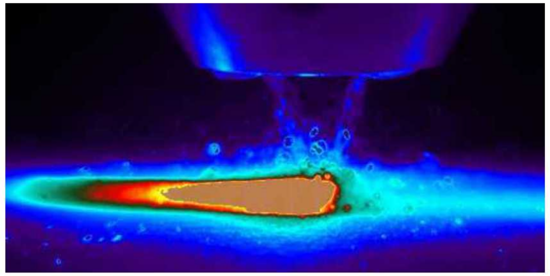
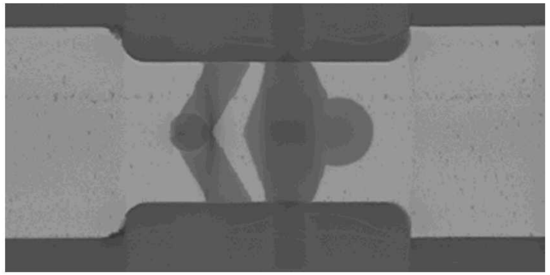
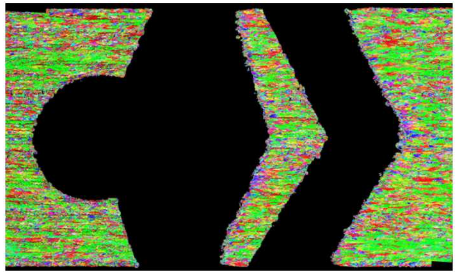
SAND2019-13853C

Improved Structural Performance Models for Additive Manufacturing Part Qualification







PRESENTED BY

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ASME IMECE
November 11, 2019

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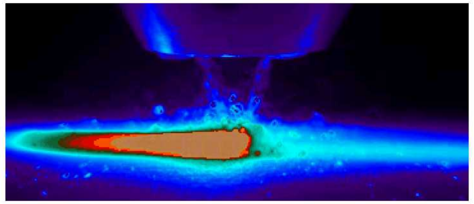
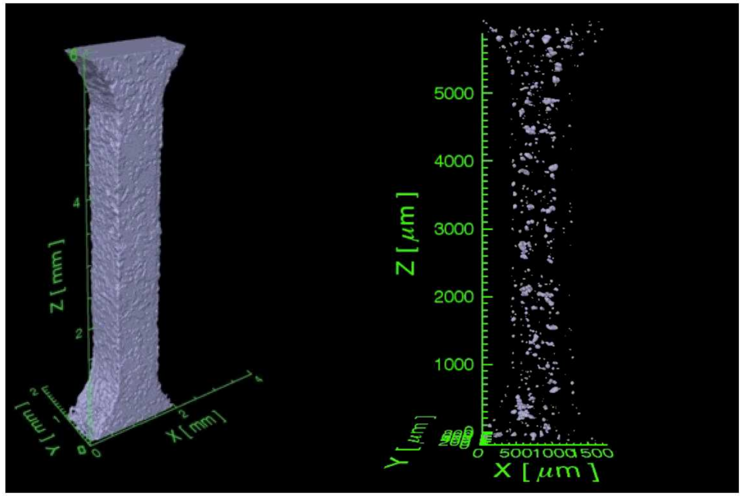
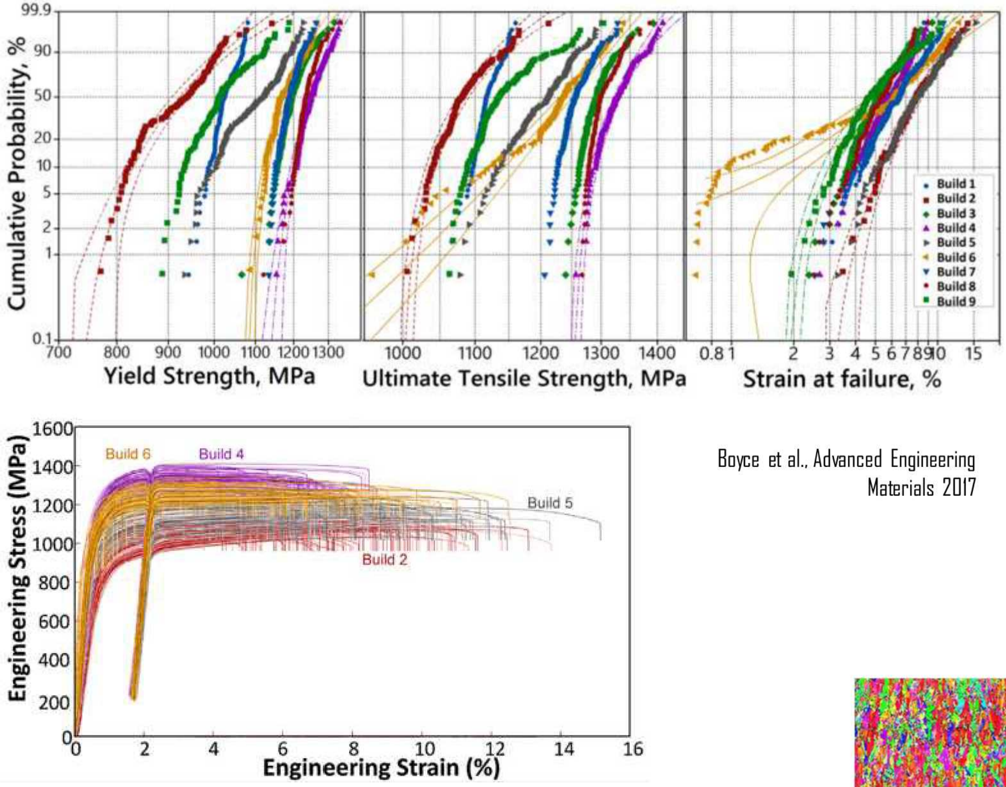
SAND2019-7028 C

Additive Manufacturing Produces Inherent Variability

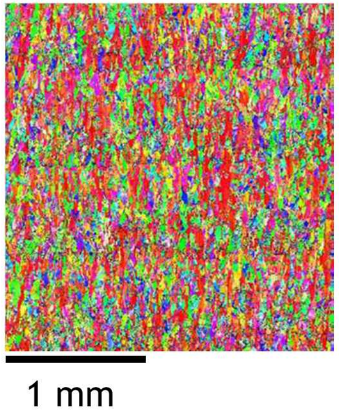


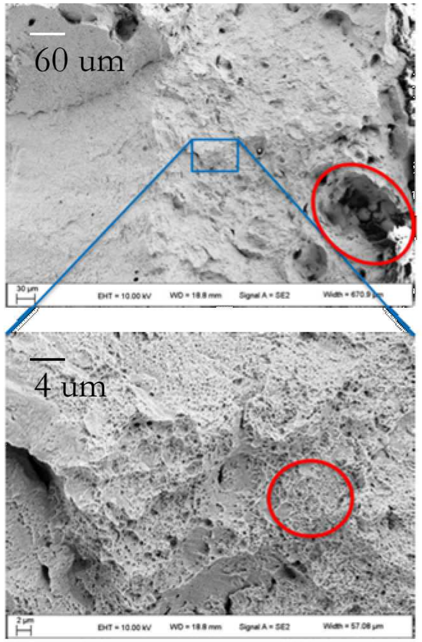


(J. Madison, T. Ivanoff, O. Underwood, SNL)



Boyce et al., Advanced Engineering Materials 2017





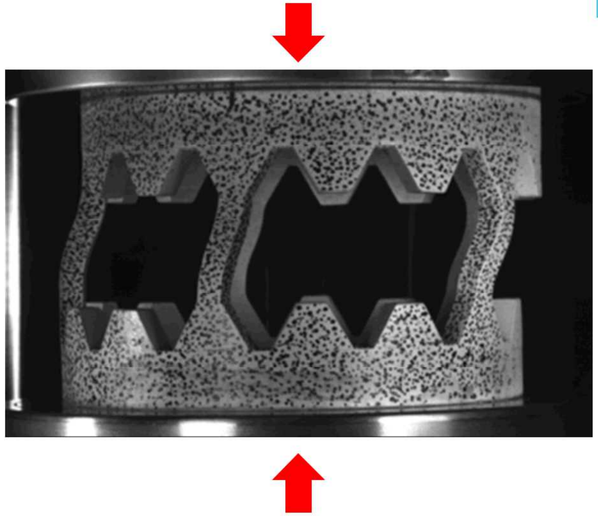
Kramer et al., IJF 2019

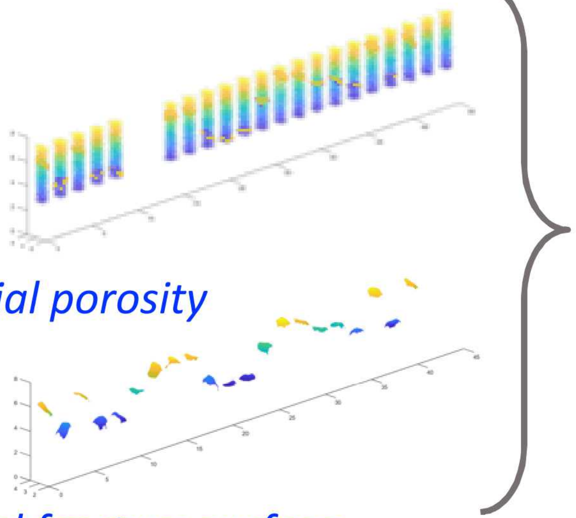
For AM metal structures, we manufacture the materials at the same time we manufacture the structure.

We have inherent variability, in addition to traditional sources of (fine-scale) variability, that drives uncertainty in structural response.

