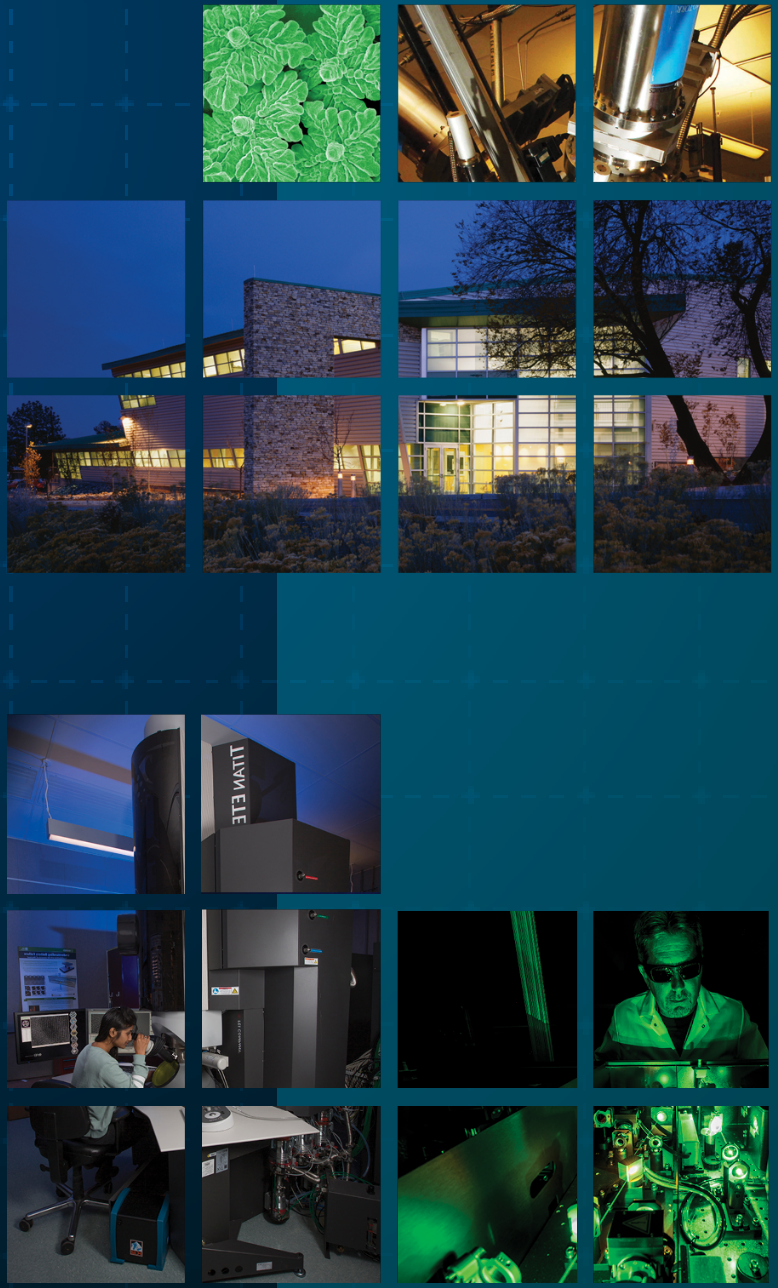

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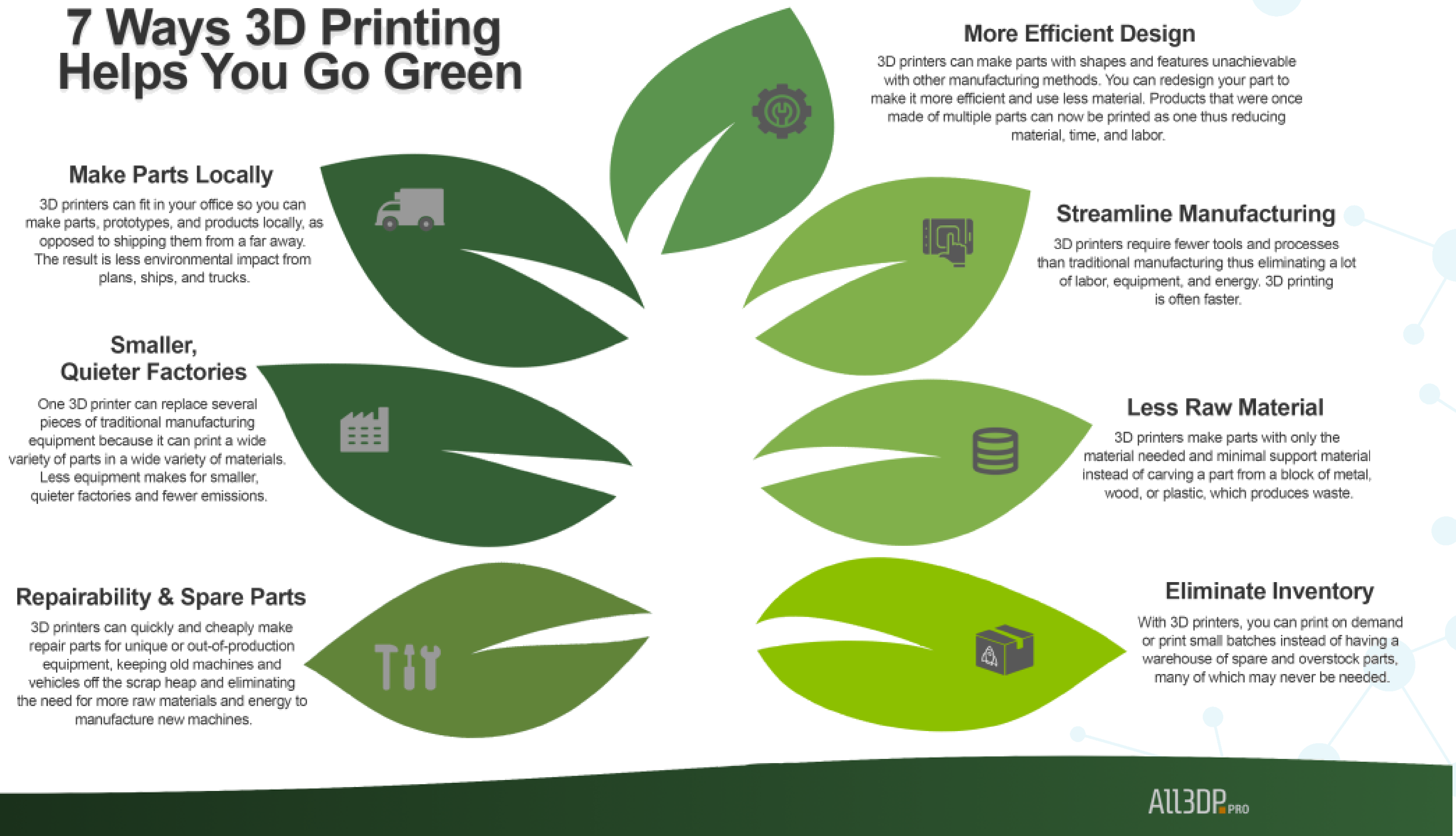
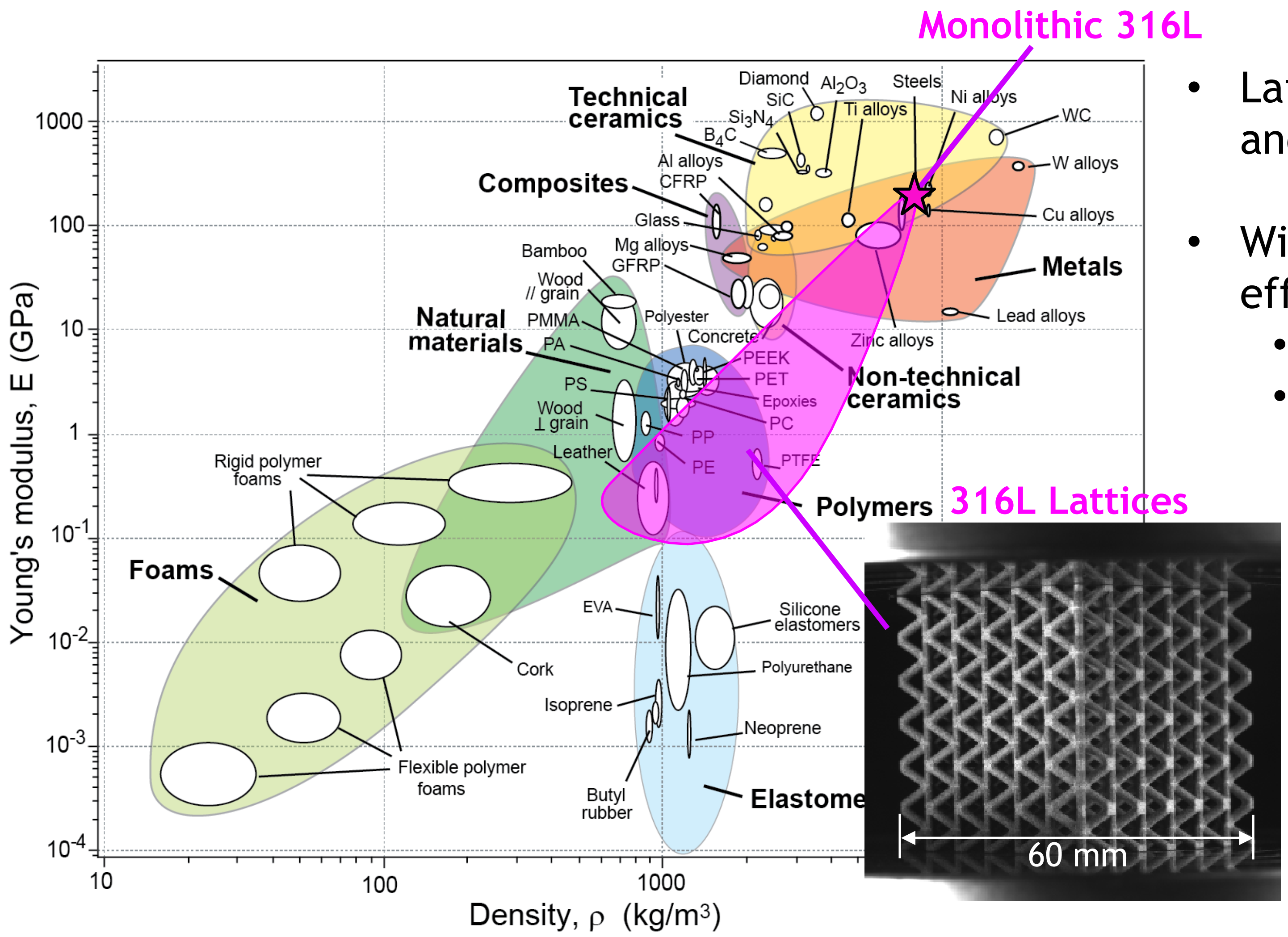
3D Printing is advancing sustainability



