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Application of 3D Characterization for Mechanical Modelling of Additively Manufactured AlSiMg

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6th International Congress on 3D Material Science

June 28, 2022

SAND2022-2545 C

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U.S. DEPARTMENT OF ENERGY

NNSA

Outline

- Motivation
- 3D Characterization
  - Statistical analysis of porosity
  - Particle tracking
- Predictive Modelling
  - Formulation
  - Sensitivities
- Conclusion

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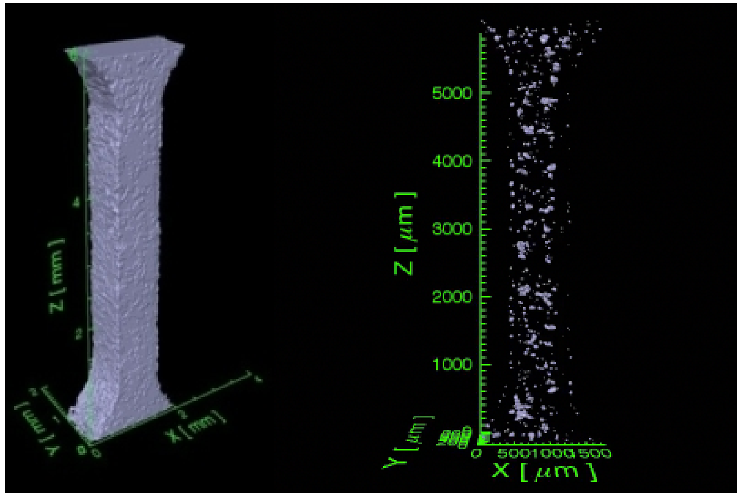
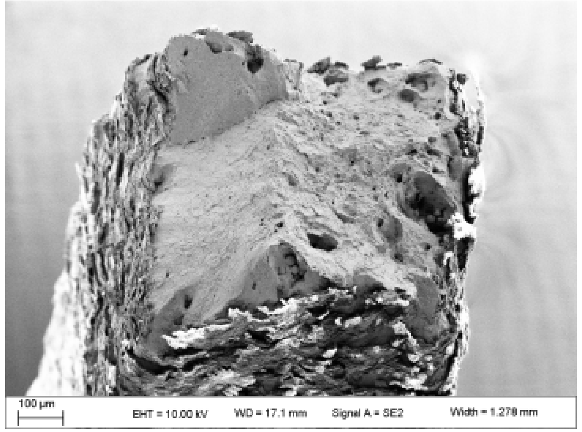
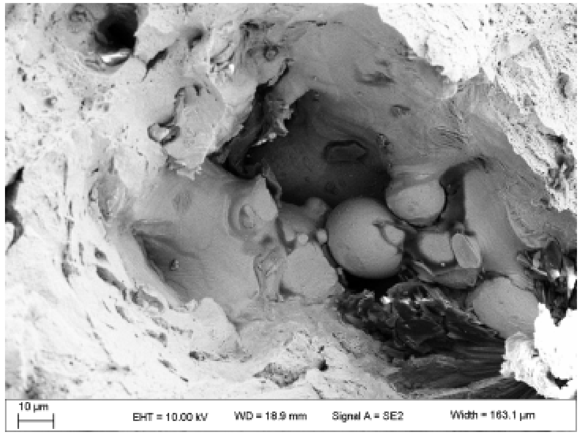
LPBF can produce significant mechanical variability

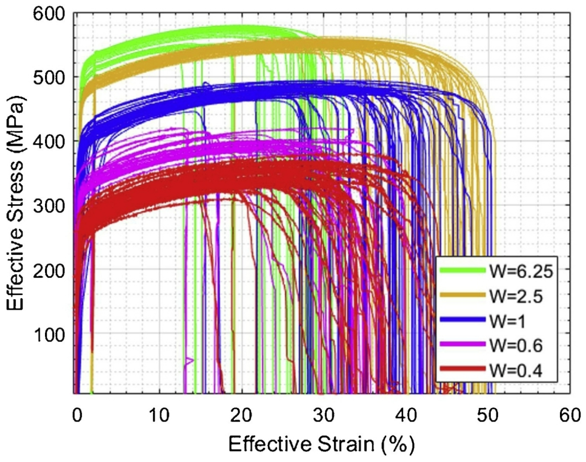


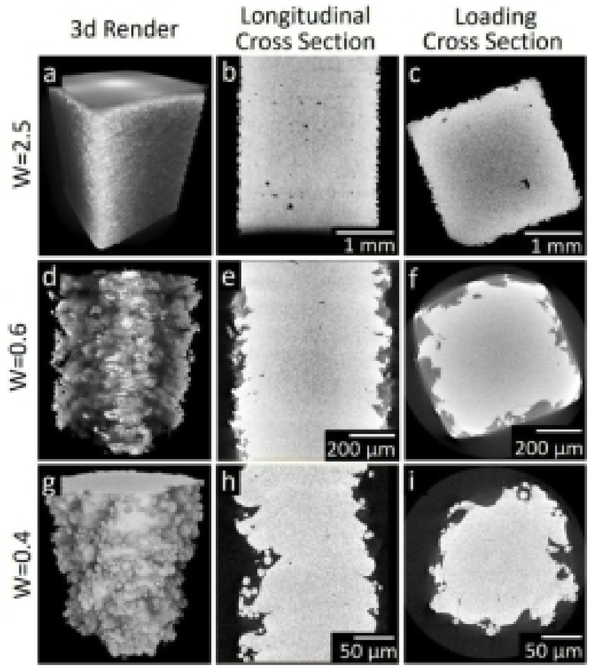
(J. Madison, T. Ivanoff, O. Underwood, SNL)





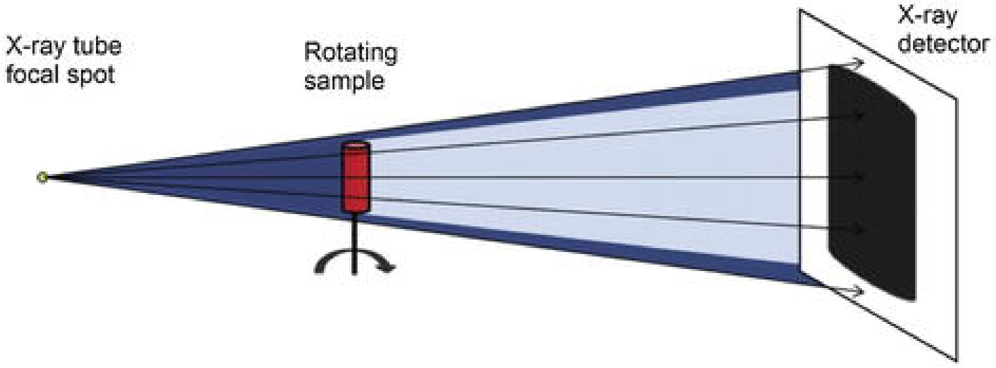
Kramer et al., *IJF* 2019

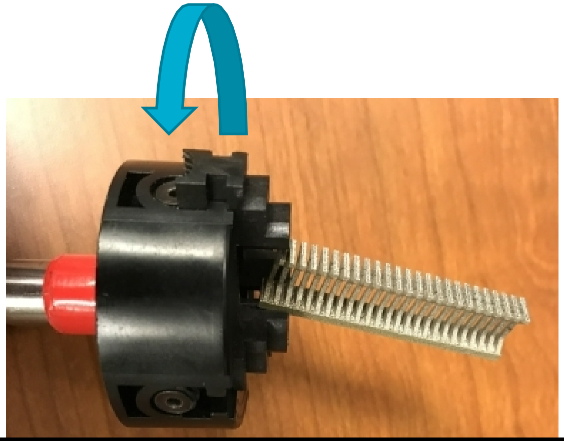


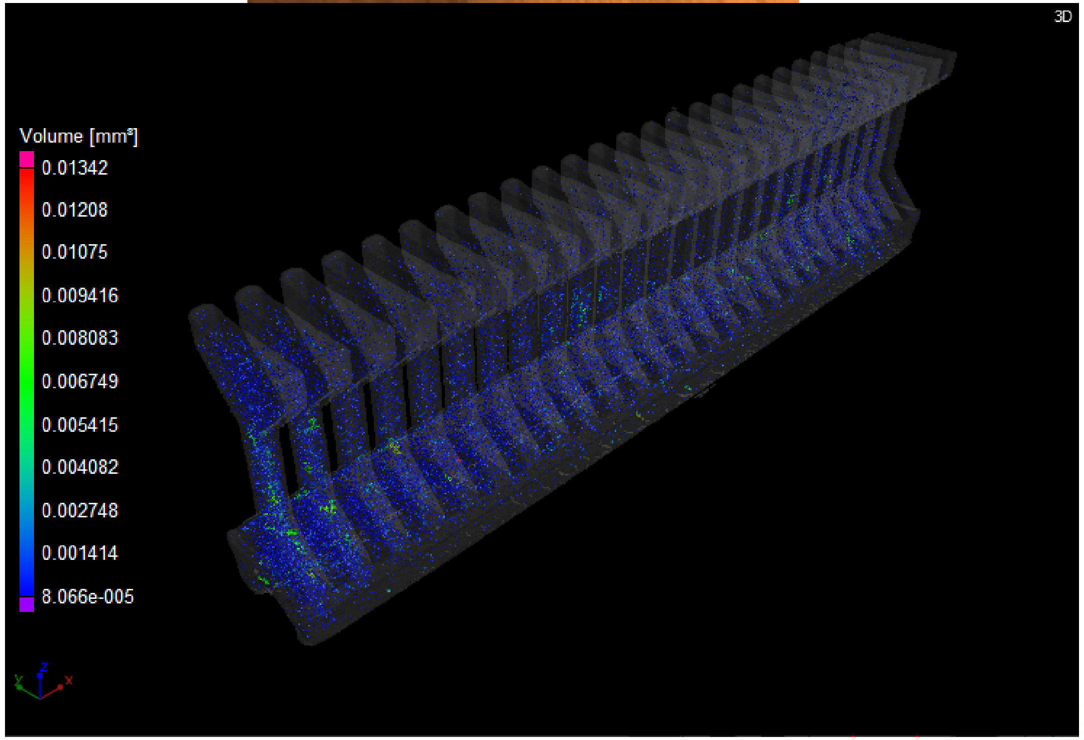


Roach, A.M. et al. *Additive Manufacturing* 2020

Computed Tomography (CT) offers a way to quantify defect structure



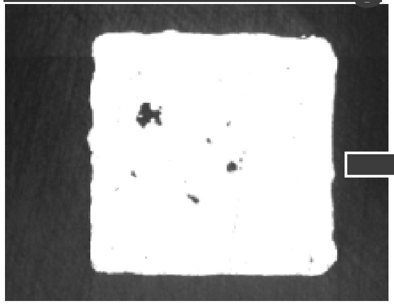




MA Vicente, J Mínguez, DC González, *Computed Tomography – Advanced Applications*, 2017
Images courtesy David Moore

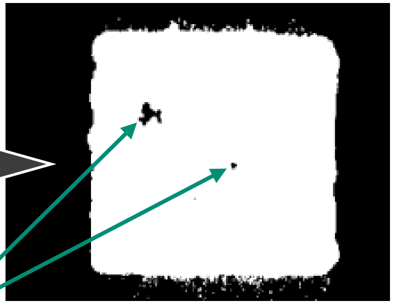
Challenges remain in use of CT data

Serial sectioning



Voids

Low threshold (80)

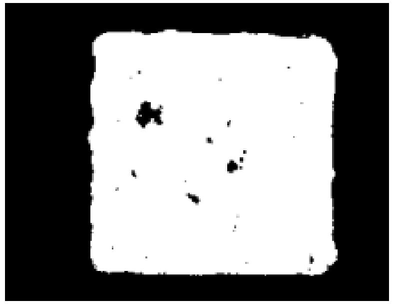


Lose image detail
Create image artifacts

Middle threshold (155)

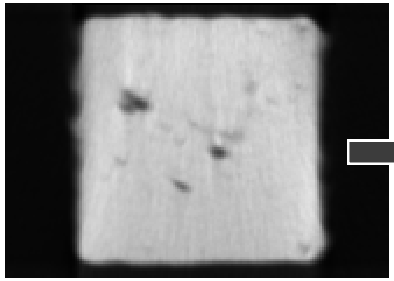
Most accurate representation

High threshold (230)

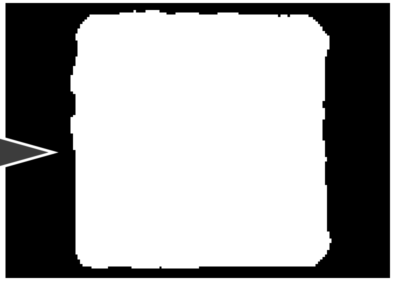


Loses object edges
False voids possible

CT

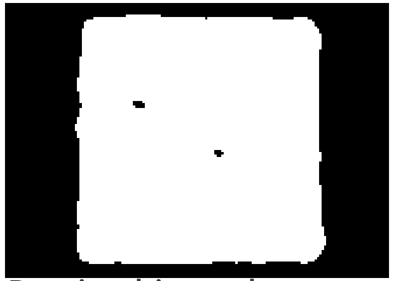


Low threshold (100)



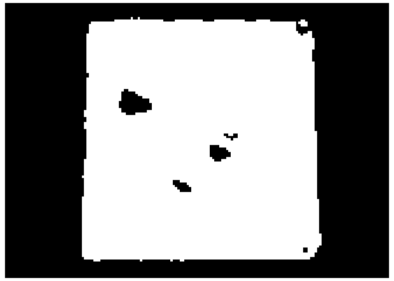
Retain object edges
Lose all void detail

Middle threshold (160)



Retain object edges
Capture some detail

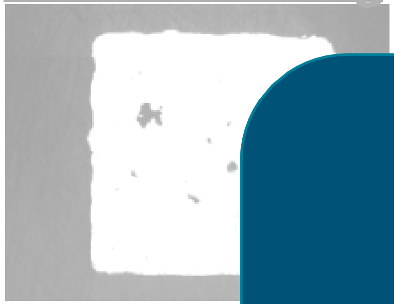
High threshold (210)



Lose object edges
Capture voids (slightly enlarged)

Challenges remain in use of CT data

Serial sectioning



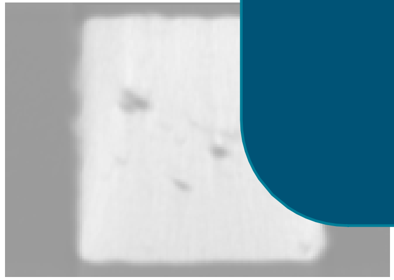
Low threshold (80)

Middle threshold (155)

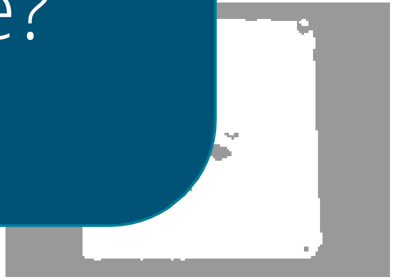
High threshold (230)

edges
ossible

CT



shold (210)



Retain object edges
Lose all void detail

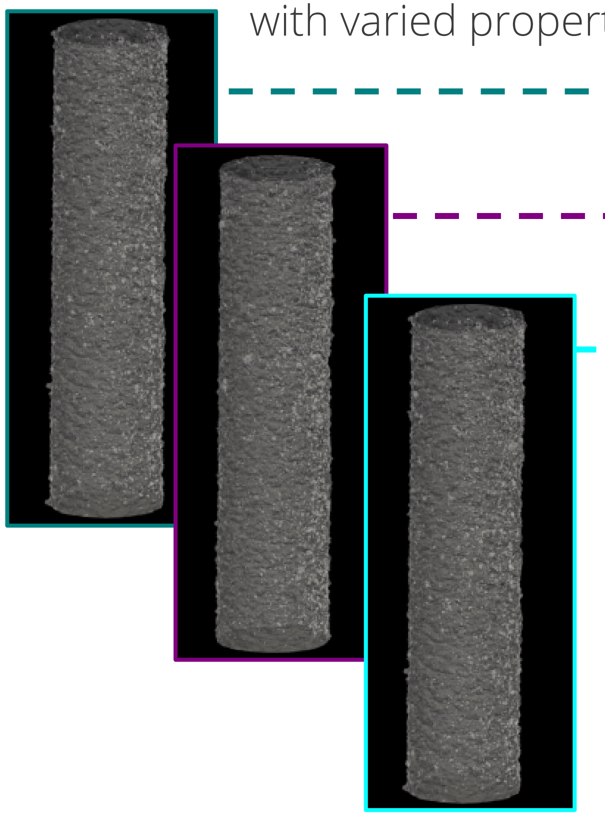
Retain object edges
Capture some detail

Lose object edges
Capture voids (slightly enlarged)

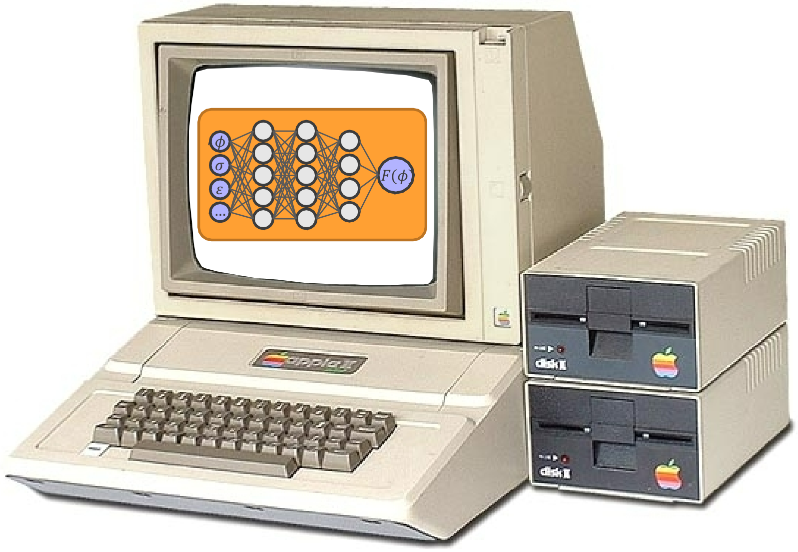
Can we make meaningful performance predictions with knowledge of defect structure?