Objectives of This Work

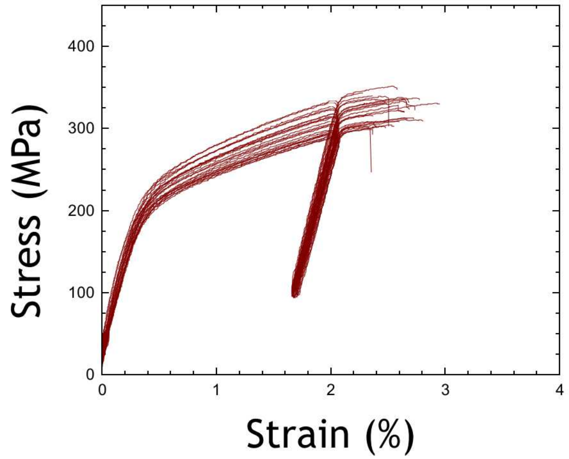
- Develop understanding of what defects in what combinations matter.
- Develop understanding of the level of fidelity necessary to make “qualifying” statements.
- Develop a validated, predictive modeling capability to readily compute metal additive manufactured (AM) material/structural performance and reliability for component qualification.
- Develop a collaborative experimental-computational project that enables agile response to customer needs for metal AM materials/structures.

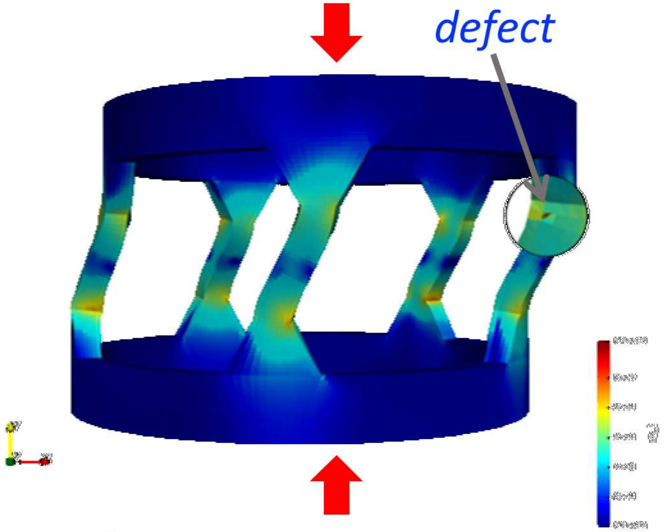




Initial porosity

Final fracture surface





Accurately estimating margins requires a capability to first characterize, then propagate the inherent variability.

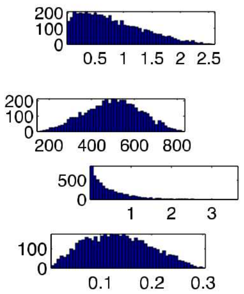
Outline

- Hierarchical Multiscale Approach
- Low Fidelity Model Description
- High Fidelity Model Description
- Application to Tensile Specimens
- Ongoing work: Validation in hollow tubes with intentional defects
- Conclusions

Hierarchical Approach

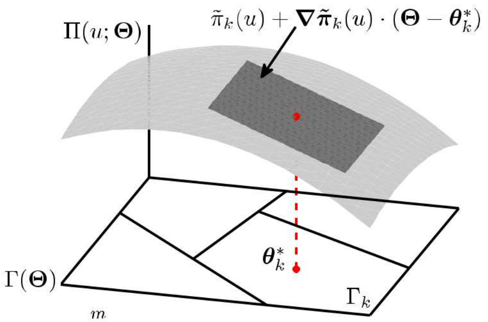
Low Fidelity Model

uncertain data



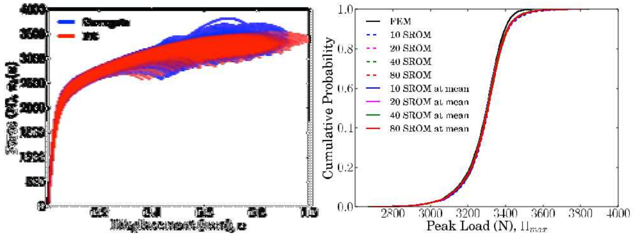
Stochastic Reduced-order Models (SROM)

MCS of engineering-scale response via SROM-surrogate

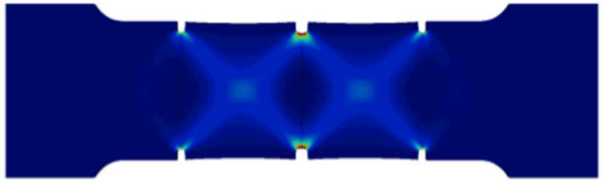


$$\tilde{\Pi}_L(u;\Theta) = \sum_{k=1}^{m} 1(\Theta \in \Gamma_k)\,[\tilde{\pi}_k(u) + \nabla\tilde{\pi}_k(u)\cdot(\Theta - \theta_k^*)]$$

Low-fidelity Probability of Failure



Hot-spot selection & prioritization

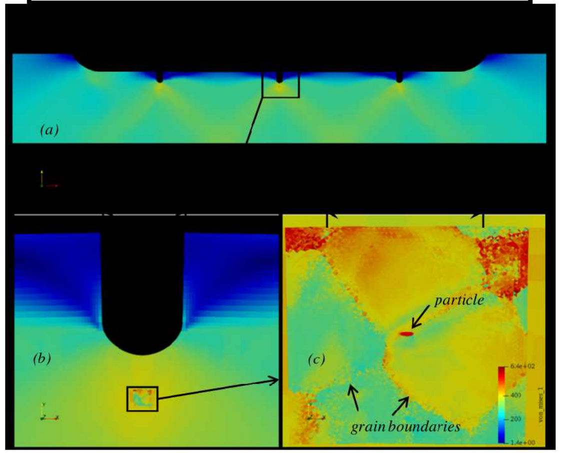


Coupled High Fidelity Model

For hotspot `i`, iterate. Repeat for all hotspots.

`i++`

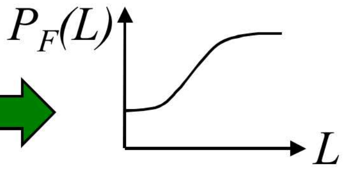
$P'_\mu(L|a_i)$



Multiscale calculation

$P''_\mu(L|a_i)$

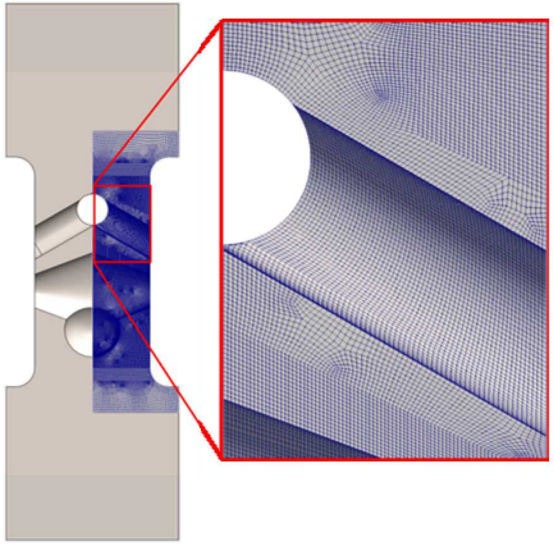
$$P_F(L) = \sum_{i}^{hotspots} P(L|a_i)P(a_i)$$

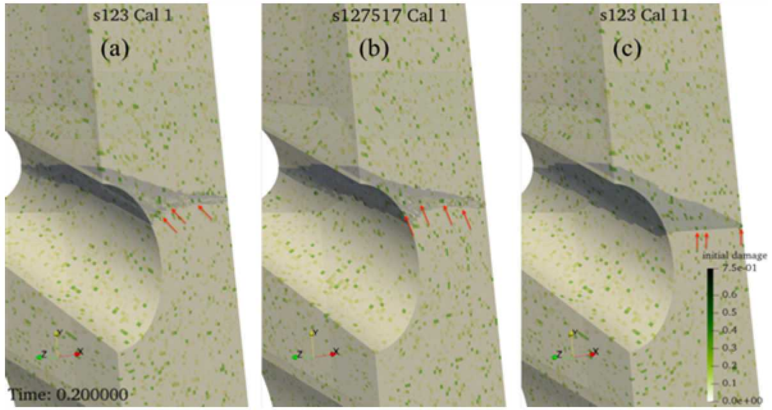


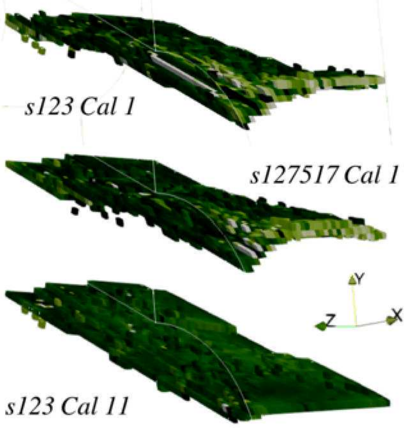
Higher fidelity prediction

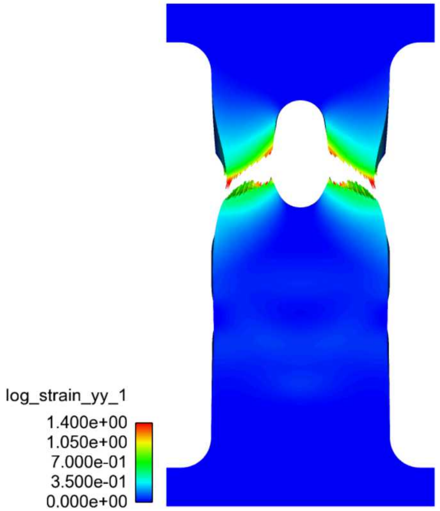
***we assume hot-spots are independent for now*