Lattice (structural metamaterials) enhance sustainability



- Lattices can allow optimized strength/weight and stiffness/weight, tailorable across a body.
- With a single source material, a wide range of effective properties can be achieved
  - Less material sourcing
  - Less material compatibility issues

Examples of lattices from the literature

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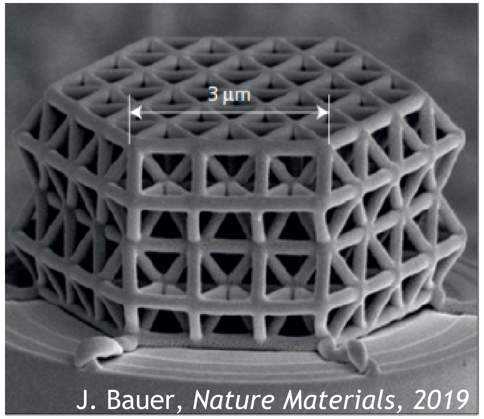
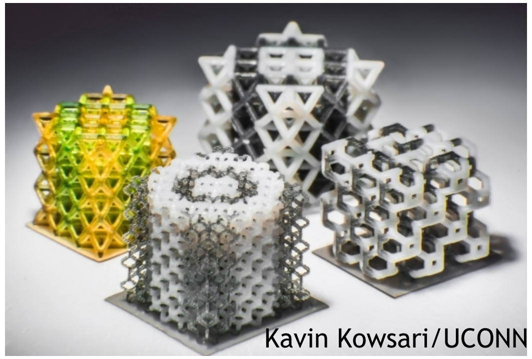
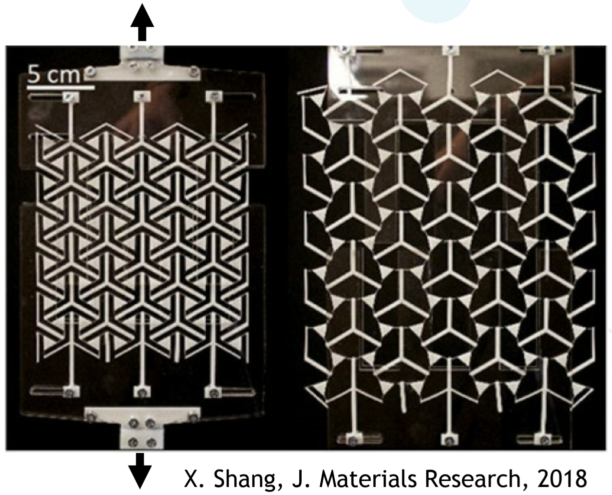


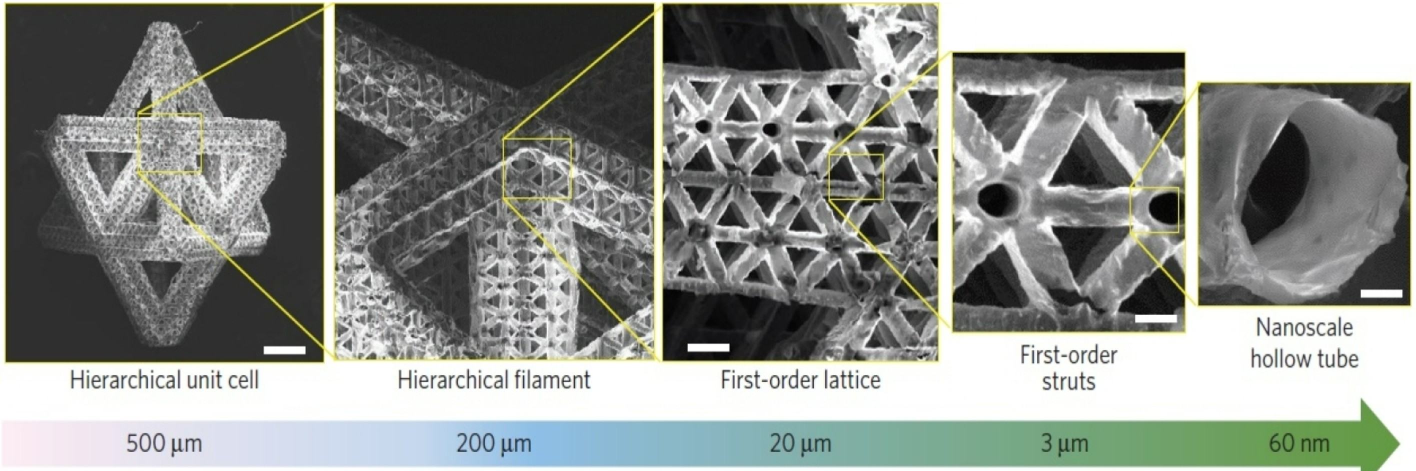
J. Bauer, *Nature Materials*, 2019



Kavin Kowsari/UCONN



X. Shang, J. Materials Research, 2018



Zheng, Nature Materials, 2016

Two practical challenges with lattices:

1. Optimal lattice design

   Example 1: Crush energy absorption via Micromorphic continuum approach

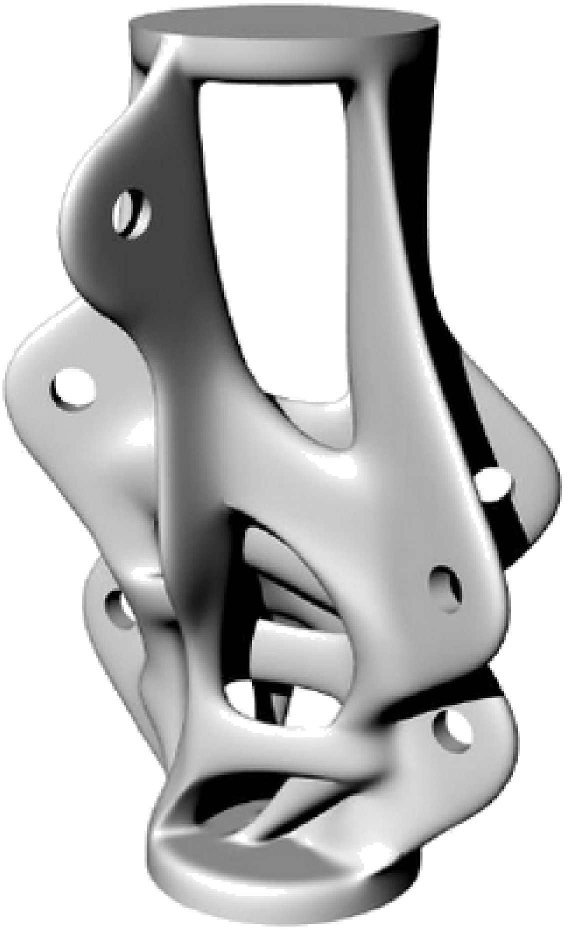
   Example 2: Manufacturing-constrained Two-objective optimization via neural networks

2. Material imperfections in lattices

   a. Effective properties are size dependent

   b. Surface roughness effects

Topology optimization has been the cornerstone of AM design



Galjaard, Hofman and Ren,
Biomimetic Lightweight…, 2015

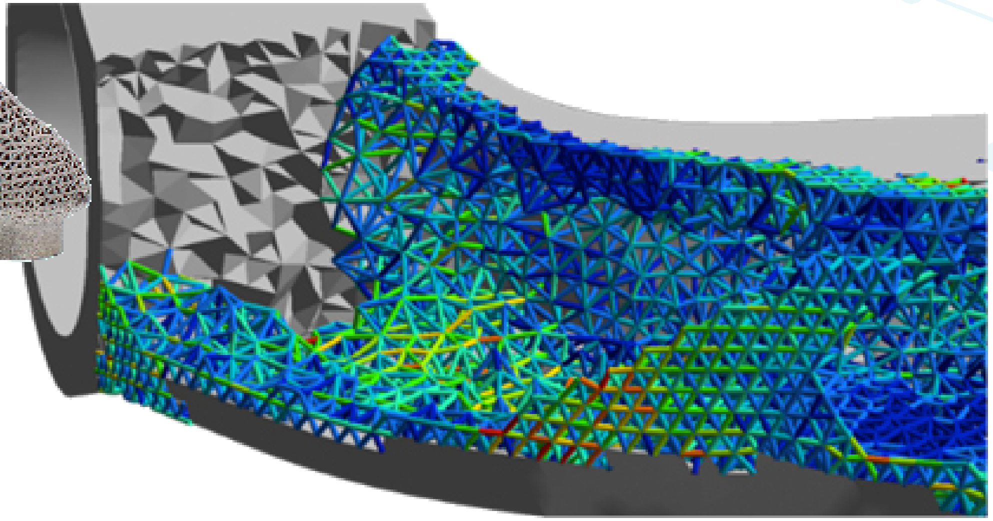
- Geometry is not drawn by the engineer
- Engineer sets objectives / constraints
- Gradient-based iterative optimization defines geometry