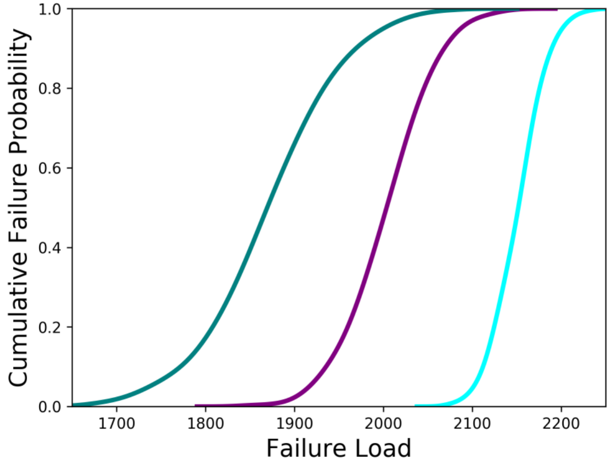
Vision: Rapid failure prediction based on microstructure enabled by Machine Learning

Synthetic Microstructures with varied properties



Simulation Code





Requirements: Training data with accurate microstructure and mechanical behavior

Image: oldcomputers.net

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In situ tensile experiment with µCT

Zeiss Xradia 620 µCT

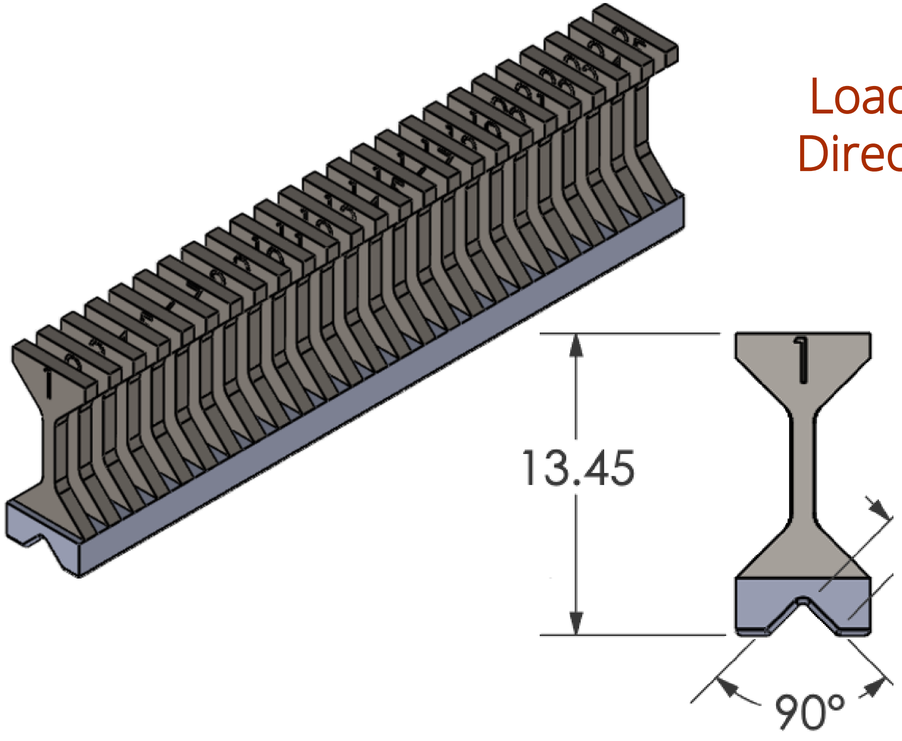
- Effective voxel size of 2.1 µm
- Intermittent scans at fixed displacements
- ~3hr per scan

Image courtesy Zeiss.com

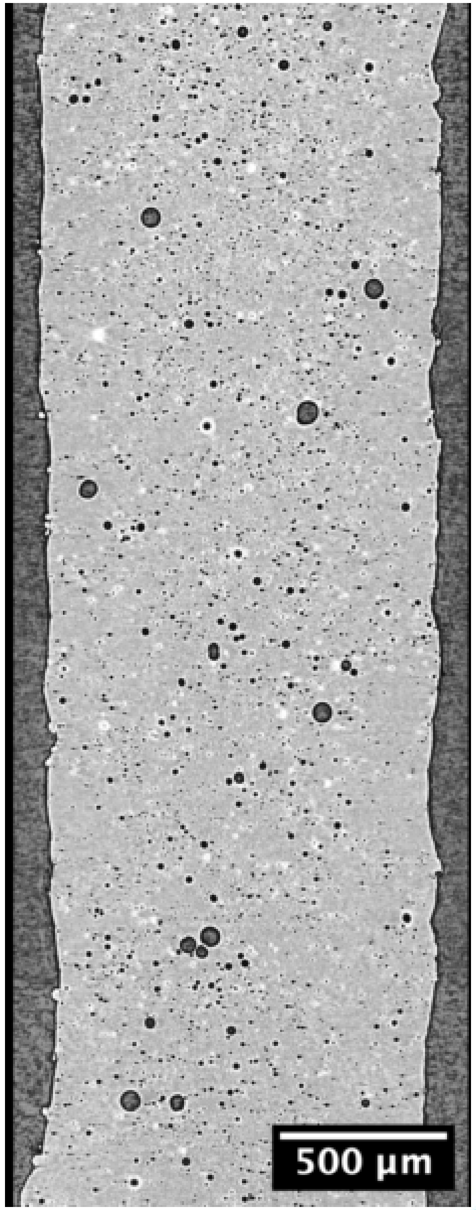
Tensile specimen

1 x 0.45 mm x 4.17 mm gauge section

- Al-10Si-Mg powder <44 µm diameter
- Printed on EOS M400-1
- Stress-relief annealed after build (550 °C)

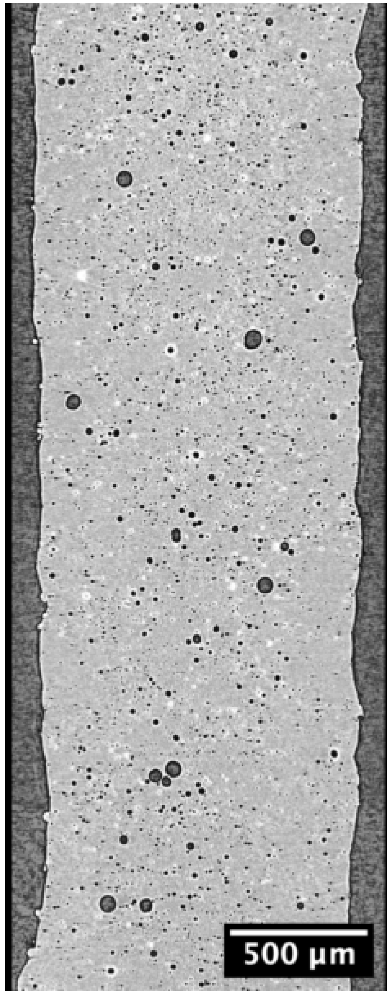


Loading Direction



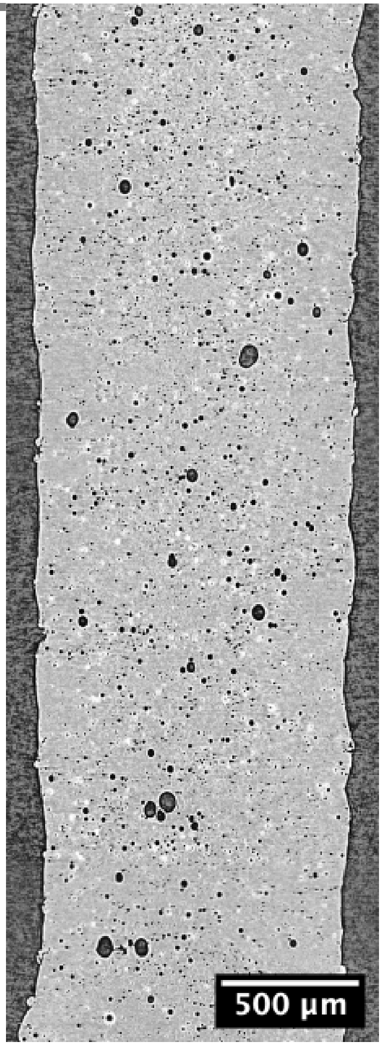
Statistical assessment of scan requires a constant sample volume

