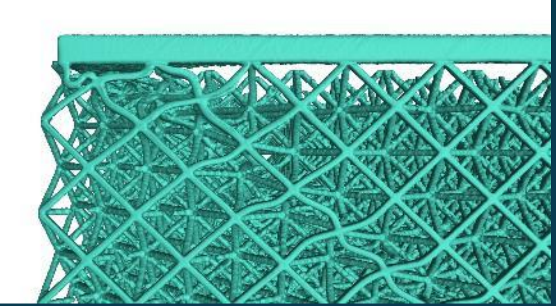
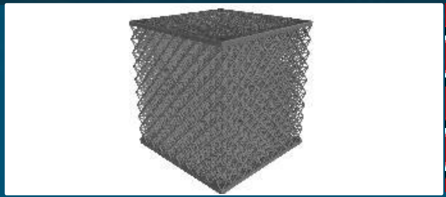
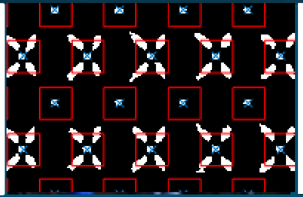
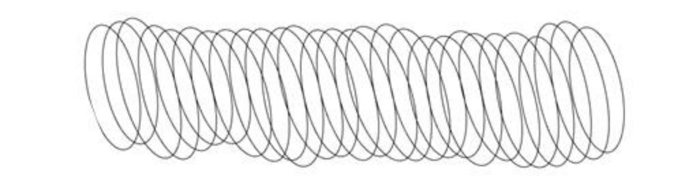
Sandia National Laboratories

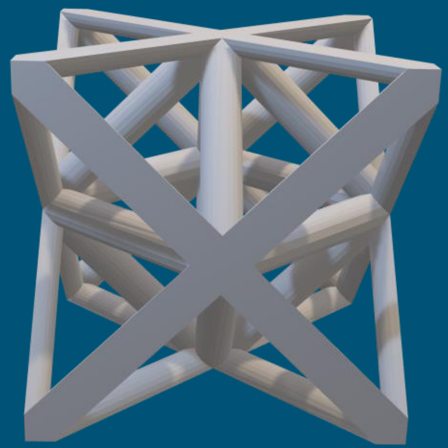
Using NDE Diagnostics to Monitor the Deformation of an Octet Truss Lattice under Constant Compression Loading











Government Laboratories Collaborating with Universities

PRESENTED BY

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Georgia Institute of Technology, Atlanta, Georgia

U.S. DEPARTMENT OF ENERGY NNSA

Outline of the Presentation

Introduction to Sandia National Laboratories (SNL), Department of Energy (DOE), National Nuclear Security Administration (NNSA)

Government and University Collaboration

Introduction to Lattices

Challenges of Additively Manufactured Components

Lattice Characterization Techniques

Mechanical Behavior of Lattices

Conclusions

The Department of Energy (DOE) National Labs fill a unique niche in United States (ST&E*) Areas

The DOE National Laboratories serve as leading institutions for scientific innovation in the United States.

*Science, Technology, and Engineering (ST&E)

THE DOE LABS: Work in the Science & Technologies Area

Research in every scientific and engineering discipline

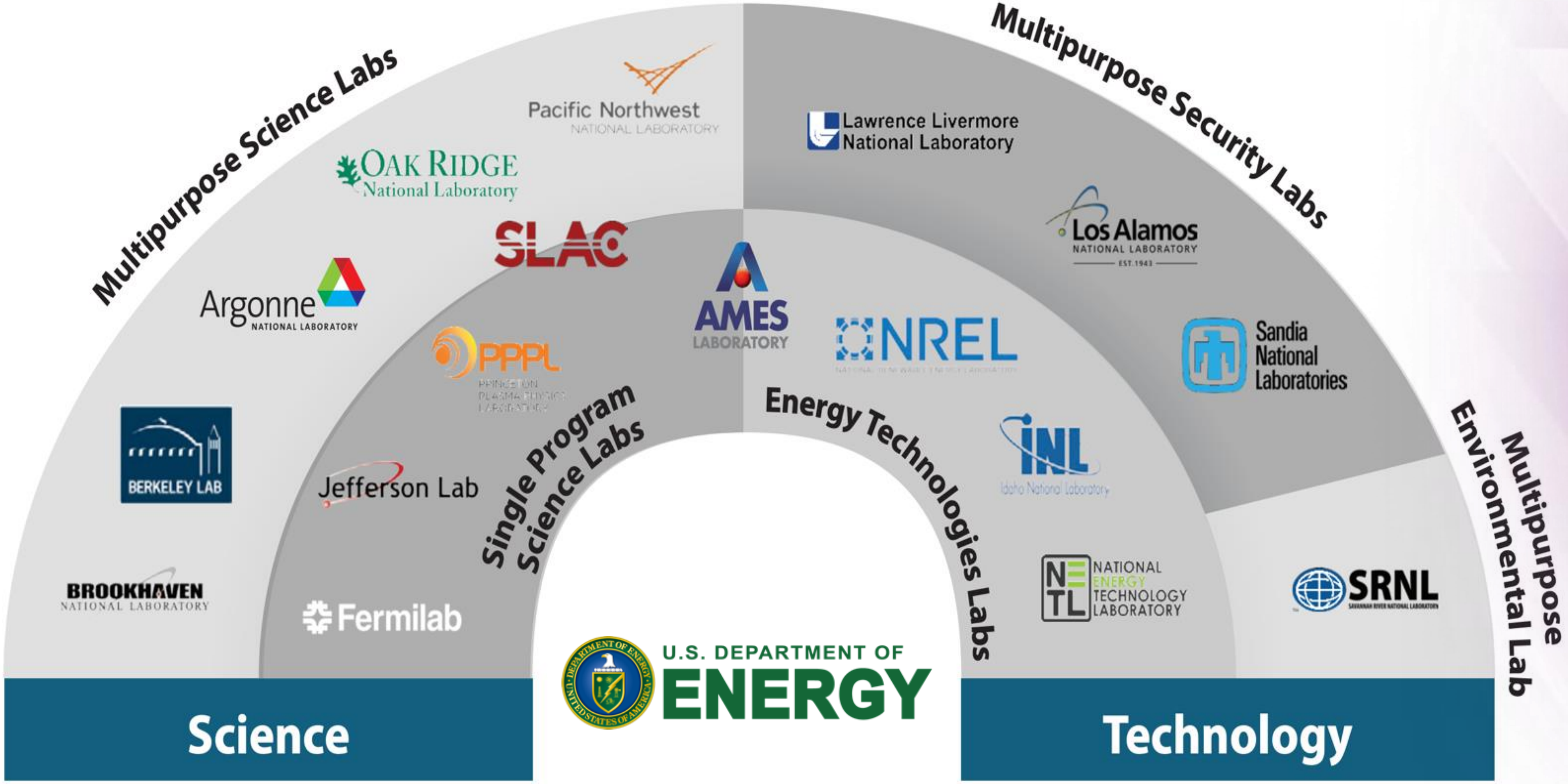
Teams range from single PIs to 100s

Over **12,000 peer-reviewed publications** annually

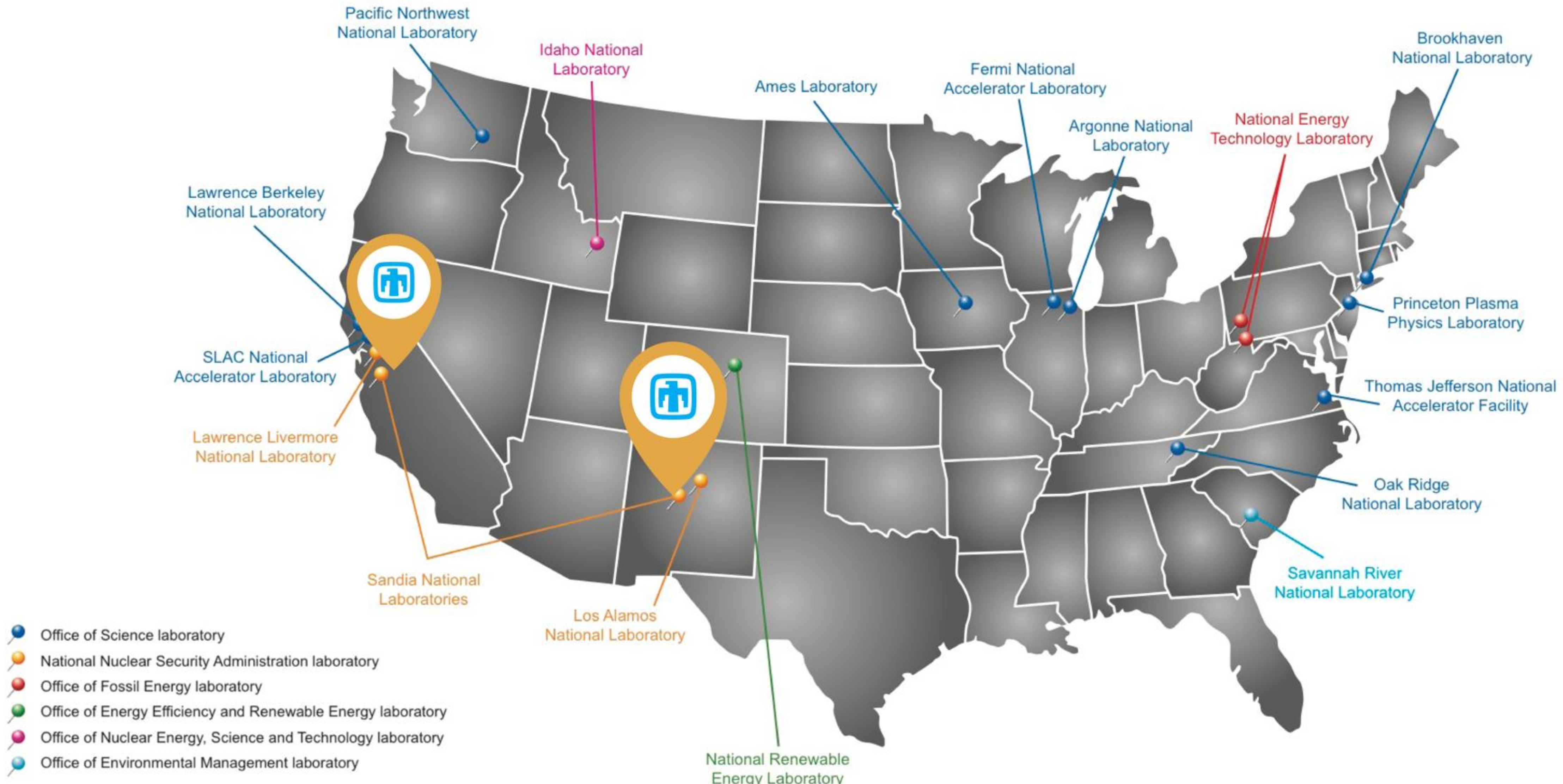
Collaborations with over 450 North American universities

>3,000	>2,000	>2,000	>1,300
undergrad students	grad students	postdocs	joint faculty appointments

THE DOE LABS Serve Multiple purposes



THE DOE LABS span the country



Introduction to Lattices

Periodic, high strength-to-weight ratio structures made possible through AM technologies.

Highly useful in aerospace applications for light-weighting components.

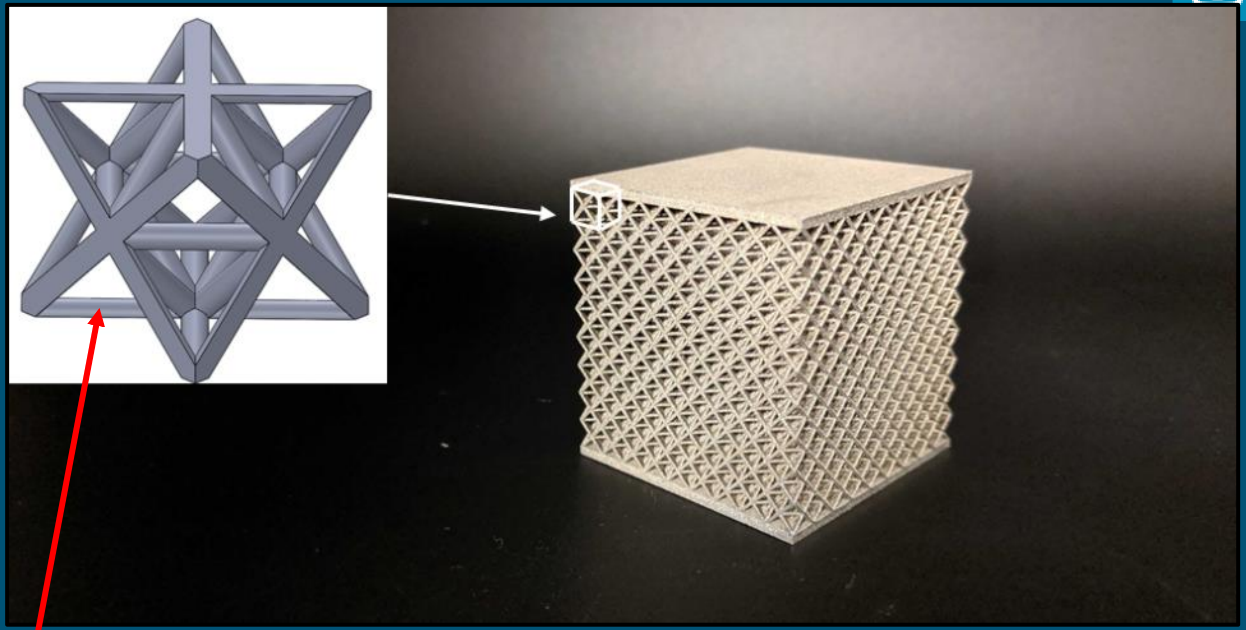
Medical applications (hip replacements)

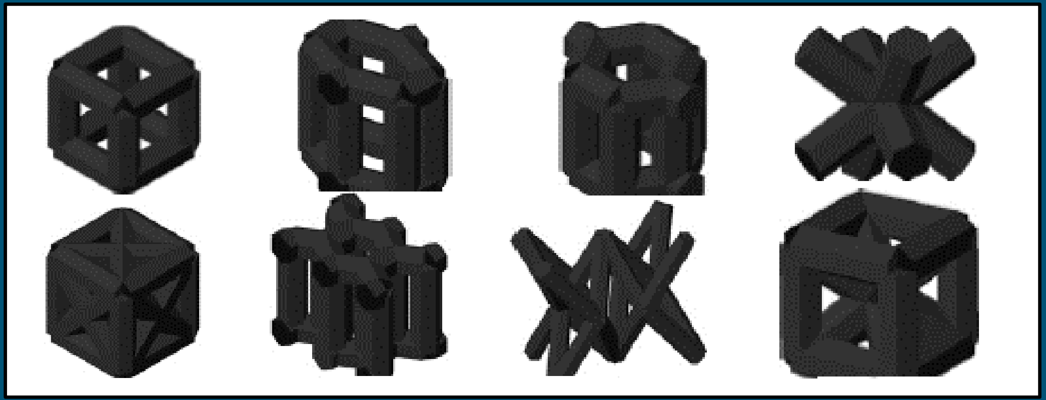
Complex structures complicate inspections

- 36 struts/cell x (10 x 10 x 10) cells = **36,000** individual struts

Cell Types: Gyroid, BCC(Z), FCC(Z), Octet.