Low Fidelity Model – Porosity Overlay

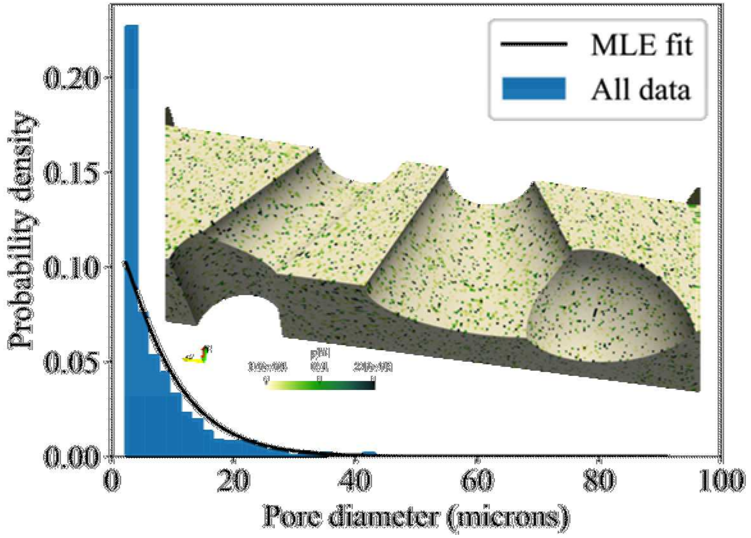


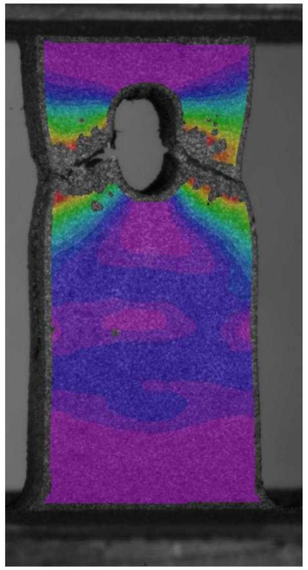






- Account for the observed porosity with a damage state variable (void-volume fraction)
- Allows for statistical approach to predict behavior when CT data is unavailable.
- We used the approach for the 3rd Sandia Fracture Challenge:
    - Porosity seed indicated by s number, i.e. s123 is a different realization than s127517
    - For the same calibration number (Cal 1), a different porosity seed yields a different crack path





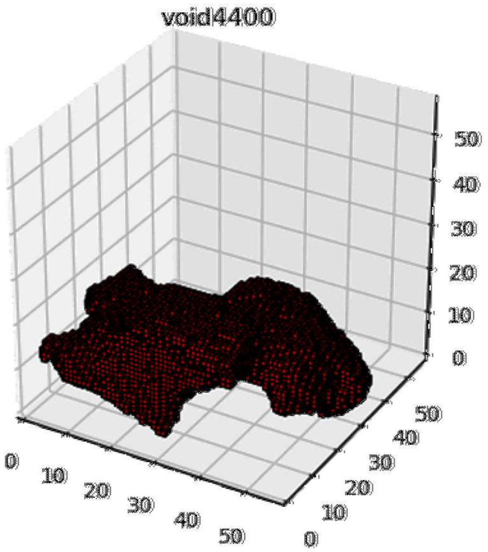
Johnson et al. IJF 2019

High Fidelity Model

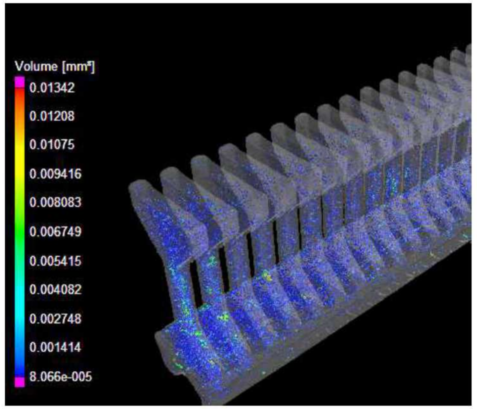
- Explicitly include large pores in geometry and mesh models
- Can use tetrahedral or hexahedral elements (Sculpt)
- We use an unstructured tetrahedral mesh

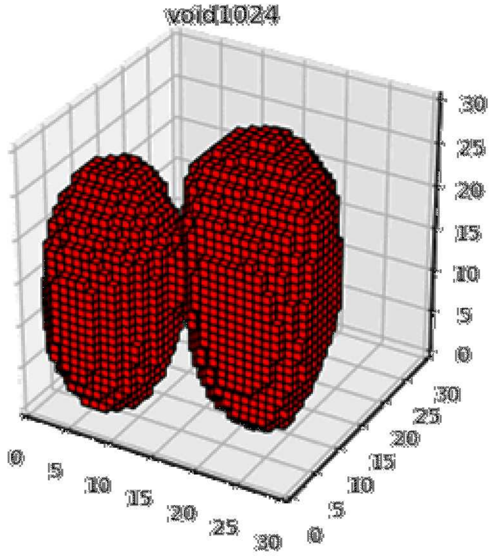
Variability and uncertainty in pore geometry

A Tale of Two CT's



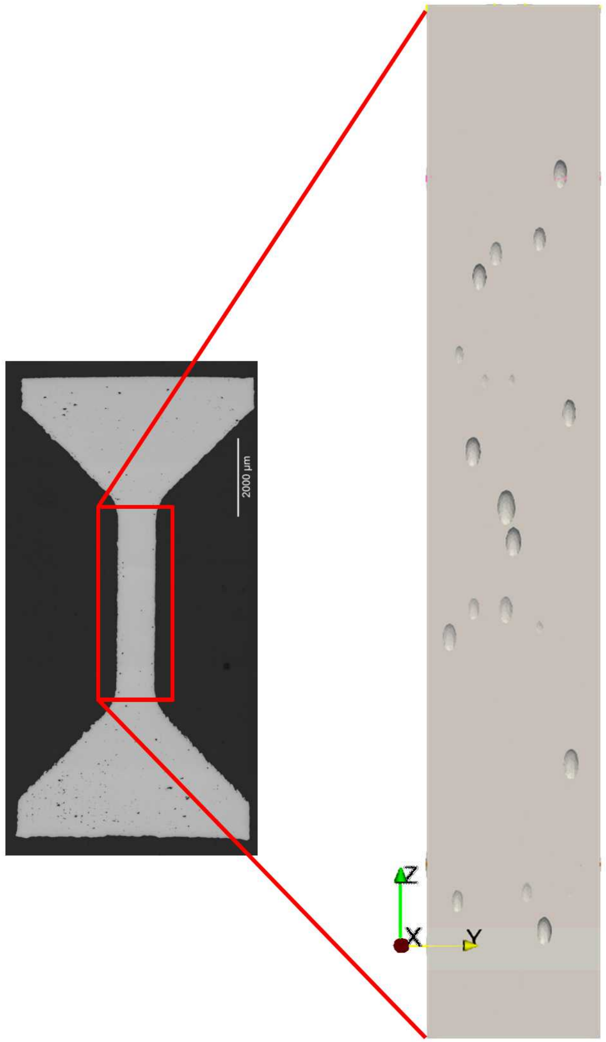
29 um resolution
1.9 um voxel size





15.6 um resolution
2.5 um voxel size

If you think CT eliminates (some of the) uncertainty, be careful!



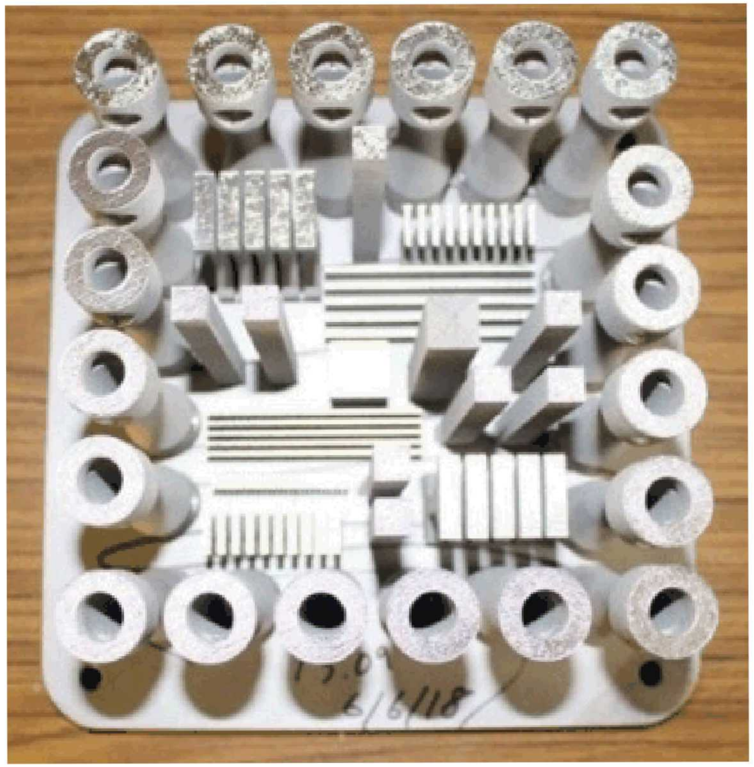
High Fidelity Model
(1.5e6 elements)

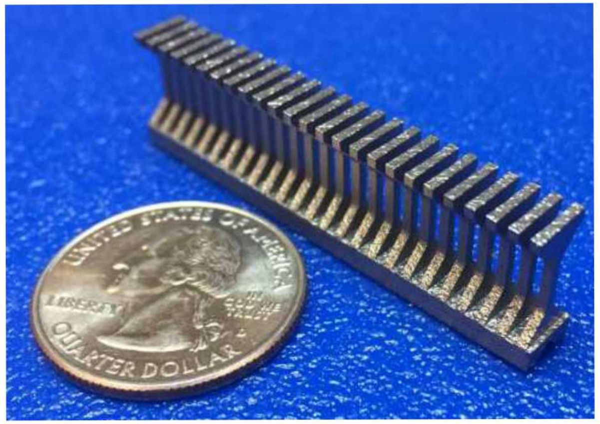
Available Data for Characterization and Validation

Three AlSi10Mg plates

- Laser power varies from 100% (optimal), 75%, and 50%
- Corresponds w/ 0.47%, 0.66%, and 5.12% porosity, respectively