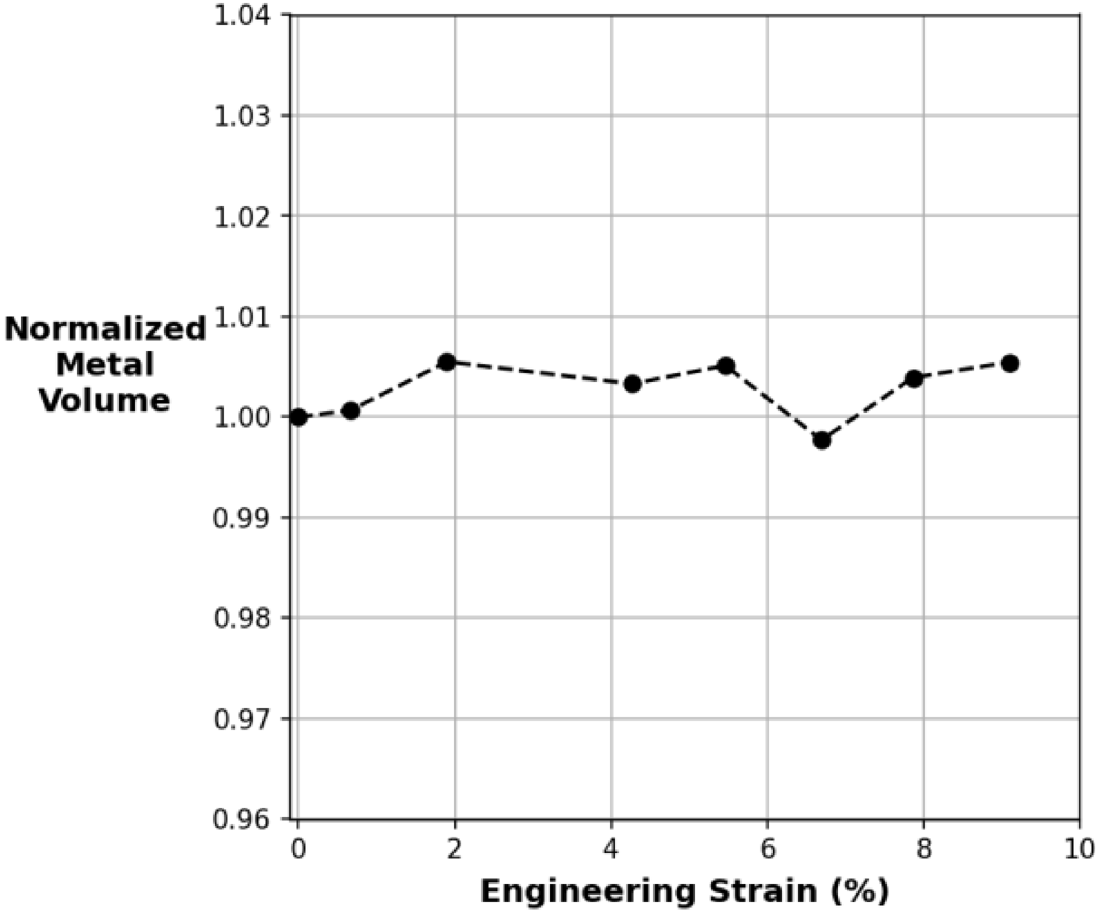
Initial Scan



Loading Direction

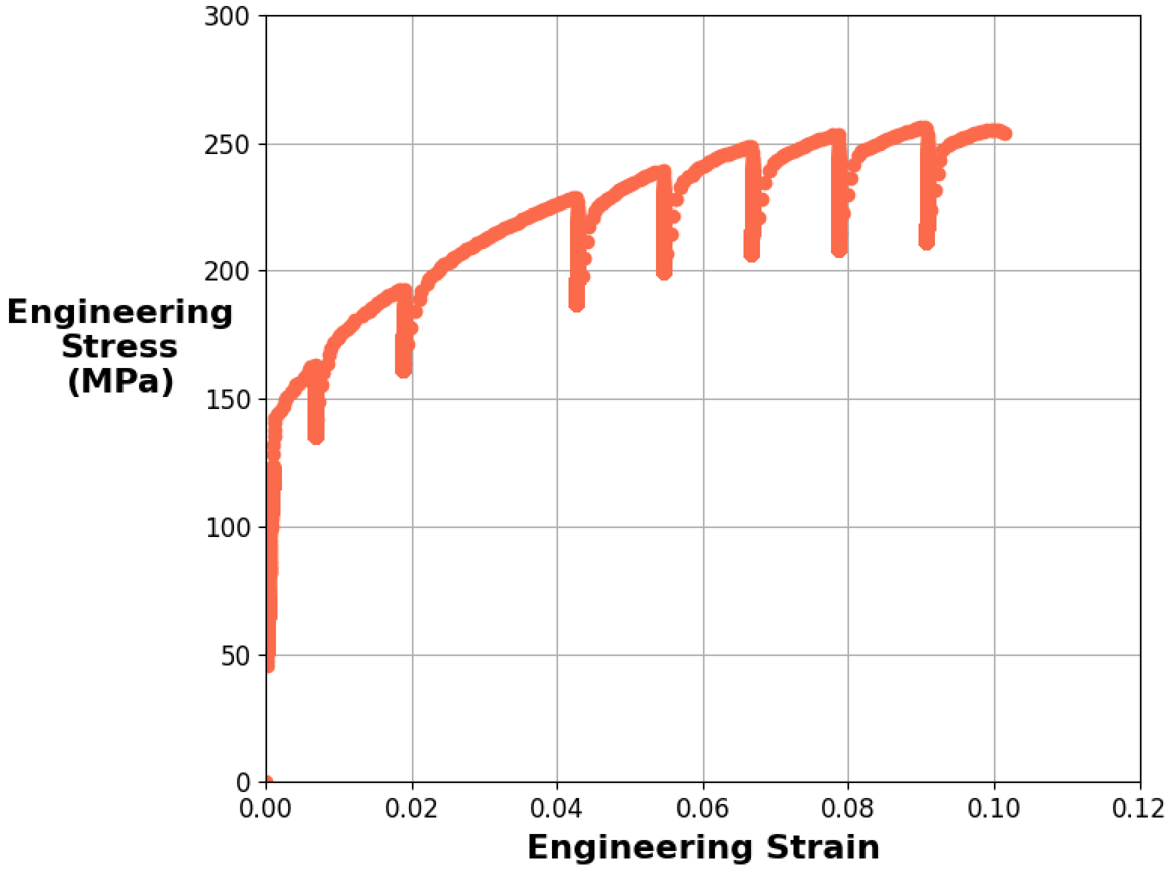
Last Intact Scan

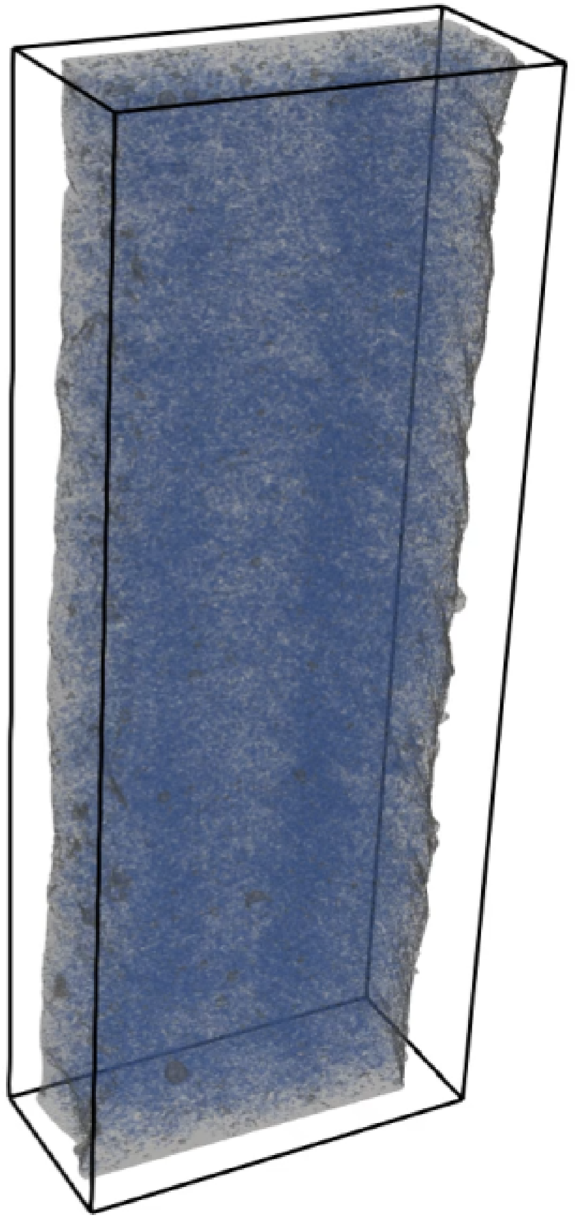




Tensile results

Stress determined using minimum cross-sectional area from initial scan





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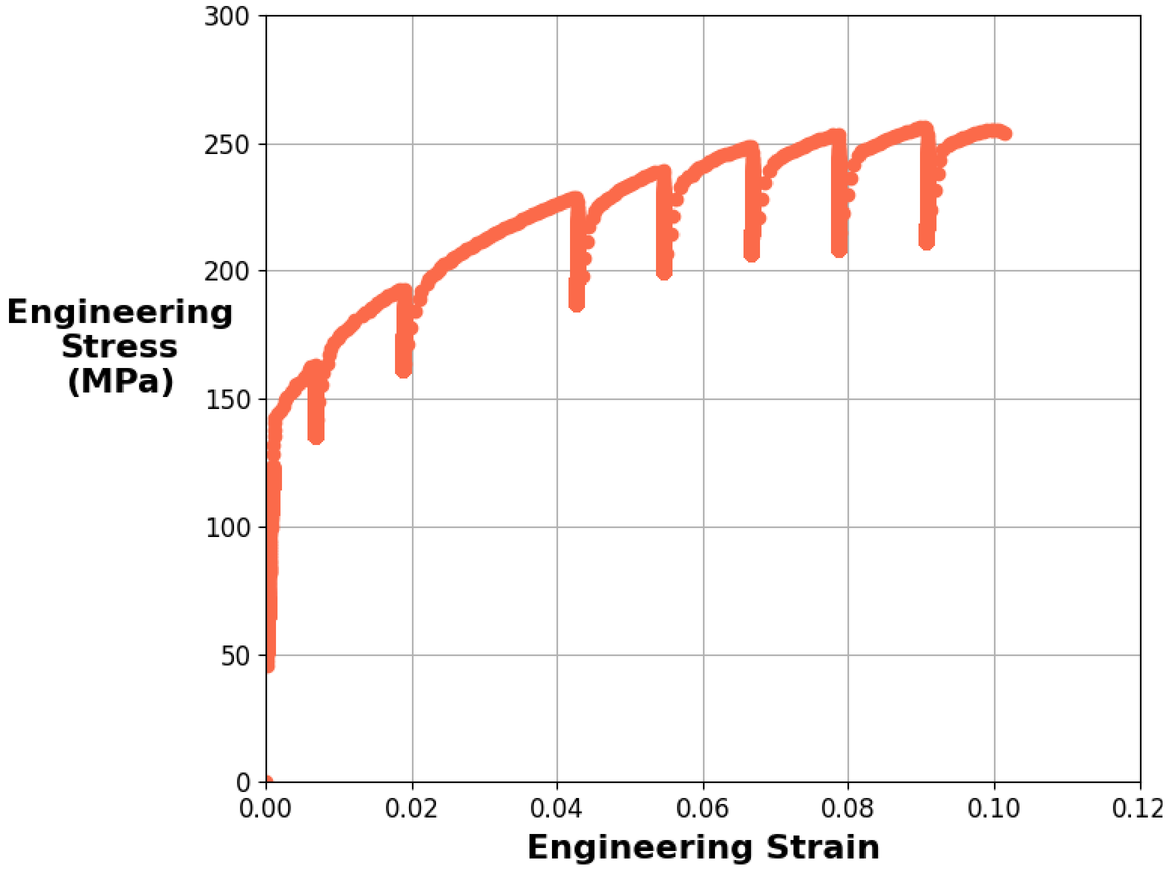
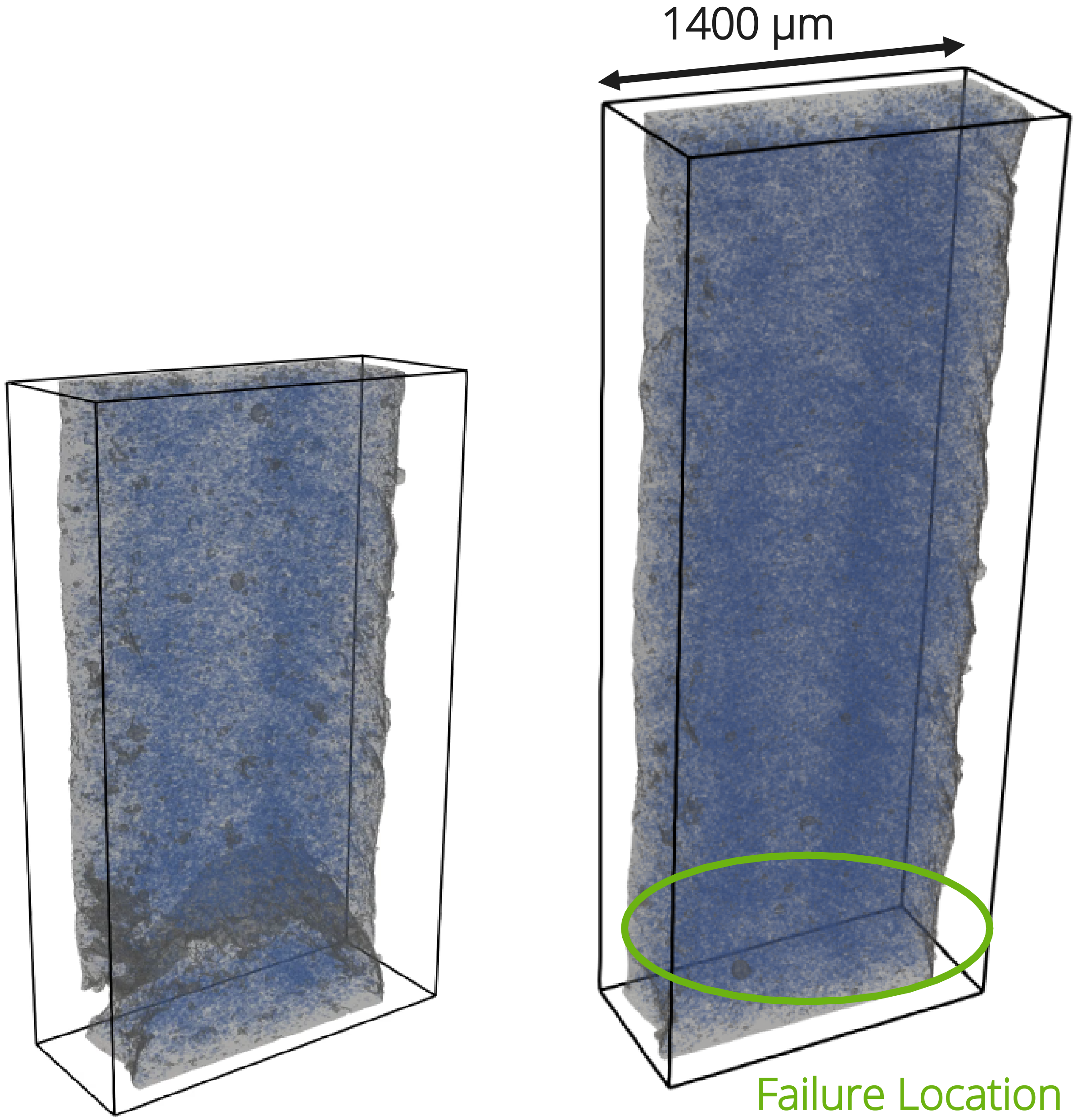
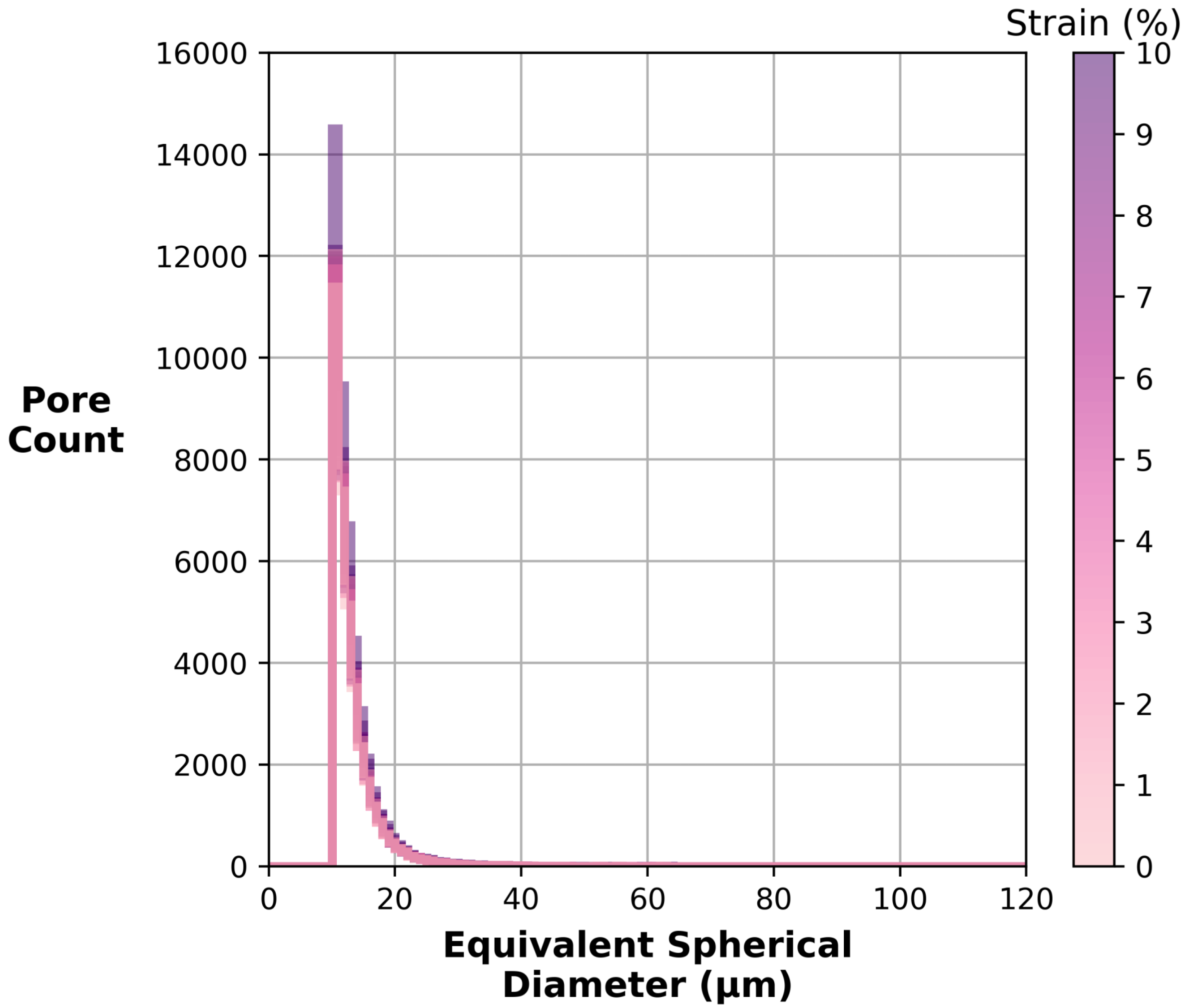
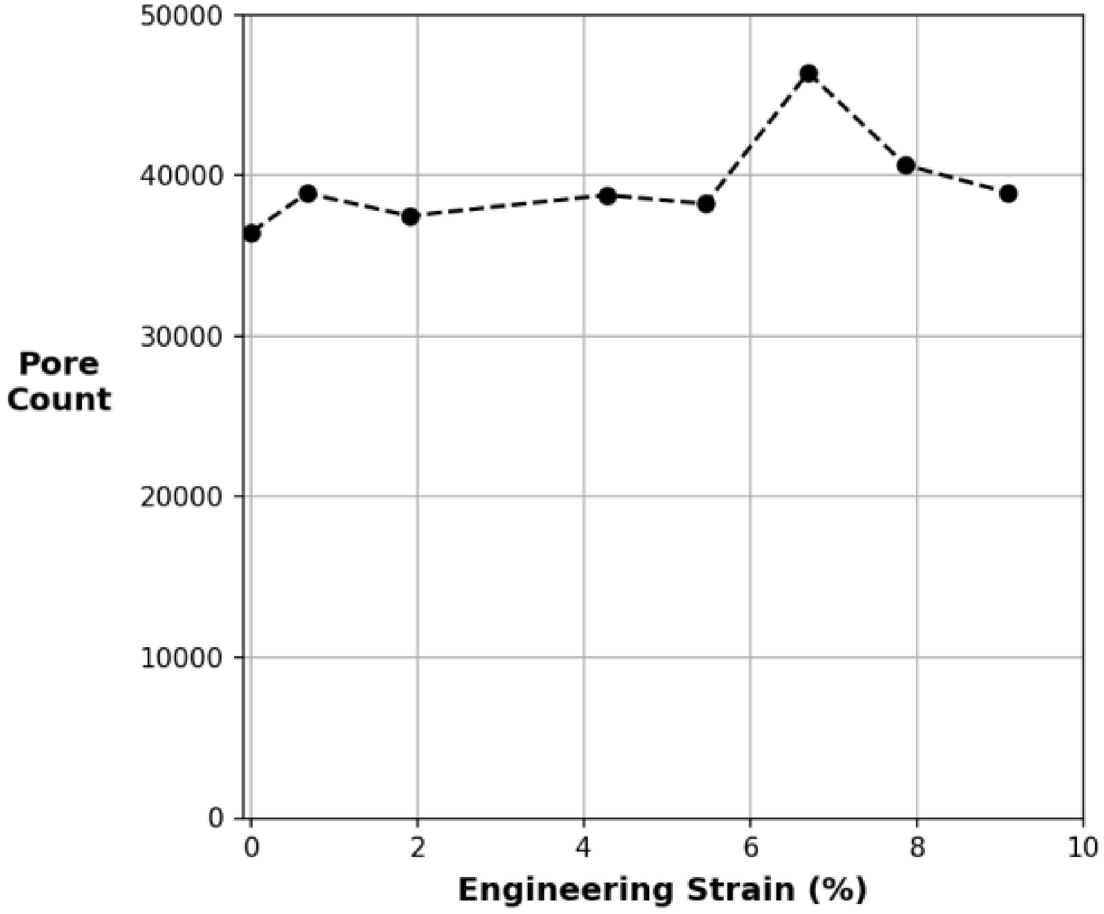




Pore size distribution increases slightly, with minimal evidence of nucleation during loading





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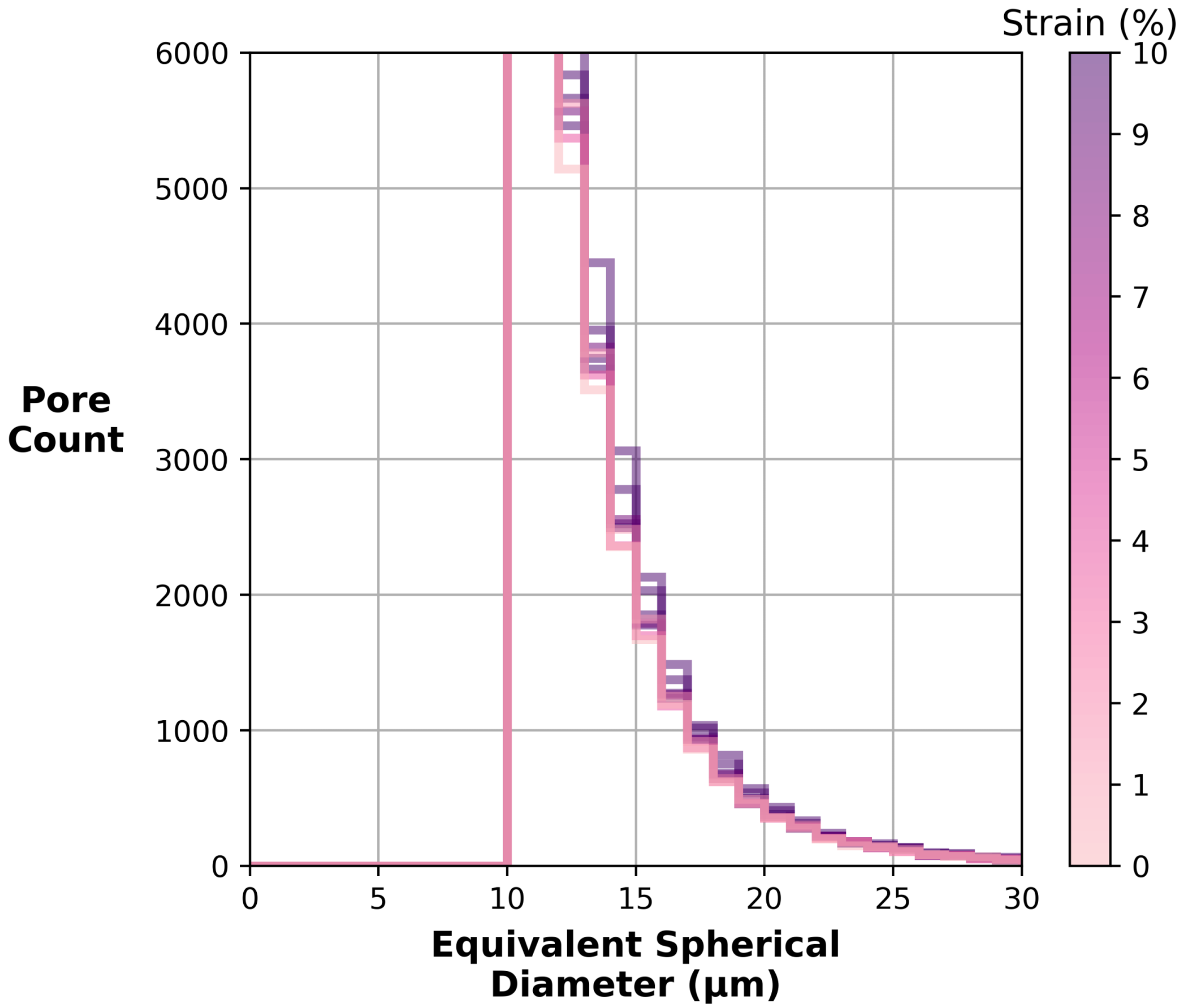
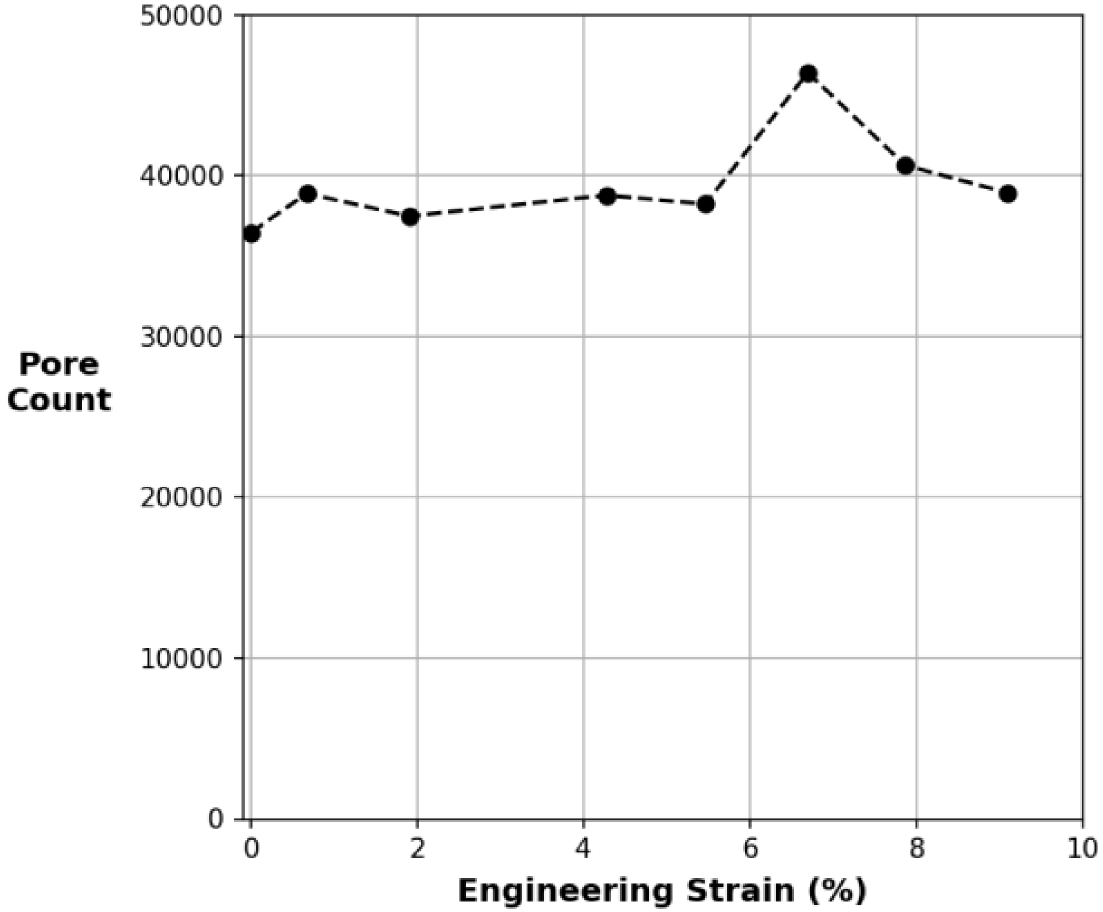
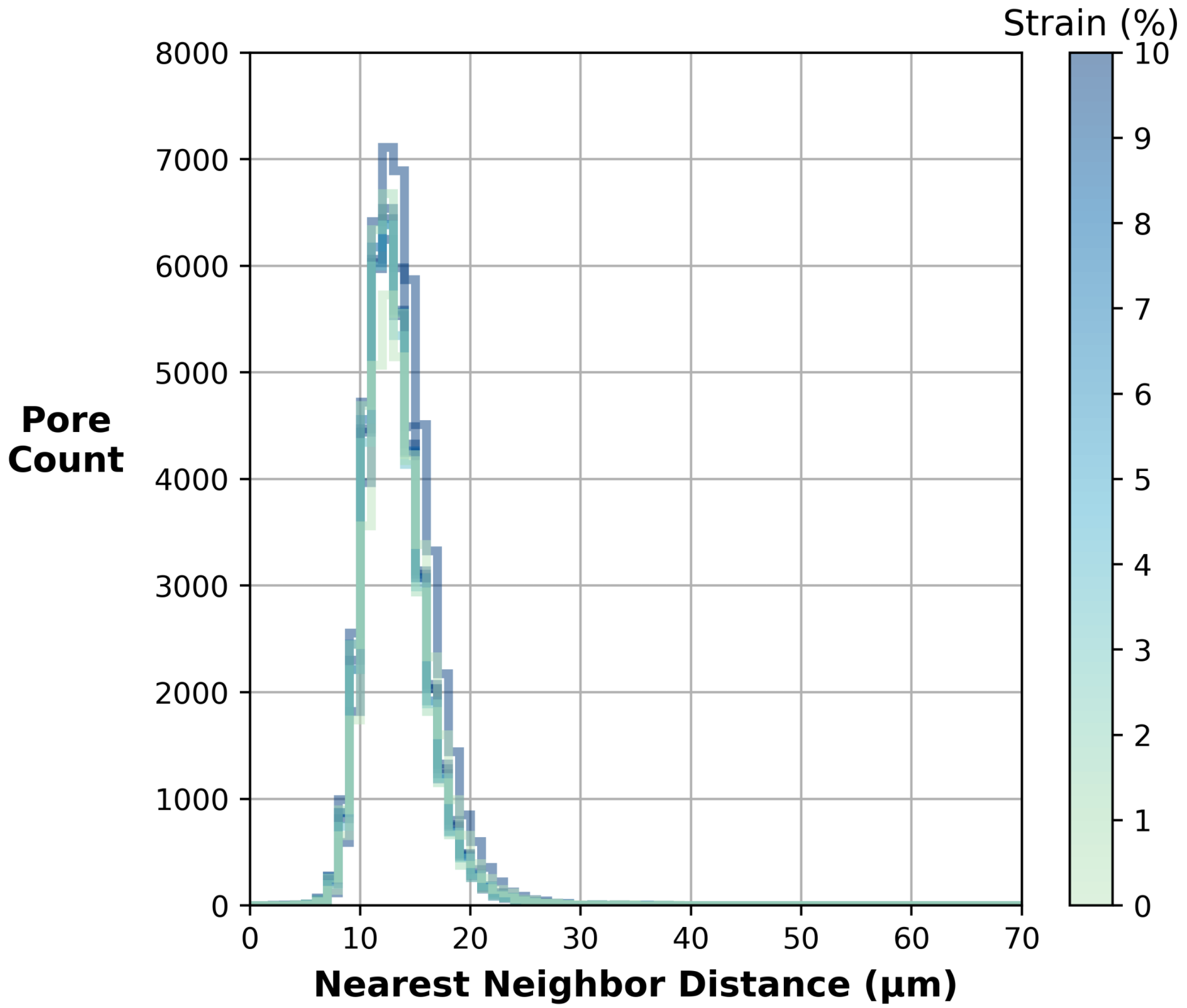
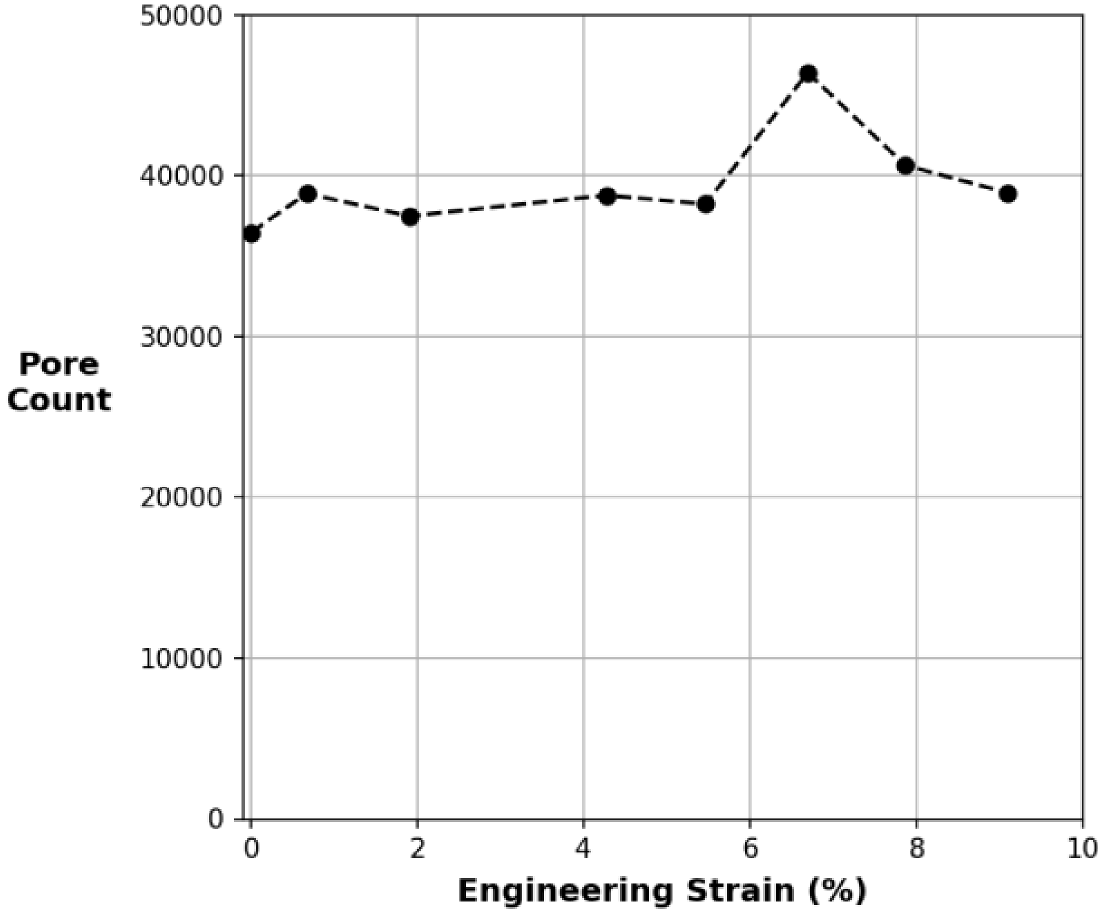