Material: Stainless Steel 316-L





[1]

[1] Beyer and Figueroa, Design and Analysis of Lattice Structures for Additive Manufacturing, 2016

Challenges of Additively Manufactured Lattices

1. Fragility
   - Difficult to build—largely due to small size of struts
   - Struts can easily be broken during build or during handling or removal from build plate
2. Complexity
   - Too many struts to easily inspect or easily make sense of
3. Inspection access
   - Internal struts difficult or impossible to reach depending on unit cell design and component size
   - Traditional inspection methods not possible
4. Post-processing
   - Lattices cannot be post-process machined to correct for internal inaccuracies
5. General AM issues
   - Surface roughness
   - Geometric inaccuracies and heterogeneities
   - Porosity

Overview of Research (Process Mapping)

1. Sample Manufacture
2. Pre Test Lattice Inspection (Computed Tomography)
3. Interrupted Mechanical Testing Ex-situ CT inspection
4. Correlation of Heterogeneities and Mechanical Performance

Compression
Inspection
Iterate until failure

Research Questions: What geometric features impact lattice deformation/failure behavior? Can we determine a critical defect criteria? Can this data be used to predict and improve lattice performance during high velocity 0.2 km/sec impact loading?

Manufacturing Parameters

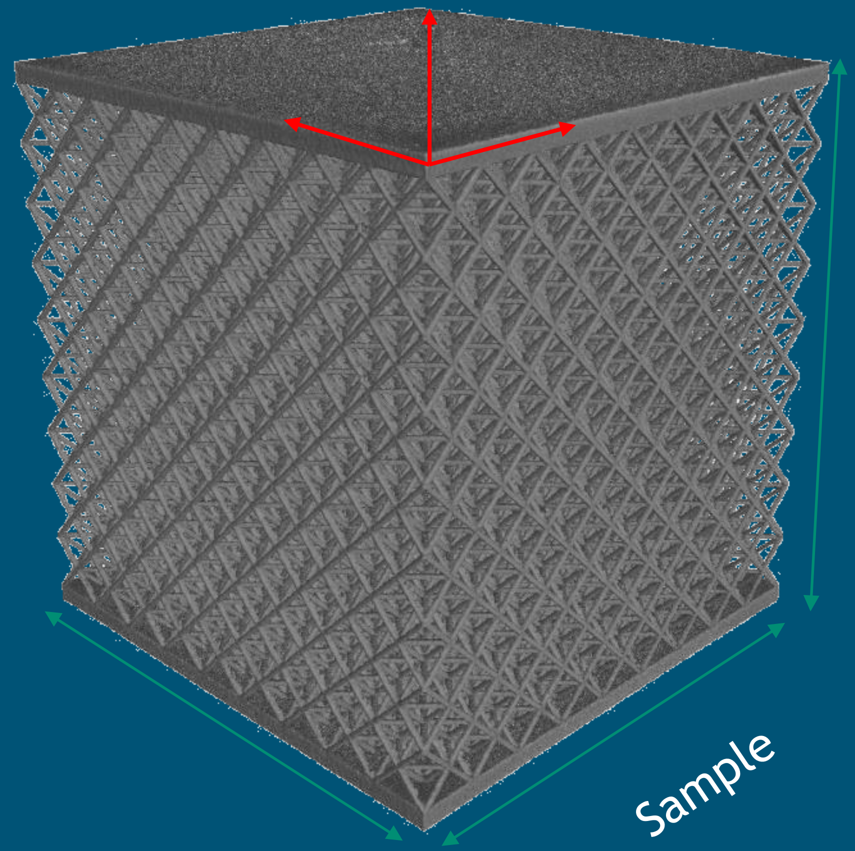
Samples were printed using a Renishaw AM250

Print parameters were optimized for lattice manufacture.

Samples are 9x9x9 octet truss unit cells

- Cell size:
- Strut Diameter
- Cell Count
- Side Length

Parameter	Value
Material Type	304-L SS
Beam Diameter	70 µm, Gaussian Distribution
Laser	200 W Nd-YAG, 1064nm
Argon Flow Rate	0.19 m^3/s
Layer Thickness	50 µm

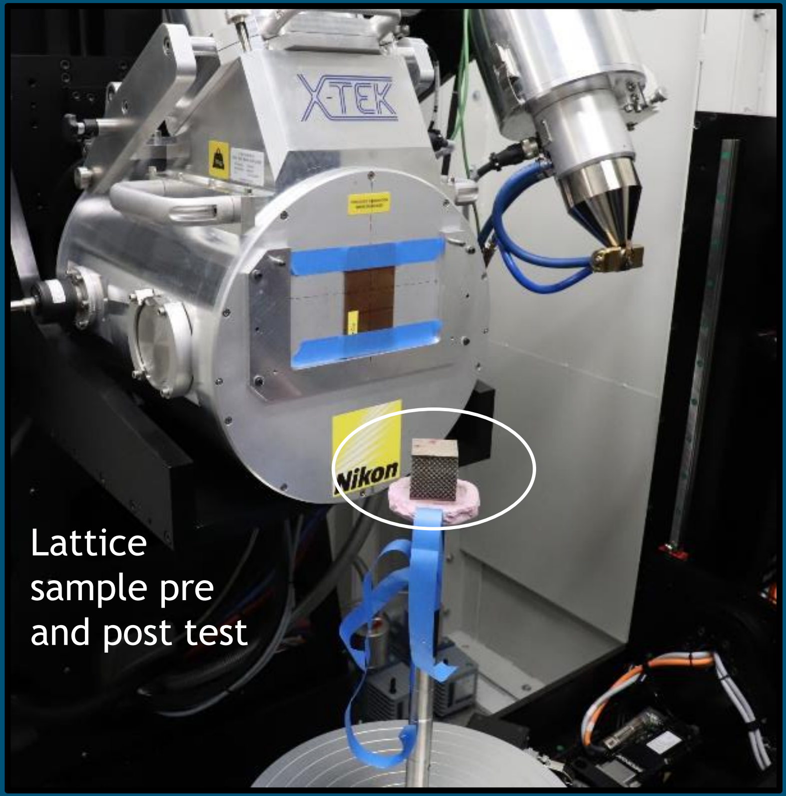


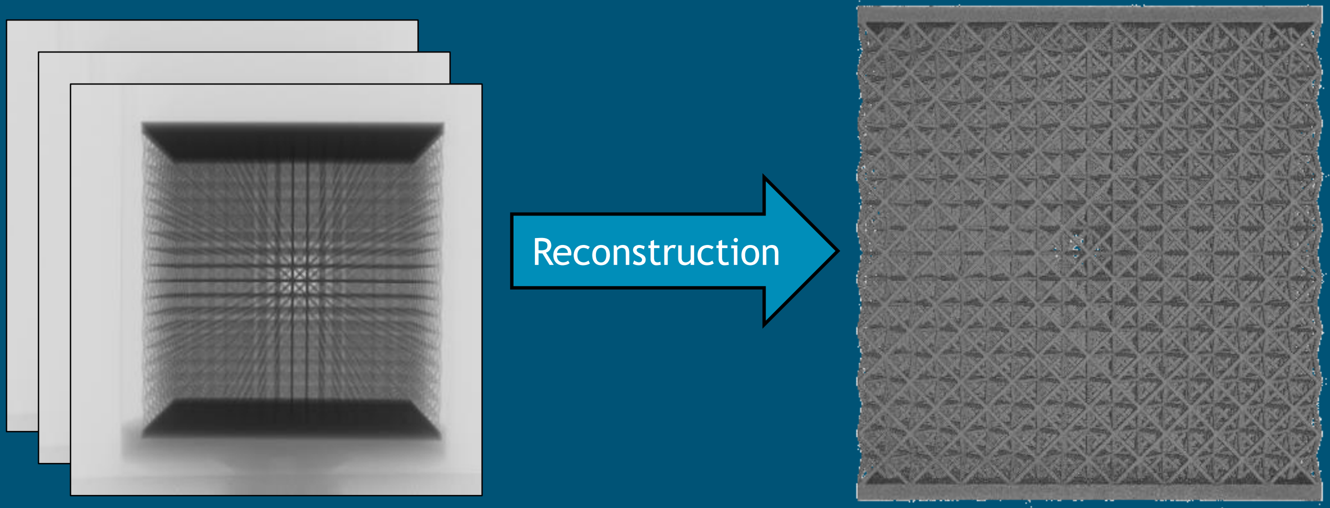
Computed Tomography (CT) Inspection

All lattices were inspected using CT scanning. A datum surface was used to ensure consistency across inspection results.

Inspections were performed using a Nikon Dual Head M2 225/450kV CT Machine

Reconstructions were performed using Nikon Metrology X-Tek CT Pro 3D.





2D Radiographs

3D CT Volume

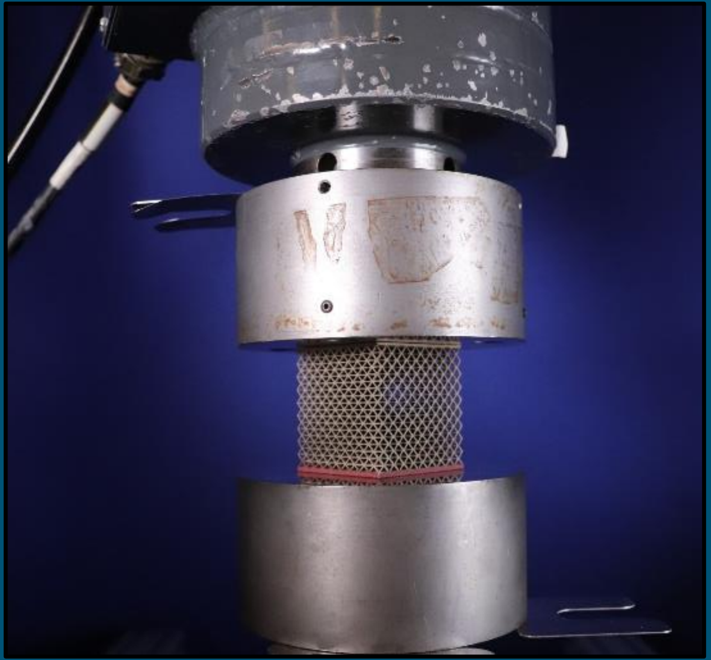
Parameter	Value
Number of Projections	3142
Voltage	440 kV
Current	225 μA
Prefiltering	2 mm Cu
Resolution	**30.2 μm/voxel**

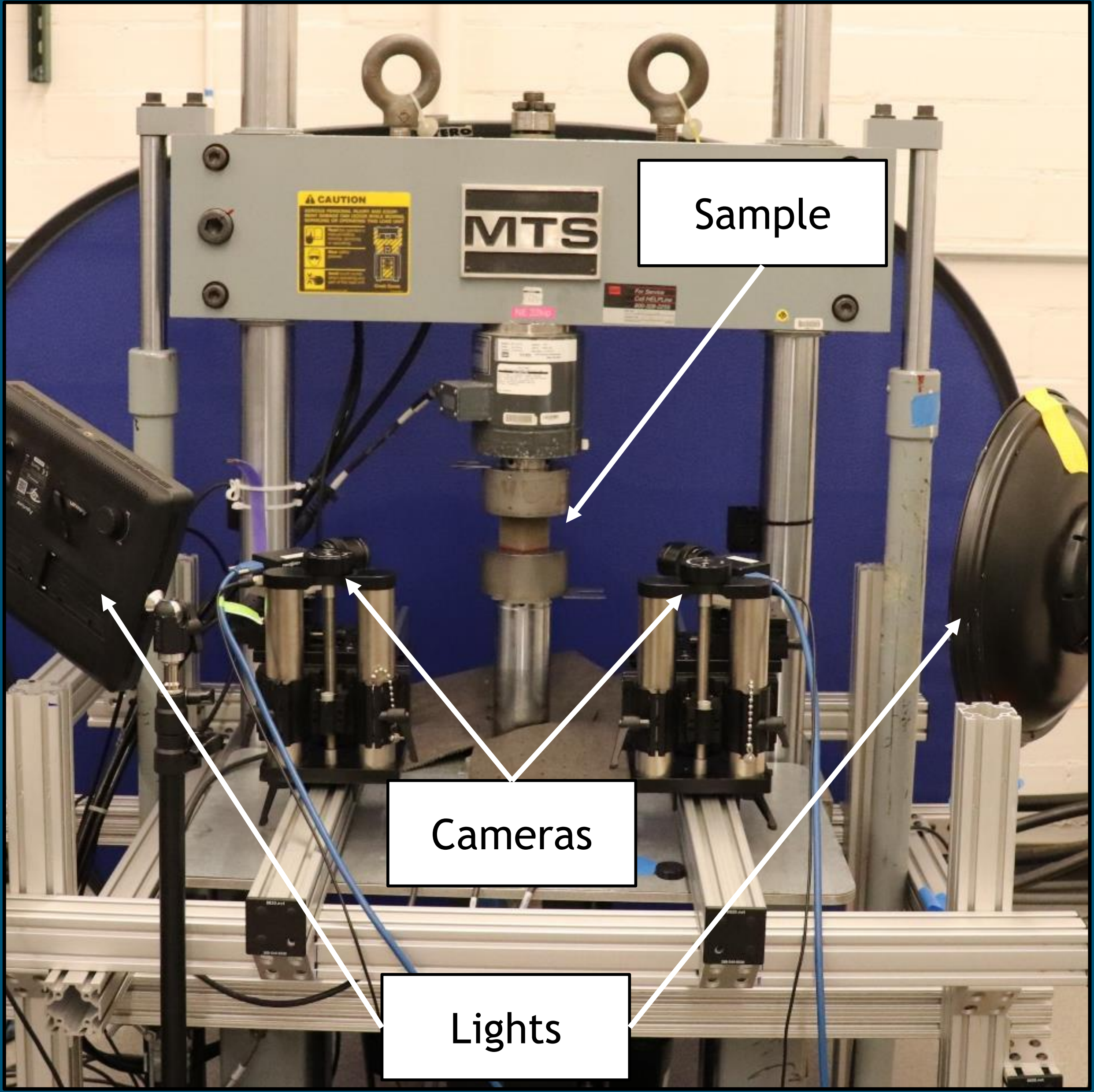
Compression Testing

Mechanical compression testing was carried out using an MTS load frame equipped with a 20kip load cell.

Friction-free boundary condition was simulated by using a oil lubricant.

Interrupted compression testing was utilized to observe deformation in lattices throughout the failure process.