One SS 316 plate printed at Sandia



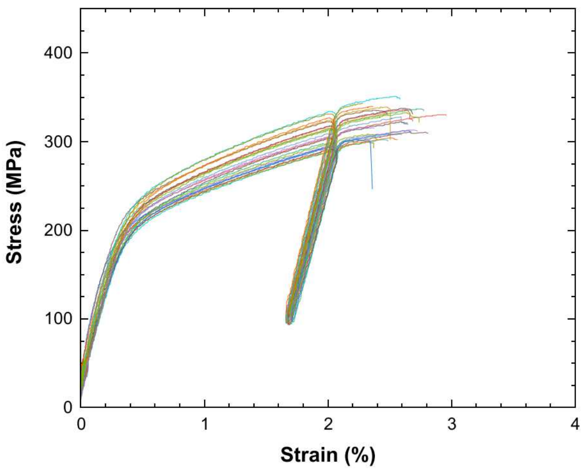


Components- pristine & 3 flaw types
Powder obelisk
Density cube
Tensile bars (multiple sizes)
Fracture samples
Metallography/Charpy samples
Fracture toughness AlSi10Mg, K_{Ic} = 40 MPa√m

Measurements to Develop the Method – Tensile Specimens

- A rack of (25) 1mm x 1mm cross-section AlSi10Mg LPBF tensile bars
- CT images for each specimen before loading provide
  - Surface geometry
  - Internal porosity
- Tensile response – Stress-strain
- Optical characterization of the resulting fracture surface

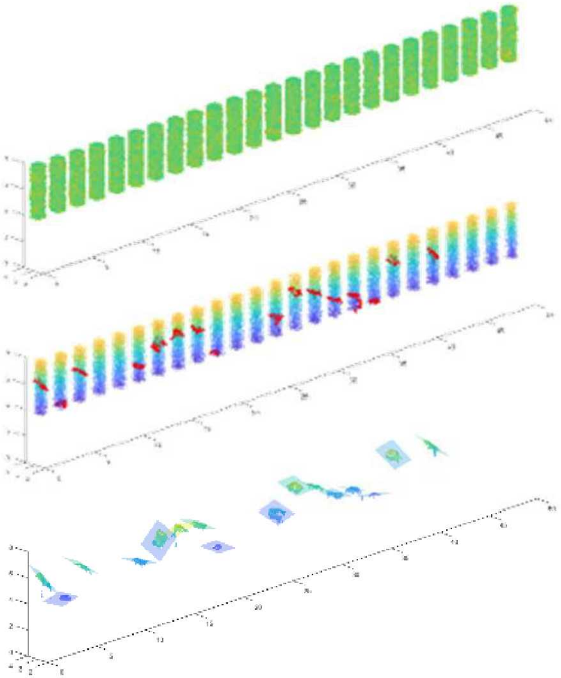
Tensile test stress-strain data

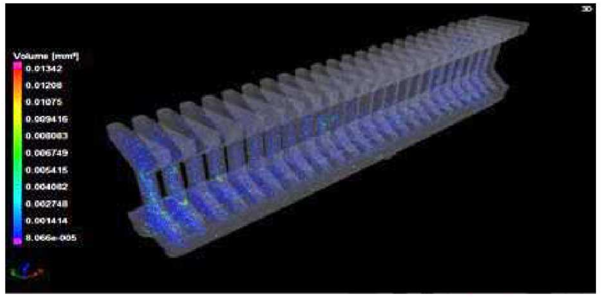


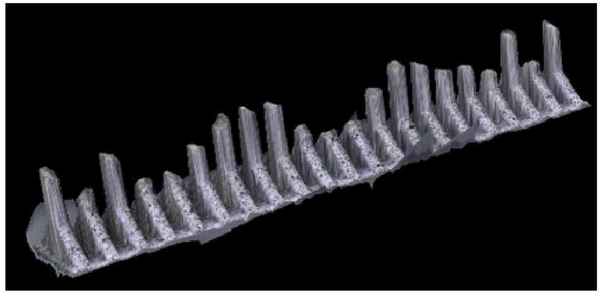
Surface features (CT)

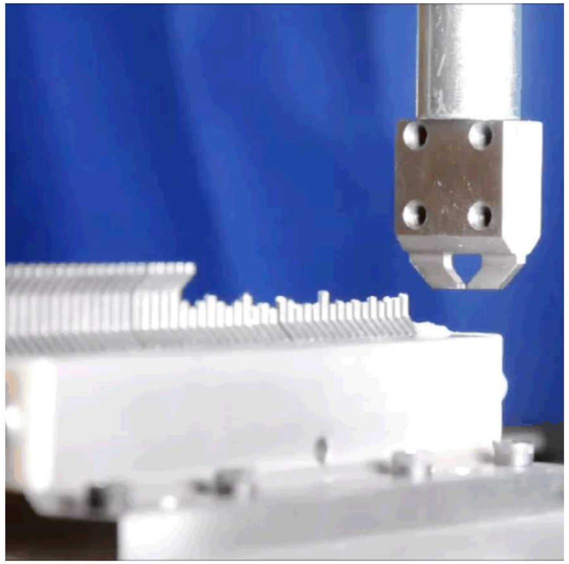
Internal Pores (CT)

Fracture surfaces (optical scans)









Boyce et al., Advanced Engineering Materials 2017

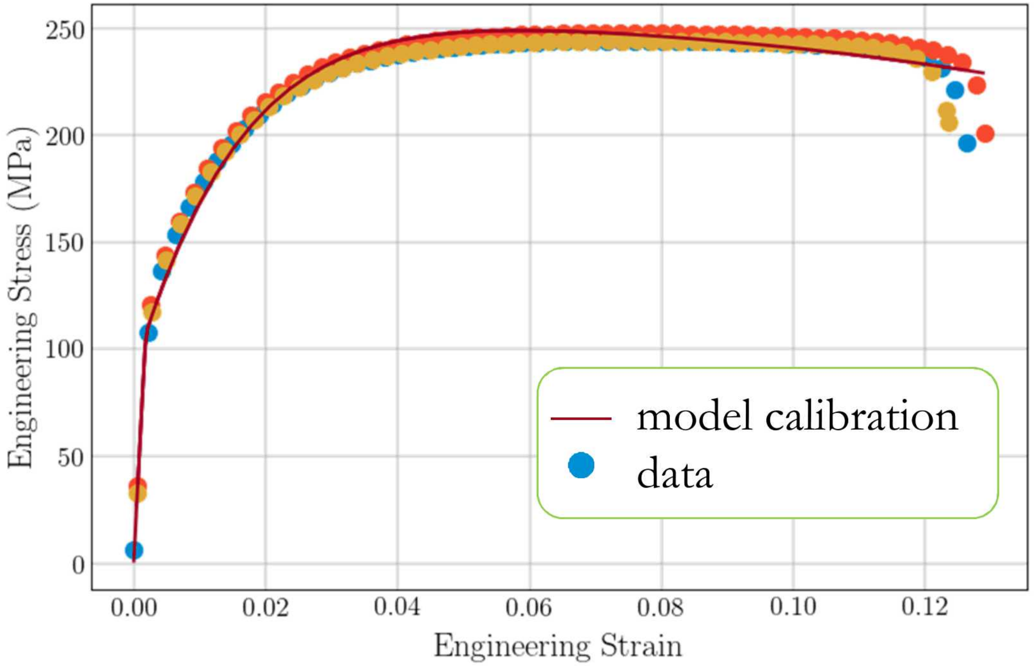
Calibration to Tensile Specimens

Voce hardening model with power-law breakdown strain rate multiplier on hardening

Decaying exponential on equivalent plastic strain saturates

Power law breakdown hardening rate multiplier helps capture gradual softening after early peak load

Strain rate data taken from literature (Rosenthal et al. 2017)

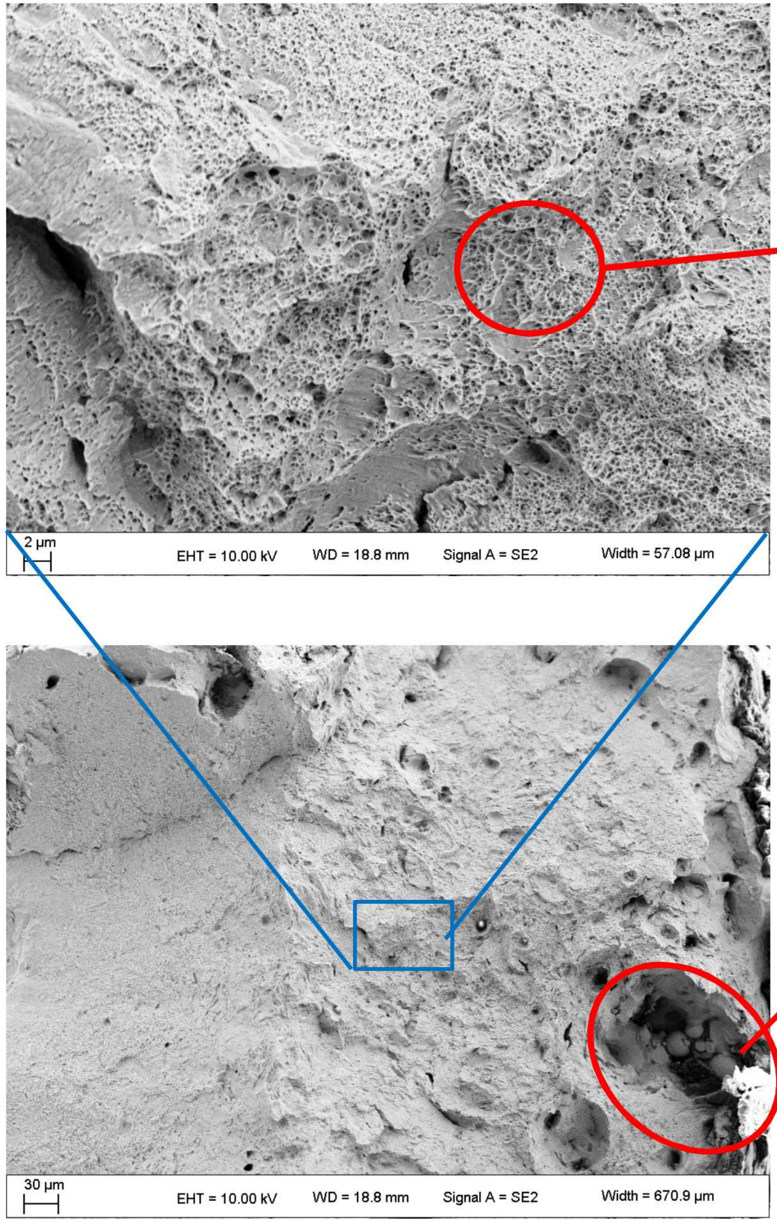


$$\bar{\sigma} = \sigma_y + A(1 - \exp(-n\bar{\varepsilon}^p))(1 + \mathrm{asinh}\left(\left(\frac{\dot{\varepsilon}^p}{g}\right)^{(1/m)}\right))$$