Nearest neighbor distances support lack of pore nucleation

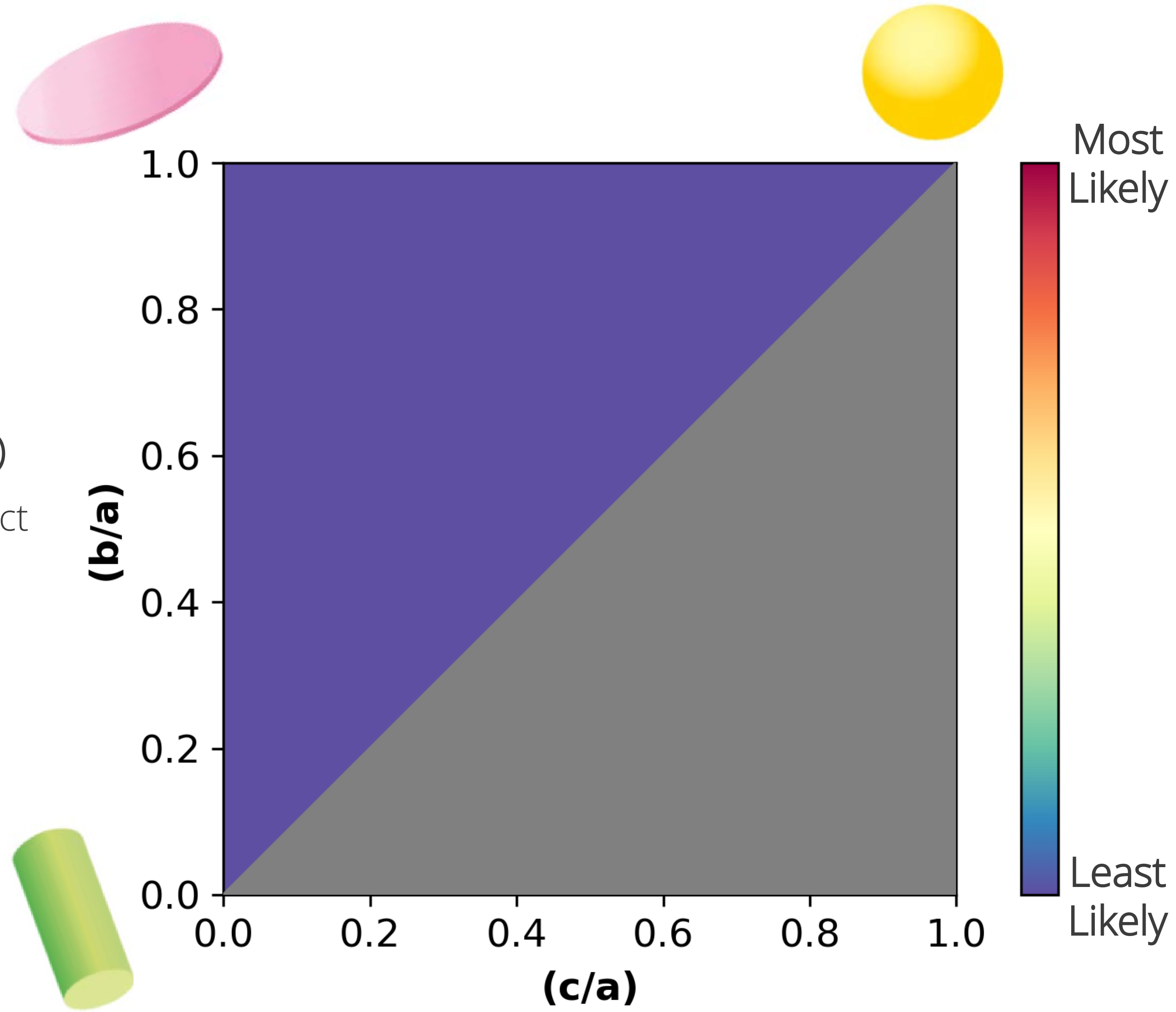




Pores are highly spherical in unloaded state

Shape distributions from best-fit ellipsoid of each pore

- Three axes in the ellipsoid: one major (a) and two minor (b, c)
- Aspect ratios are defined as (b/a) and (c/a)
- Can create 2D histogram of ellipsoid aspect ratios, given:
  - a > b > c (gray region is non-physical)
- Rod-like features (2 low aspect ratios)
- Plate-like features (1 high aspect ratio)
- Spherical features (2 high aspect ratios)



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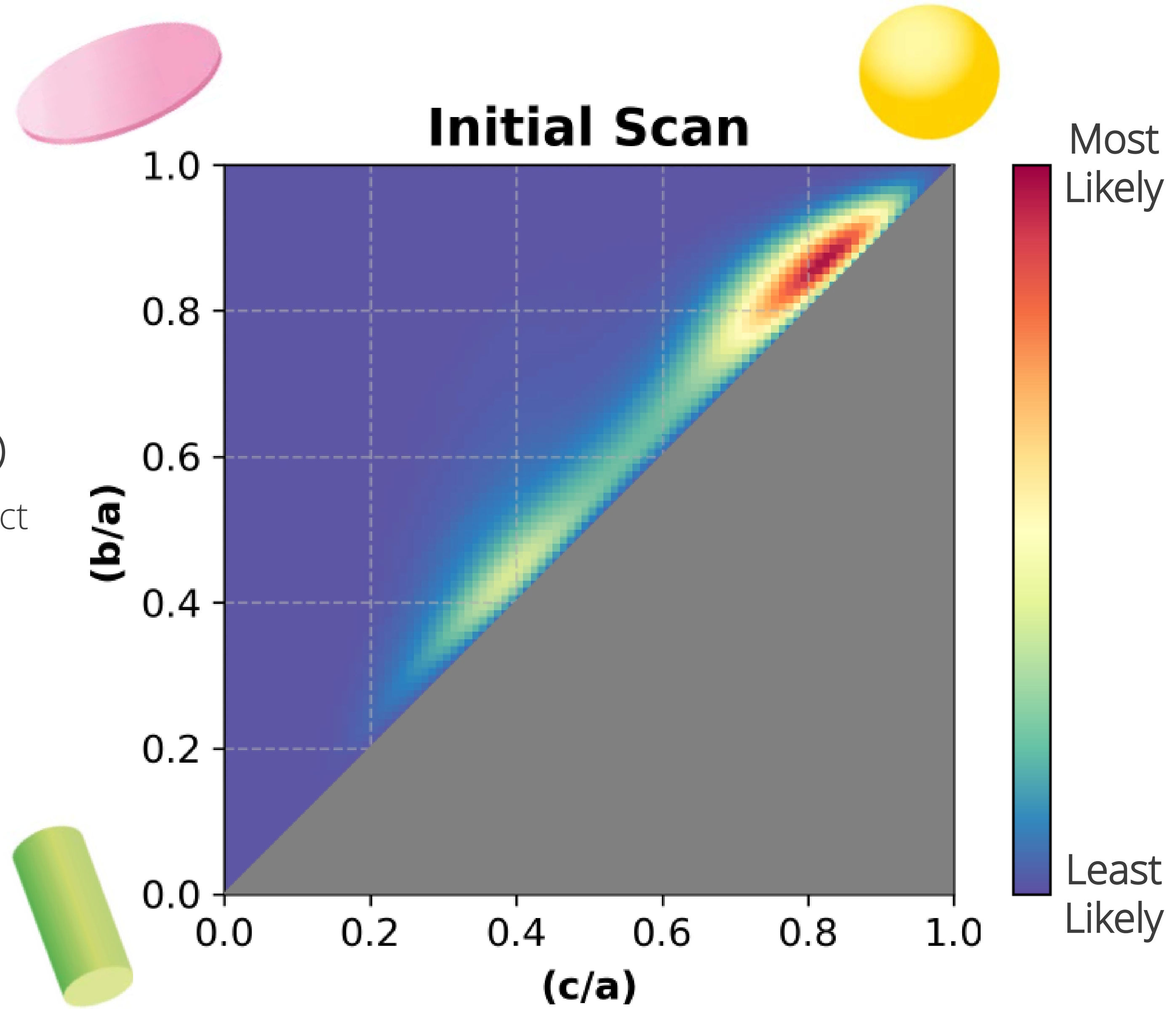
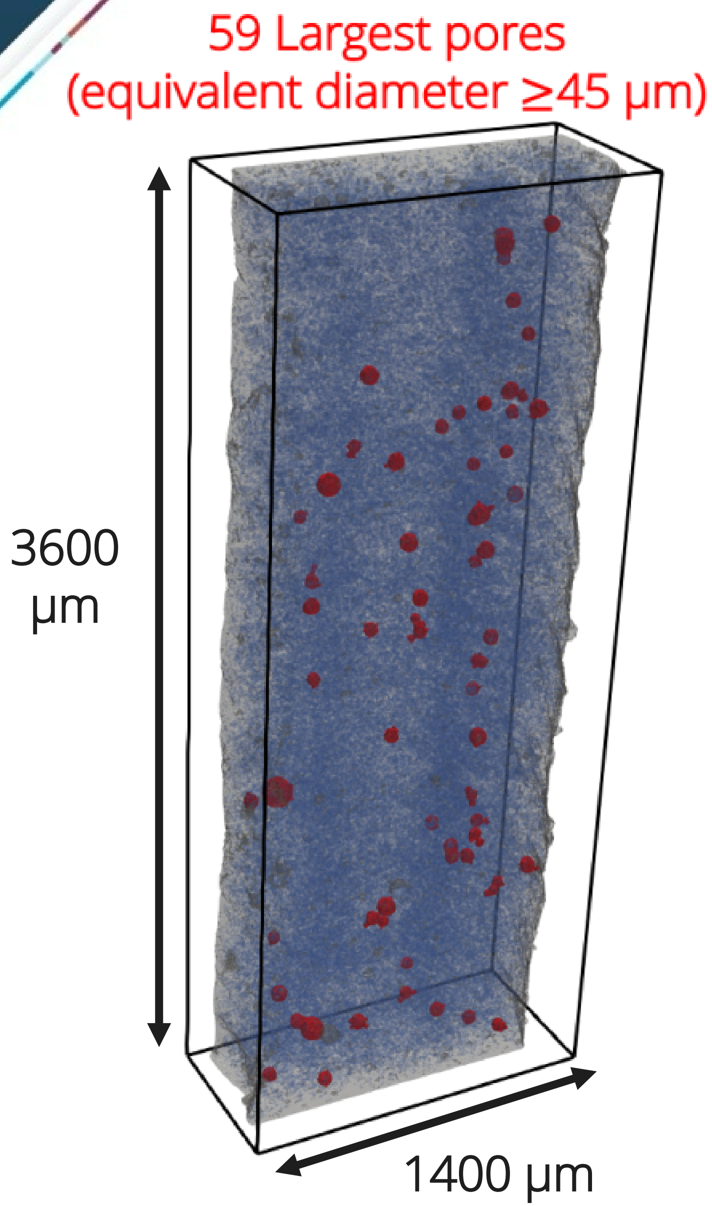


Can analyze pore growth by tracking the largest pores in the volume



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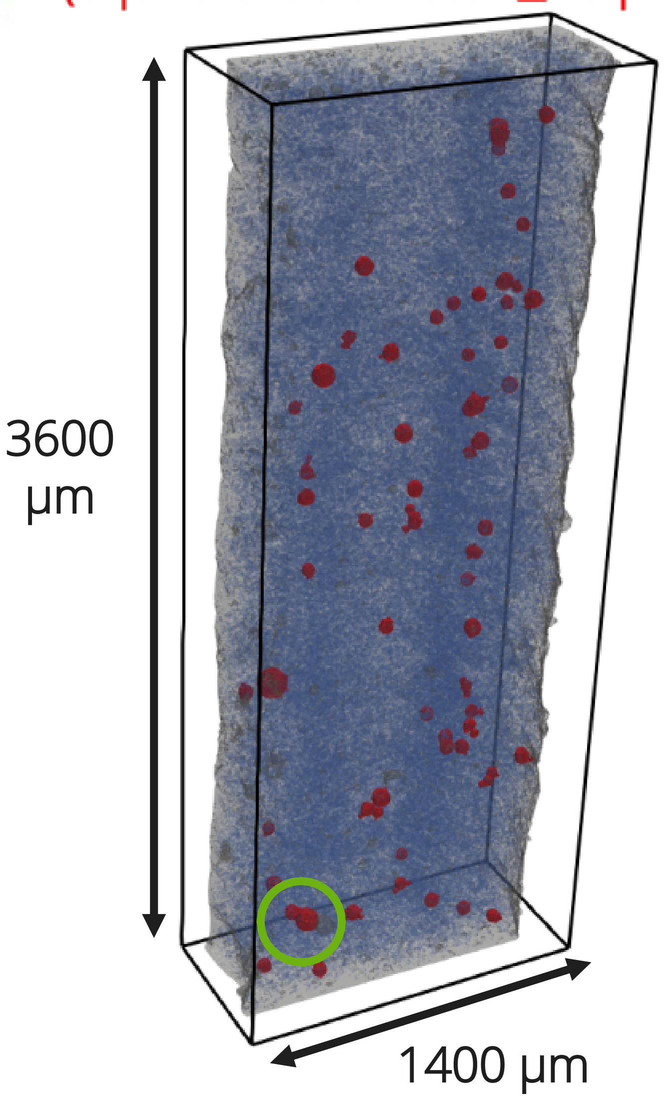
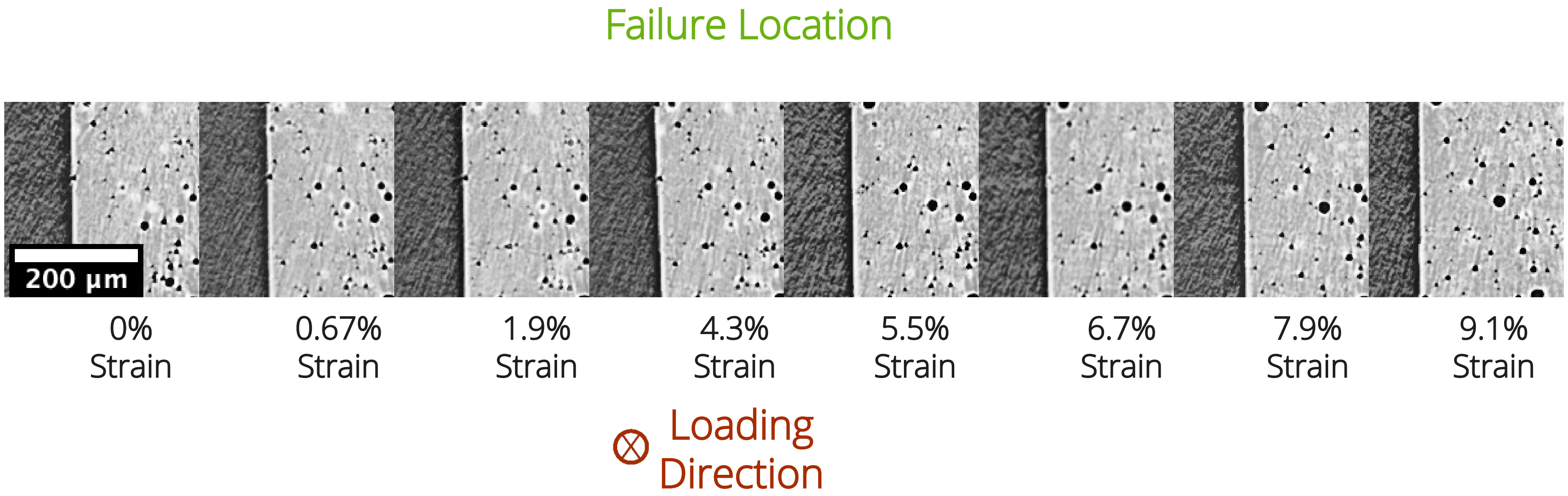
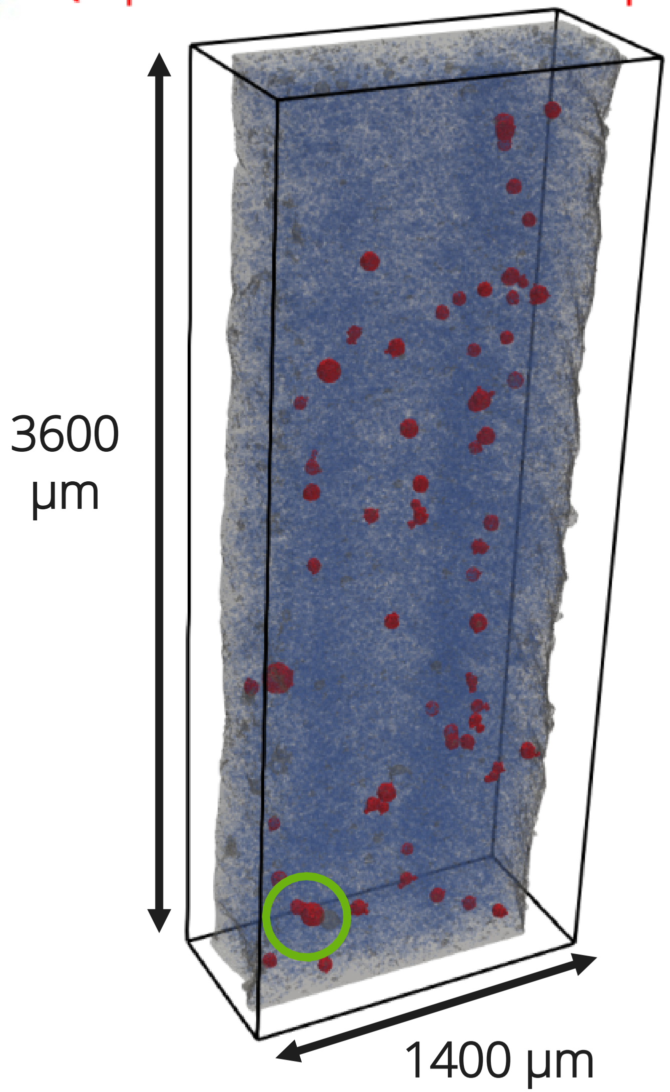


Normalized cross-correlation in Fourier space can track small regions of the volume



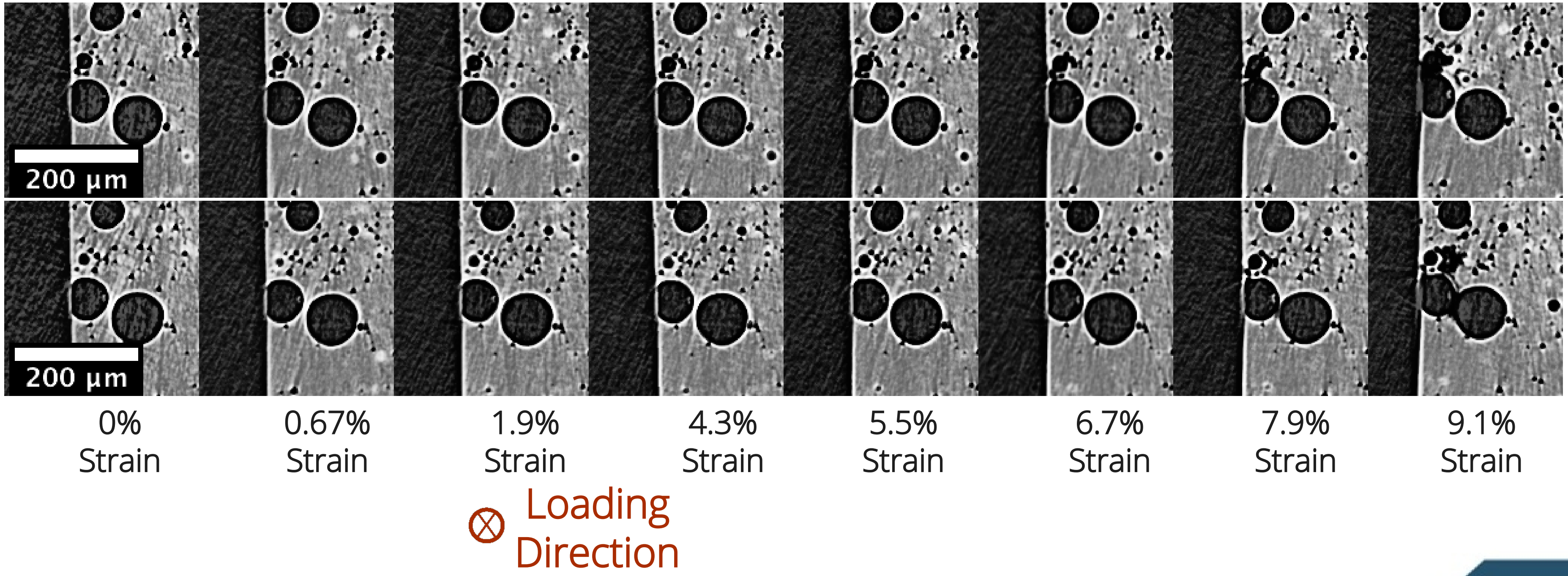
Can analyze pore growth by tracking the largest pores in the volume