Lattices are computationally expensive for FEA

Renishaw's titanium optimized spider support

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

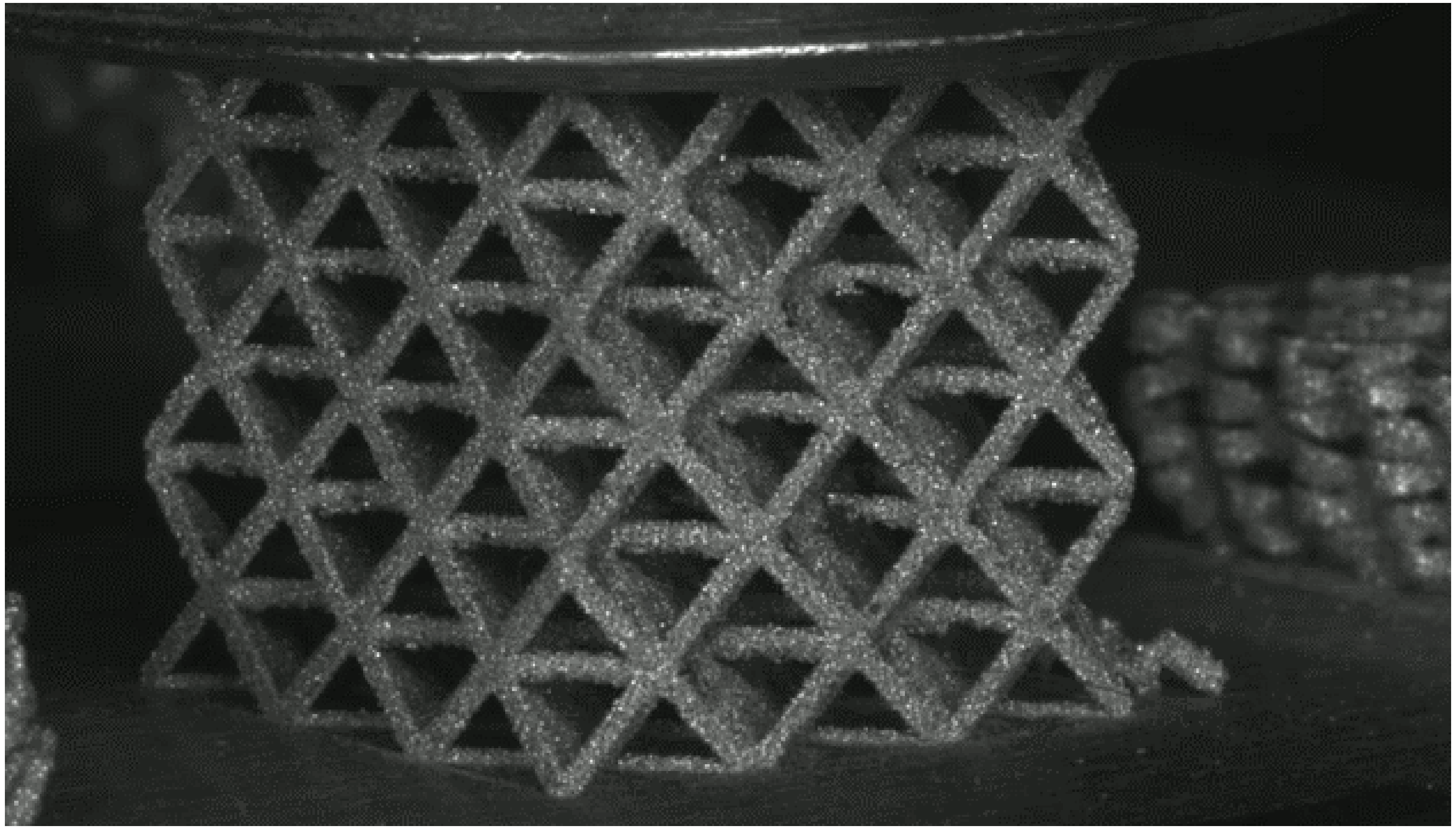
10,000 struts x 100 elements = 1 million elements



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?

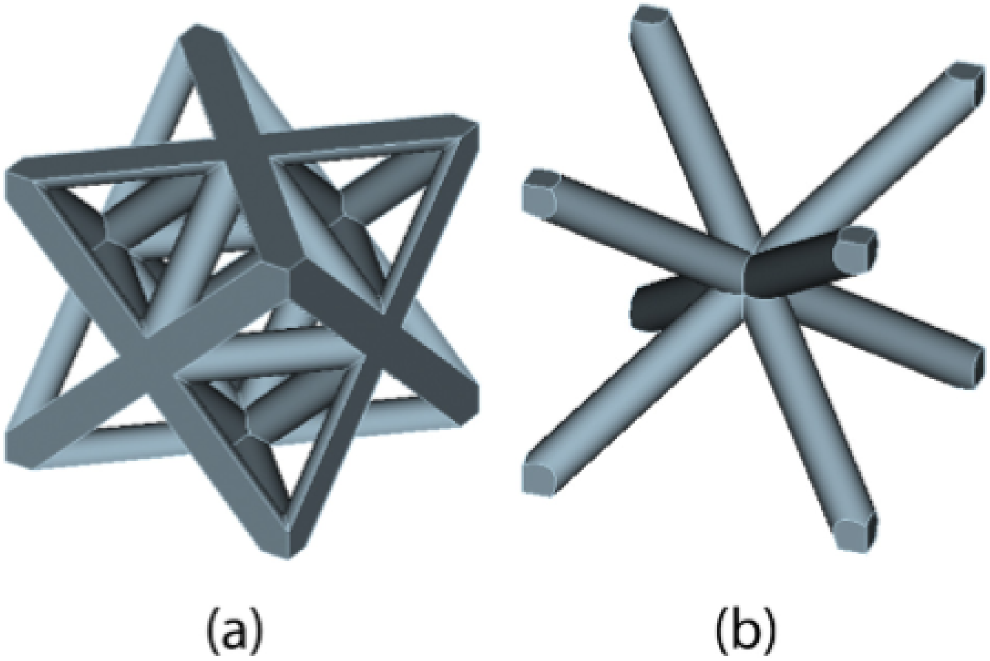


Fig. 1. Unit cell architectures used as constituents of of multi-morphology lattices: (a) Stretch-dominated FCC, and (b) bending-dominated BCC.

Homogenization techniques for periodic structures

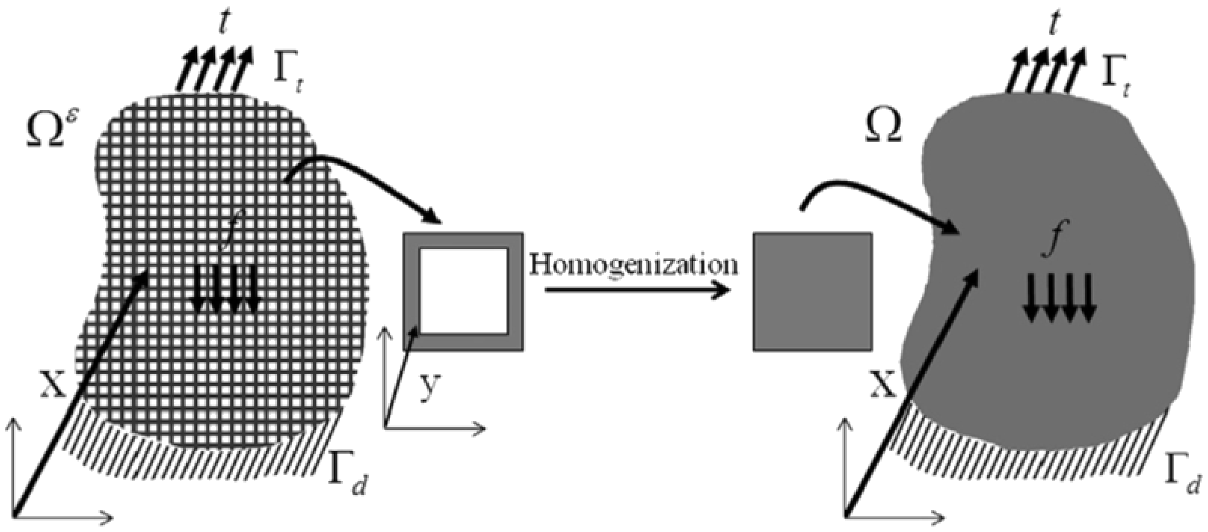


Fig. 2. Homogenization concept of a cellular structure.

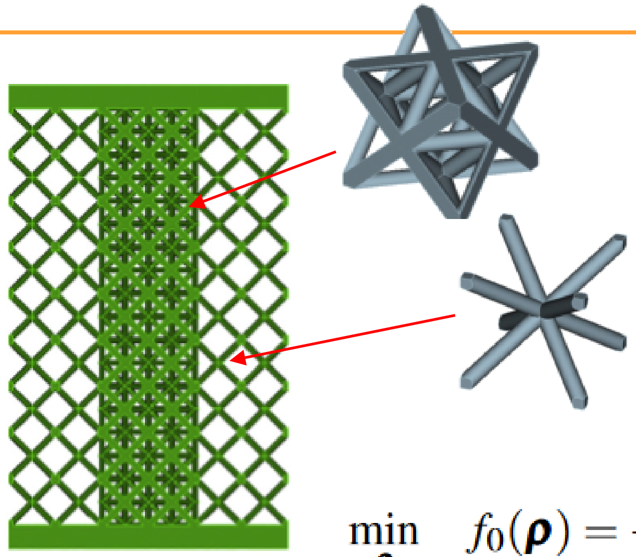
Arabnejad and Pasini, *Int. J. Mech. Sci.*, 2013

Review: Hassani and Hinton, Computers & Structures, 1998

<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

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

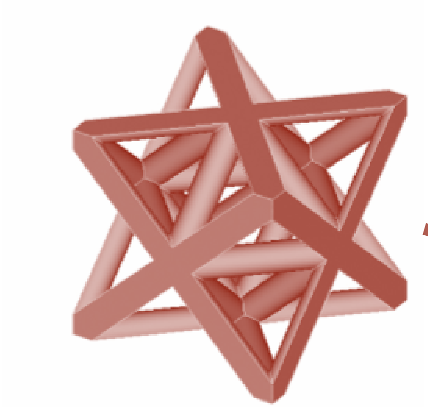
$$\boldsymbol{H}^k(\hat{\boldsymbol{u}}^k, \hat{\boldsymbol{u}}^{k-1}, \boldsymbol{c}^k, \boldsymbol{c}^{k-1}, \boldsymbol{\rho}) = \boldsymbol{0}, \quad k = 1, 2, \ldots, n,$$

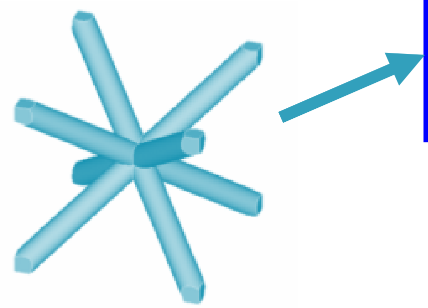
Implicit global and local PDE constraints from enforcing equilibrium