Voce Hardening

Power Law Breakdown Strain Rate Multiplier

Damage Model Accounts for Growth of Existing Pores and Pore Nucleation



Johnson et al. IJF 2019, Kramer et al. IJF 2019

Void Nucleation

Fine scale voids (< 1μm) indicate nucleation

$$\dot{\eta} = \eta\dot{\epsilon}_p \left(N_1 \left[\frac{4}{27} - \frac{J_3^2}{J_2^3} \right] + N_2 \frac{J_3}{J_2^3} + N_3 \frac{\langle p \rangle}{\sigma_e} \right)$$

Void Growth

Pre-existing voids captured by void growth

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

Total Damage

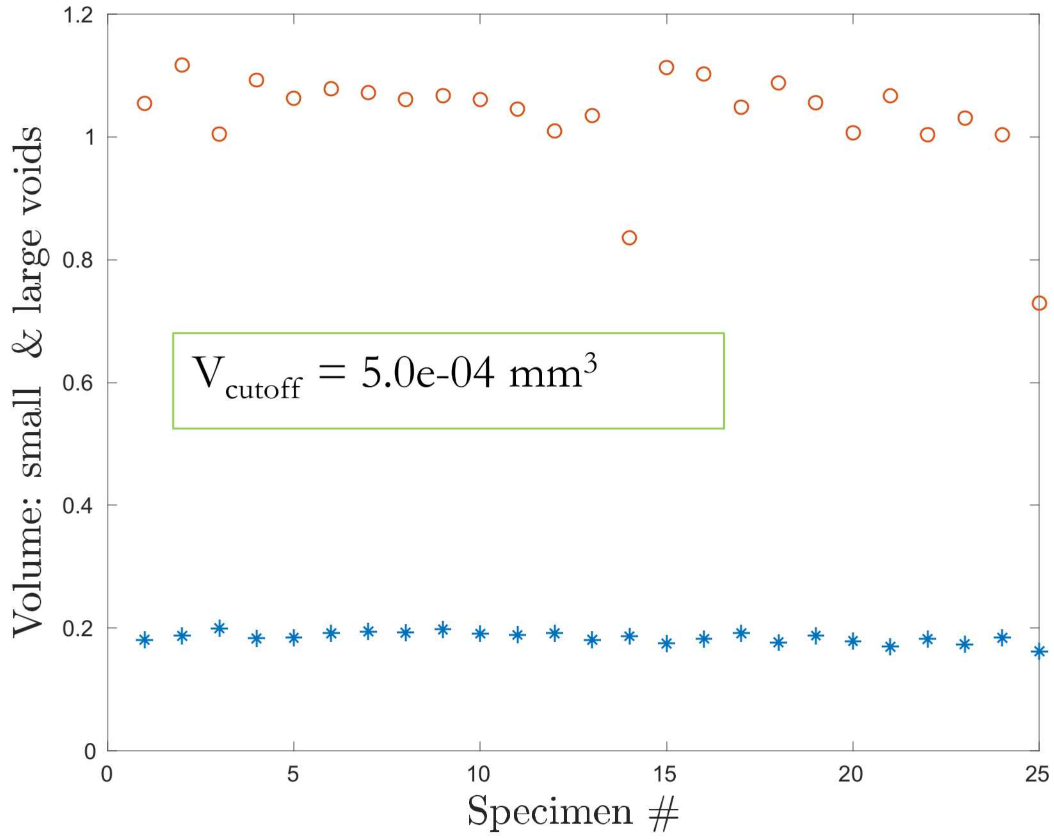
$$\phi = \frac{\eta v_v}{1 + \eta v_v}$$

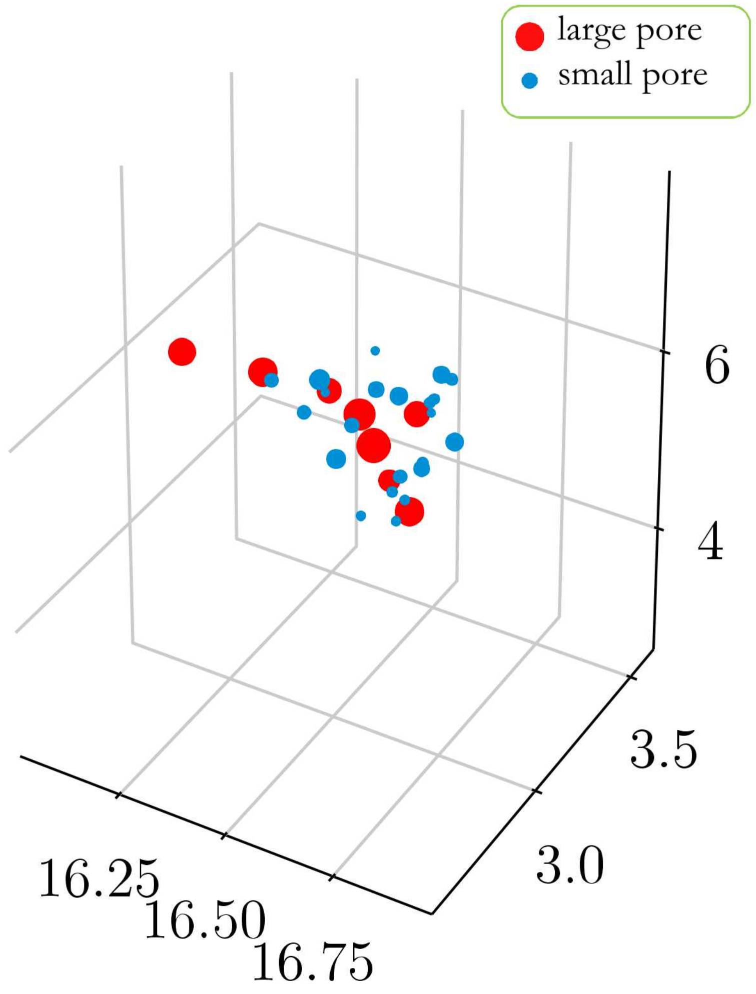
(Horstemeyer & Gokhale 1999)

Analysis of the CT and optical data

It is impractical to consider all the pores.

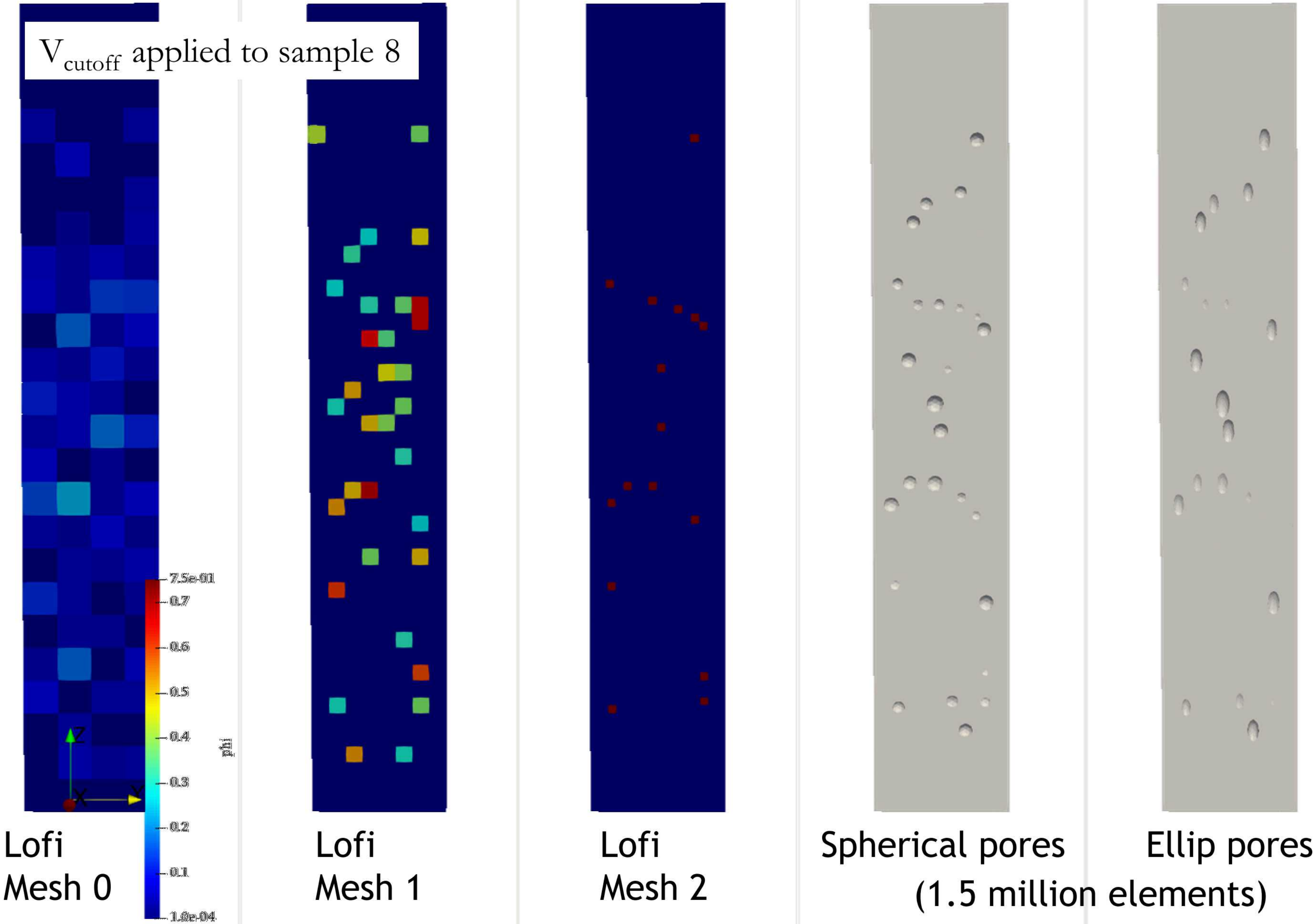
Which pores are important?