59 Largest pores
(equivalent diameter ≥45 μm)



Normalized cross-correlation in Fourier space can track small regions of the volume

Failure Location



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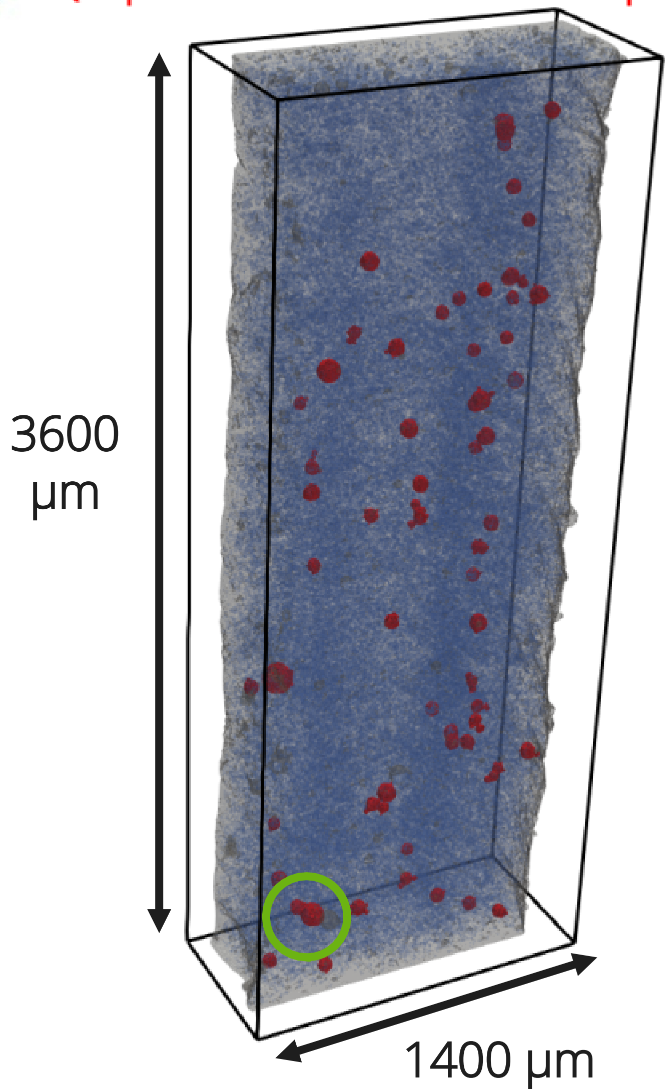

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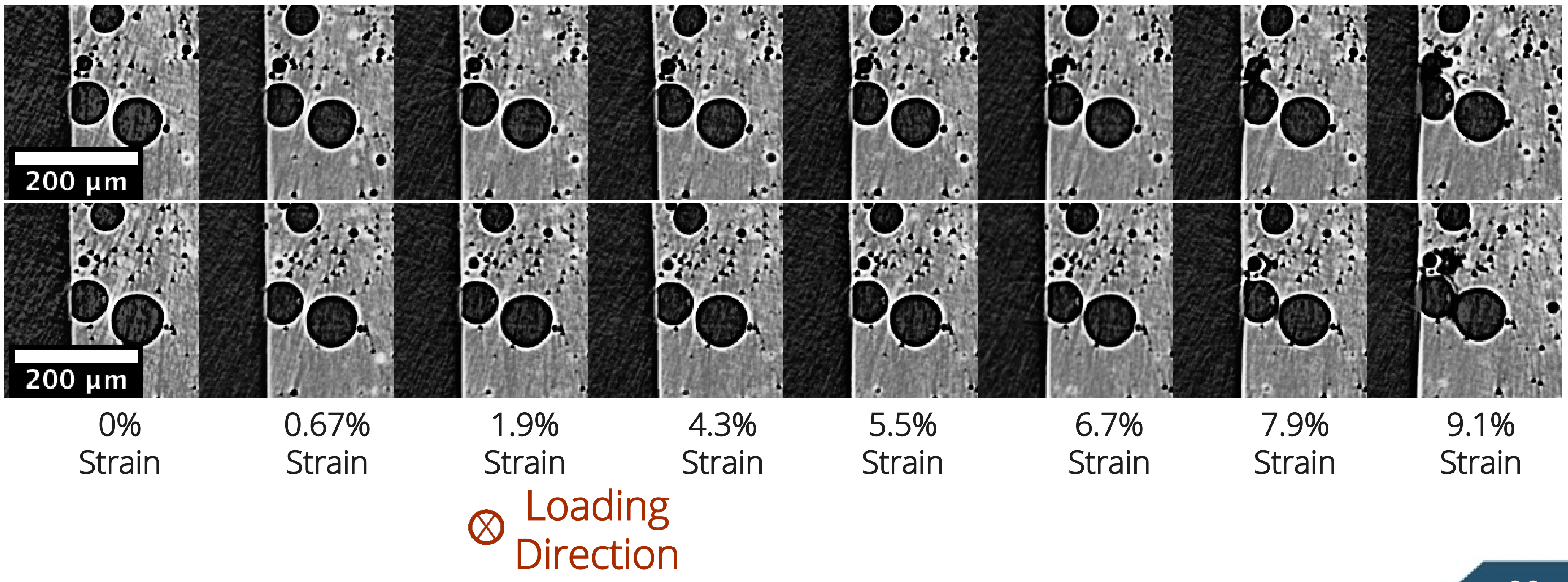

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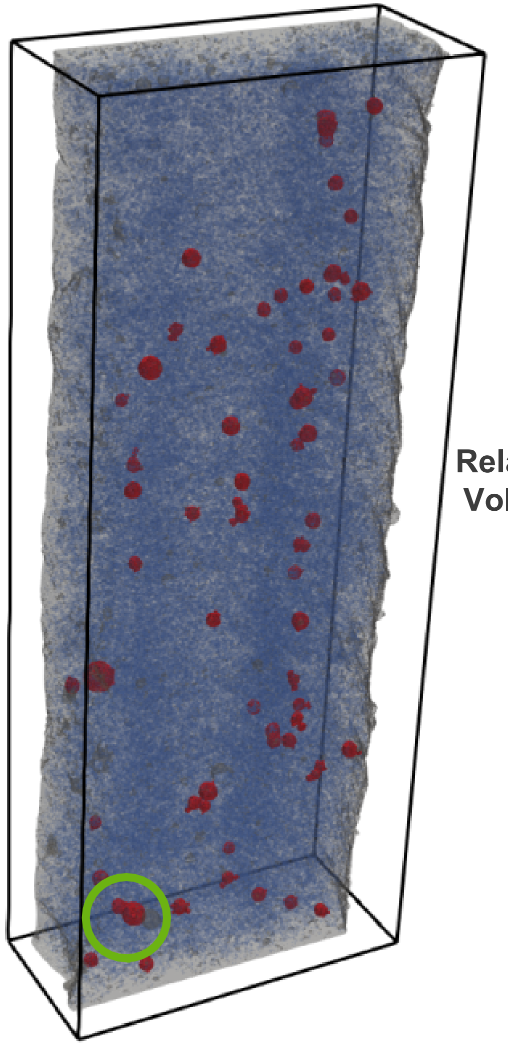

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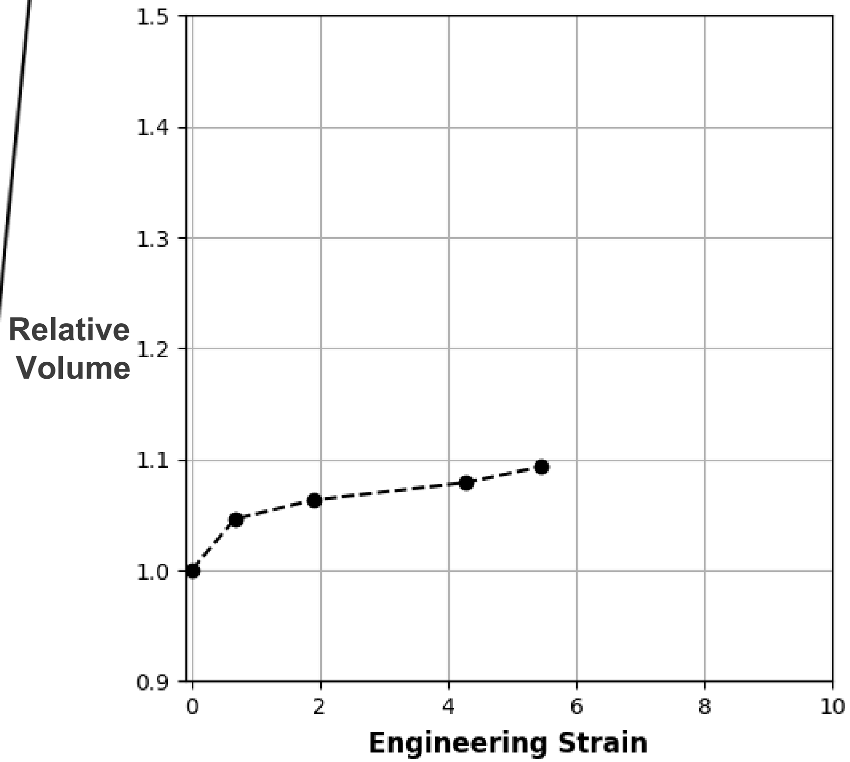

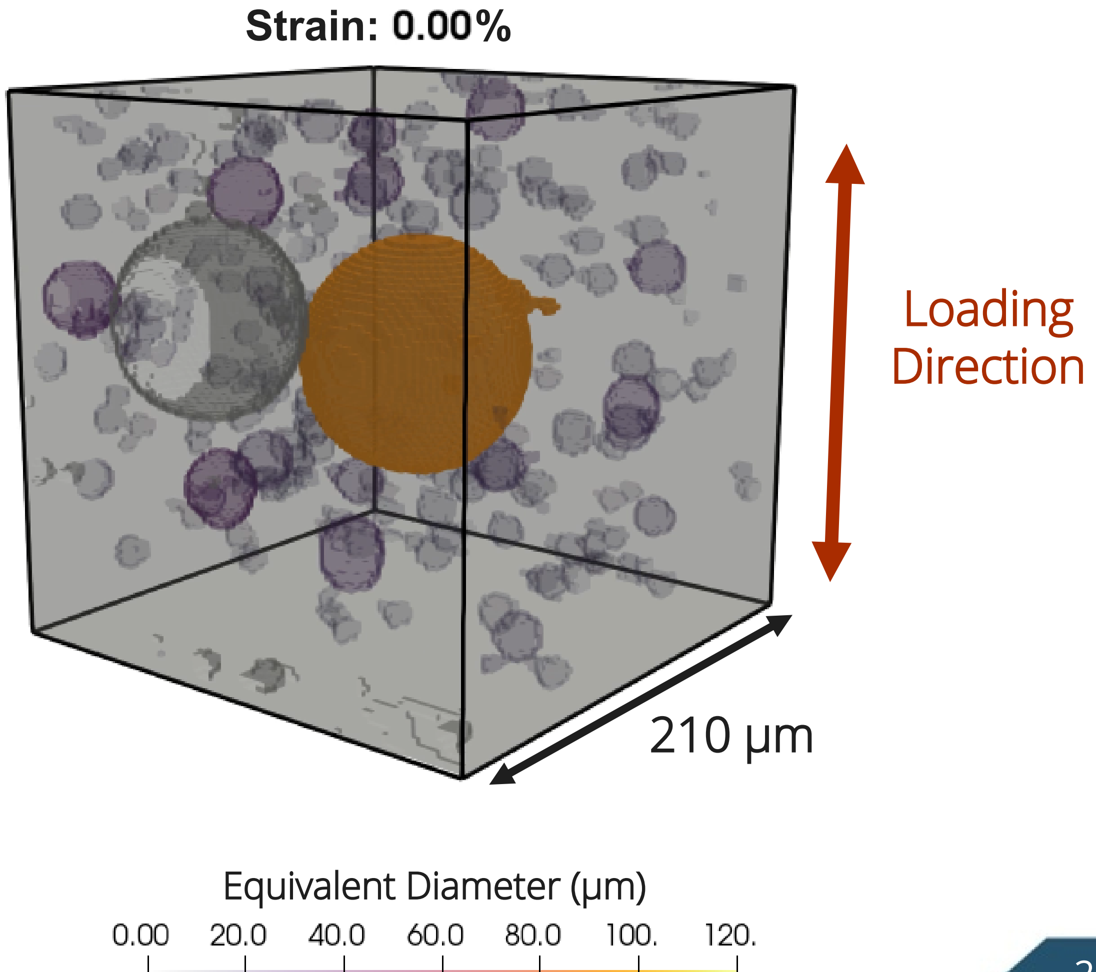

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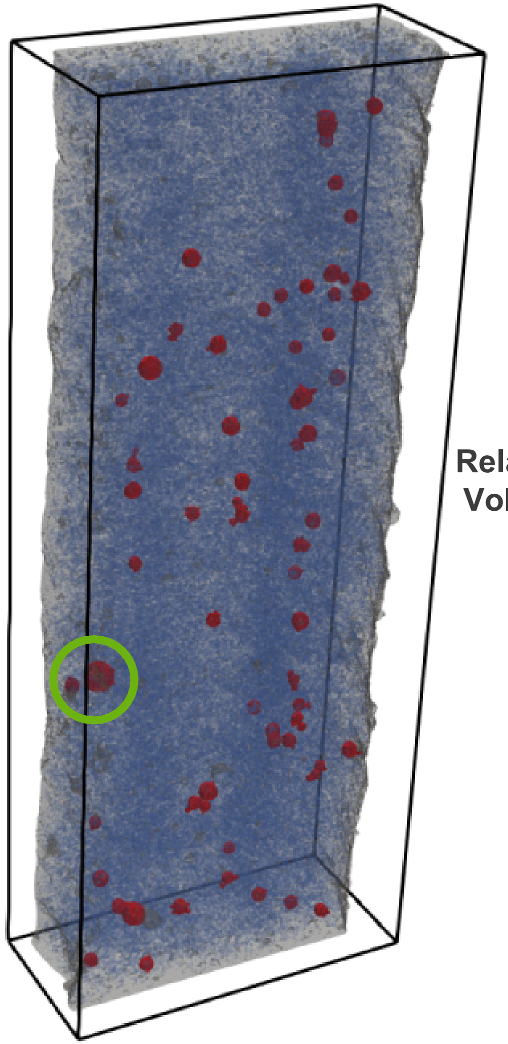
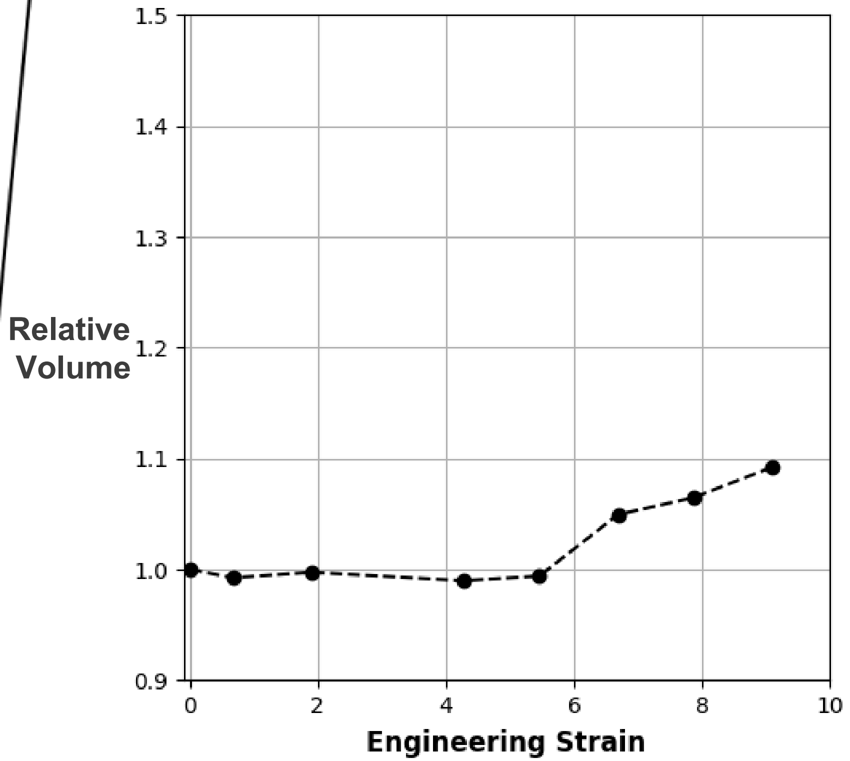
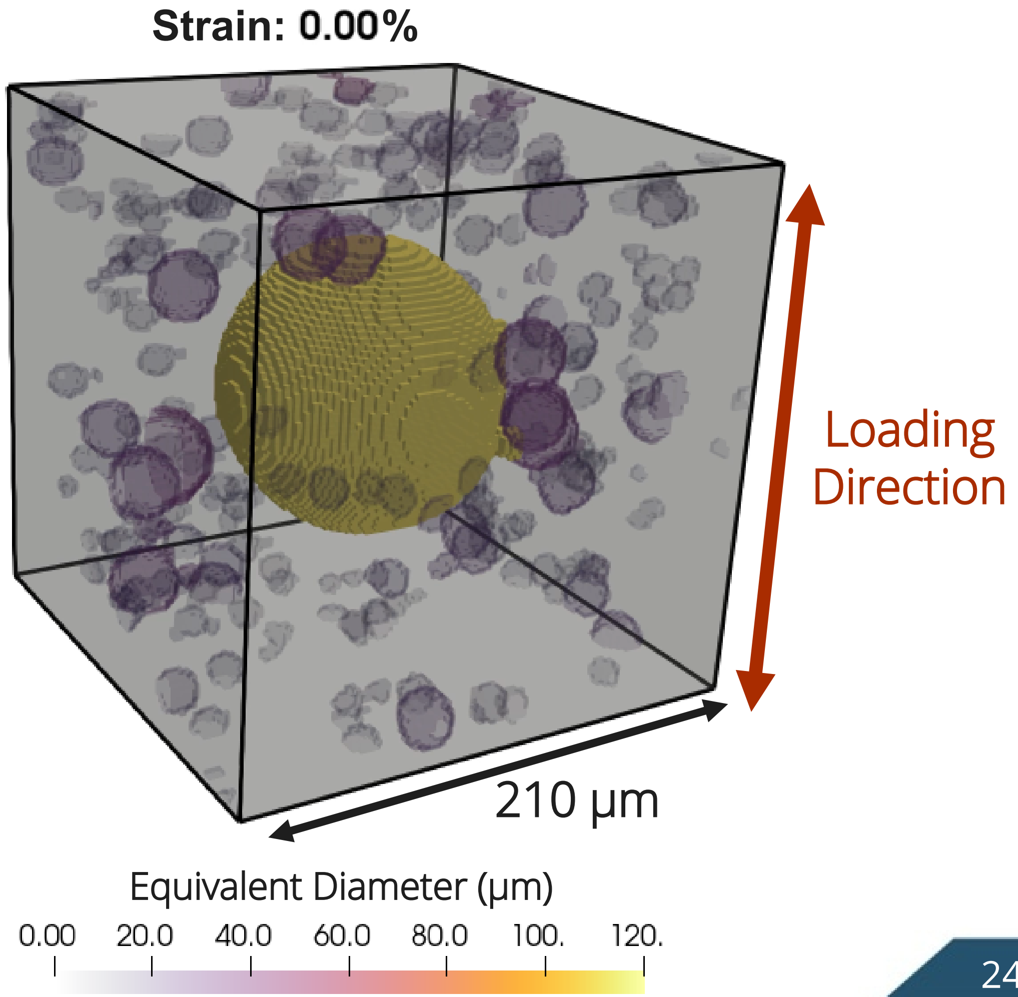