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

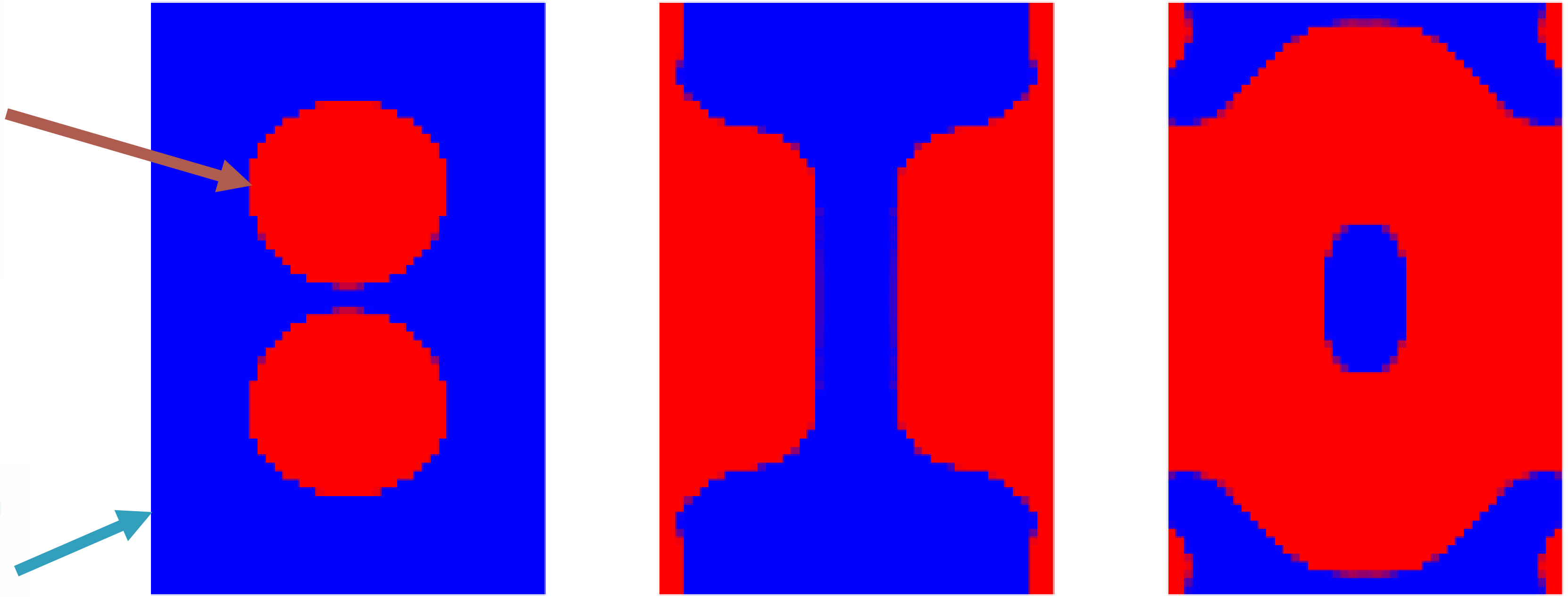
Constrain density

Result: optimal tiling for different volume fractions





25% dense 50% dense 75% dense

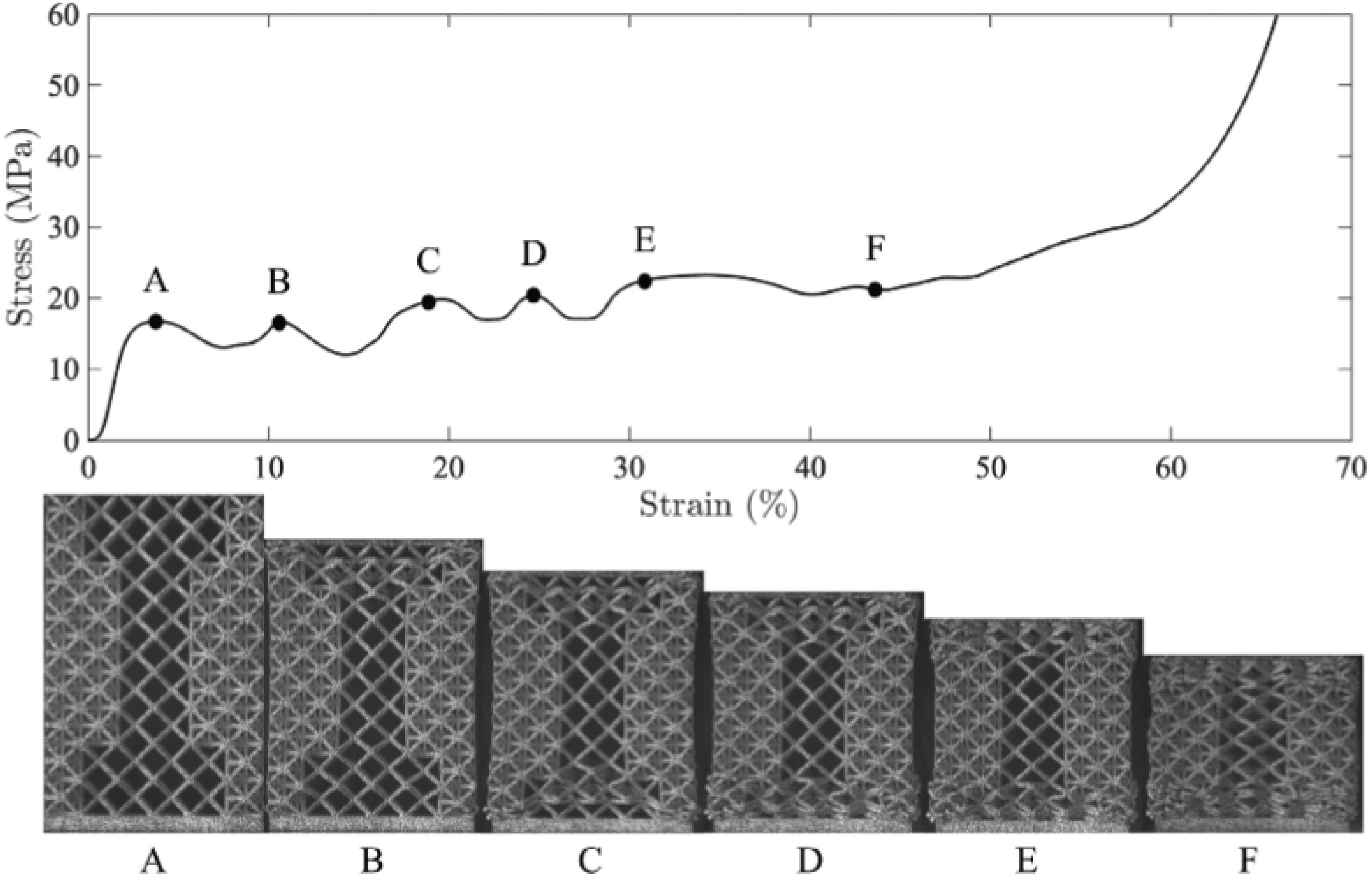


(a) $V_f = 0.25$ (b) $V_f = 0.5$ (c) $V_f = 0.75$

“meso-I”

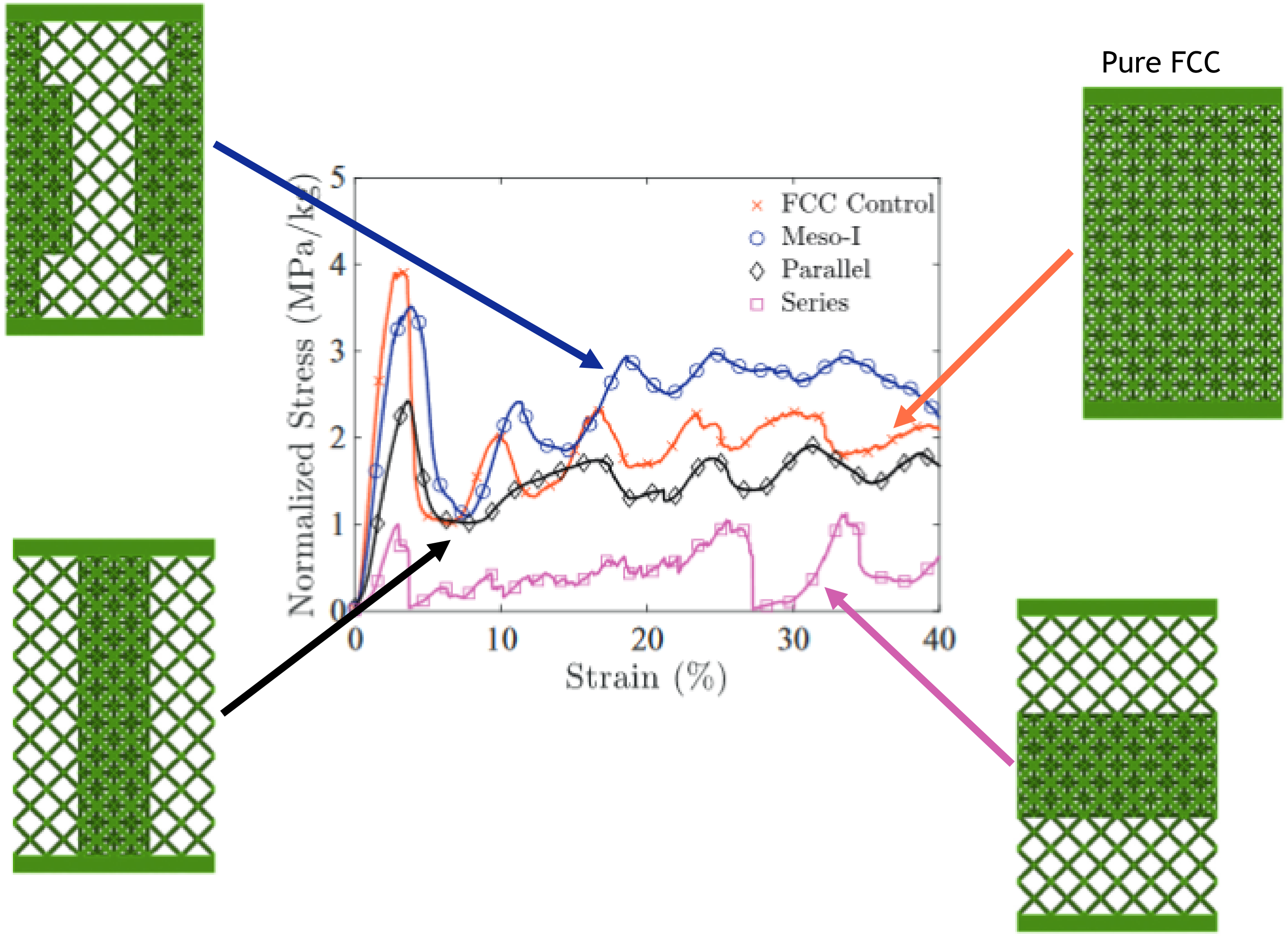
Alberdi, et al., *Materials & Design*, 2020