V_{cutoff} applied to sample 8

Low Fidelity and High Fidelity Models



Lofi
Mesh 0

Lofi
Mesh 1

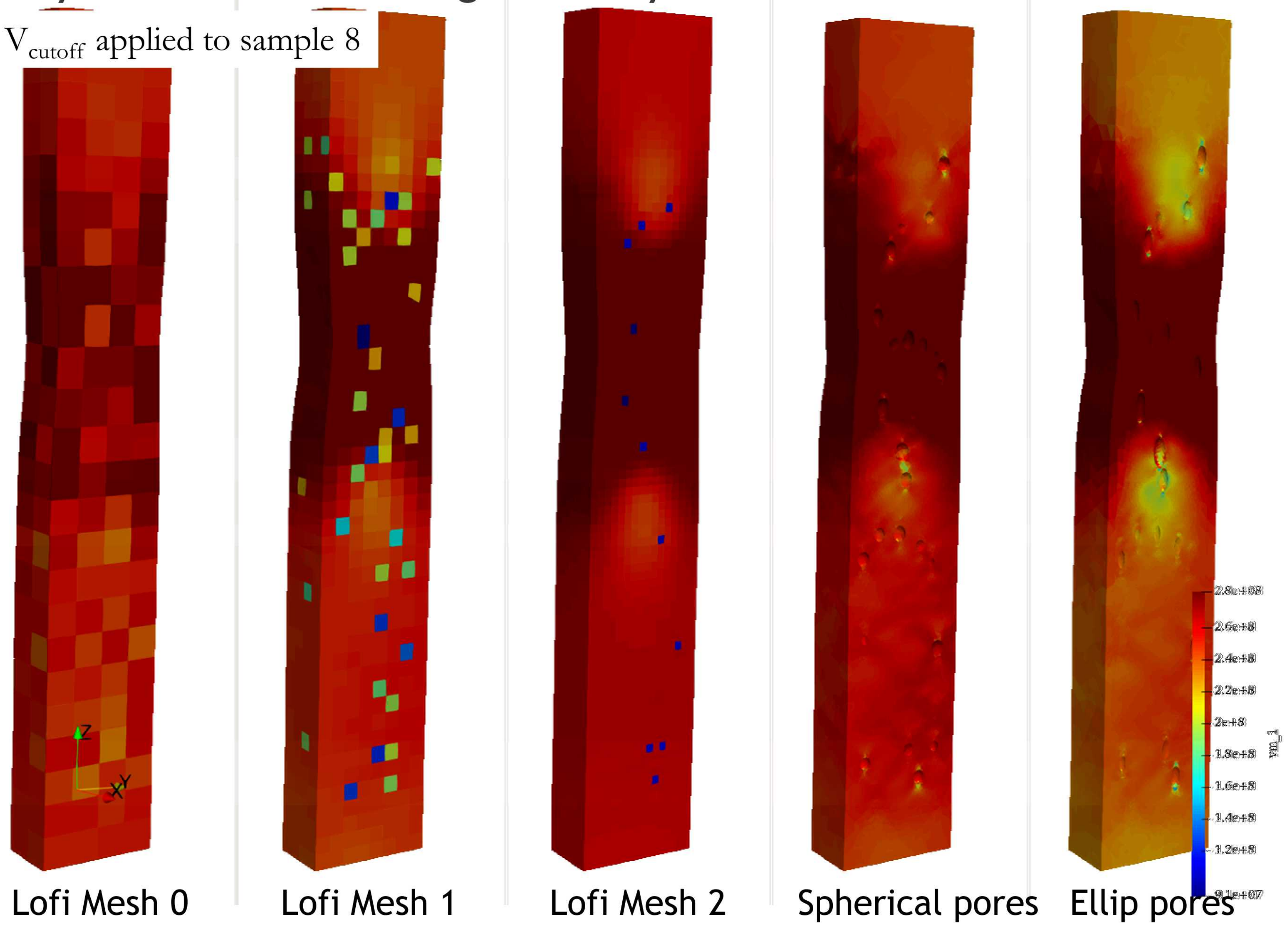
Lofi
Mesh 2

Spherical pores

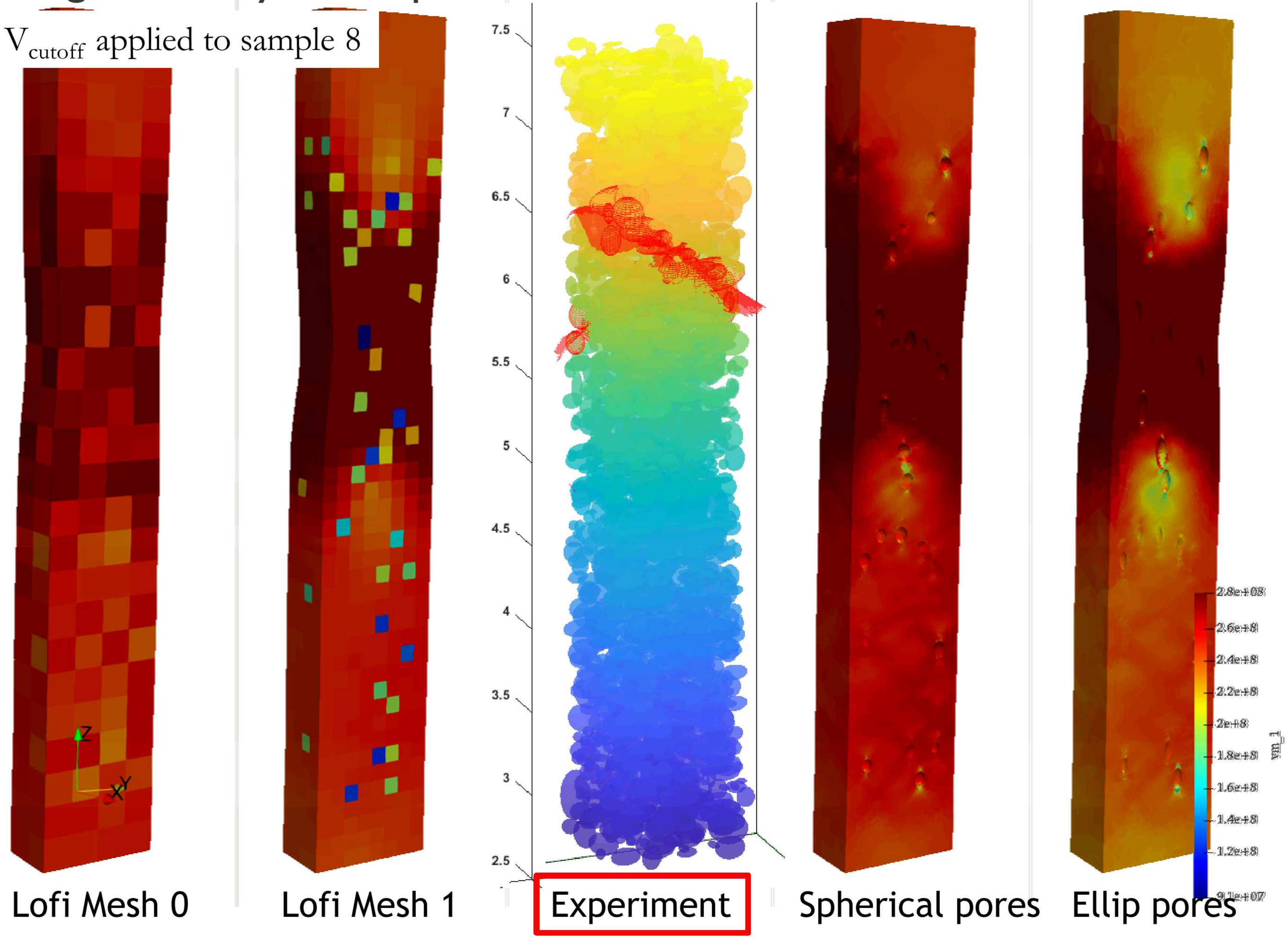
Ellip pores

(1.5 million elements)

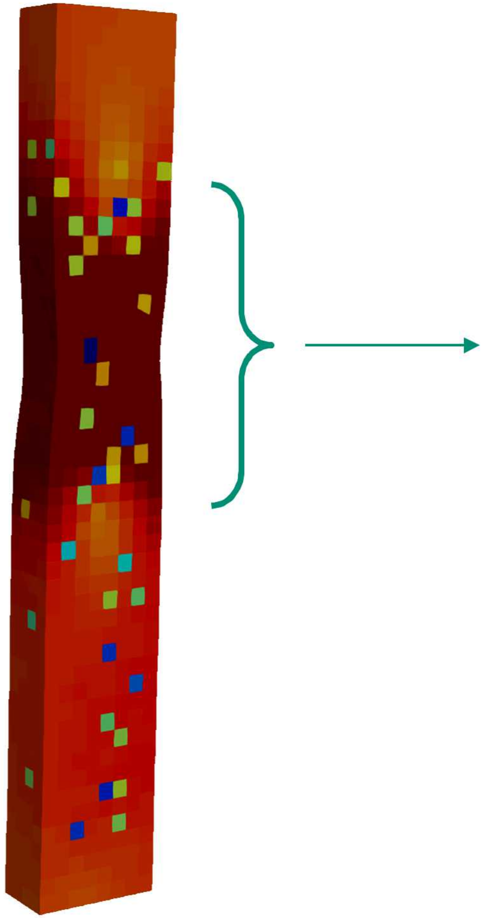
Low Fidelity Predictions vs. High Fidelity Prediction