Largest Pore in Volume





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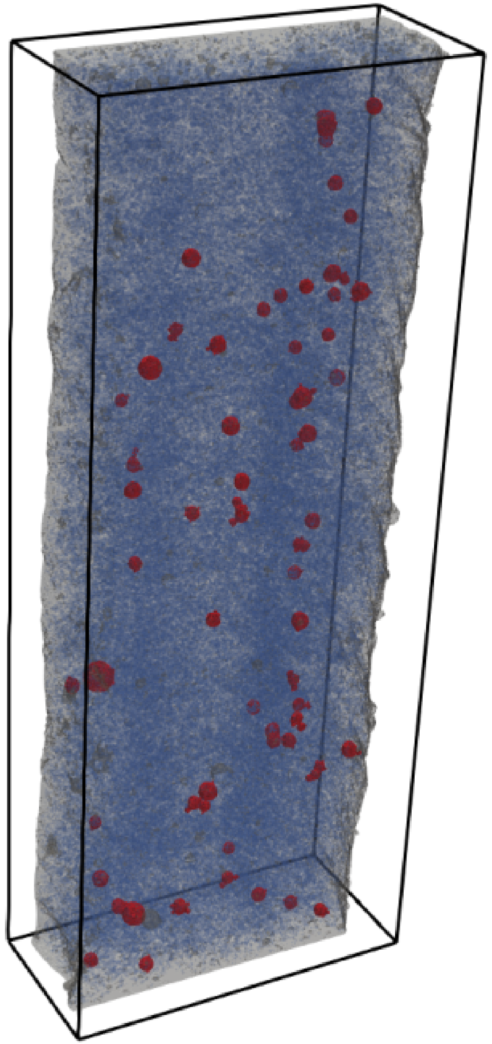
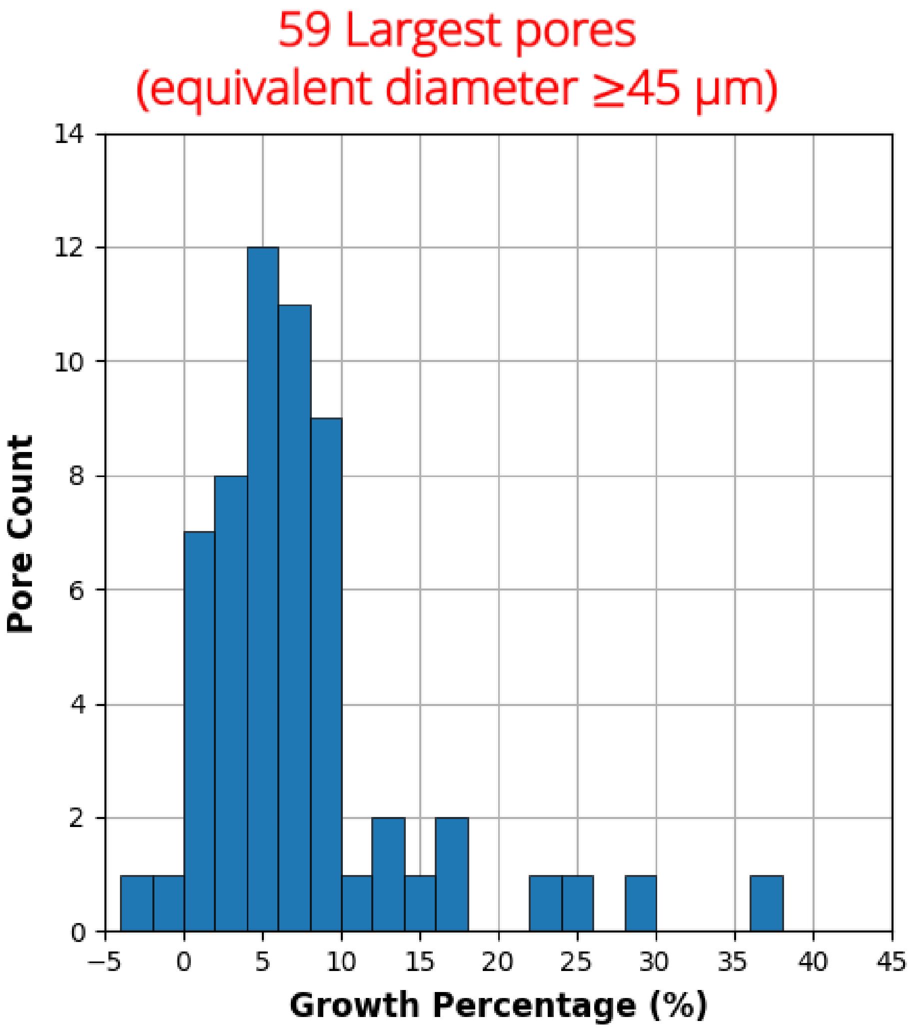
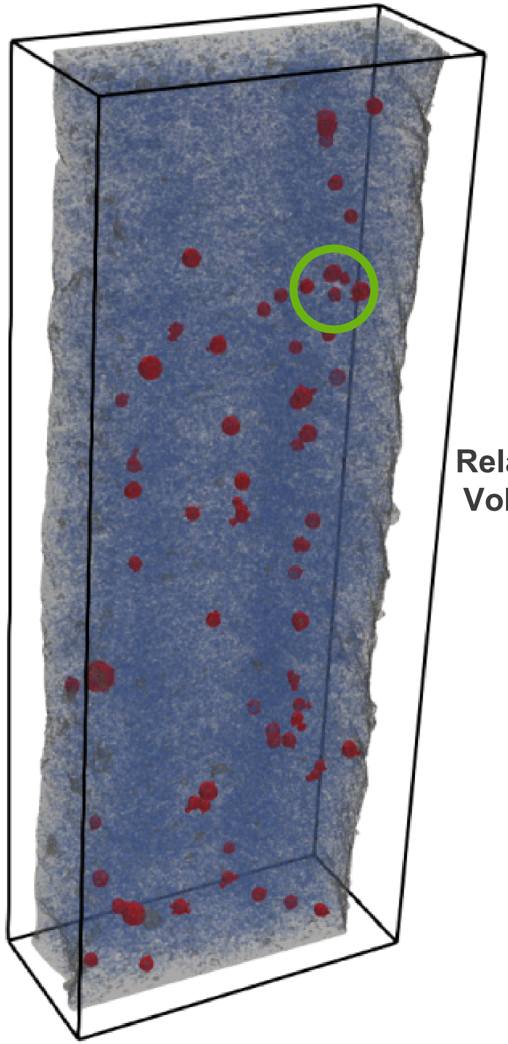


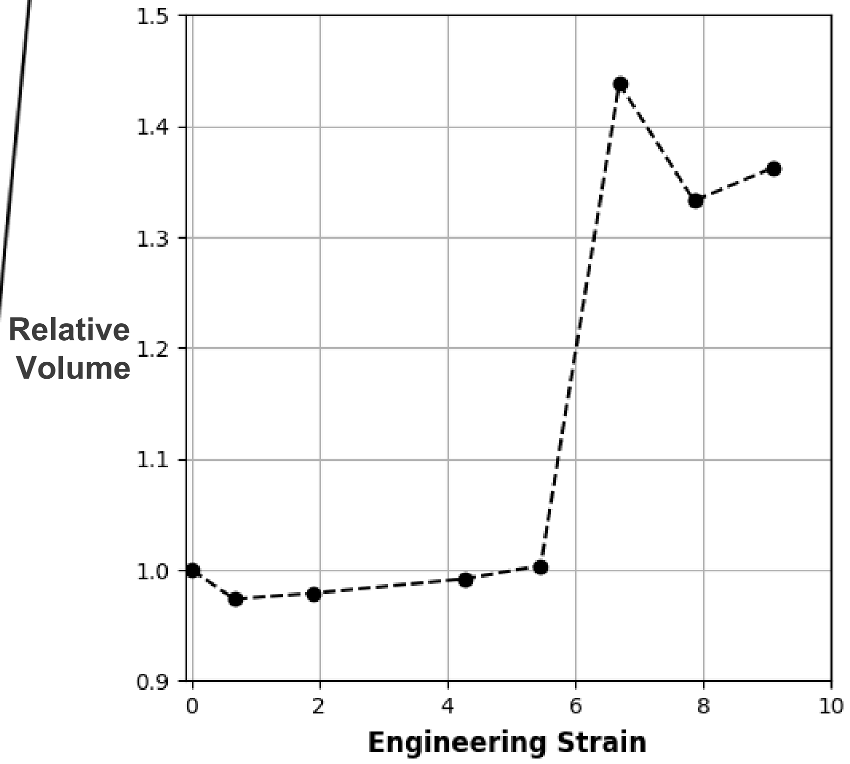


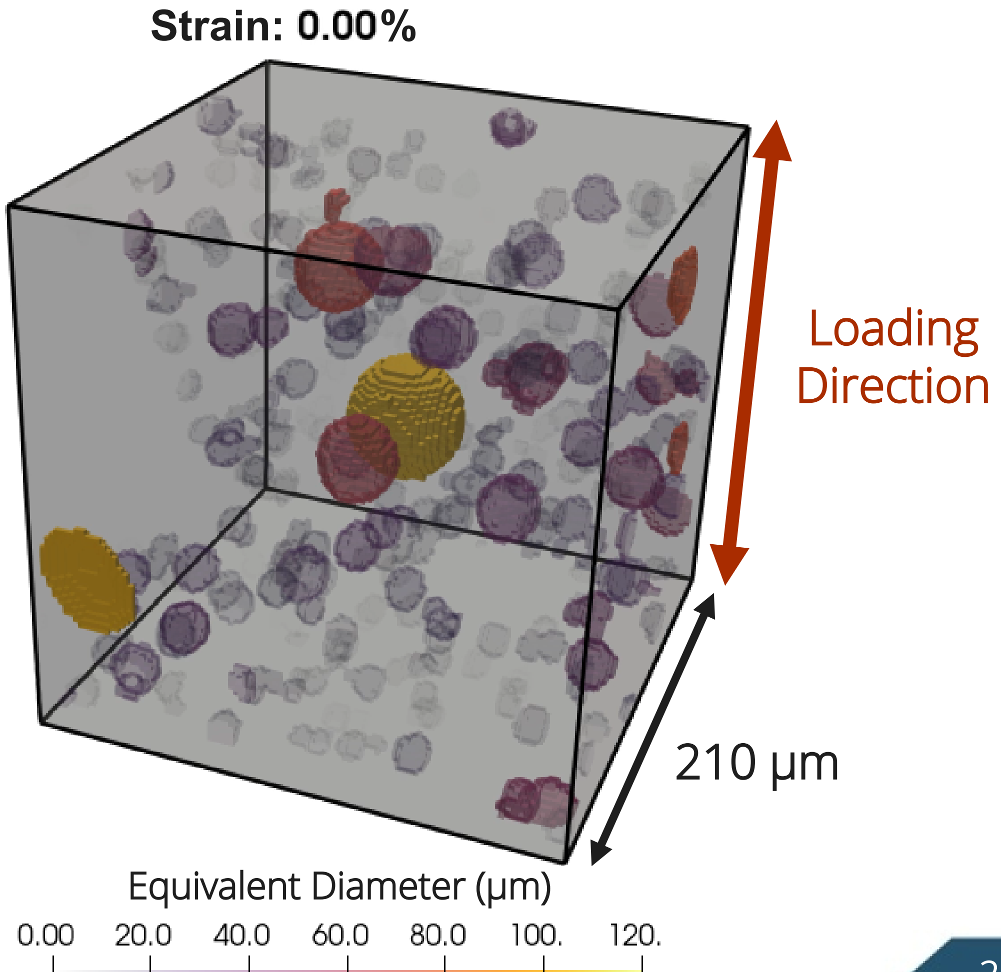
- Most large pores grow in volume between 2-10%
- Only two pores found to shrink
- Some pores appear to get much larger, due to pore merging

Can analyze pore growth by tracking the largest pores in the volume

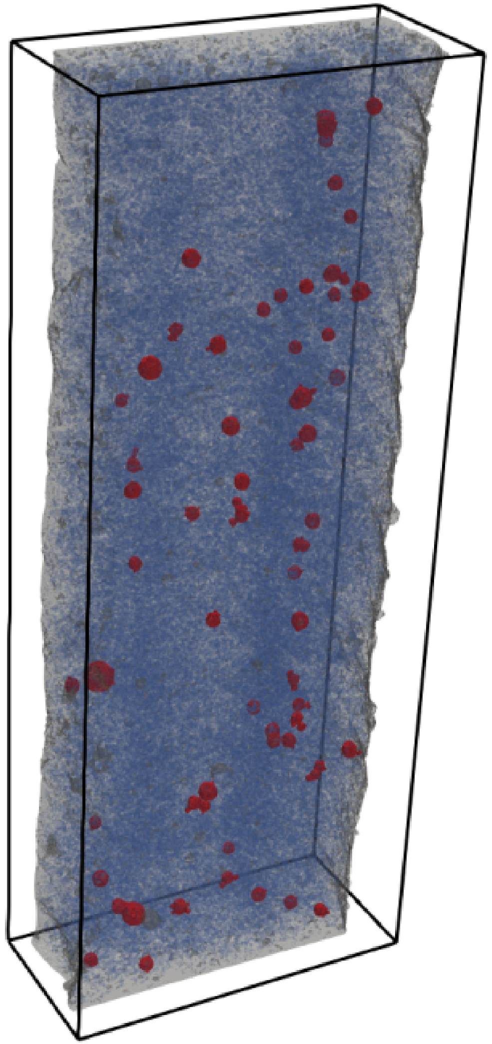


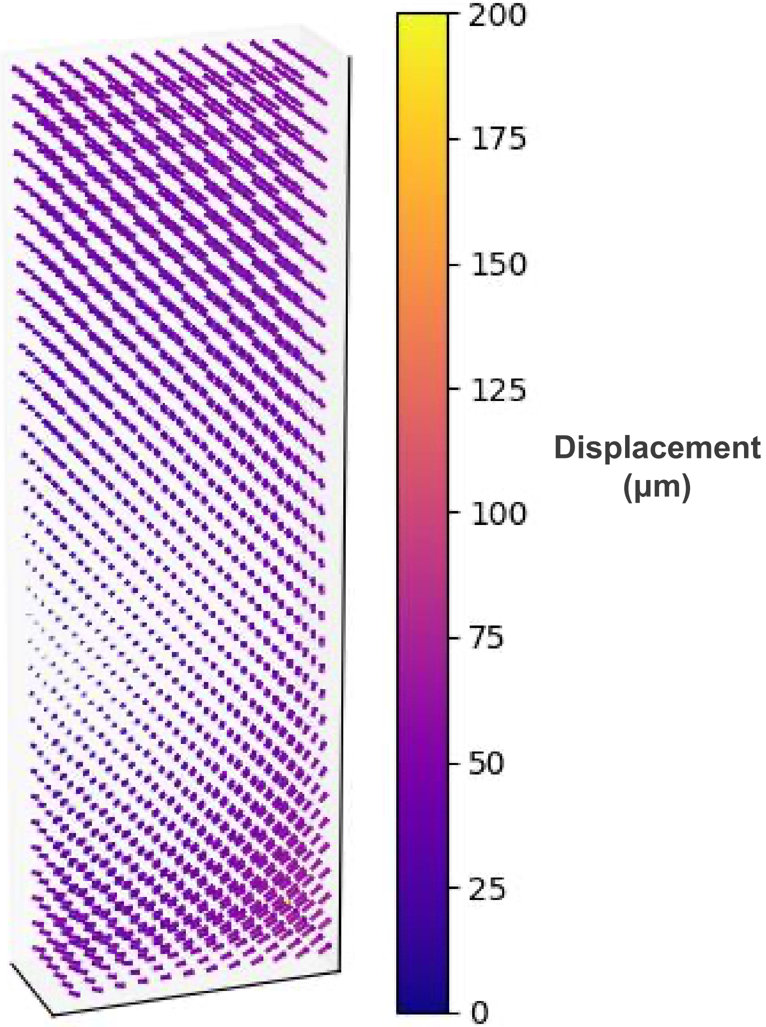
Pore Merging





Particle tracking can be extended to generate displacement fields for the entire volume





- Uses thin plate spline algorithm with tracked particles as control points
- Plan to convert this to local strain measurements to compare to FEA modelling

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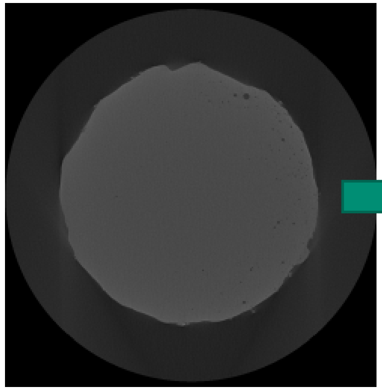
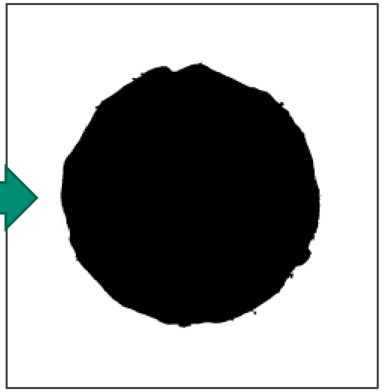
Modeling Workflow

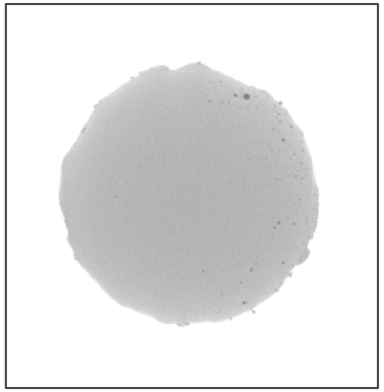
CT Processing

Import Image



Threshold

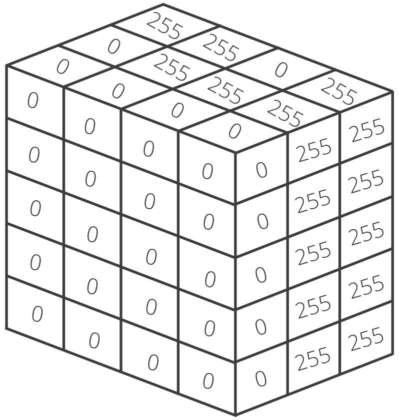




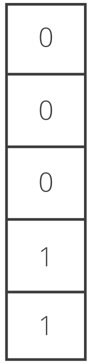
“High Res” Tiff Stack

Meshing

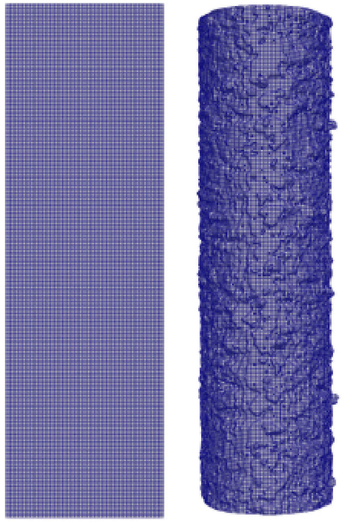
Numpy Array



SPN File



Cubit/Sculpt Mesh



Simulation

Calibrate plasticity parameters

With plasticity parameters fixed, calibrate damage parameters porous mesh

Predict failure in porous samples using varying resolution

Model Setup

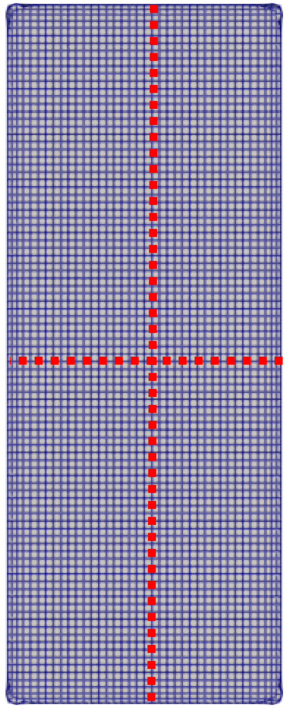
- Implicit tension models run in Sierra FEA code
- "Pads" added on top and bottom of part to provide force buffer for boundary conditions. *Unnecessary if portion of grips are included in scan
- Cubit/Sculpt creates mesh by converting cartesian grid voxels to hexahedral elements and smoothing edges
- Constitutive response captured with plasticity and local damage models