Lattice Characterization Techniques

Lattice Characterization

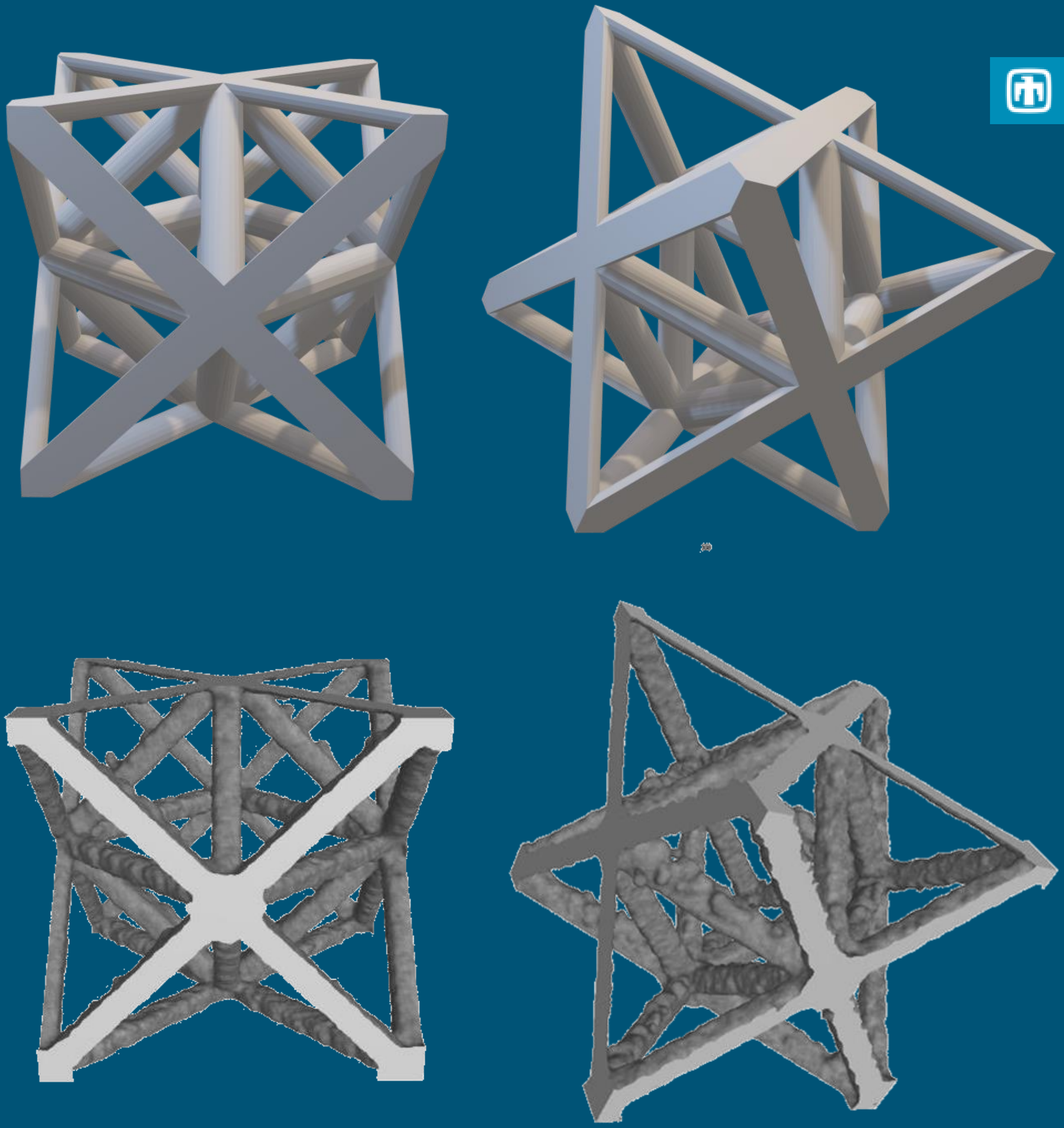
Computed Tomography is a powerful tool for 3D image acquisition

A variety of lattice features are of interest:

- Strut cylindricity
- Strut diameter/node diameter
- Medial Axis/Skeletonization
- Porosity
- Hanging, extraneous features

Characterization of lattices is important for:

- Development of standardized inspection techniques
- Understanding common defects that may compromise material performance



Lattice Characterization – Ellipse Fitting Algorithm

Algorithm developed in MATLAB to fit ellipses to 2-dimensional images of lattice cross-sections perpendicular to axis of struts.

A variety of print heterogeneities exist for lattices.

This algorithm can be used to investigate:

- Strut cylindricity
- Strut waviness

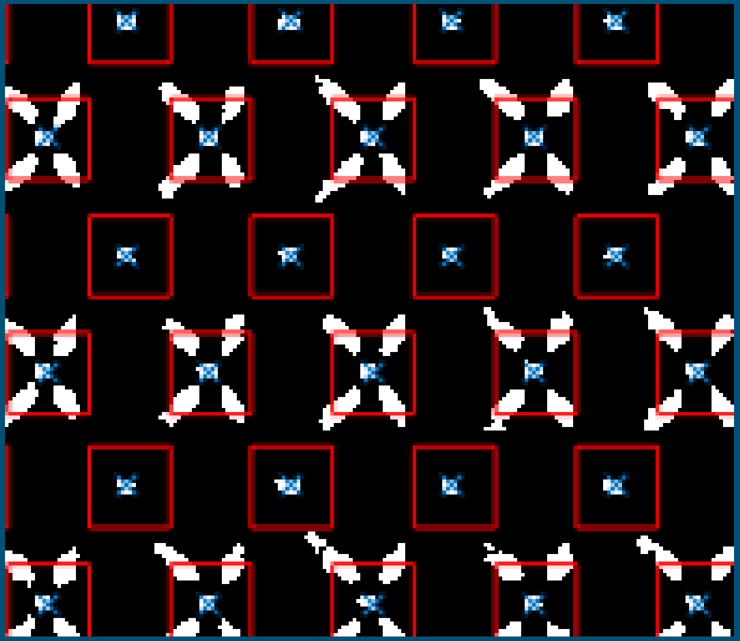
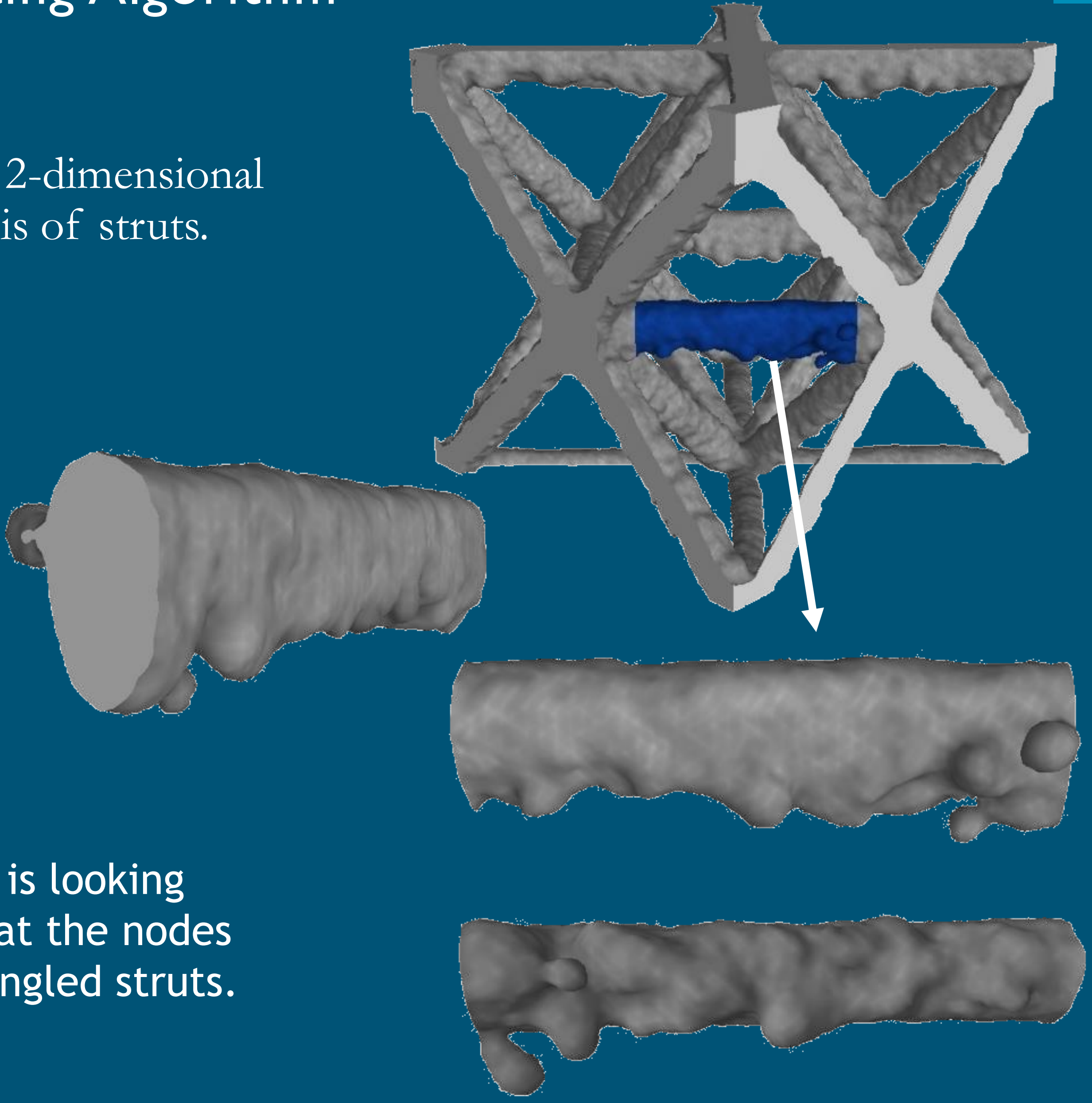
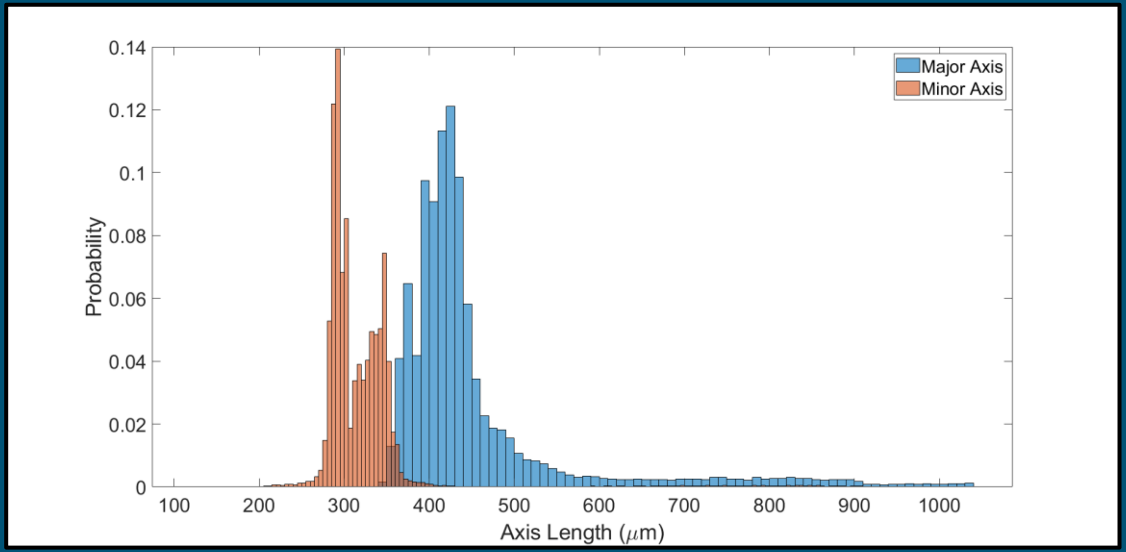
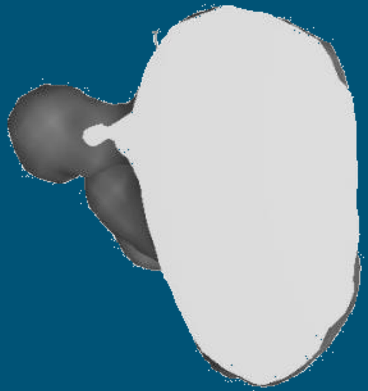


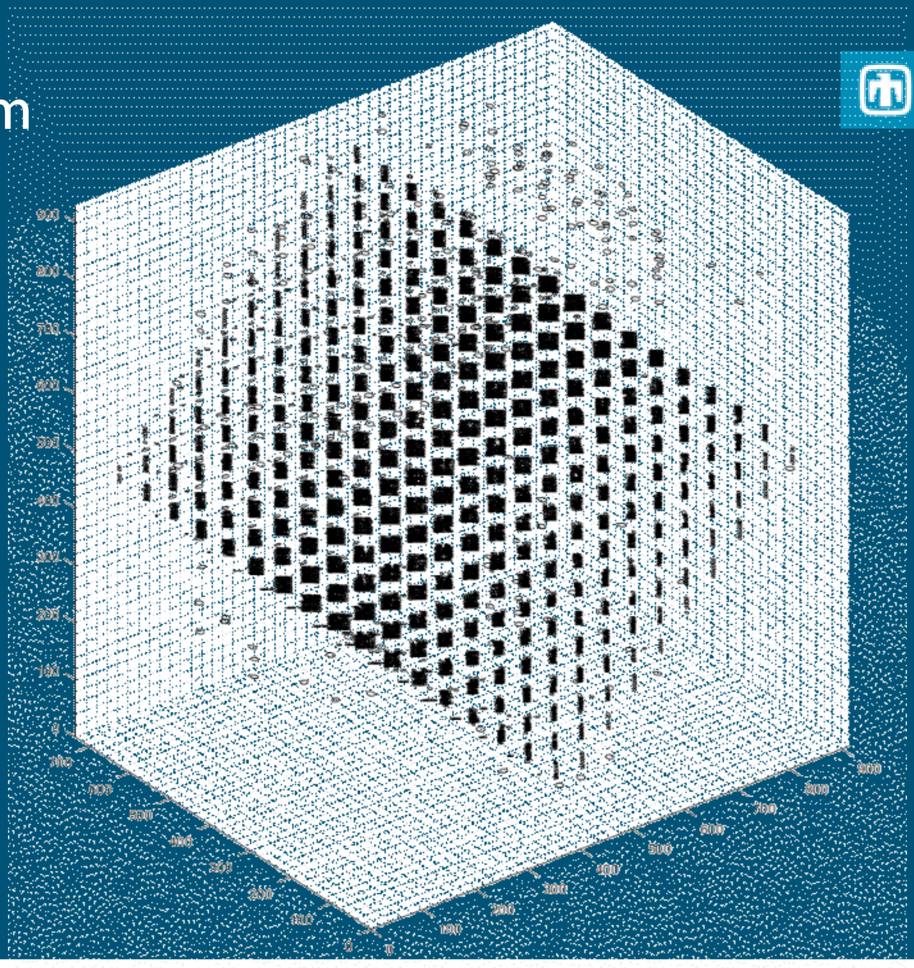
Image is looking down at the nodes with angled struts.

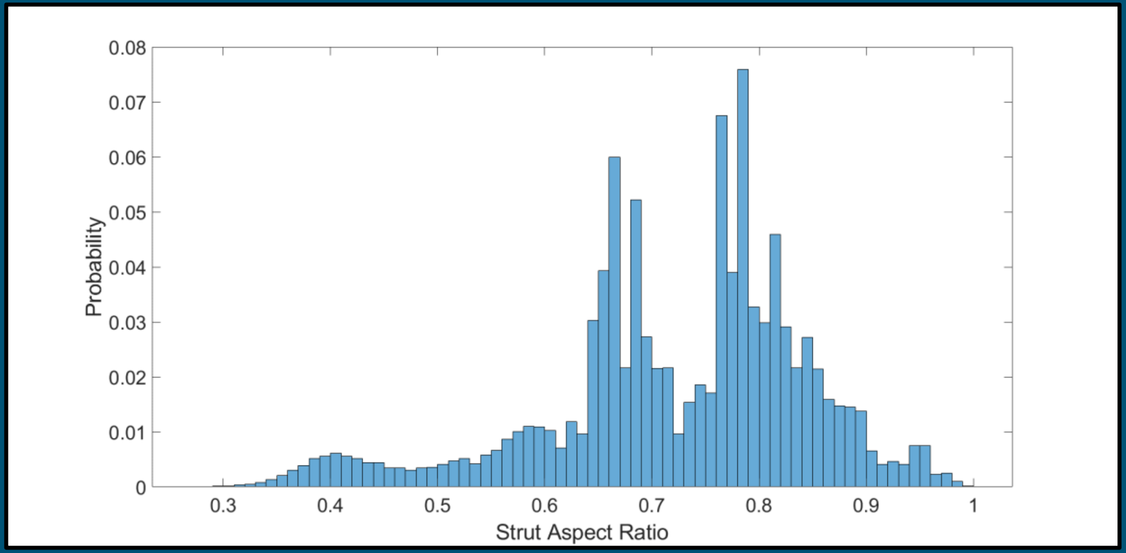


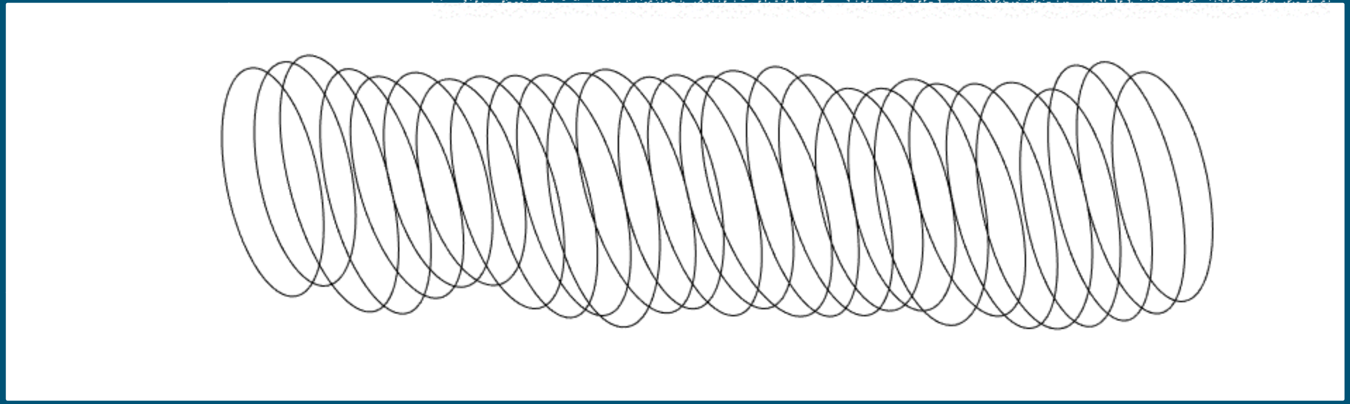
Lattice Characterization – Ellipse Fitting Algorithm