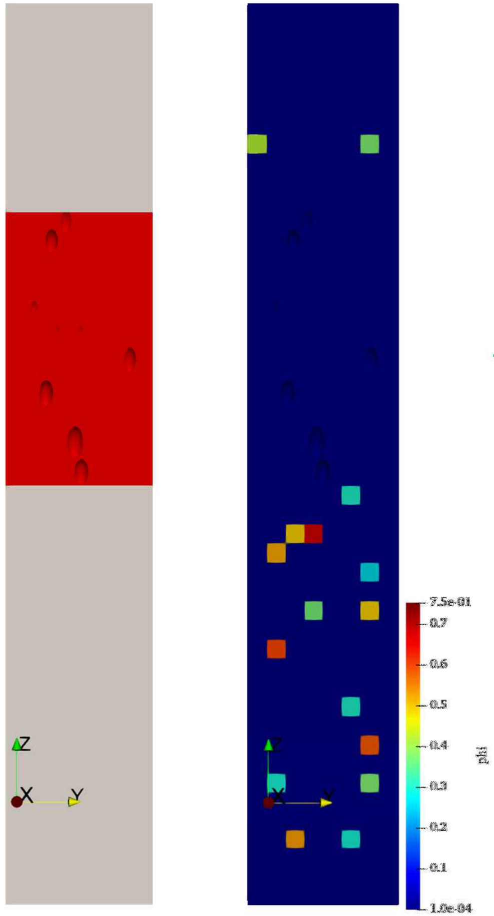
Low and High Fidelity vs. Experiment



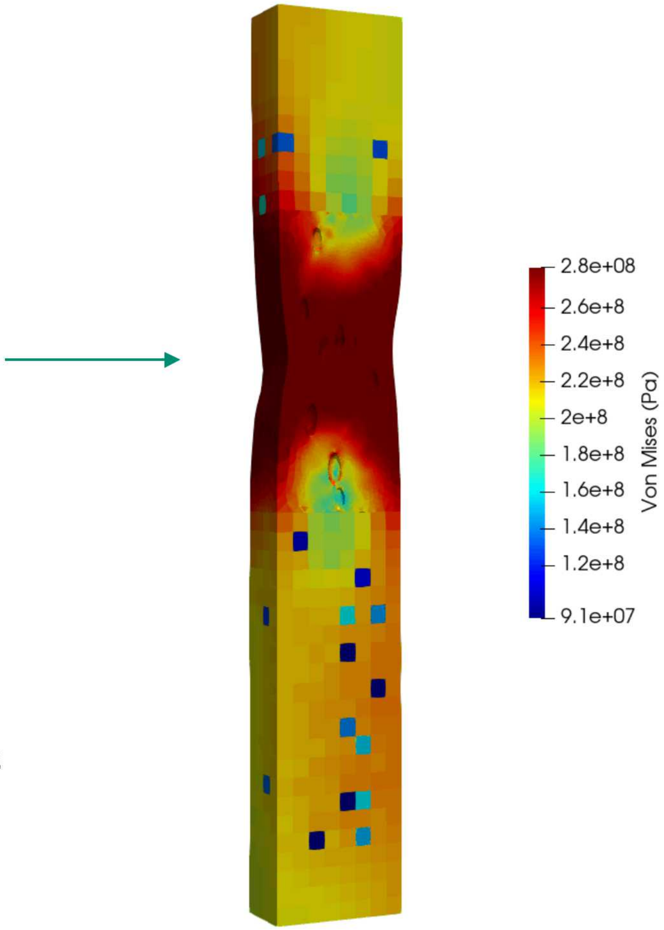
Multiscale Model: High Fidelity Mesh in Hotspot Concurrently Coupled With Surrounding Low Fidelity Mesh



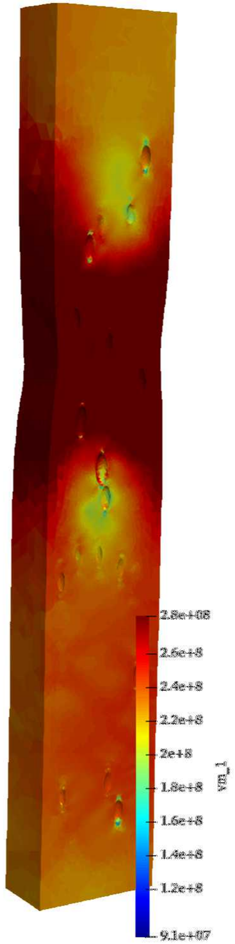
Hotspot Detection in Lofi Mesh



Coupled Lofi/Hifi Mesh via Multi-Point Constraints

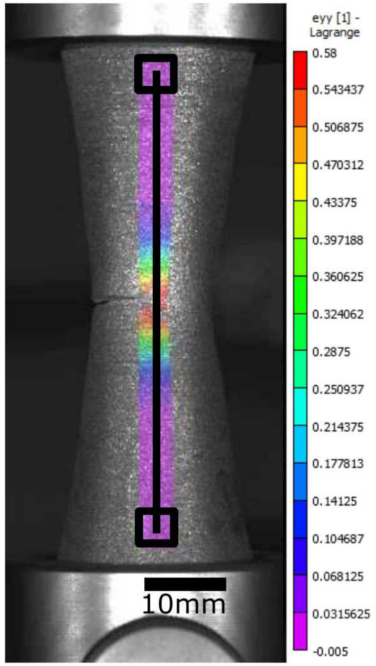


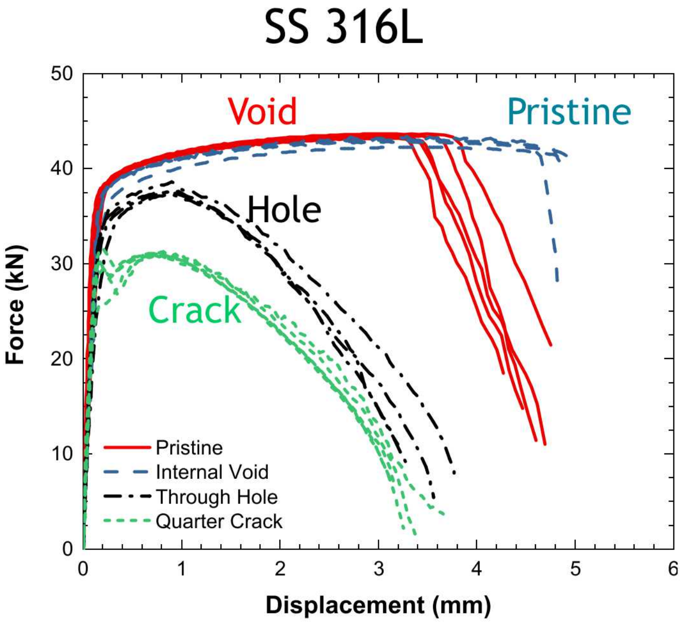
Coupled Response with Higher Accuracy in Hotspot ~520k elements, 100 cpus

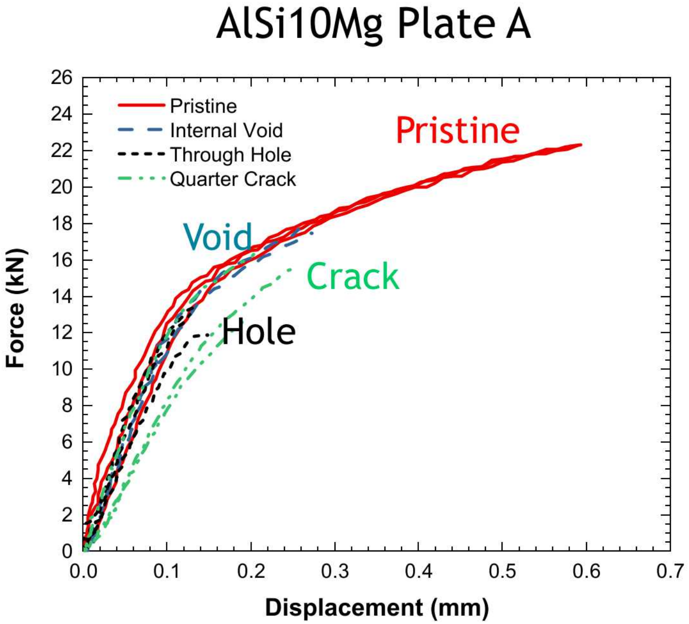


High Fidelity Results 1.5M elements, 360 cpus

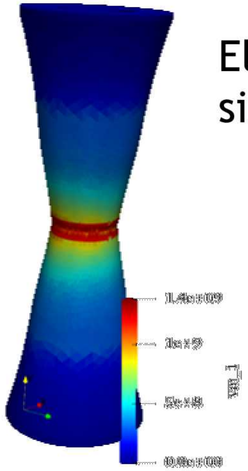
Ongoing Effort: Validation Tubes with Intentional Defects