Voce[1] Hardening

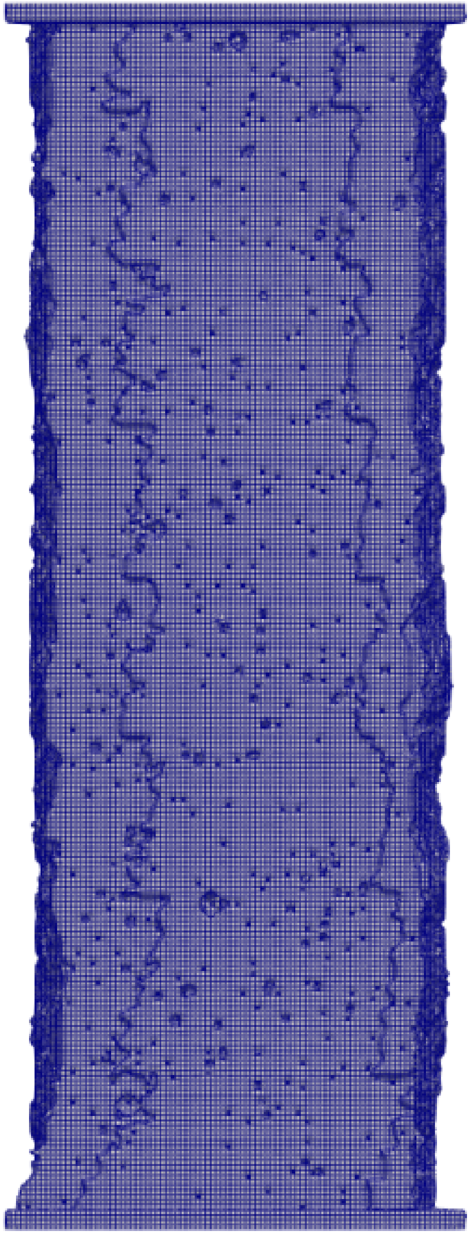
$$\bar{\sigma} = \sigma_y + A(1 - \exp(-n\bar{\varepsilon}^p))$$

Cocks-Ashby[2] Void Growth

$$\dot{\phi} = \sqrt{\frac{2}{3}}\dot{\epsilon}_p \frac{1-(1-\phi)^{m+1}}{(1-\phi)^m} \sinh\left[\frac{2\,(2m-1)}{2m+1}\frac{\langle p \rangle}{\sigma_e}\right]$$

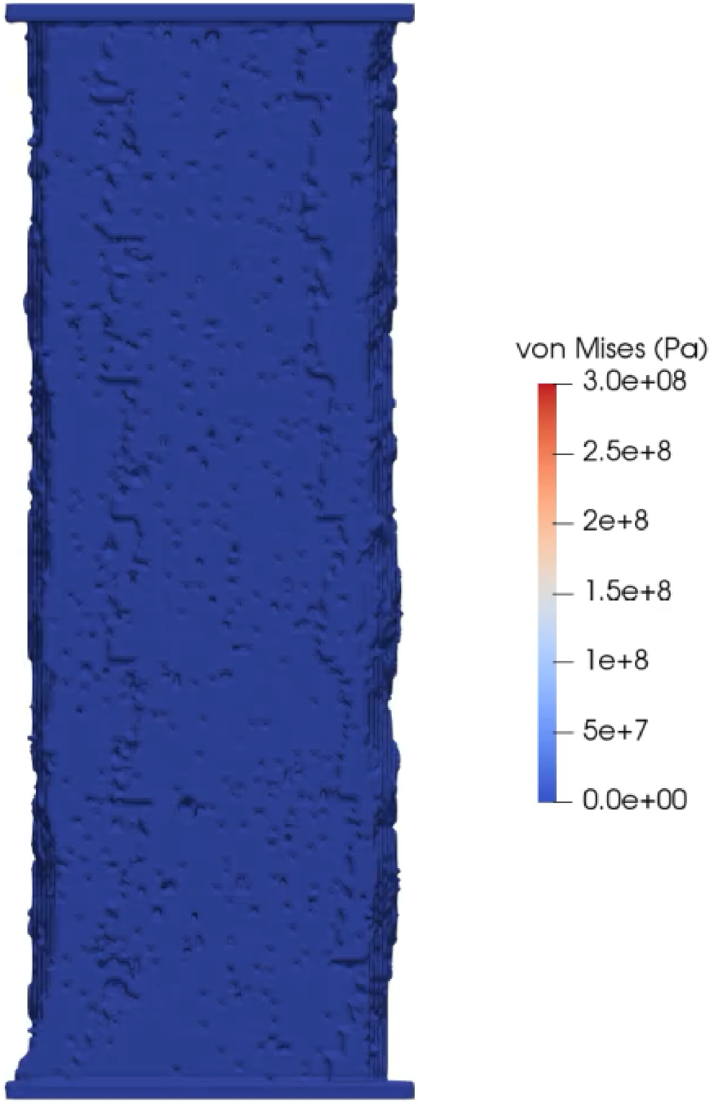


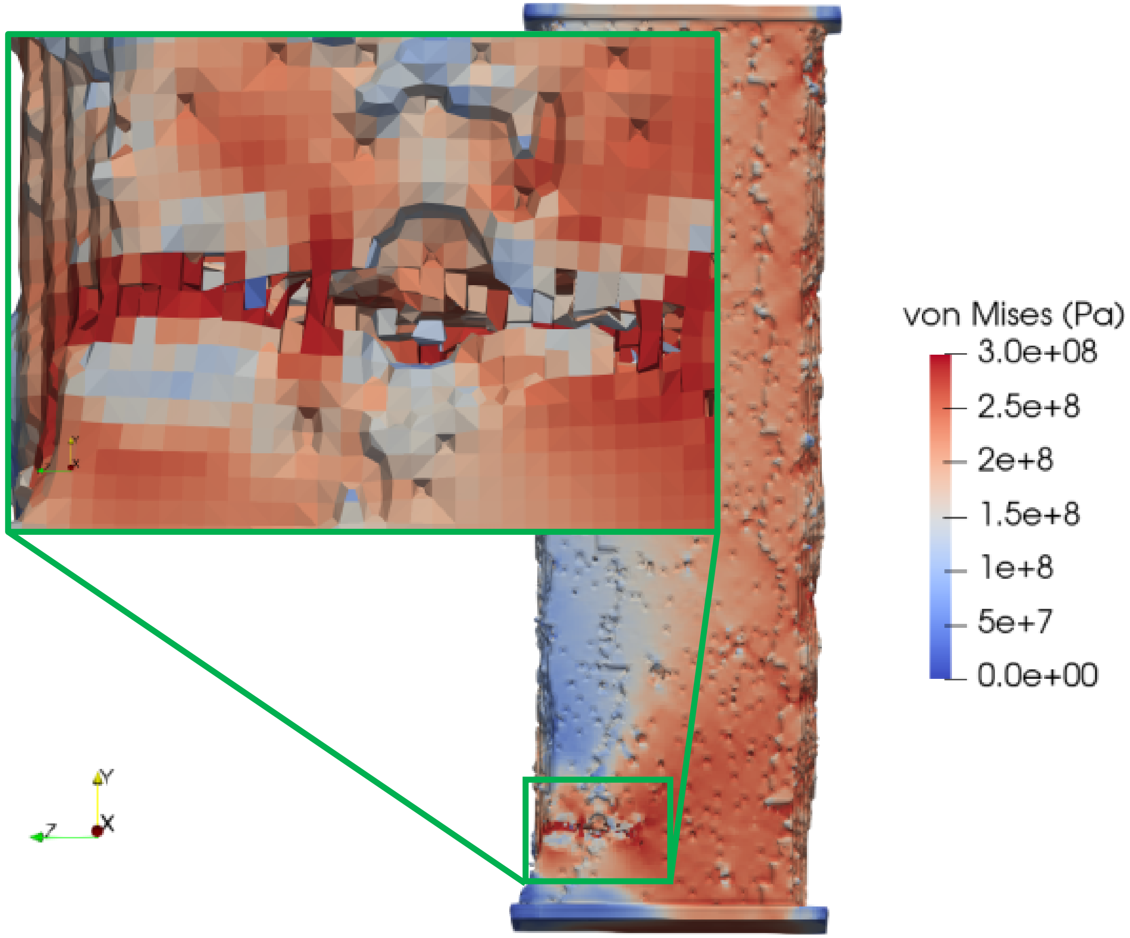
Nodal lateral constraints applied on red lines for Poisson contraction



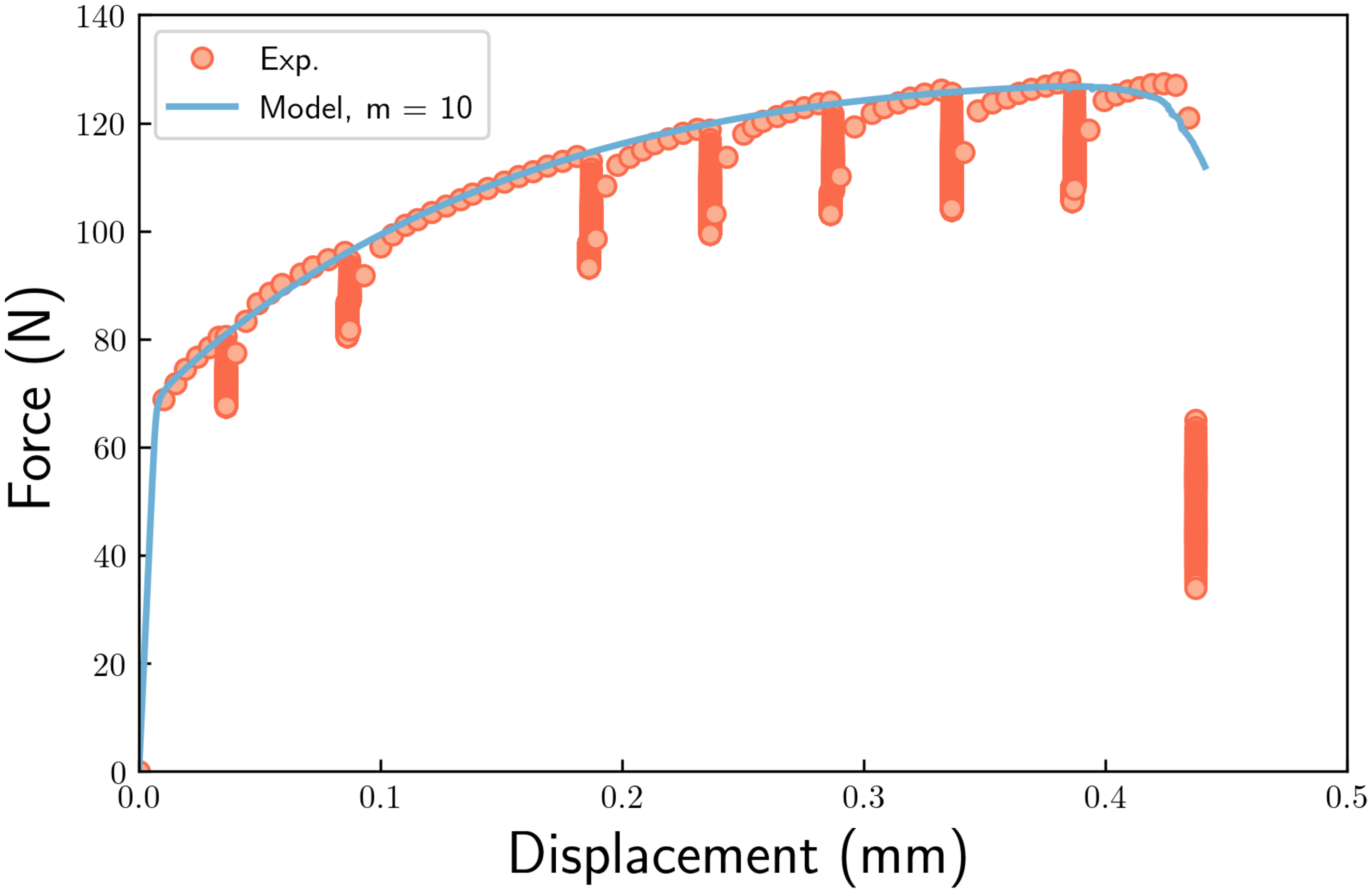
[1]Voce, E., J. Inst. Metals 1948
[2]Cocks, A.C.F. and Ashby, M.F., Metal Science 1980

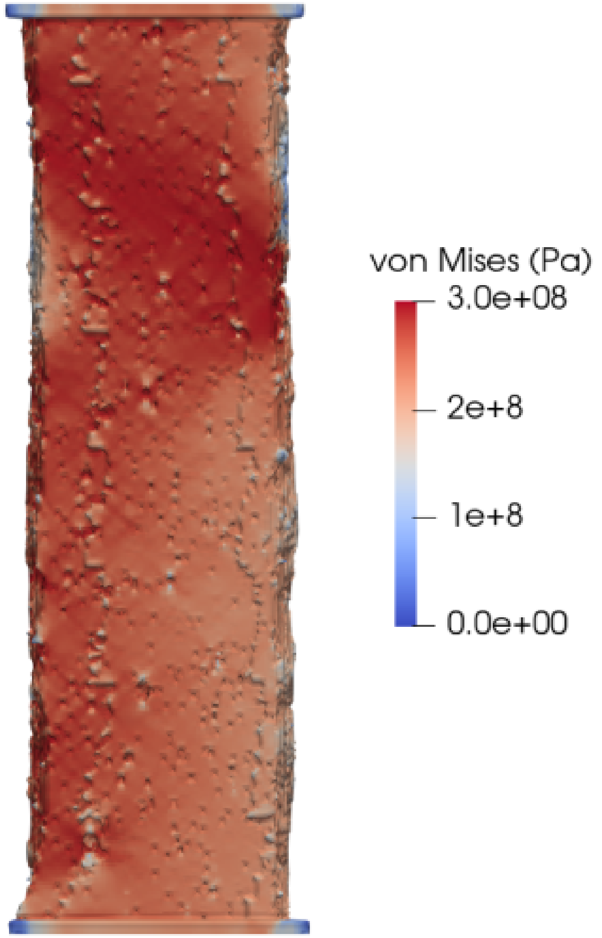
Failure location can be accurately predicted with sufficient mesh resolution and calibration (15 micron mesh size, m=20)



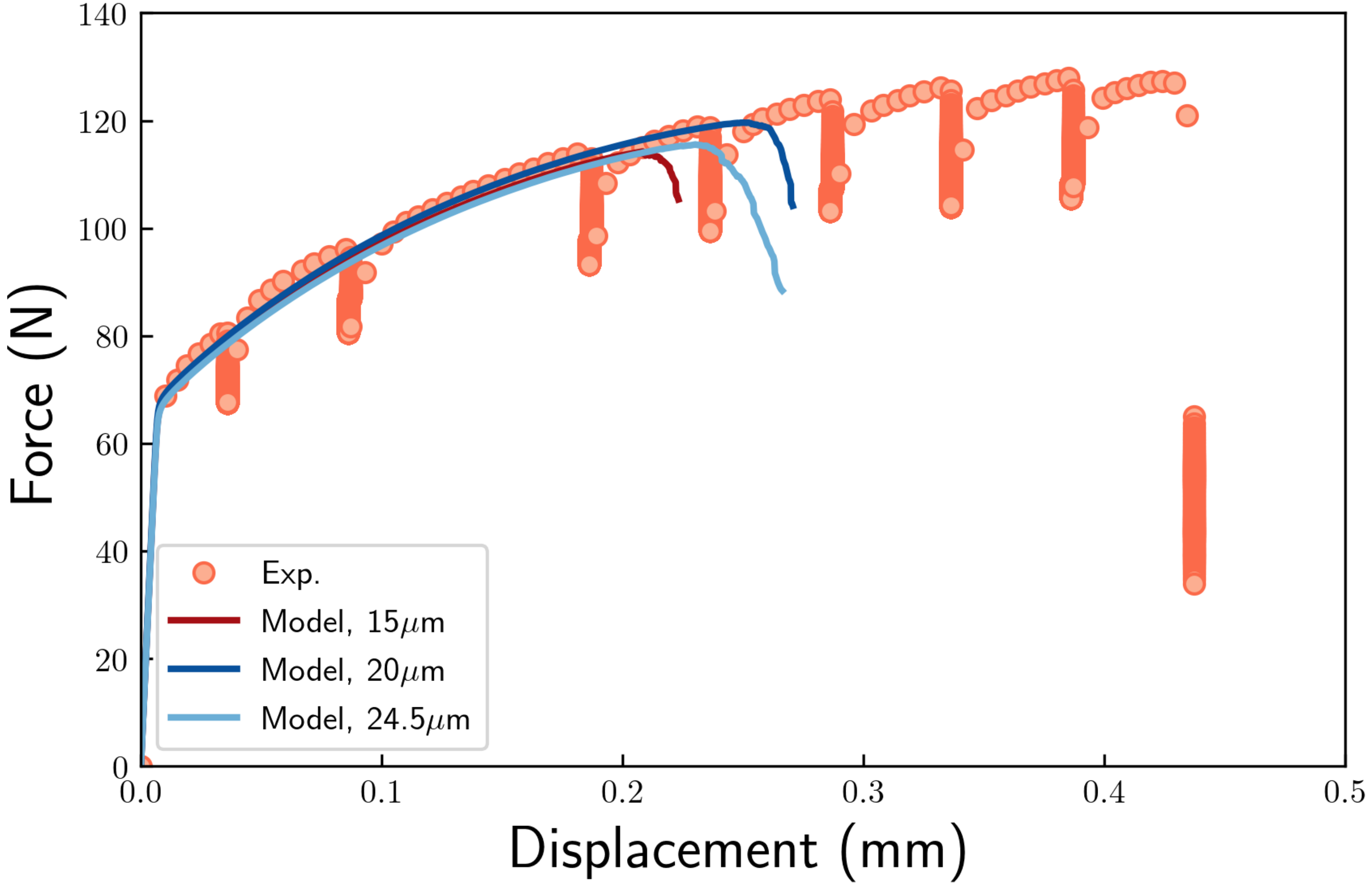


Calibration to force-displacement data alone can be insufficient

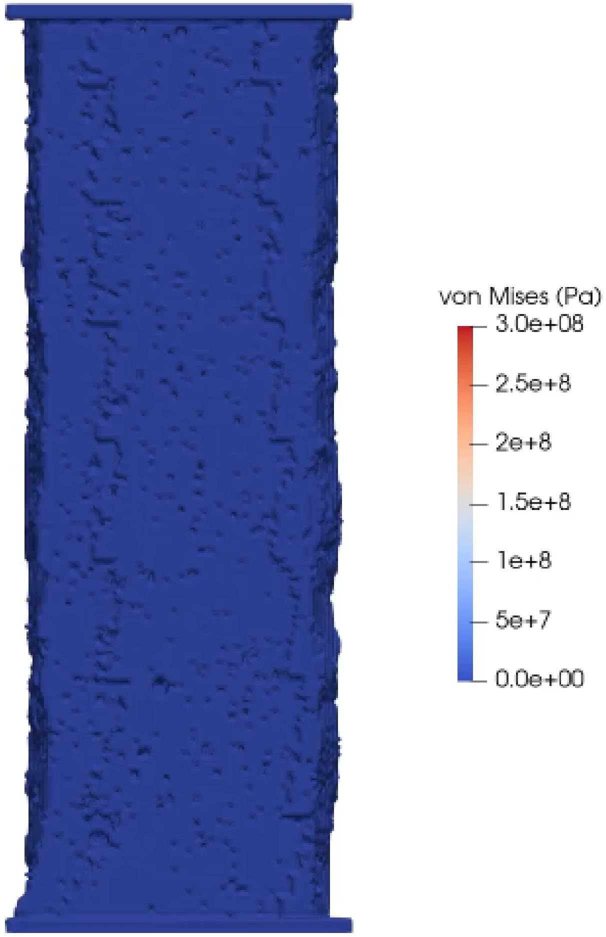




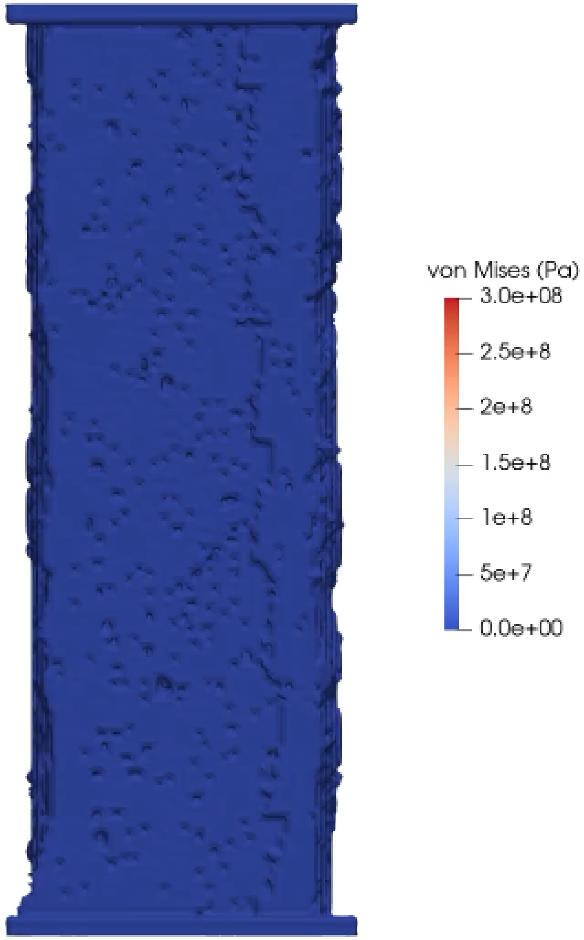
Force-displacement response– fixed damage parameters, different voxel sizes