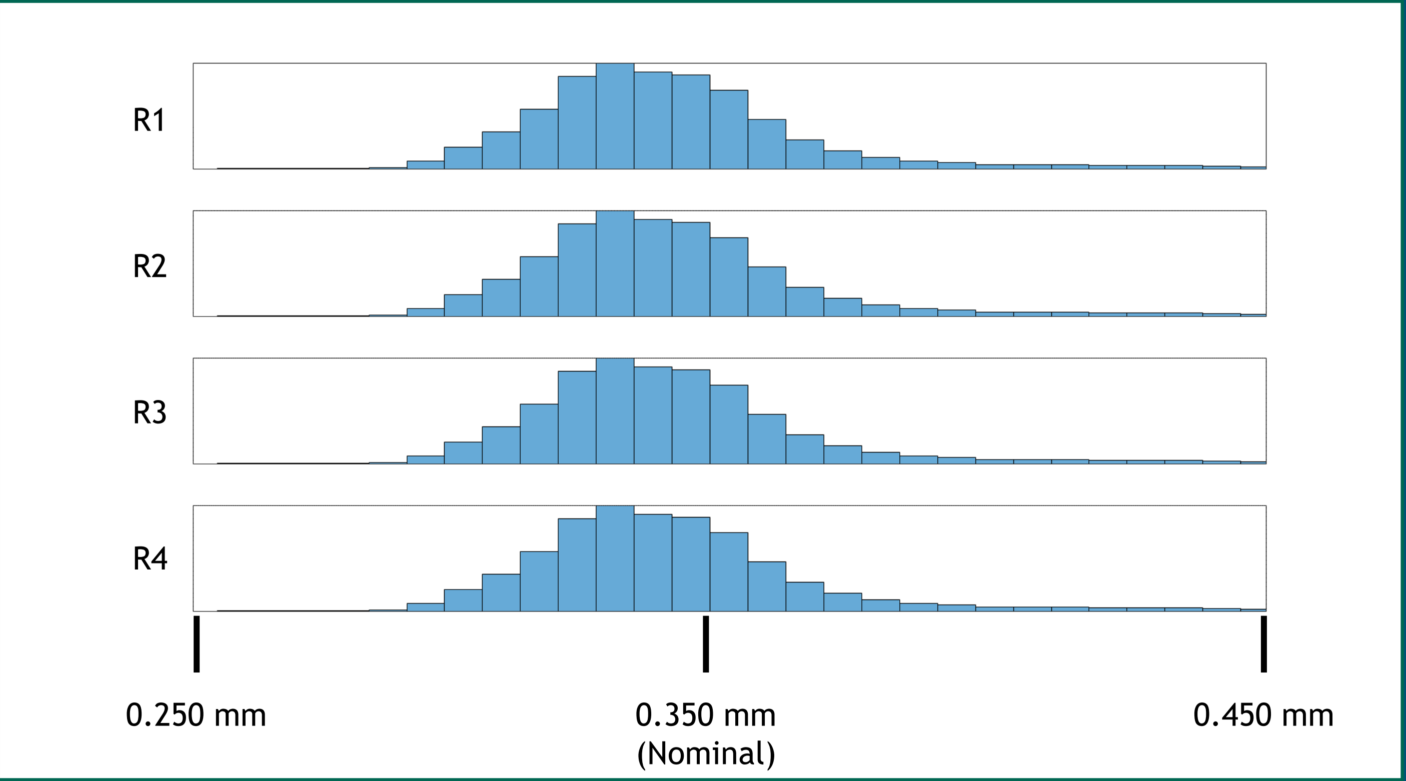


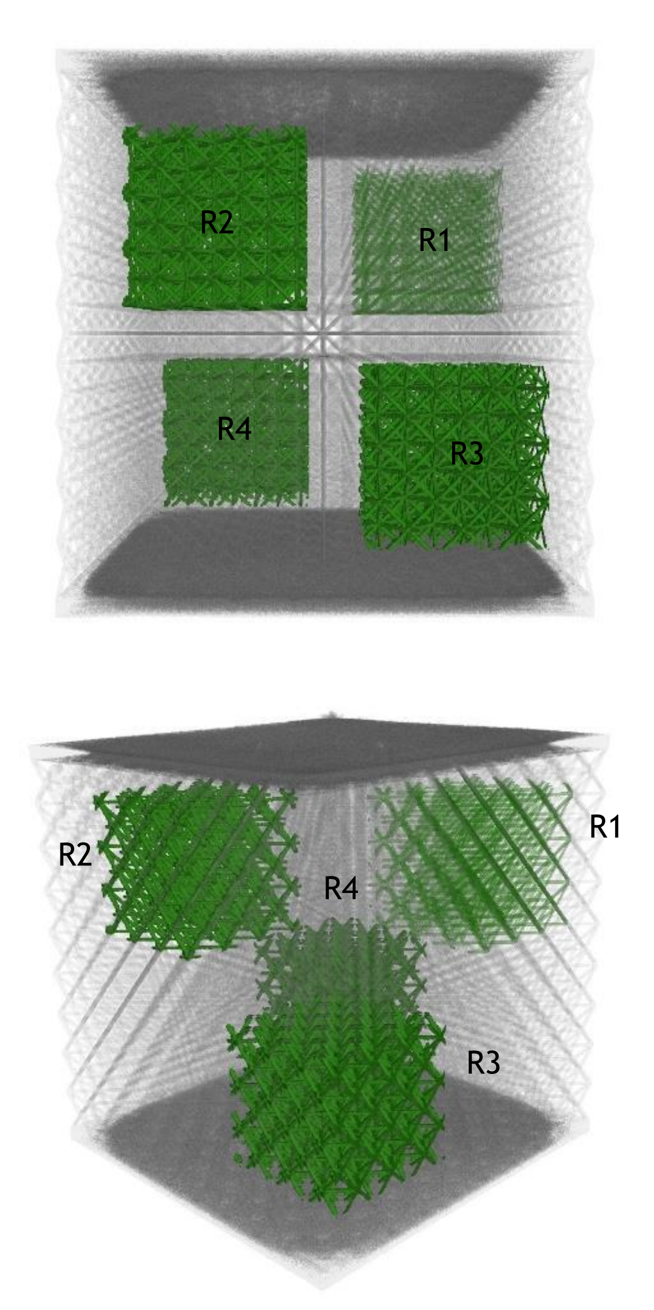


Lattice Characterization – Strut Thickness Measurement

Strut thickness was measured using 3D image processing techniques on the segmented CT volume using Volume Graphics software.

Ensuring struts are properly sized is important to quality control and parts performing as intended. Several regions were selected to gather statistics (R1 – R4).

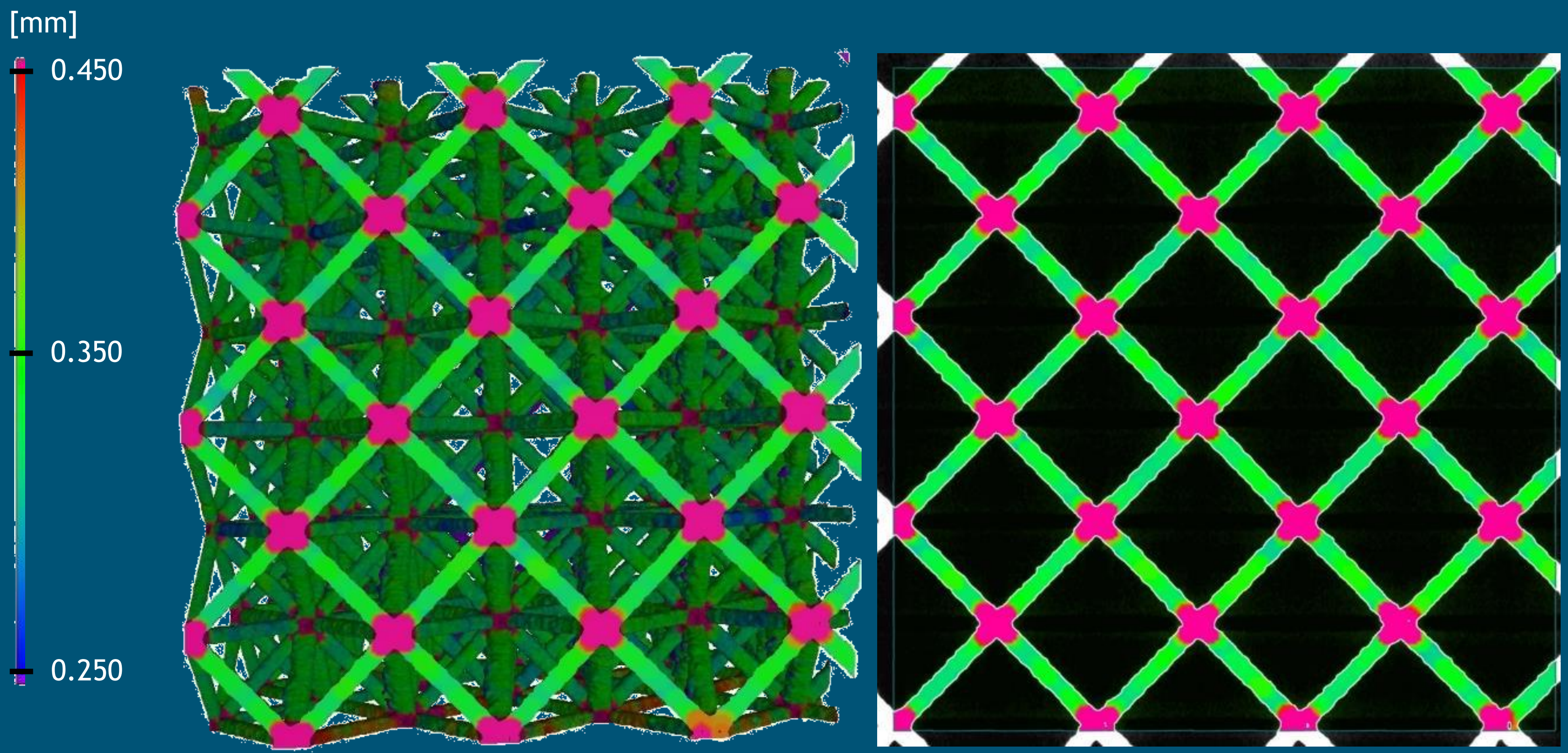


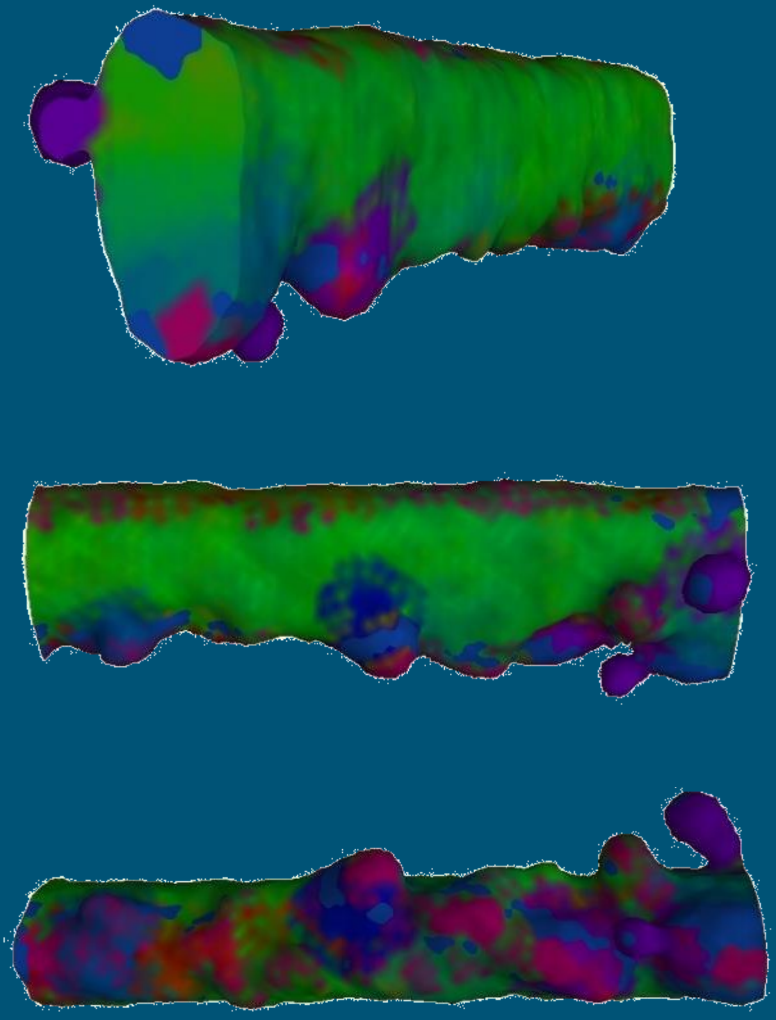


Lattice Characterization – Strut Thickness Maps

Strut thickness maps can serve as a quick visual tool to identify heterogeneities in the AM lattices.