Experimental validation of the “meso-I” structure



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

The “meso-I” improves over simpler architectures



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

Second example: two objectives & manufacturing constraints

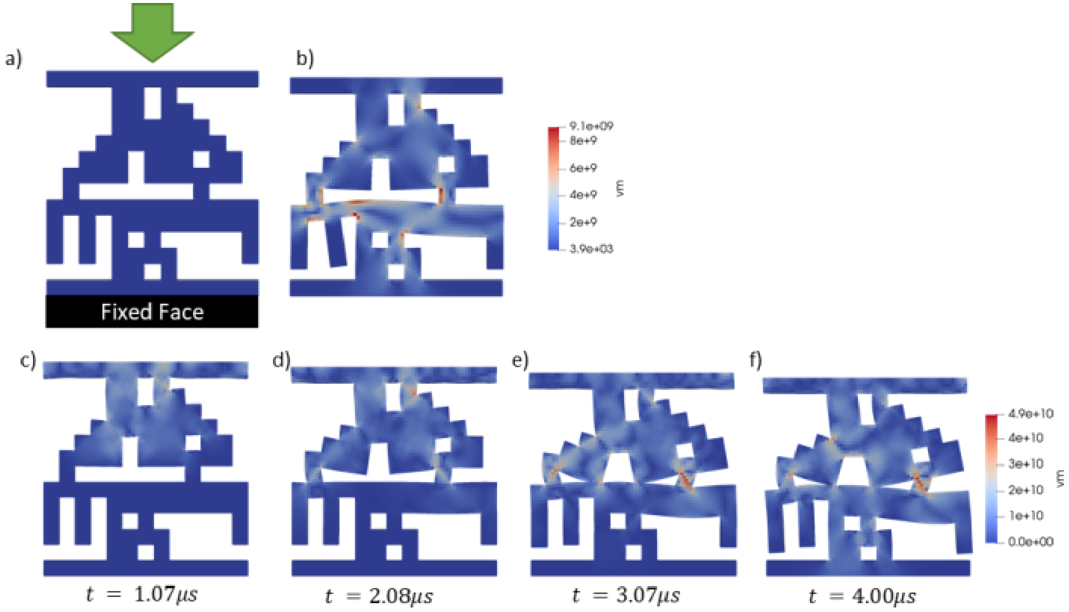
Optimizing for multiple objectives and manufacturing constraints

Two mechanical objectives:
Objective 1: Maximize stiffness
Objective 2: Minimize the effective elastic wave speed (maximize transmission time of a shock)

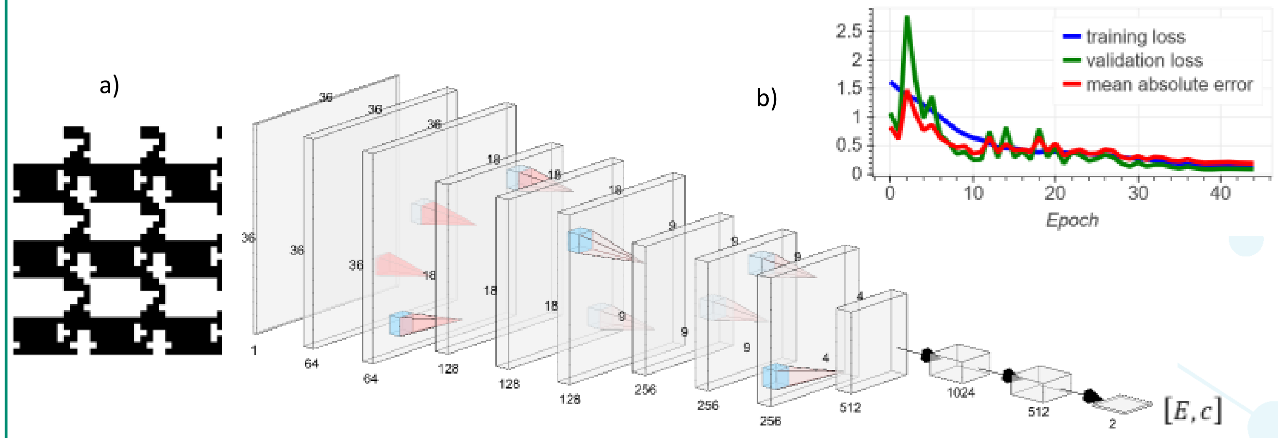
Five design/manufacturing constraints:
Constraint 1: all features must be contiguous (no floaters)
Constraint 2: a minimum feature size is set
Constraint 3: unsupported overhangs are forbidden
Constraint 4: unit cells must tile by connecting on their sides
Contratint 5: Supported overhangs must be below a threshold dimension
Constraint 6: density is between 40% and 60%

Replace costly explicit FEA with a CNN

Explicit FEA



Convolutional Neural Network



For more details…

AI/Data informatics: Design of Structural Materials — AI/ML for Design of Structural Alloys & Additively Manufactured Materials

Sponsored by: TMS Materials Processing and Manufacturing Division, TMS Structural Materials Division, TMS: Mechanical Behavior of Materials Committee, TMS: Computational Materials Science and Engineering Committee, TMS: Integrated Computational Materials Engineering Committee

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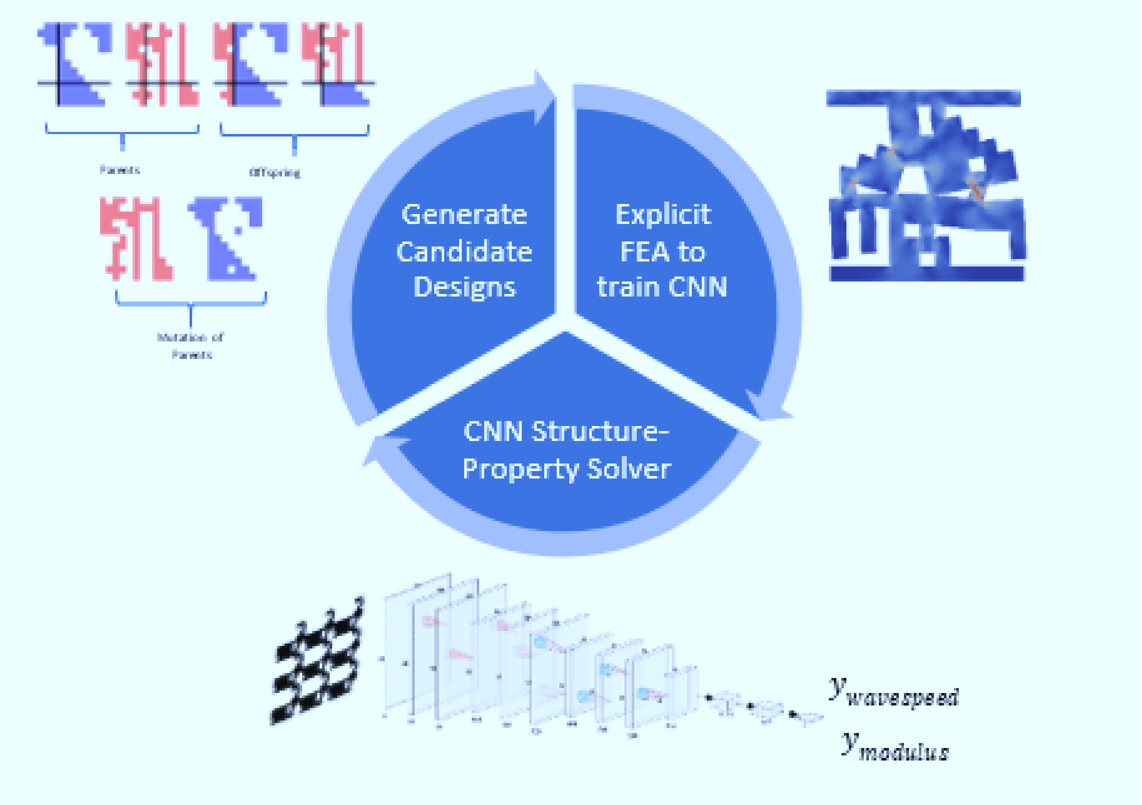
Tuesday PM **March 16, 2021**

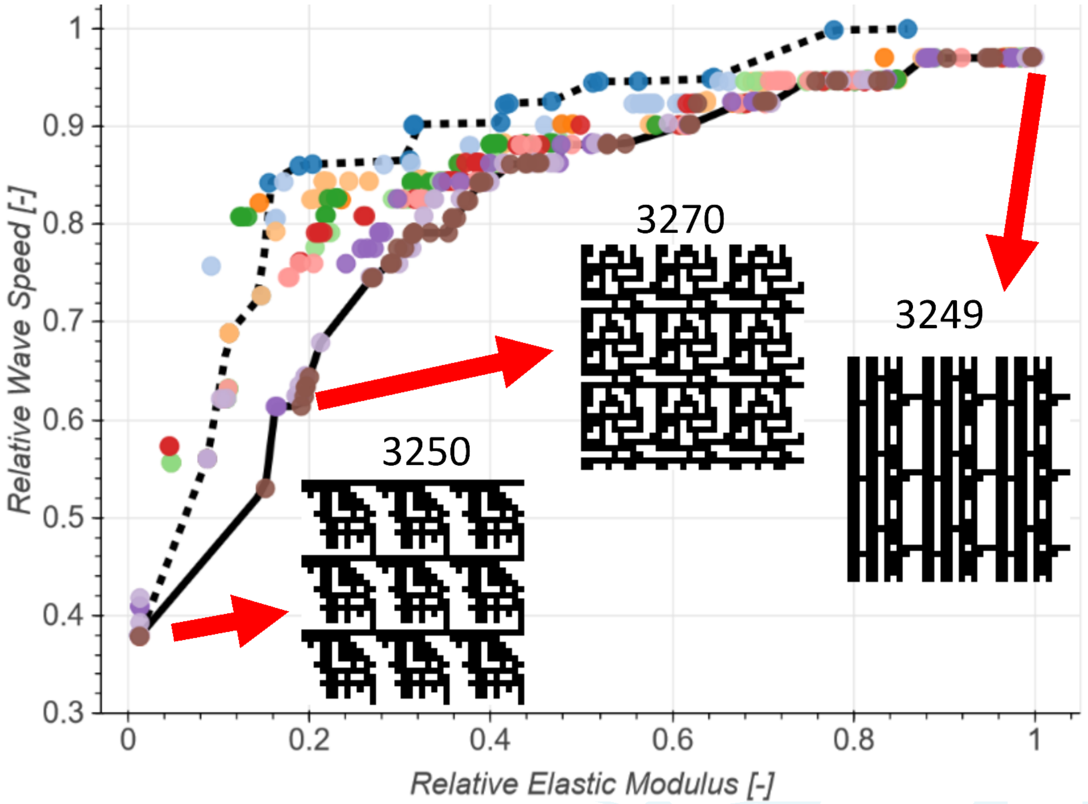
3:10 PM Invited

Multi-objective Lattice Optimization Using an Efficient Neural Network Approach: *A. Garland*[1]; B. White[1]; B. Boyce[1]; R. Alberdi[1]; [1]Sandia National Labs