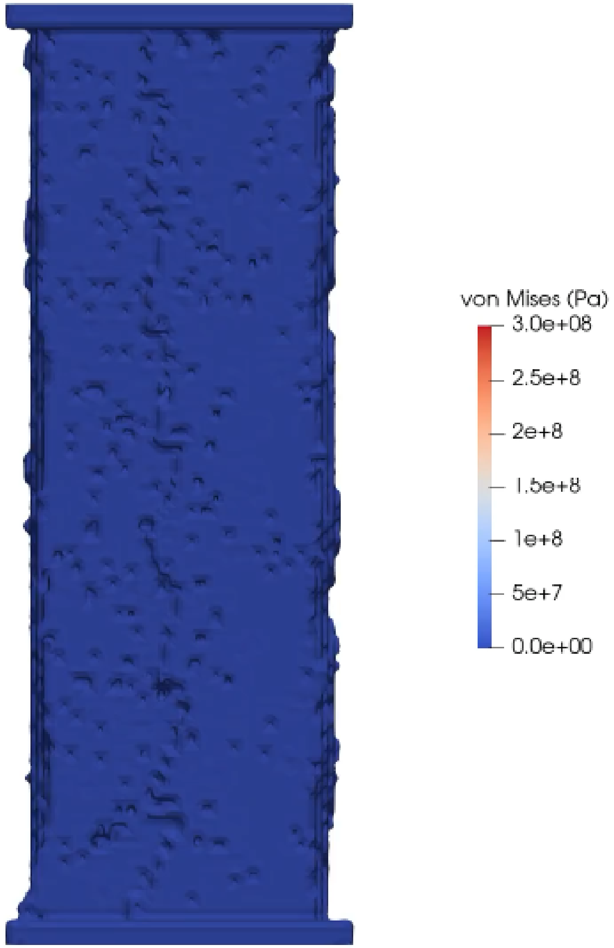
Mesh size results



767k elements
155 cpus
3.7 hr wall time



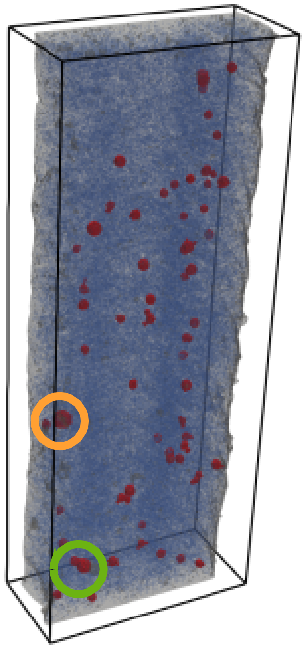
340k elements
70 cpus
4.2 hr wall time

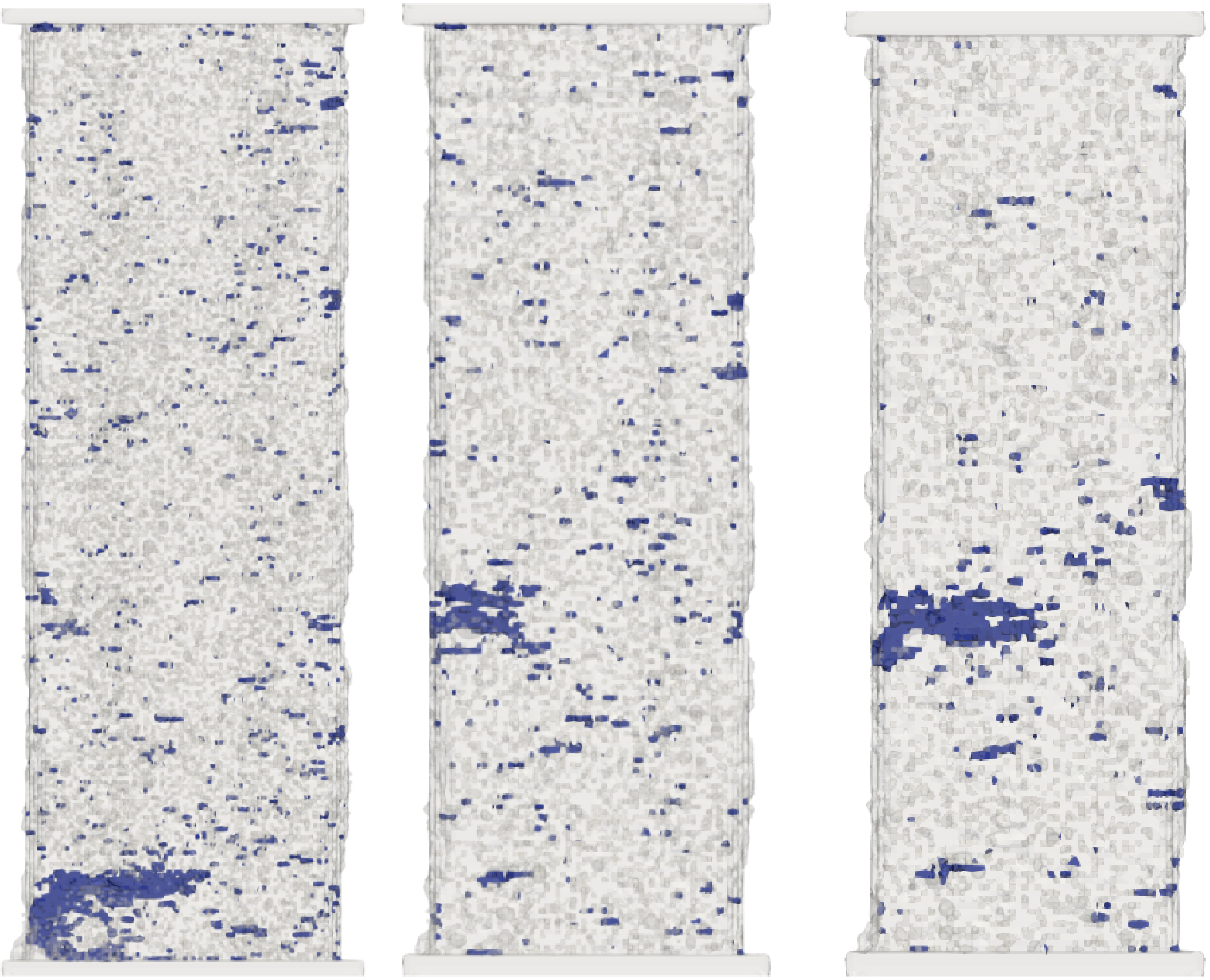


189k elements
40 cpus
3.7 hr wall time

Fracture locations – fixed damage parameters, different voxel sizes

- Deleted elements shown in blue
- Fracture location changes lower resolution meshes
- Local damage parameters are inherently mesh-size dependent





15µm voxel size 20µm voxel size 24.5µm voxel size

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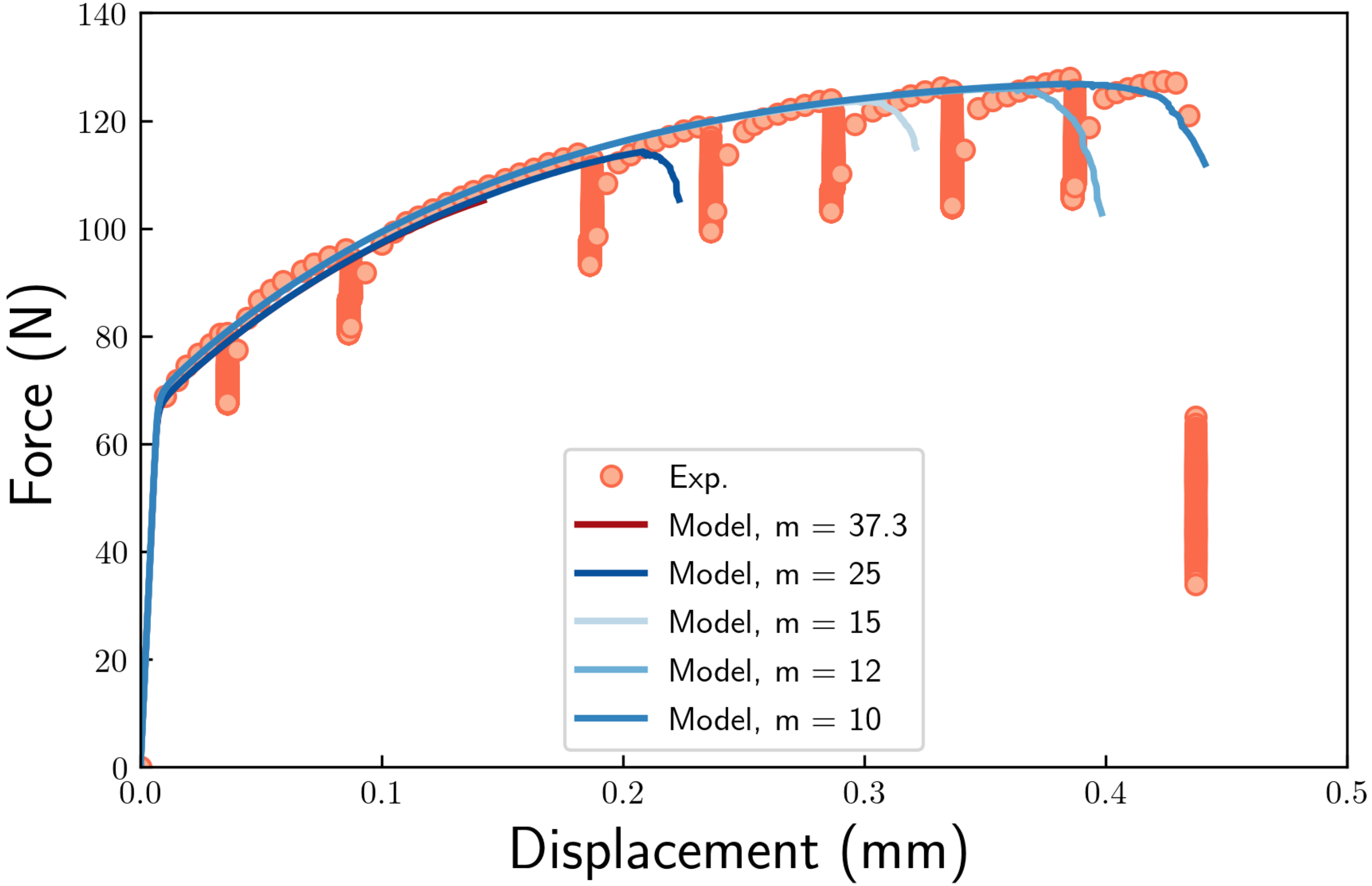
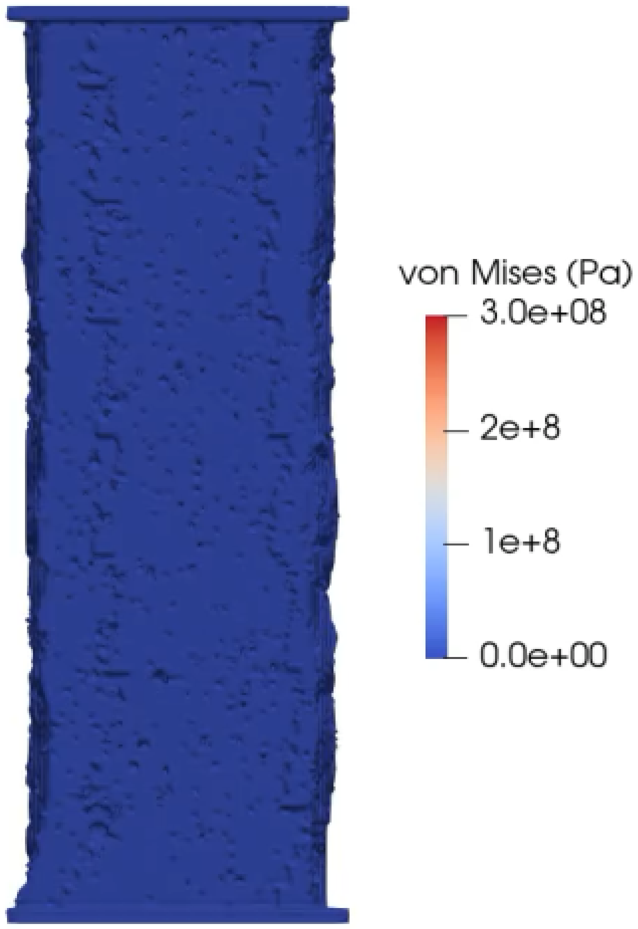
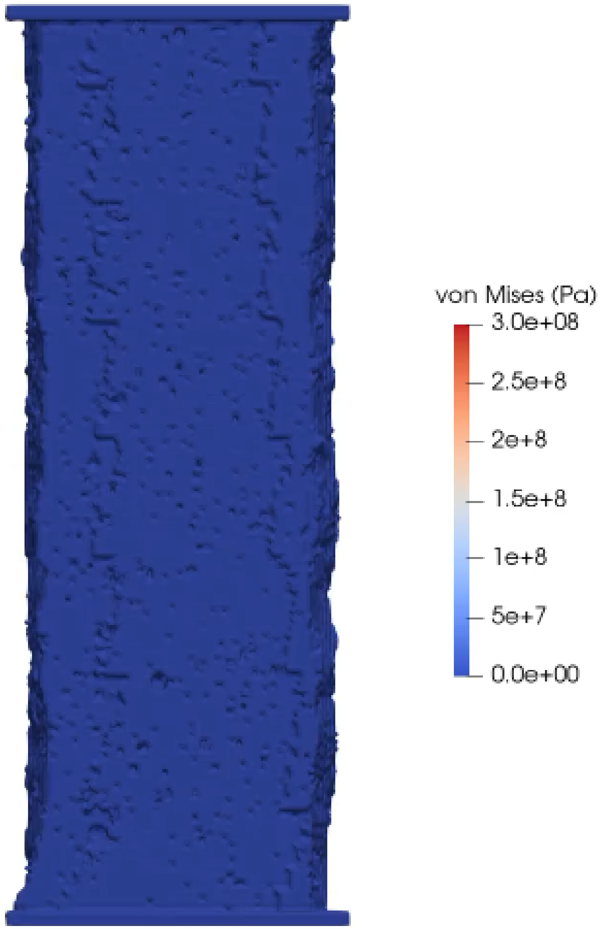
Force-displacement response– fixed 15μm voxel size, different damage parameter m



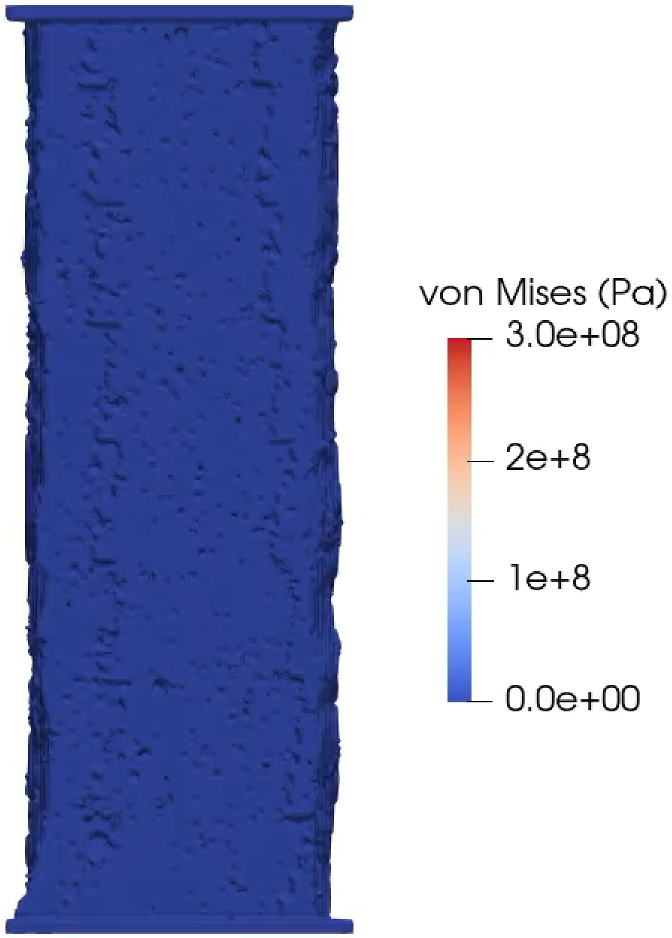
Von Mises response– fixed 15μm voxel size, different damage parameter m



m=20



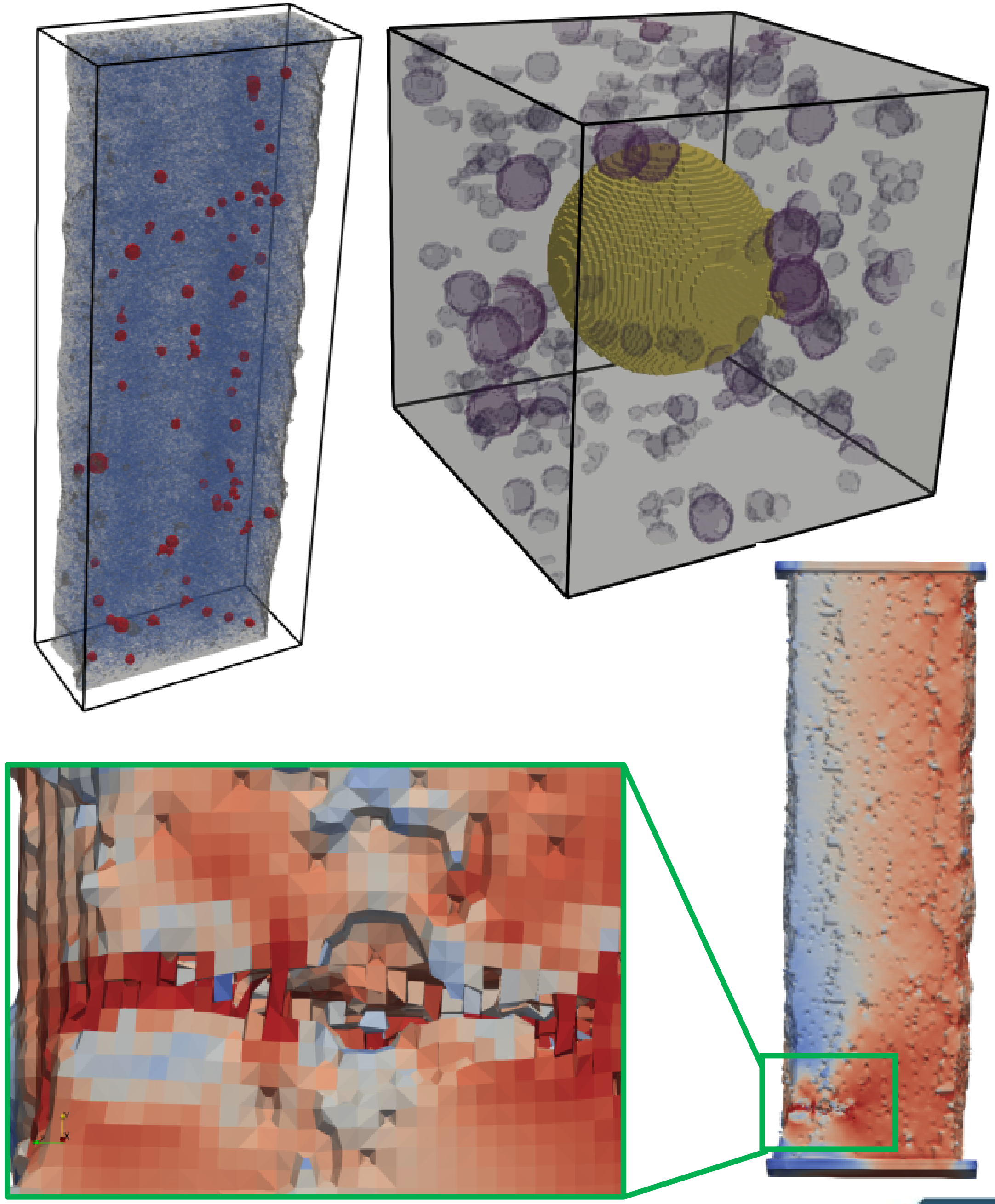
m=15



m=10

Conclusions

- In situ 3D characterization enables comprehensive analysis of pore statistics and porosity evolution under loading
- Microstructure response was dominated by pore growth, with largest pores growing ~5% in volume under similar % strains
- Failure location in AM parts can be predicted via FE modeling
- Calibration to global metrics (force-displacement) may be insufficient to predict failure sites
- Model parameters and predictive capabilities are sensitive to mesh size and computational limitations
- 3D characterization without grips in tensile experiments poses numerous challenges to FE modelling



Backup