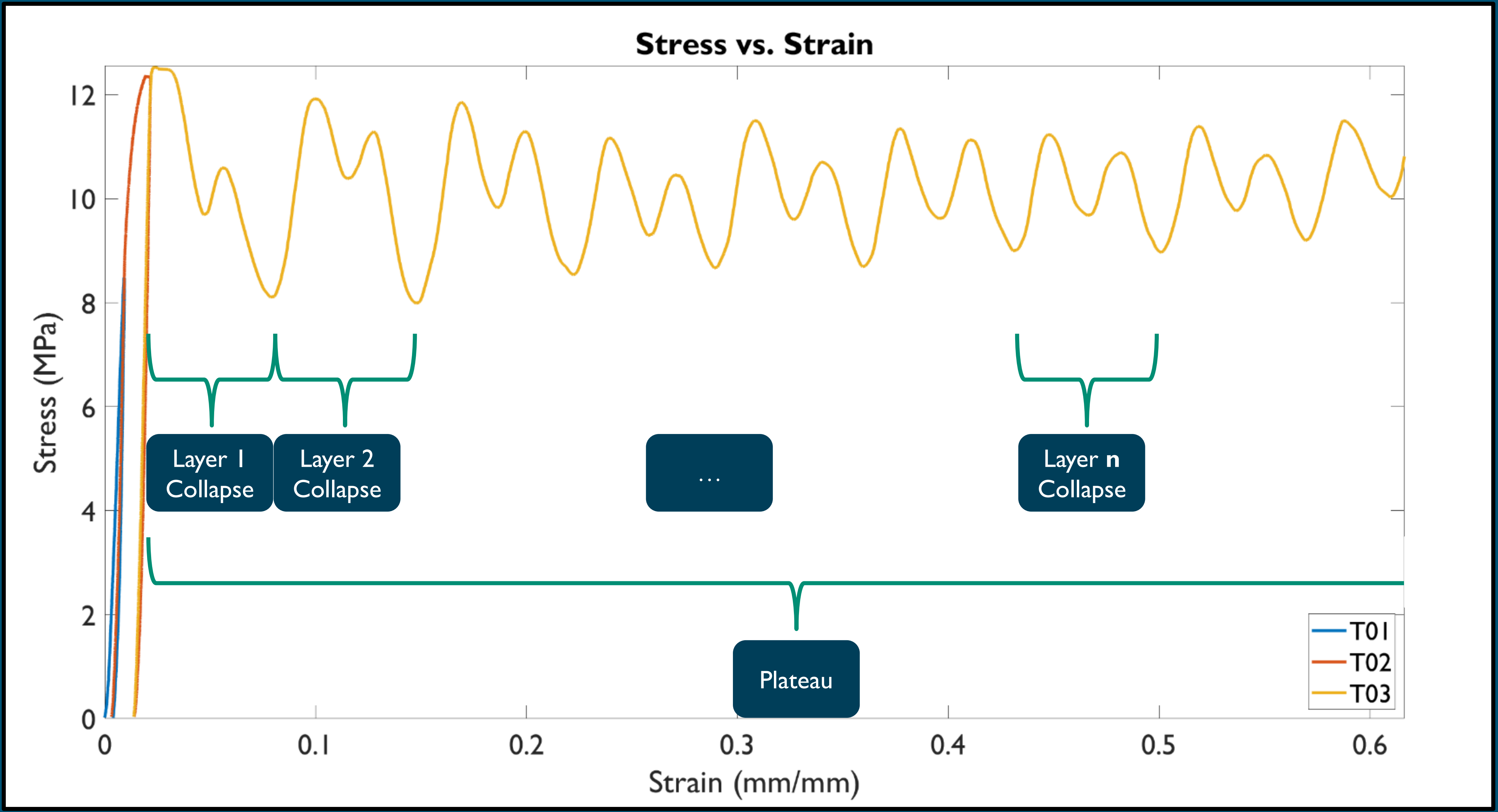
Struts are fairly consistently sized and exhibit periodicity in their defects, repeating in each unit cell.



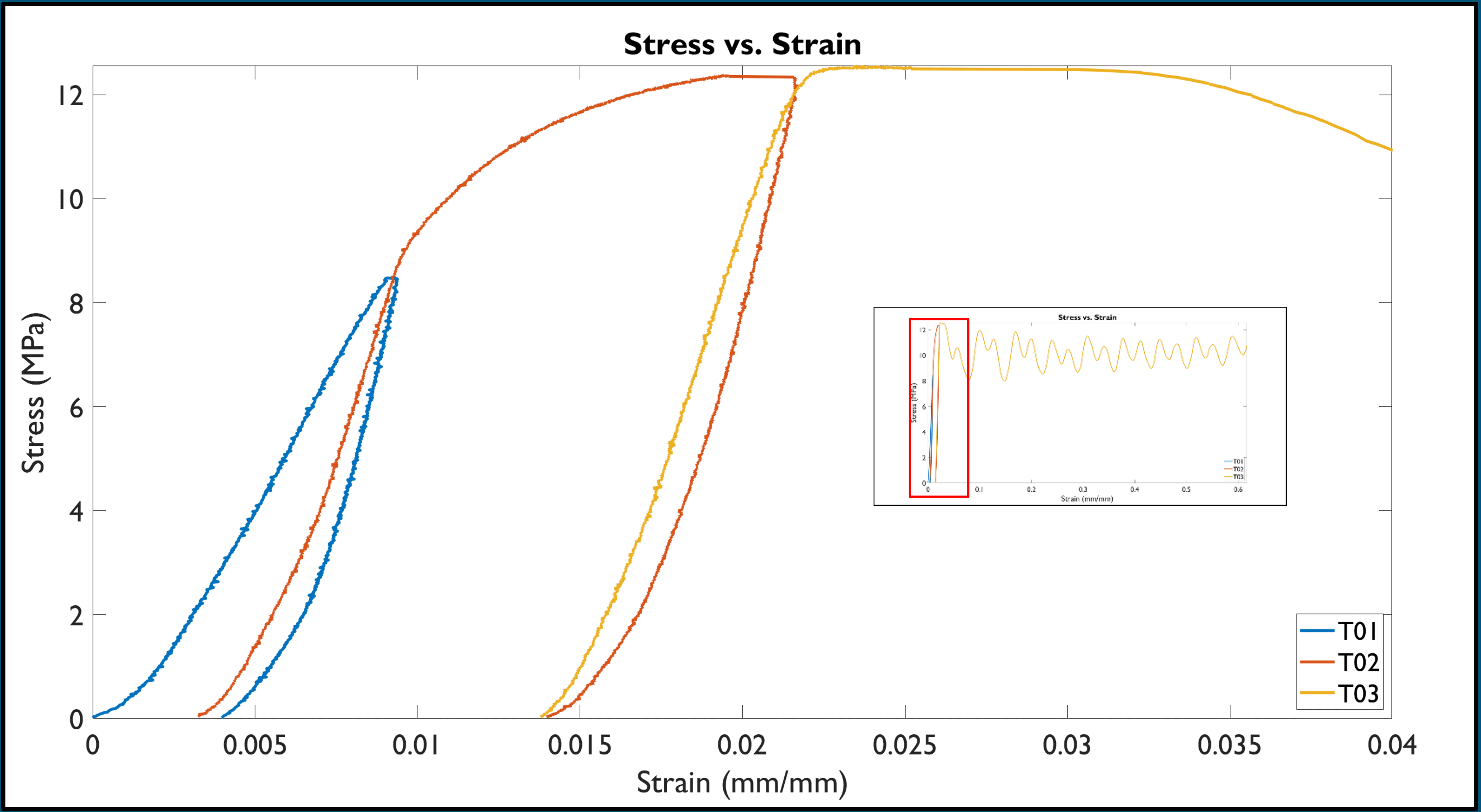


Mechanical Behavior of Lattices

Sample 1 Compression Curve (1 of 2)



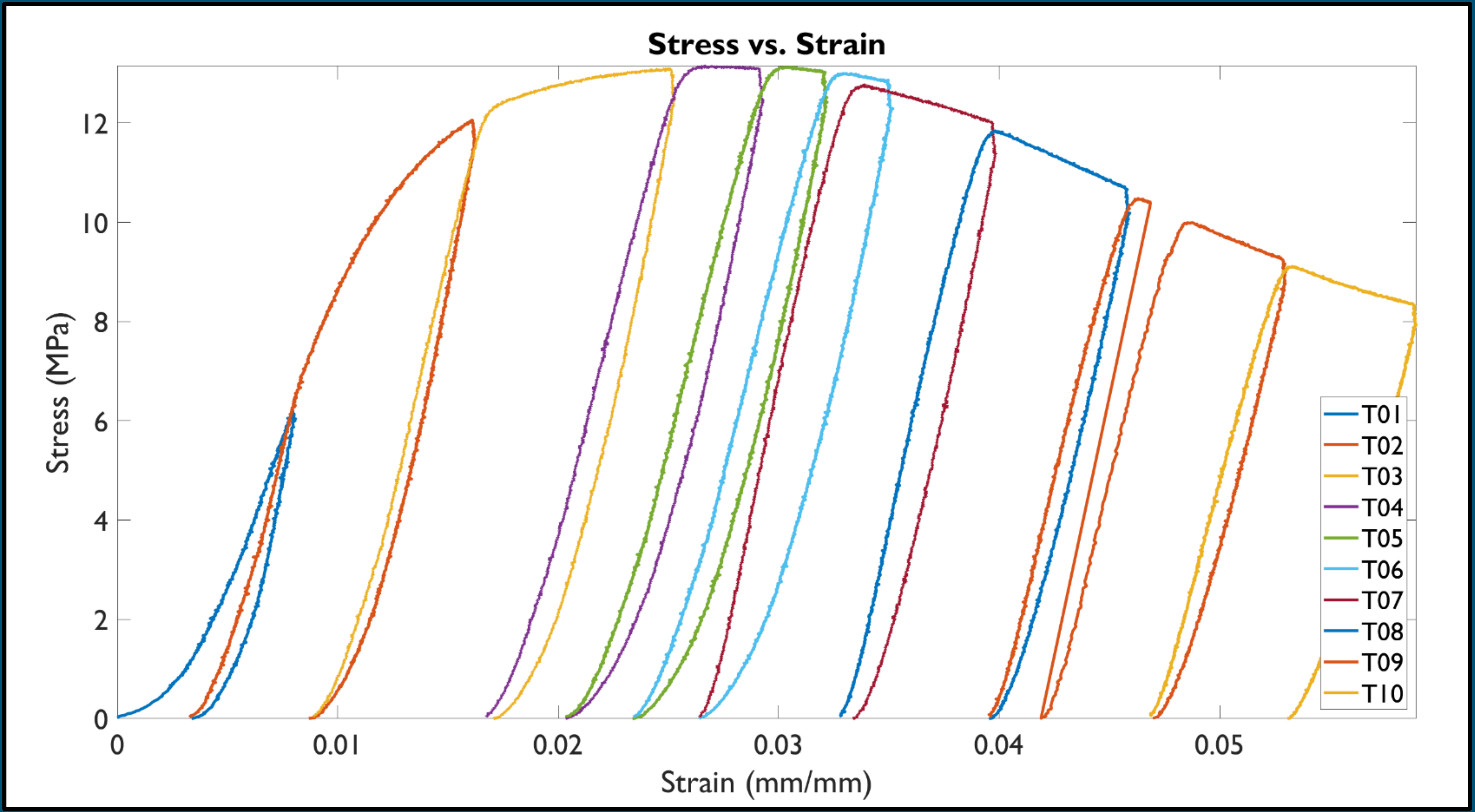
Sample 1 Compression Curve (2 of 2)



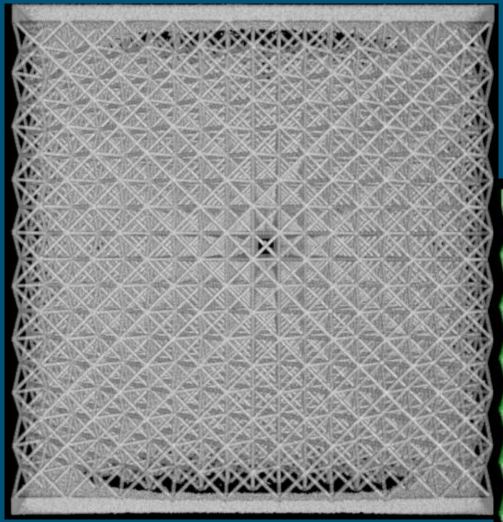
Sample 1 Failure Behavior

Sample 2 Failure Behavior

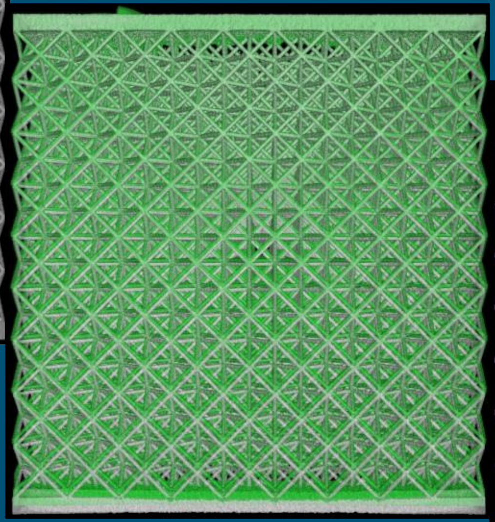
Sample 2 Compression Curve



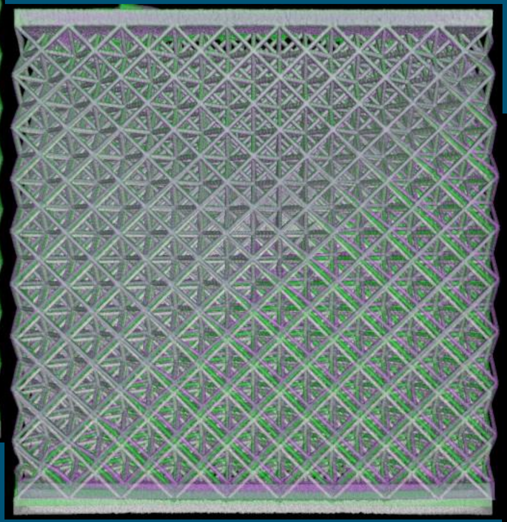
Sample 2 Face 1 Progression of Lattice Failure



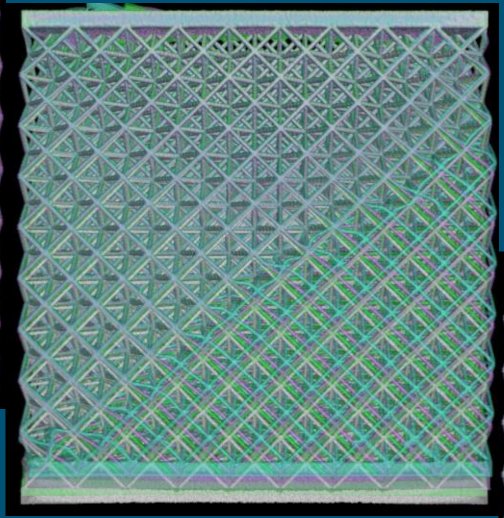
Strain free state



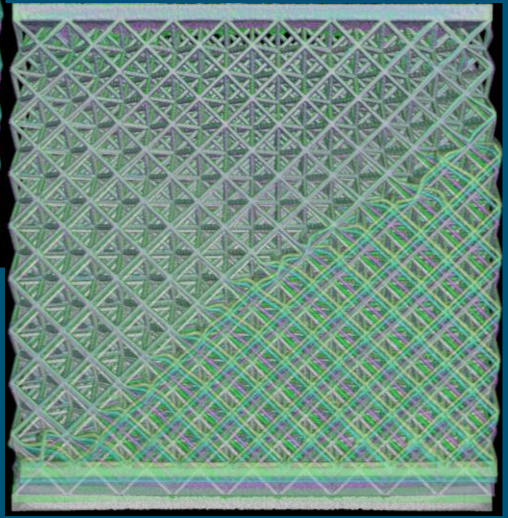
ε = 0.8%



ε = 2.4%

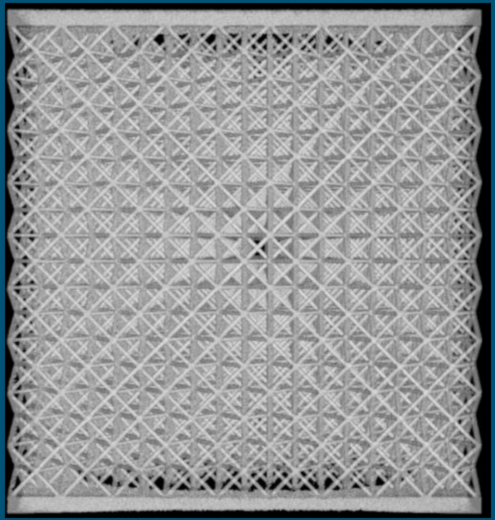


ε = 3.9%

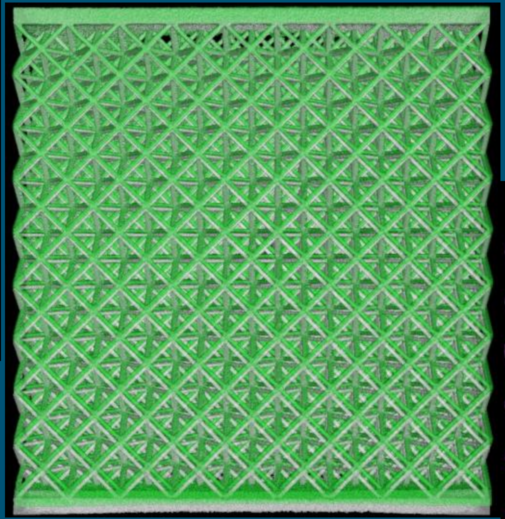


ε = 5.9%

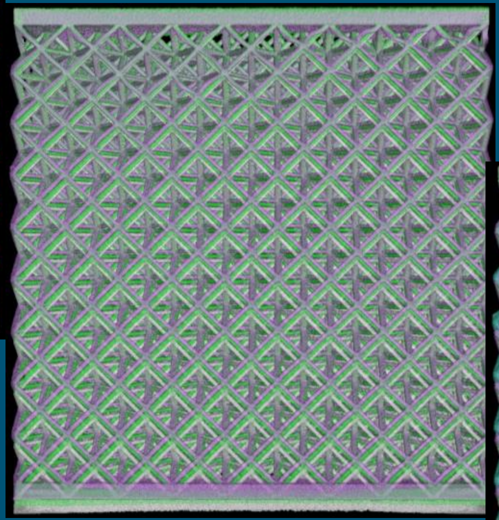
Sample 2 Face 2 Progression of Lattice Failure