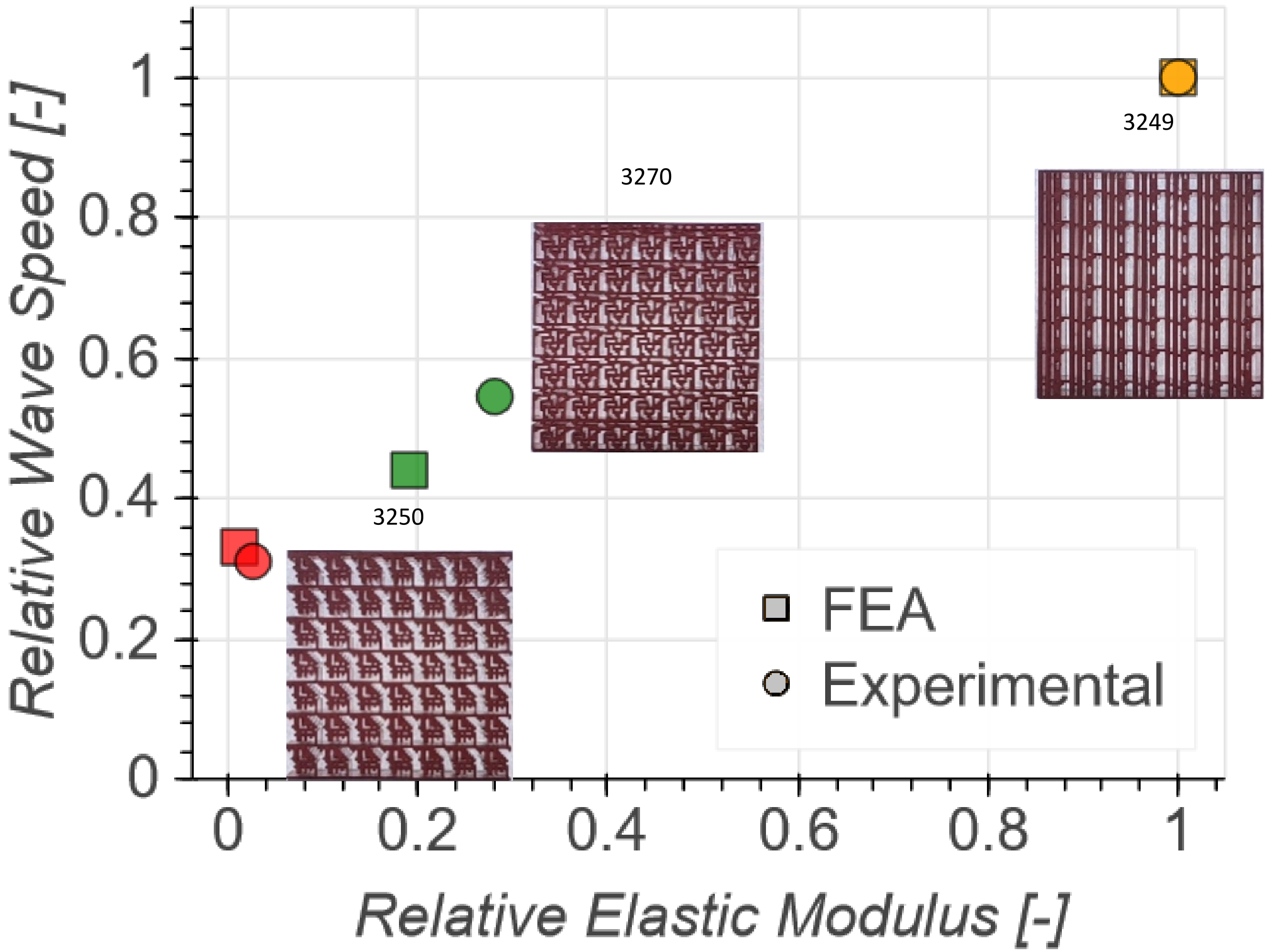
Active-learning based lattice design:
two objectives: stiffness and elastic wave delay

- Initial seed designs are randomly generated
- The initial designs are predicted by FEA (stiffness and effective wavespeed)
- The FEA results train a CNN, which is 6 orders faster than FEA
- The best solutions are hybridized by splicing two parents into offspring
- Offspring are screened based on the CNN



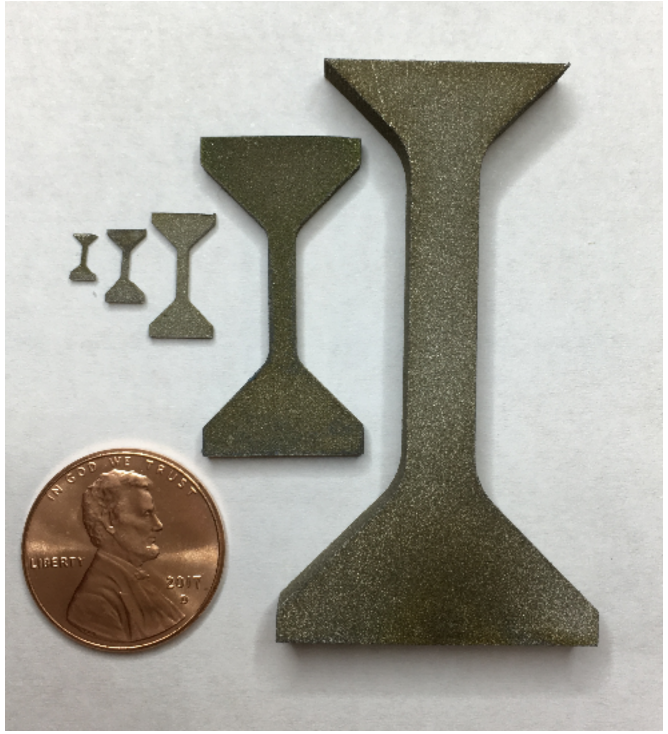


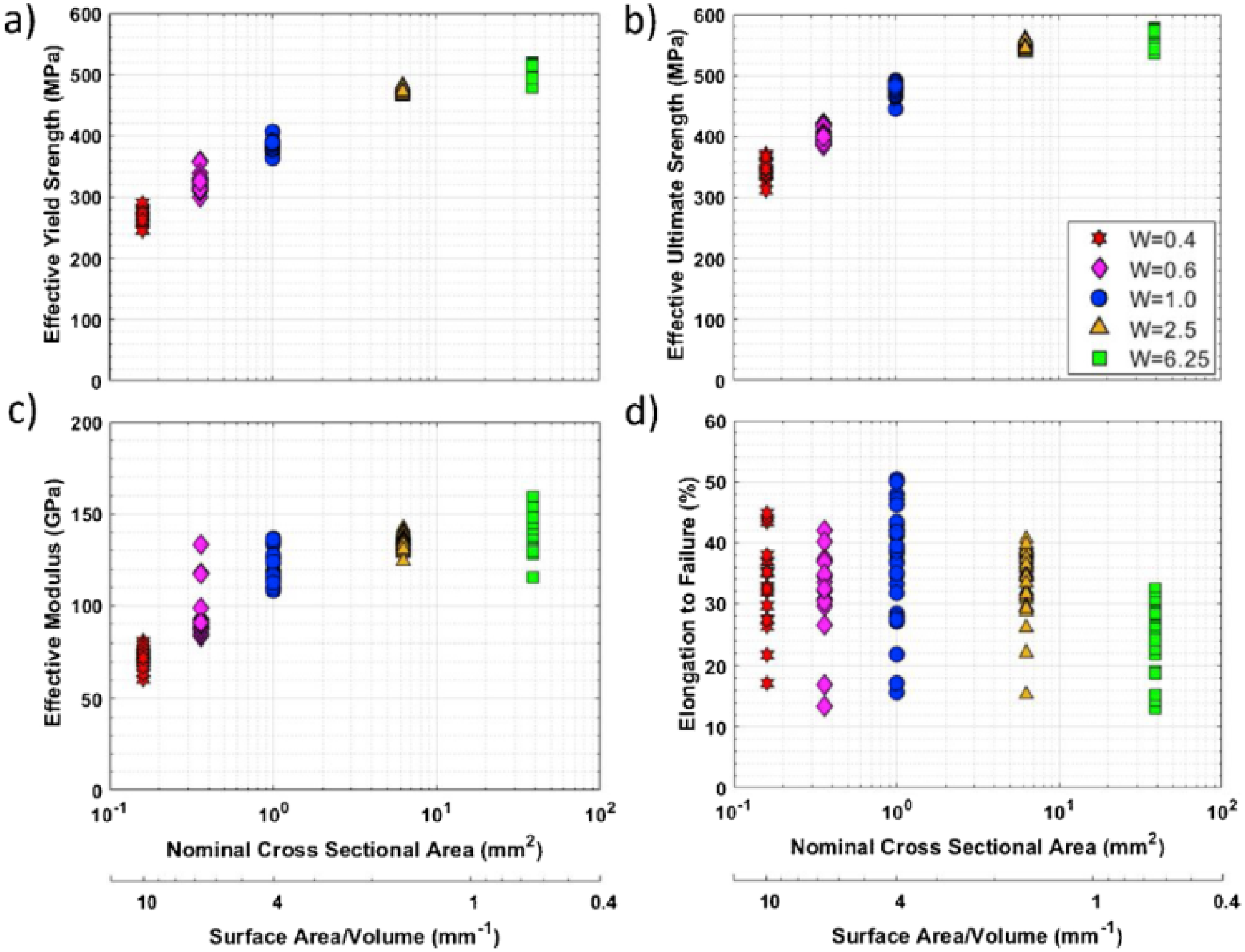
Experimental validation



These models assume the struts behave like bulk, isotropic material

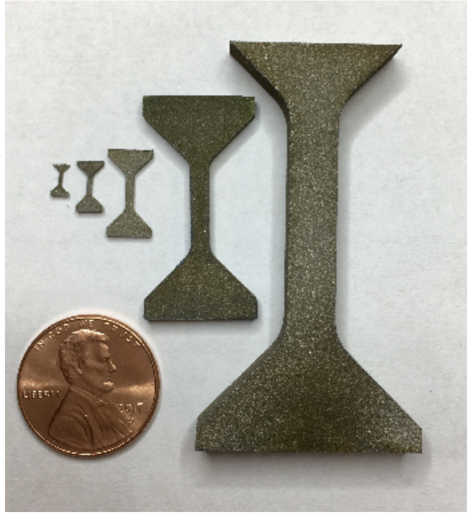
Effective mechanical properties of AM are strongly size-depe