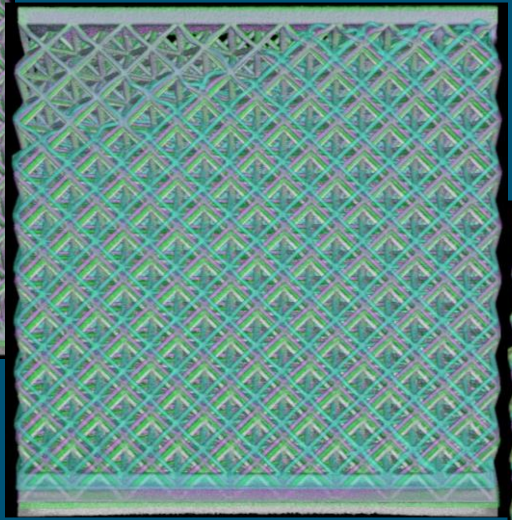
Strain free state



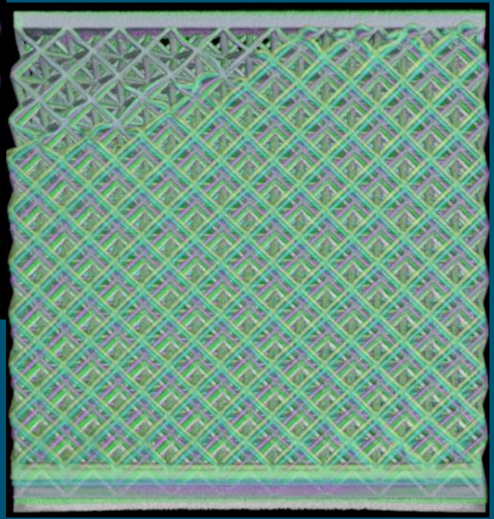
ε = 0.8%



ε = 2.4%

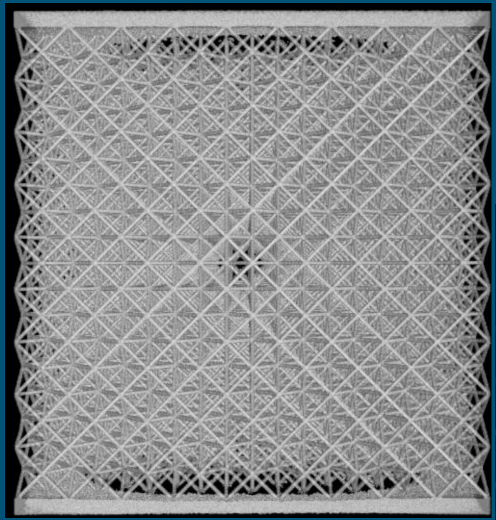


ε = 3.9%

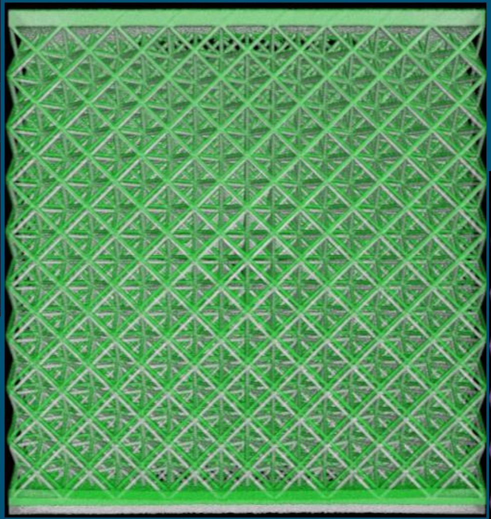


ε = 5.9%

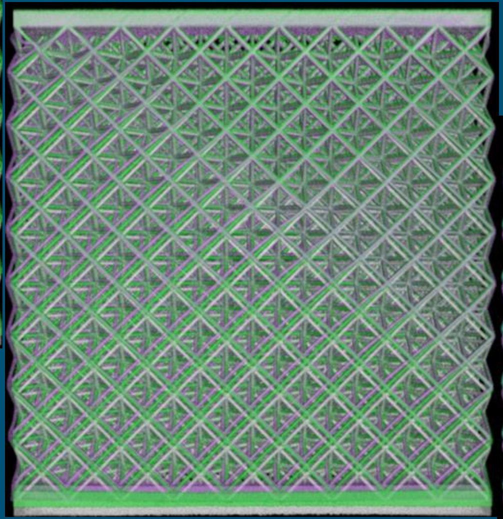
Sample 2 Face 3 Progression of Lattice Failure



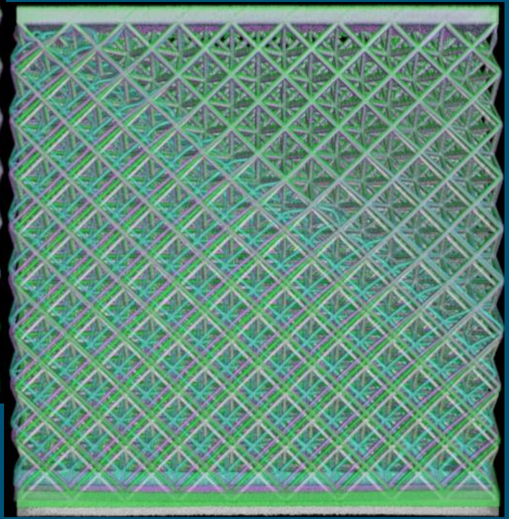
Strain free state



ε = 0.8%

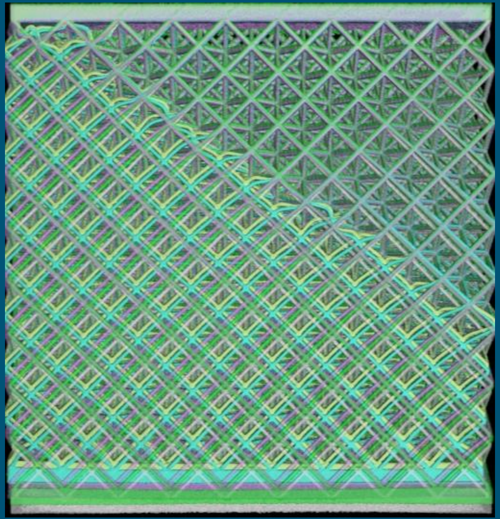


ε = 2.4%

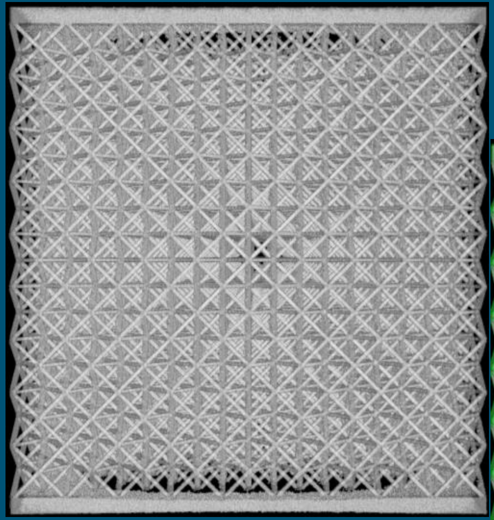


ε = 3.9%

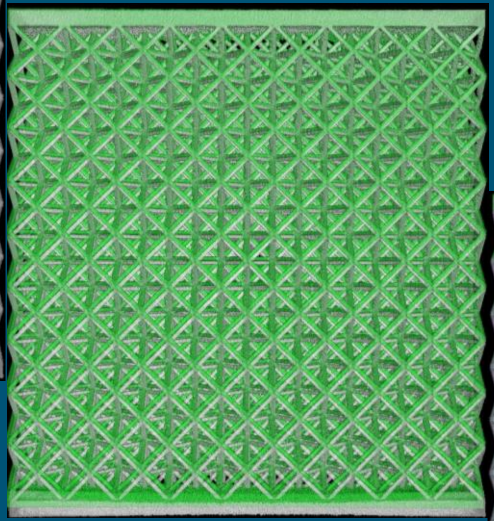
ε = 5.9%



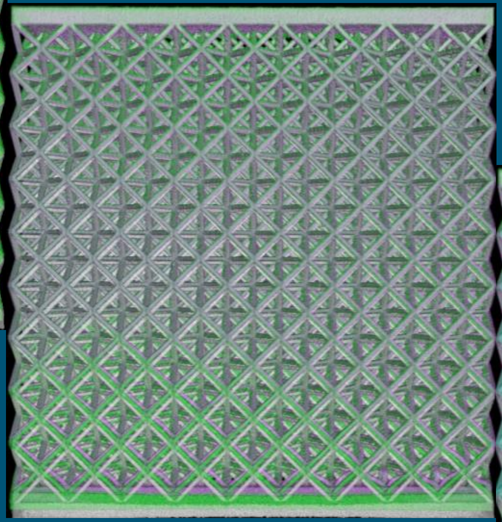
Sample 2 Face 4 Progression of Lattice Failure



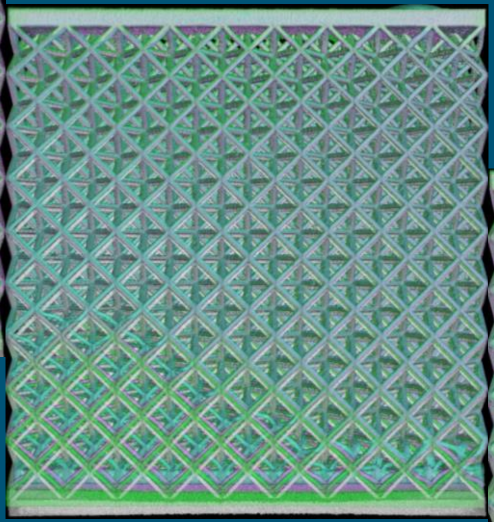
Strain free state



$\varepsilon = 0.8\%$

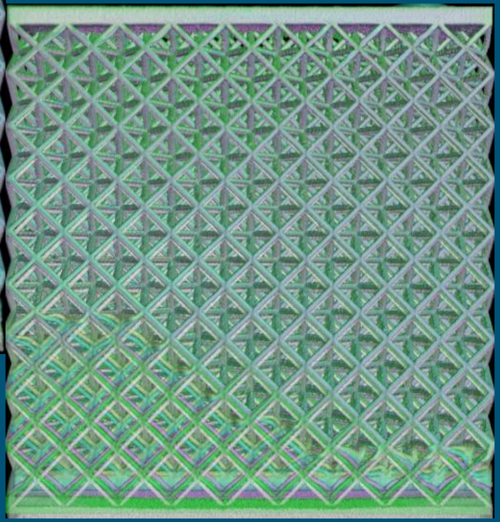


$\varepsilon = 2.4\%$

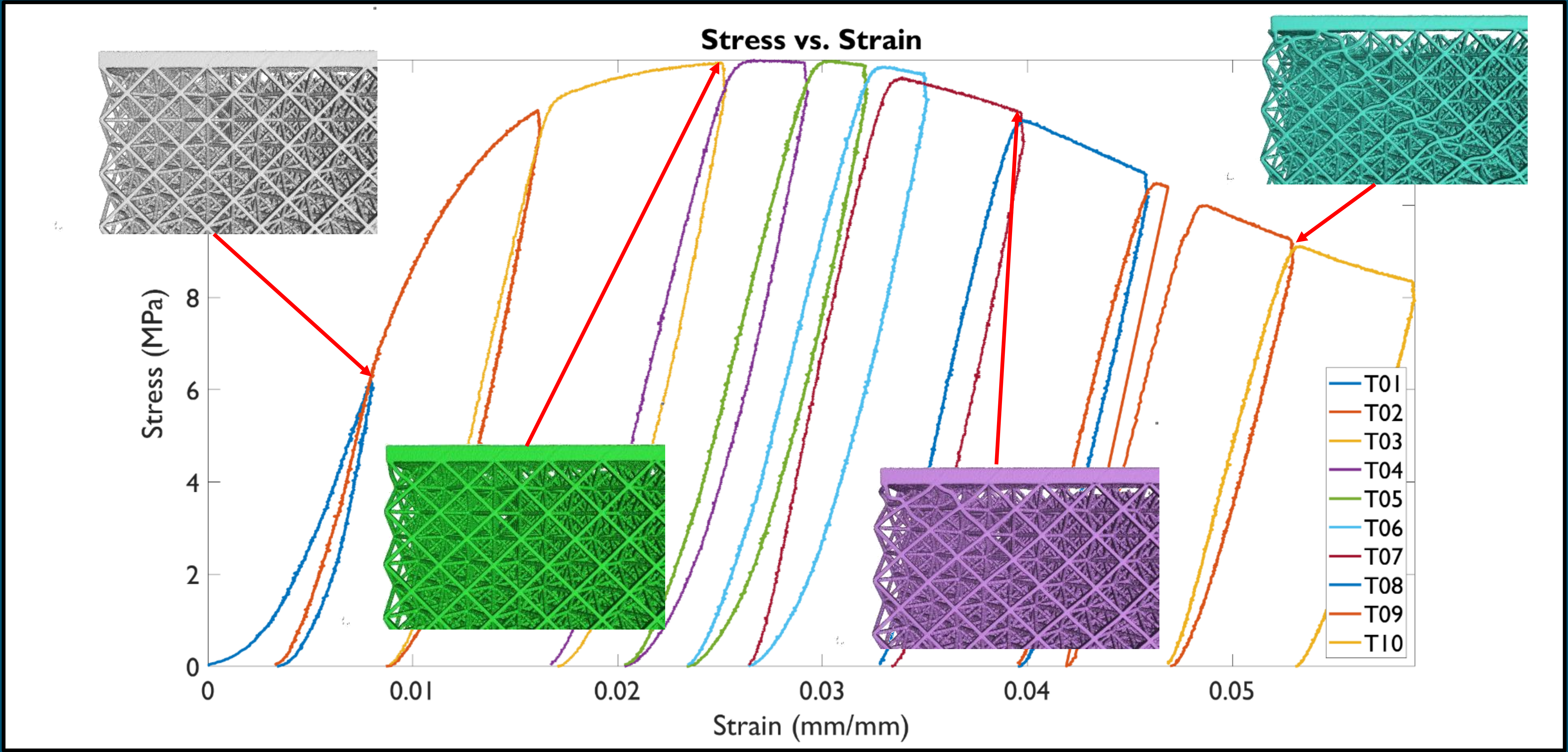


$\varepsilon = 3.9\%$

$\varepsilon = 5.9\%$

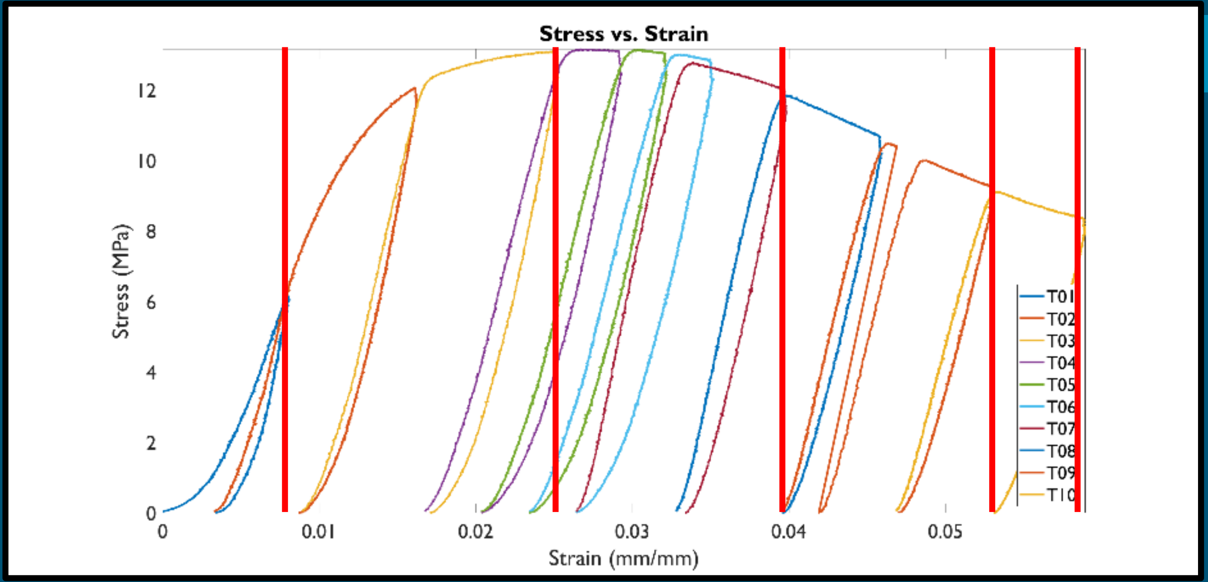


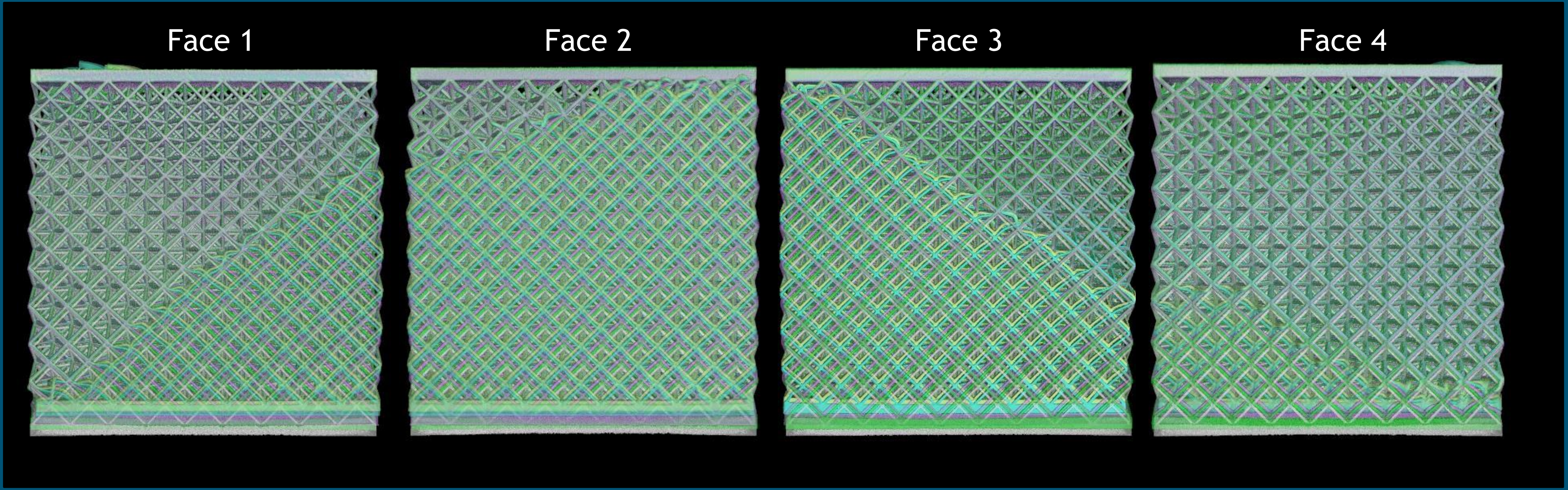
Sample 2 – Failure Evolution



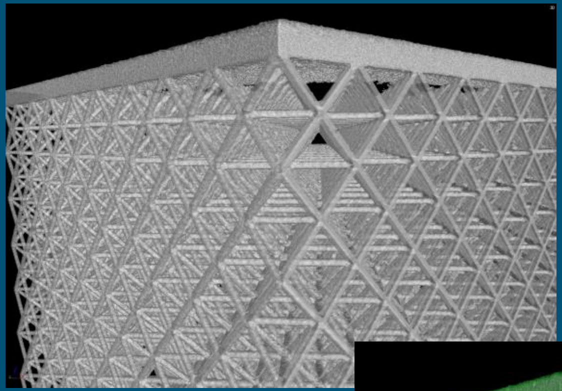
Sample 2 Deformation Summary

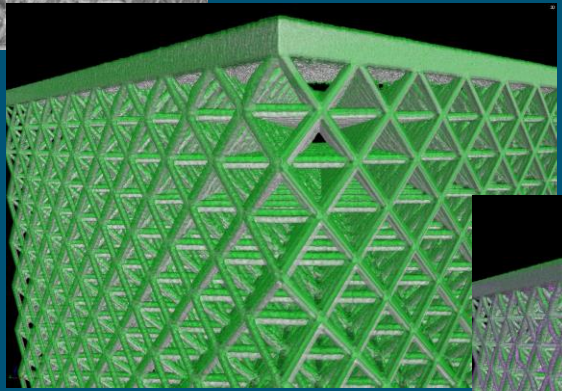
There is a preferred failure plane in the lattice structure. The lattice always fails at a free boundary condition. It appears that the failure is caused by a bending of a strut at a node to strut interface.



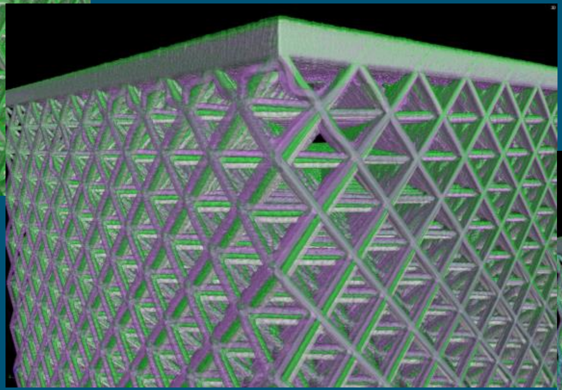


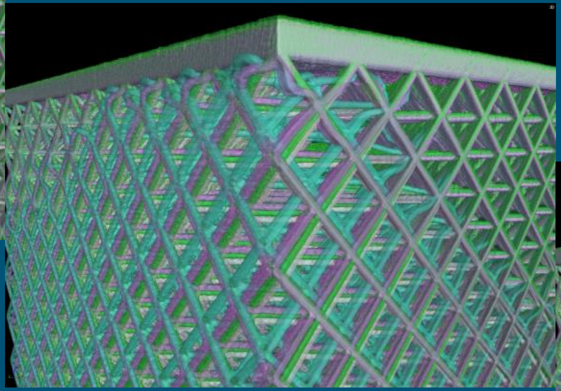
Sample 2 - Deformation Initiation Location

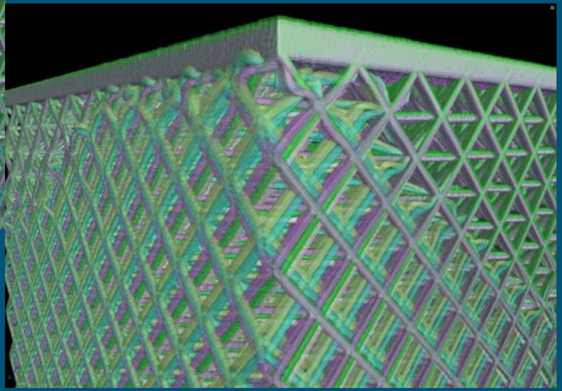




A kink occurs at the node-strut-plate interface. The strut starts to bend and changes the stress distribution to the adjacent nodes and struts. The load transfers to the additional struts and “preferred” failure starts to occur.