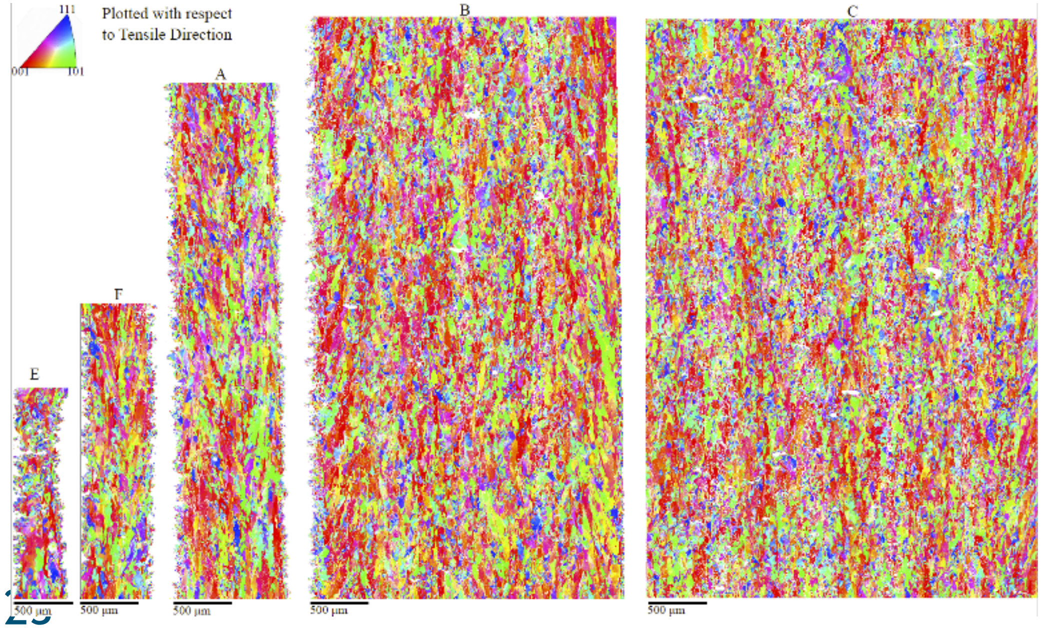


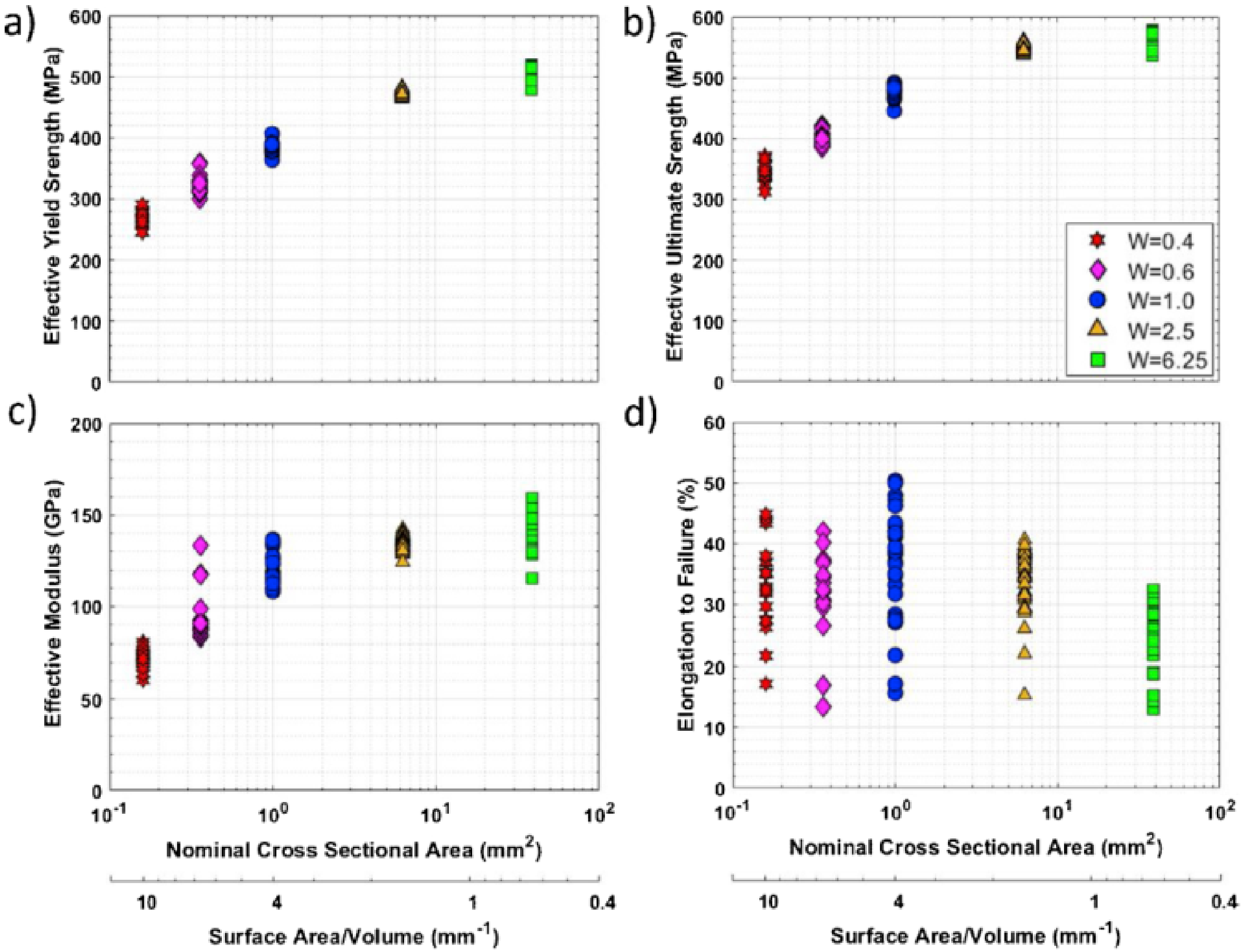


A. Roach, et al., Additive Manufacturing, 2020

Its not the microstructure that causes size dependence!



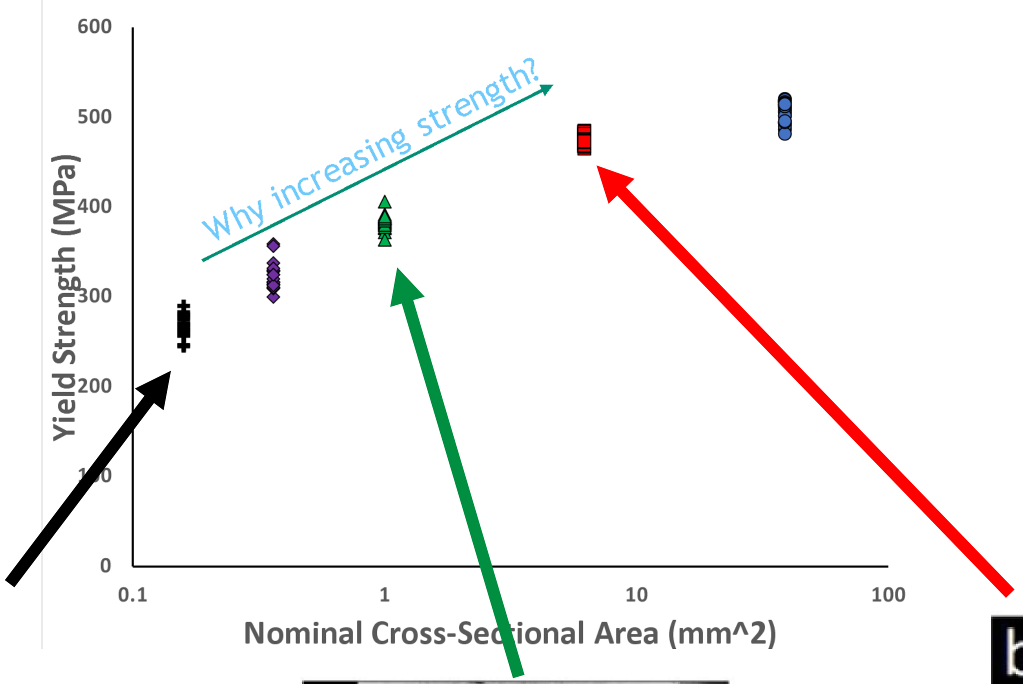


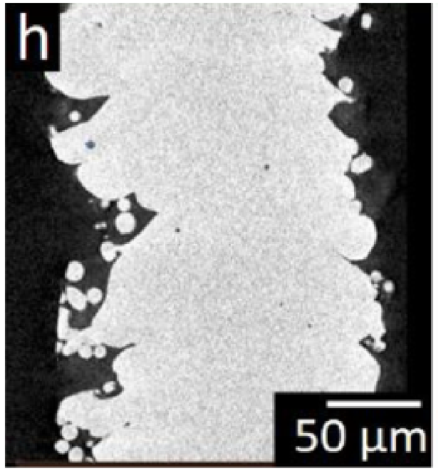


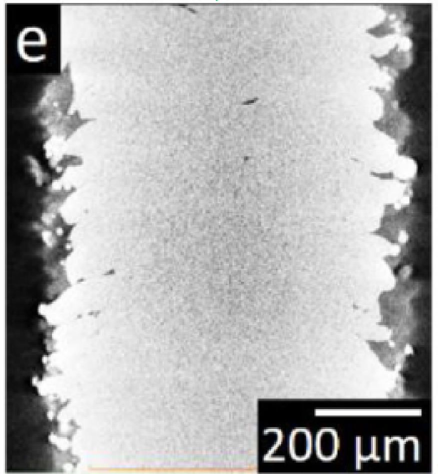
A. Roach, et al., Additive Manufacturing, 2020