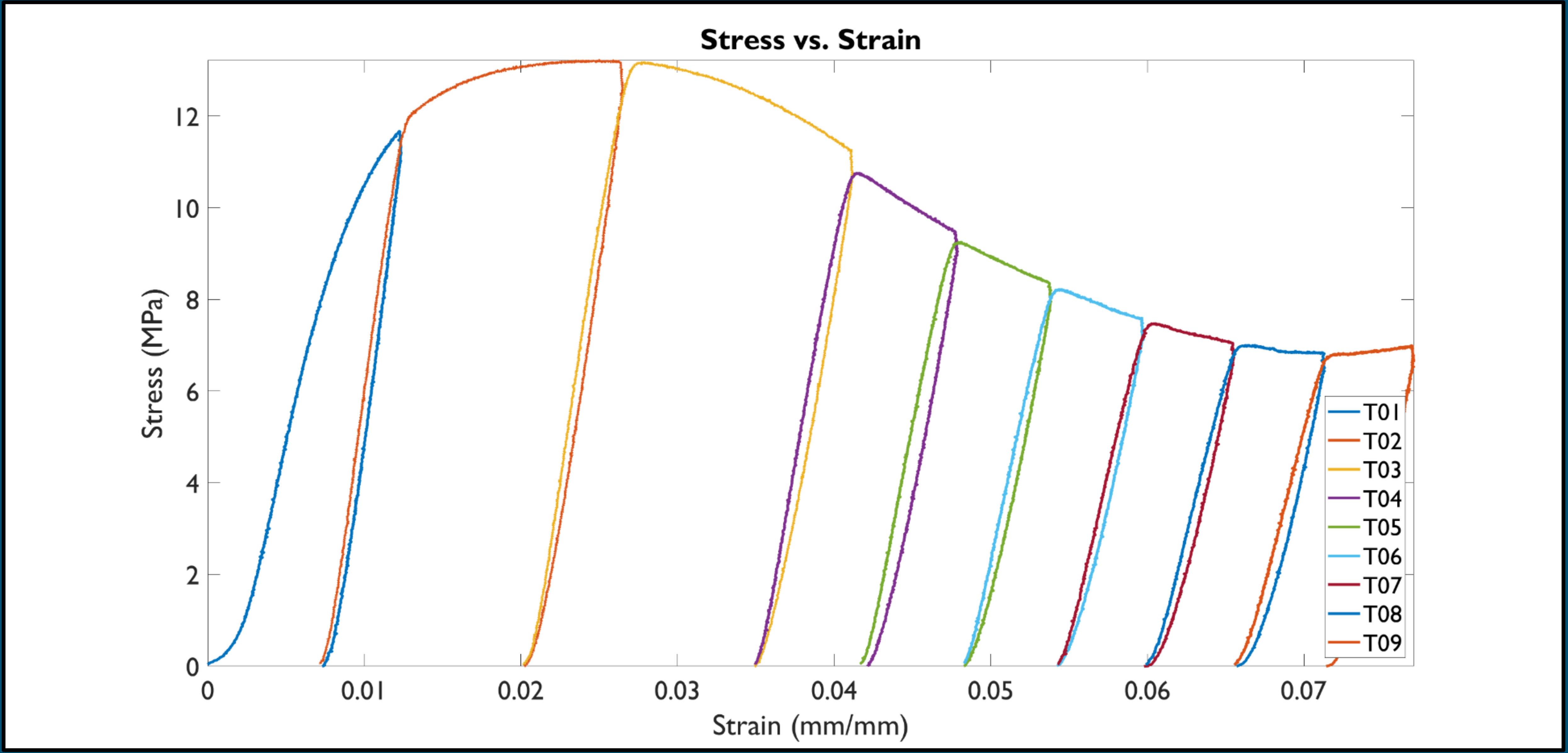






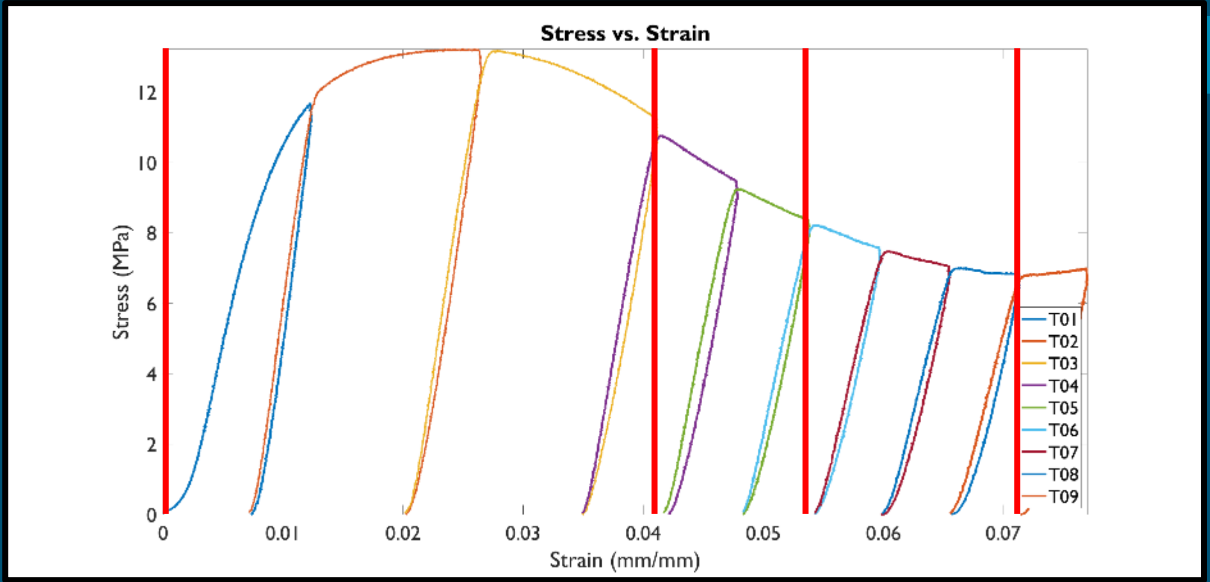
Sample Failure Behavior

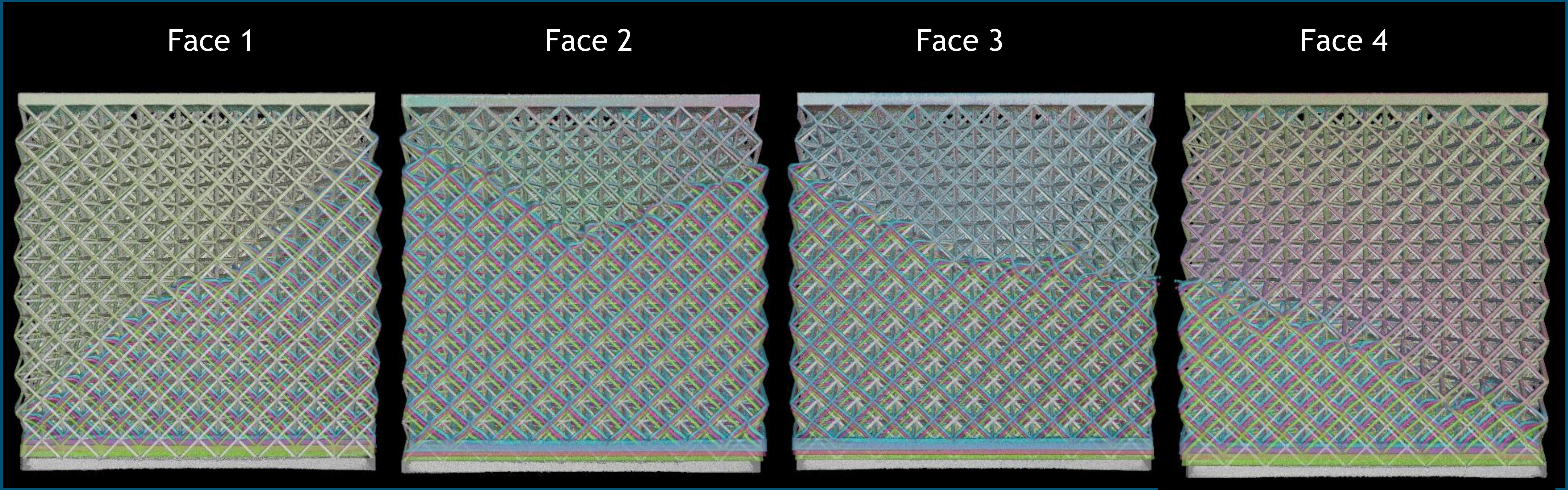
Sample 3 Compression Curve



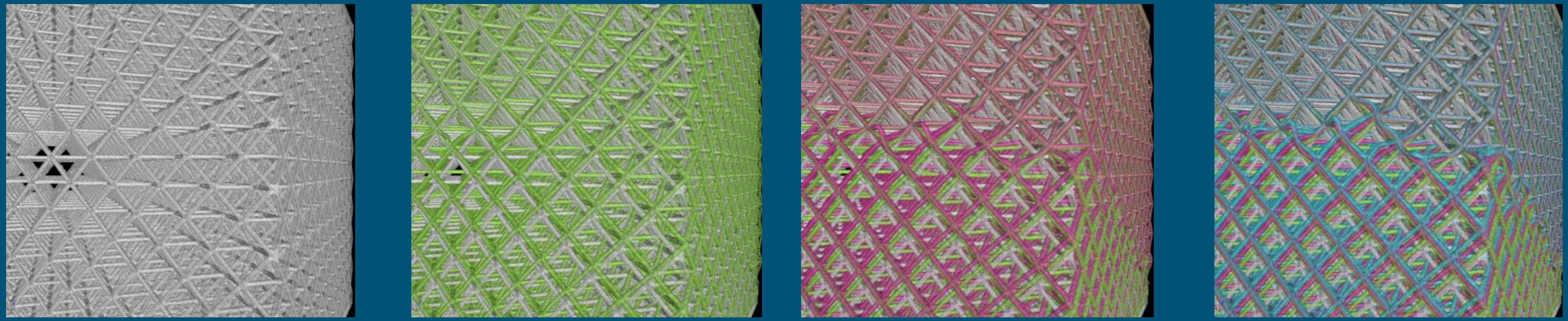
Sample 3 Deformation Summary

There is a preferred failure plane in the lattice structure. The lattice always fails at a free boundary condition. It appears that the failure is caused by bending of a strut at a node to strut interface. The four red lines to the right are where the strains were recorded and the CT inspection was taken.



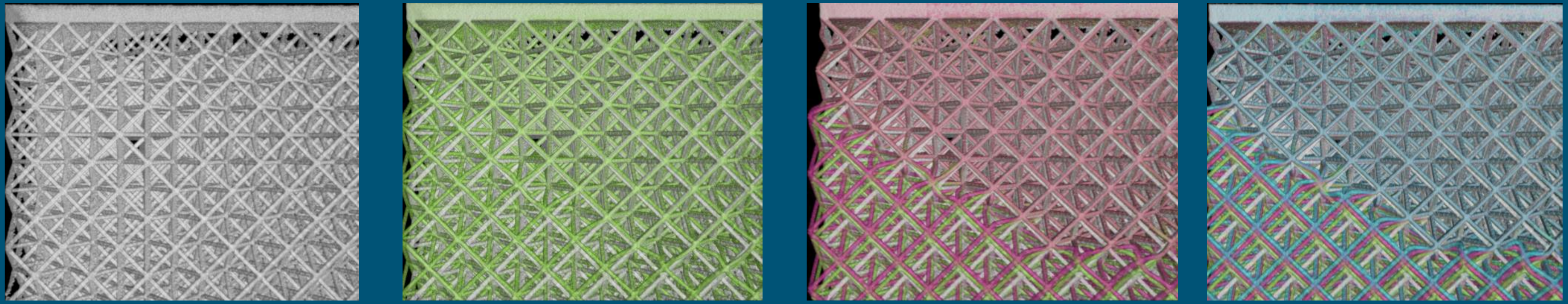


Sample 3 - Deformation Initiation Location



Face 3

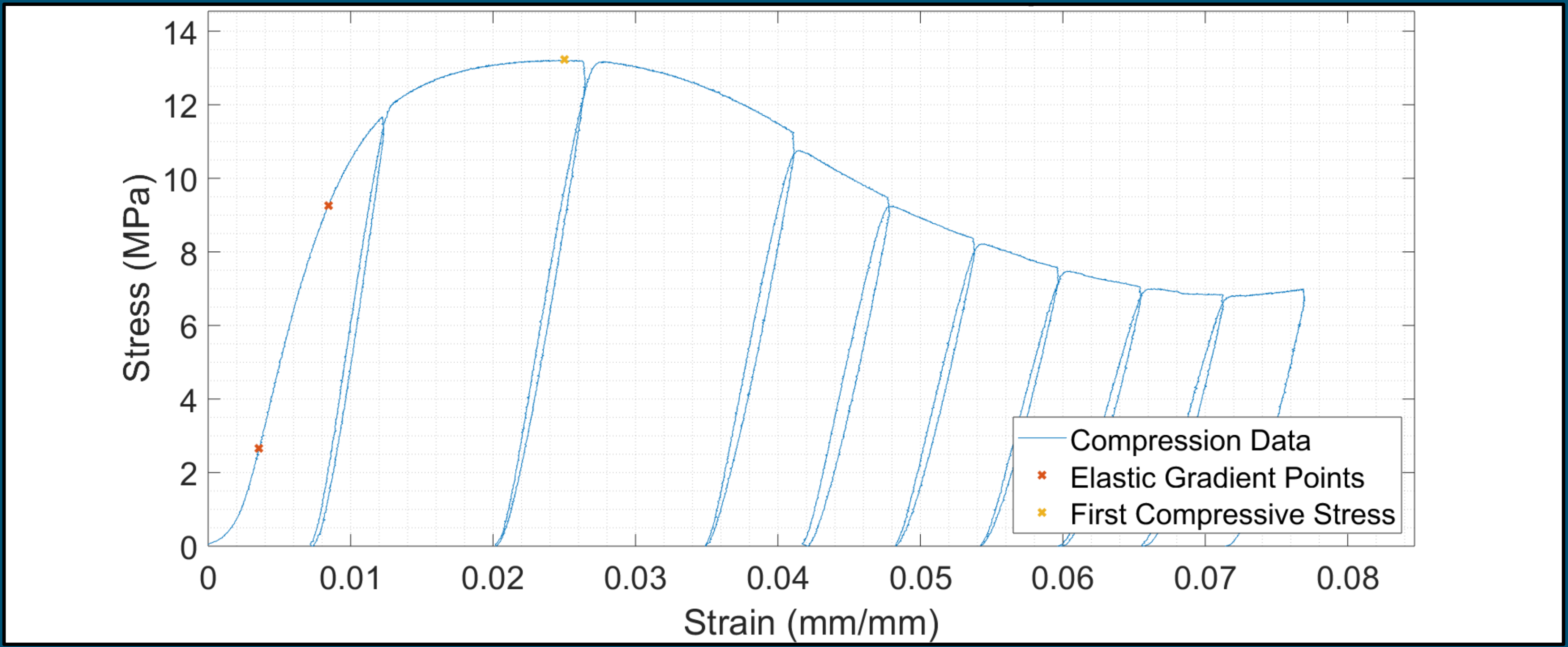
There is a preferred failure plane in the lattice structure. The lattice starts to fail at a free boundary condition. In this case on face 3 at the corner. The failure is caused by bending of a strut at a node to strut interface and moves in a diagonal direction towards face 2 corner.



Face 2

Summary of Property Comparison

Sample 3 Stress Strain Properties



Sample	Max Compressive Strength (MPa)	Strain @ Max Compressive Strength (mm/mm)	Elastic Gradient (GPa)
Sample 1	12.55	0.0244	1.088
Sample 2	13.15	0.0275	1.167
Sample 3	13.22	0.0250	1.352

Conclusions

Lattice structures contain small length to diameter ratios and are problematic to produce with additively manufactured processes. Computed Tomography is the only practical technique that can inspect the lattice structure.

The major influences on the build process is un-melted particles on the surface of the lattices and node points. Small defects (gas pores) are hard to detect and quantify. The biggest challenge is to develop an inspection criteria for surface roughness.

The optimal strut diameter is a trial-and-error process. Once the build process is optimized for strut diameter, CT inspection can not measure every diameter. Statistical methods are the best technique determine strut uniformity. Strut thickness maps are a quick visual tool to identify heterogeneities in the AM lattices. This process will consistently size the lattices but not identify defects with the nodes or struts (gas porosity). Pores connected to the surface can not be quantified using traditional voxel-optimized methods.

There is a preferred failure plane in the lattice structure. The lattice always fails at a free boundary condition. It appears that the failure is caused by bending of a strut at a node-to-strut interface. Computed tomography can be used to track the failure of lattices during compression testing.

Thank You

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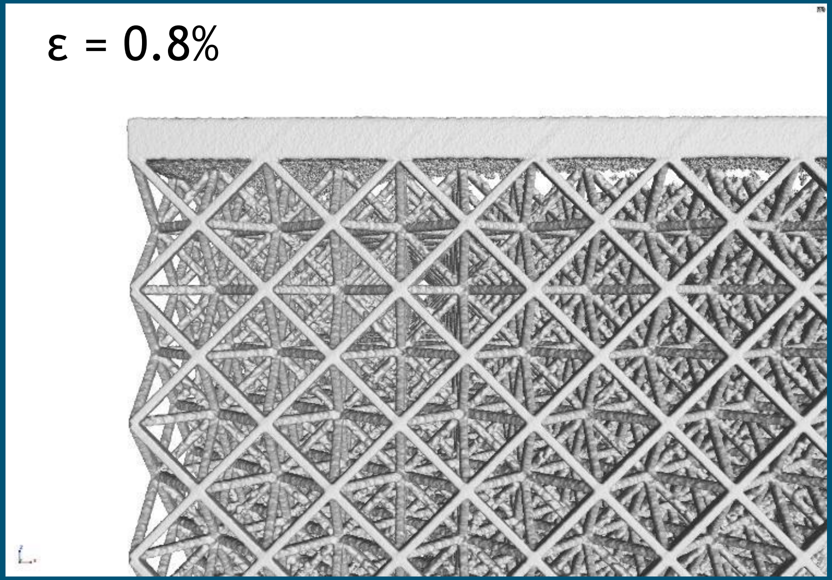
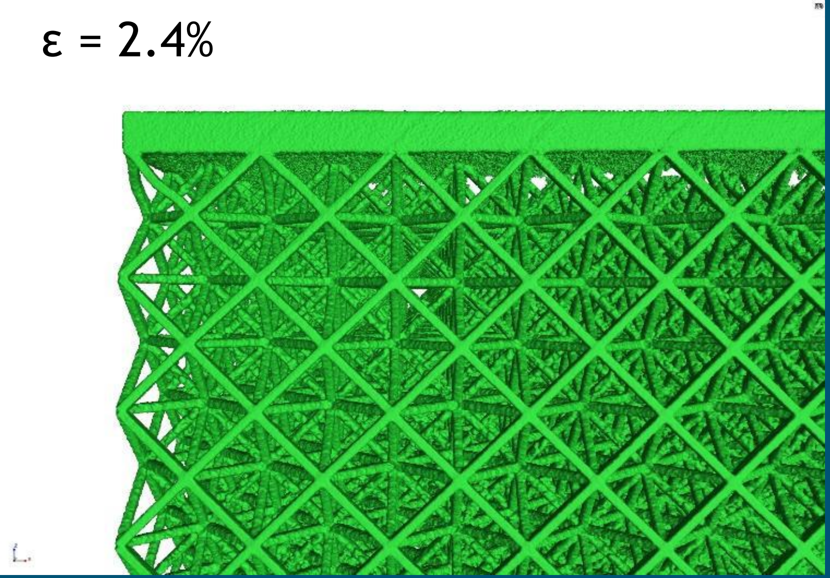
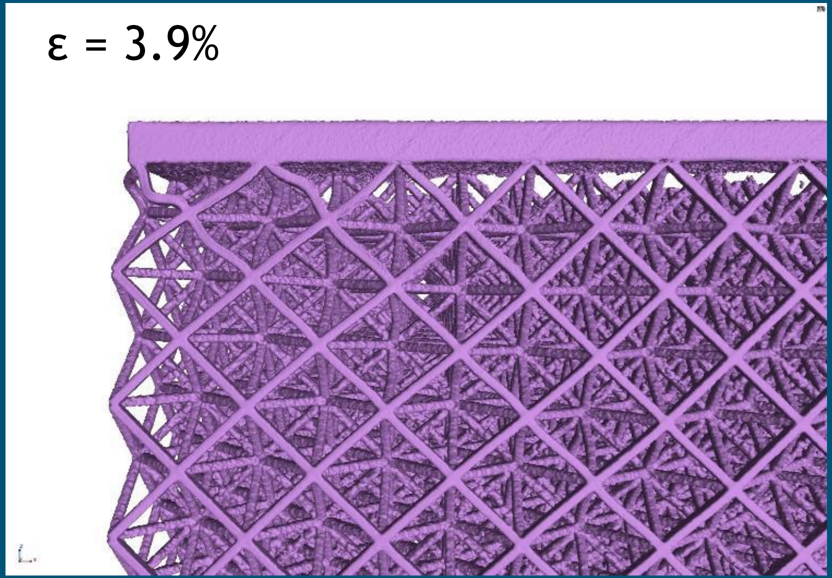
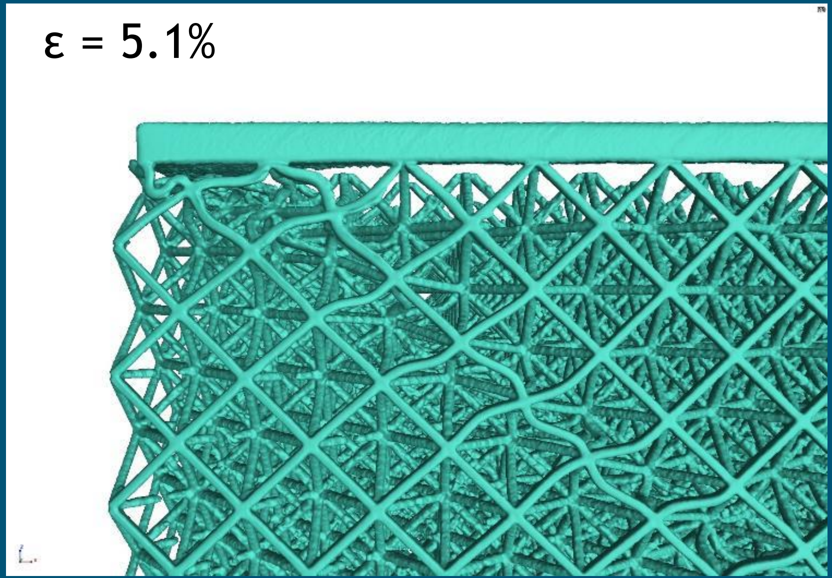
Back Up

Sample 2 Strain Progression for Lattice Failure









Sample 2: Final Deformation Lattice Rotation

Comparative CT (4D CT) shows lattice structure at various stages of the deformation process (4th dimension).