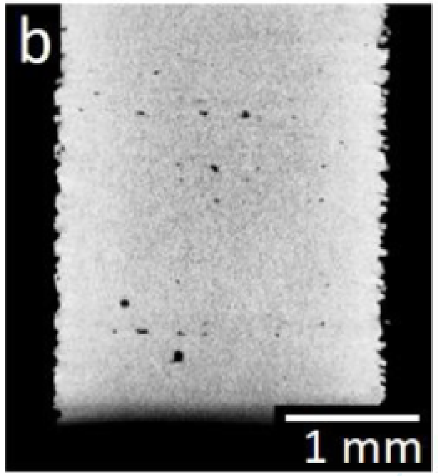
It's the surface roughness

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



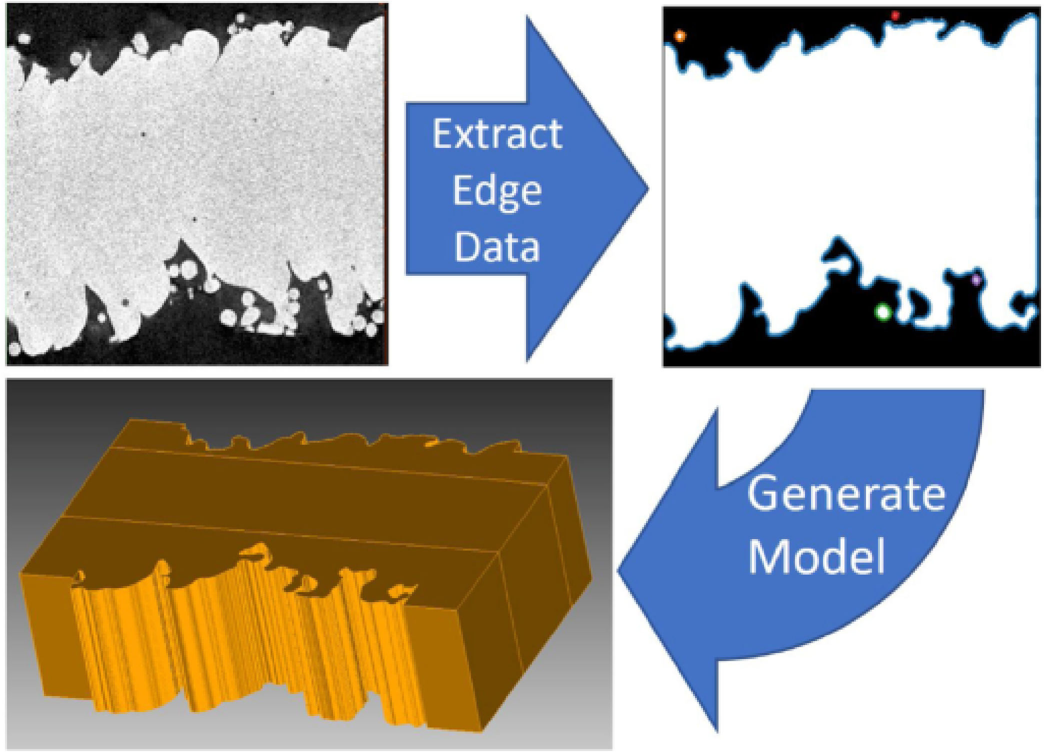


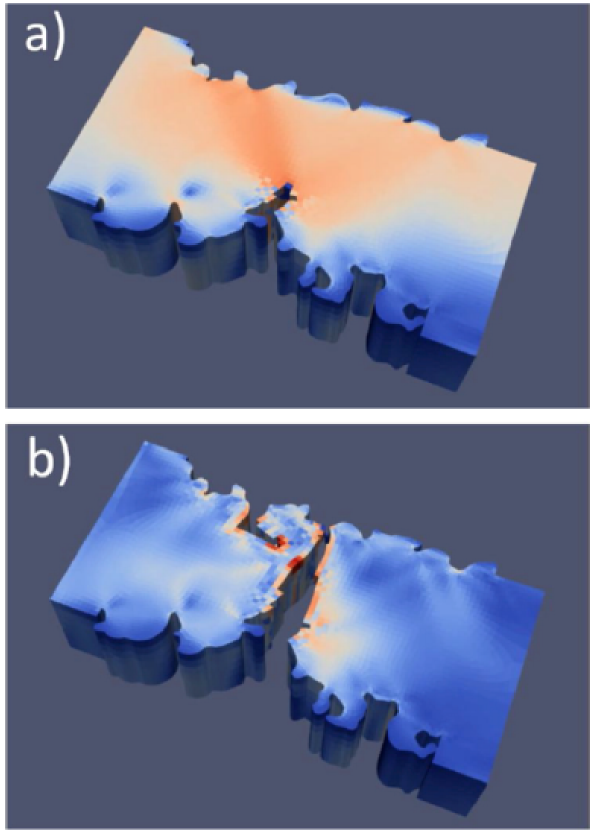


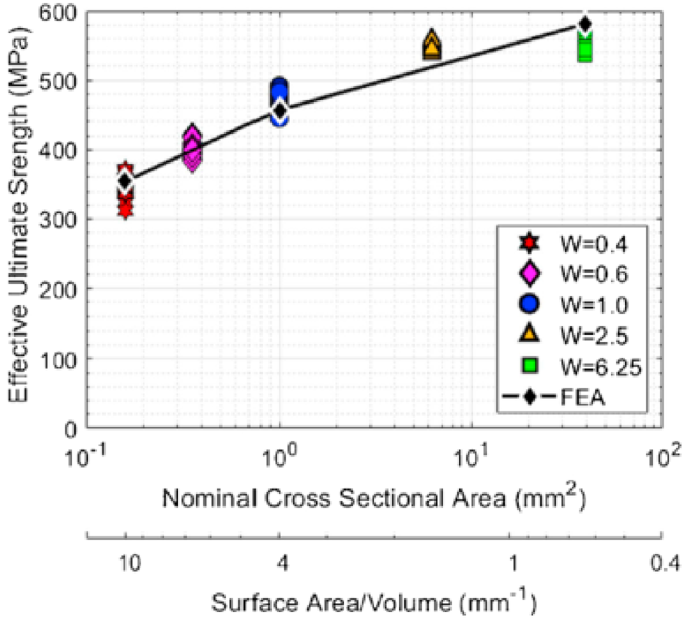


A. Roach, et al., Additive Manufacturing, 2020

FEA validates roughness effect

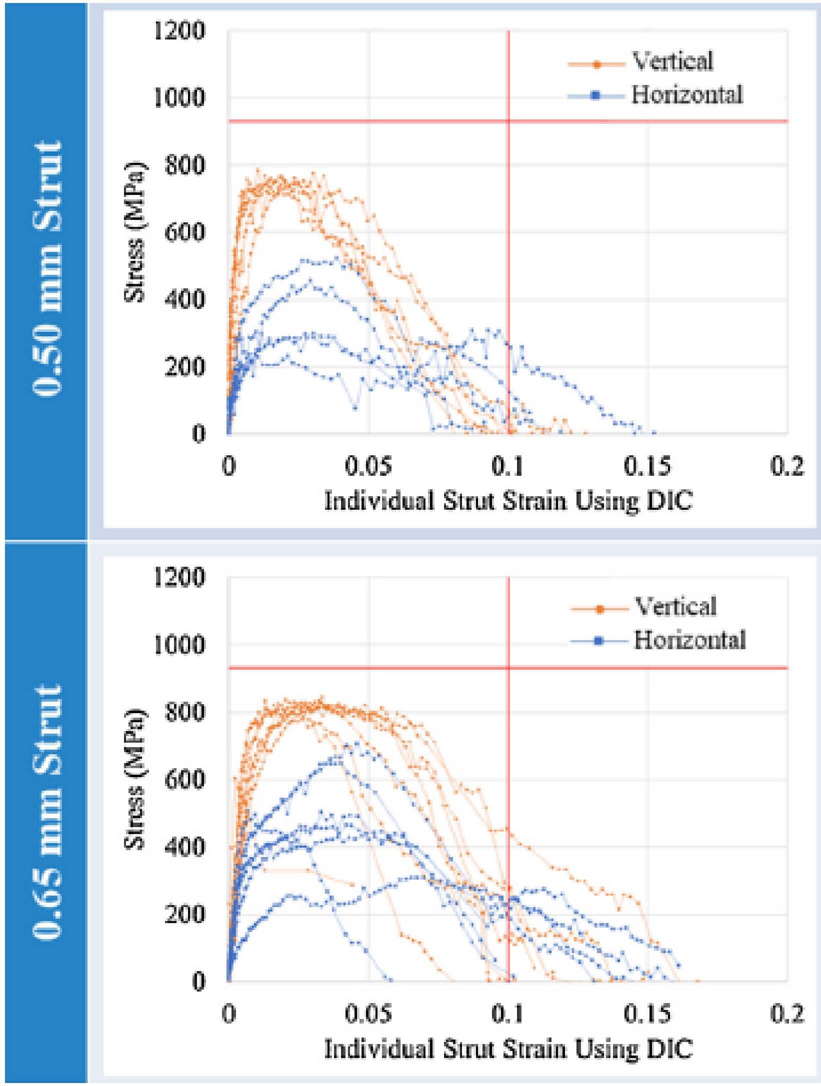






A. Roach, et al., Additive Manufacturing, 2020

Struts do not behave like bulk material



- Orientation dependence comes from building on top of loose powder
- Not only size-dependent but highly stochastic

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

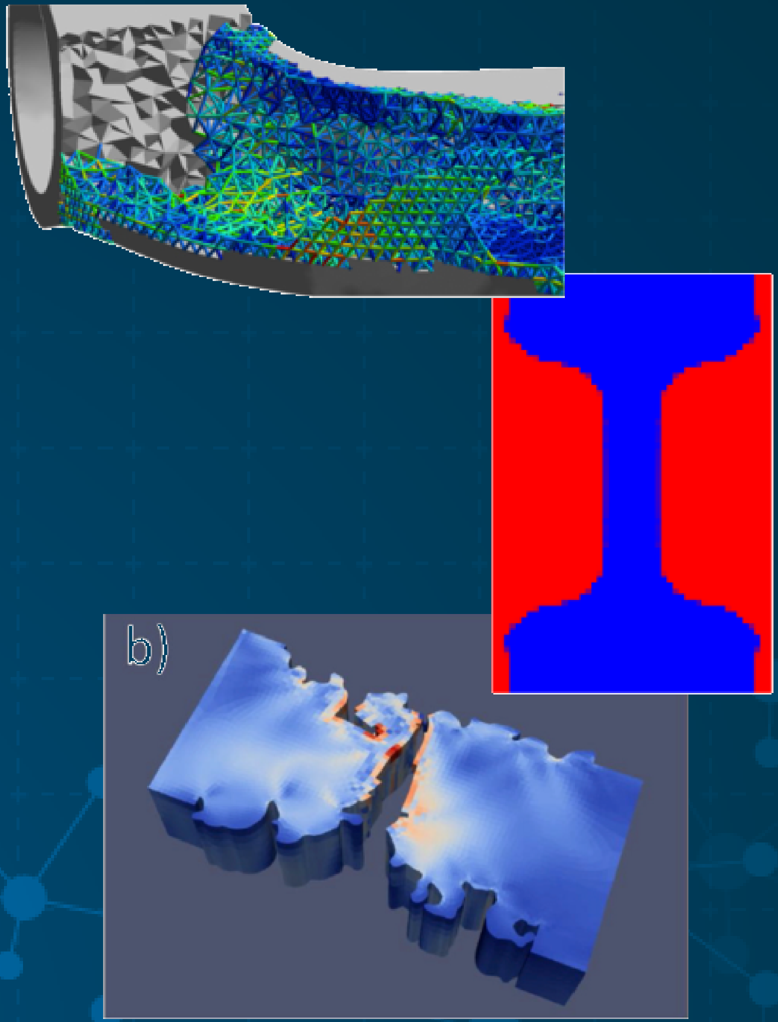
Take-home messages

1. Additively manufactured lattices can help enable sustainable metals usage

2. Optimized lattices maximize performance and minimize material usage / weight

3. Reduced order models, such as the micromorphic continuum method and neural networks can be employed to efficiently optimize lattices

4. In the future, it will be beneficial to incorporate more material realism in these models, such as representation of stochastic surface roughness.



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