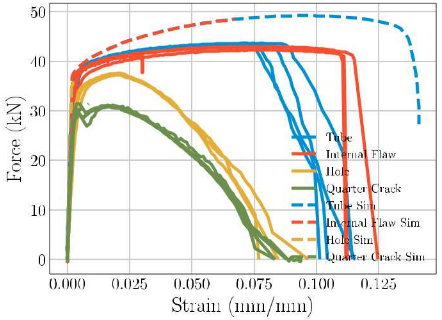






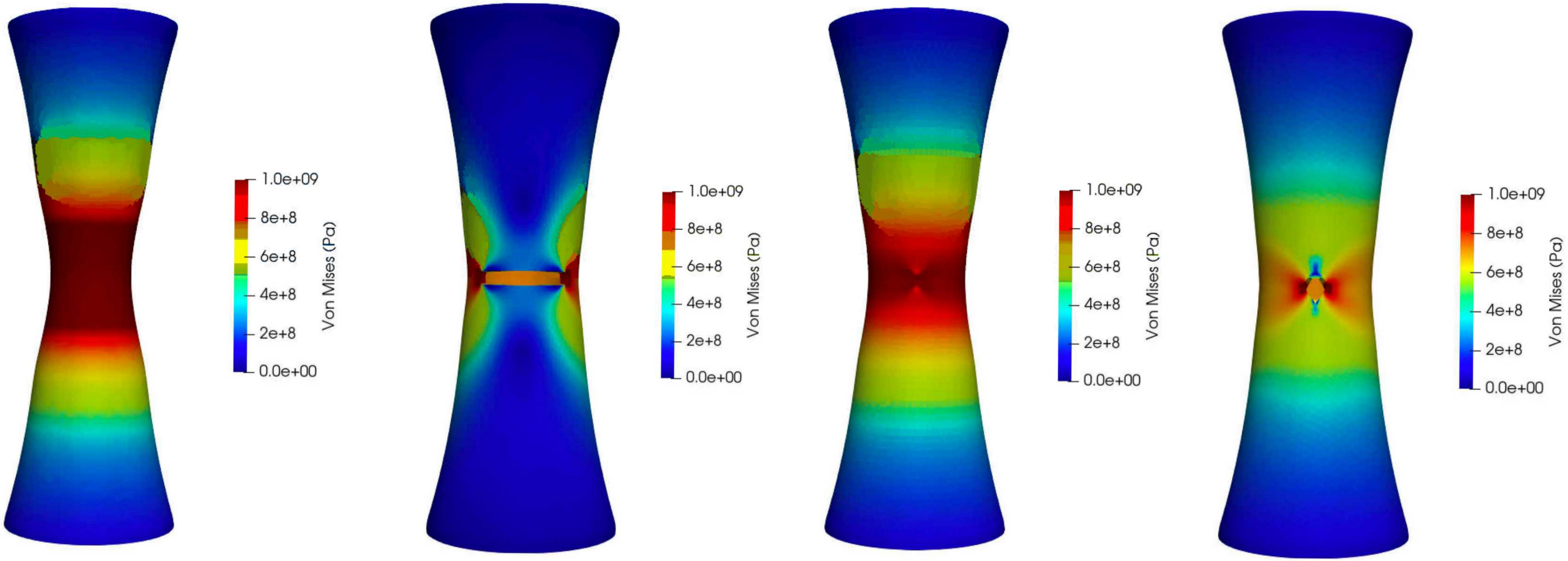
Elastoplastic simulation



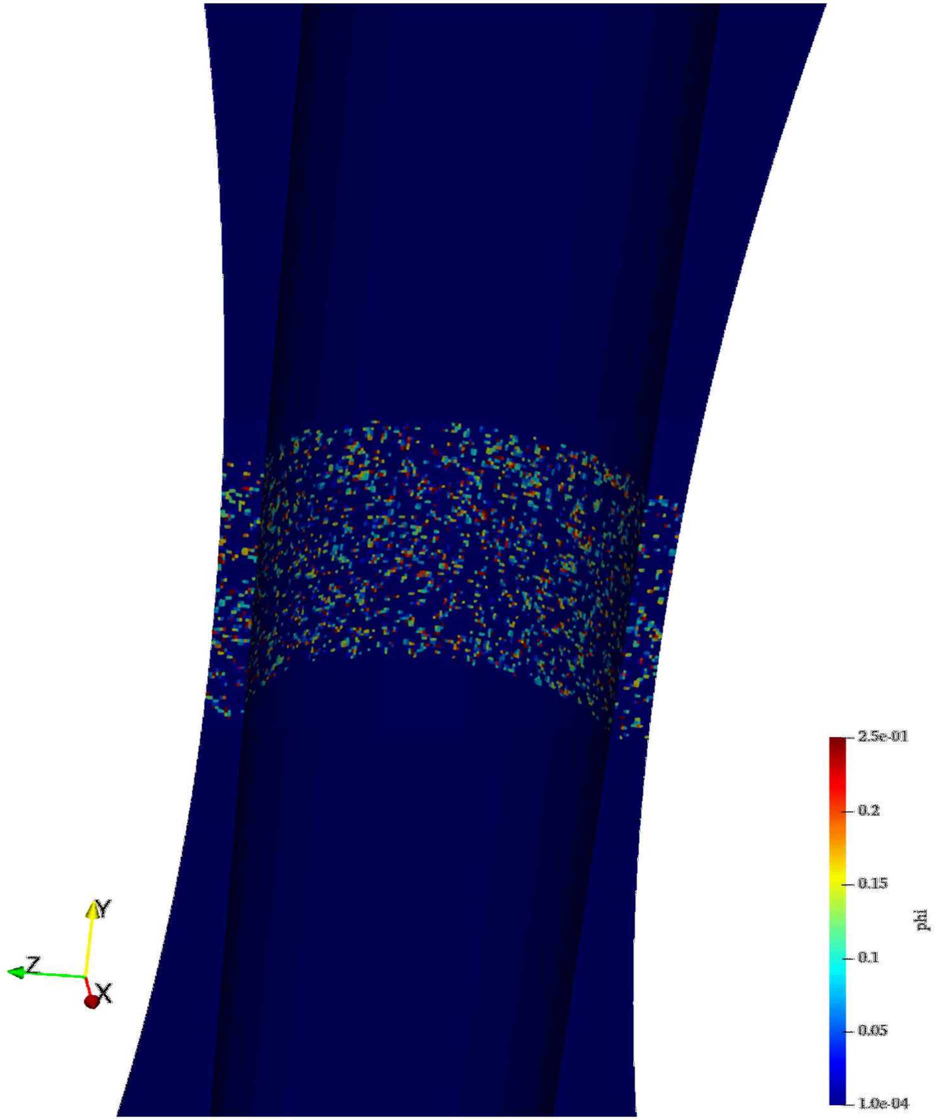


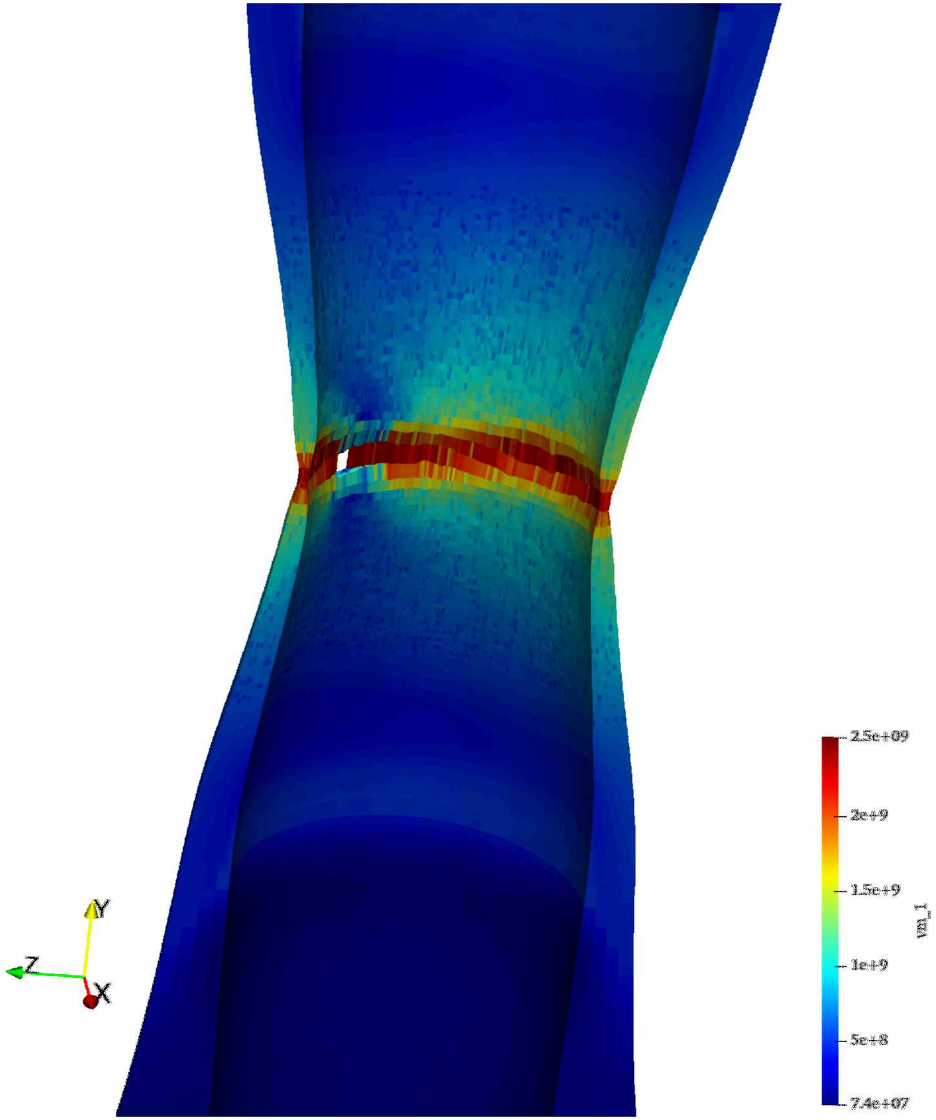
We have collected validation data for two different alloys and the four geometries (pristine + defected)

Low Fidelity Results Show Different Hotspot Locations for High Fidelity Mesh to be Applied

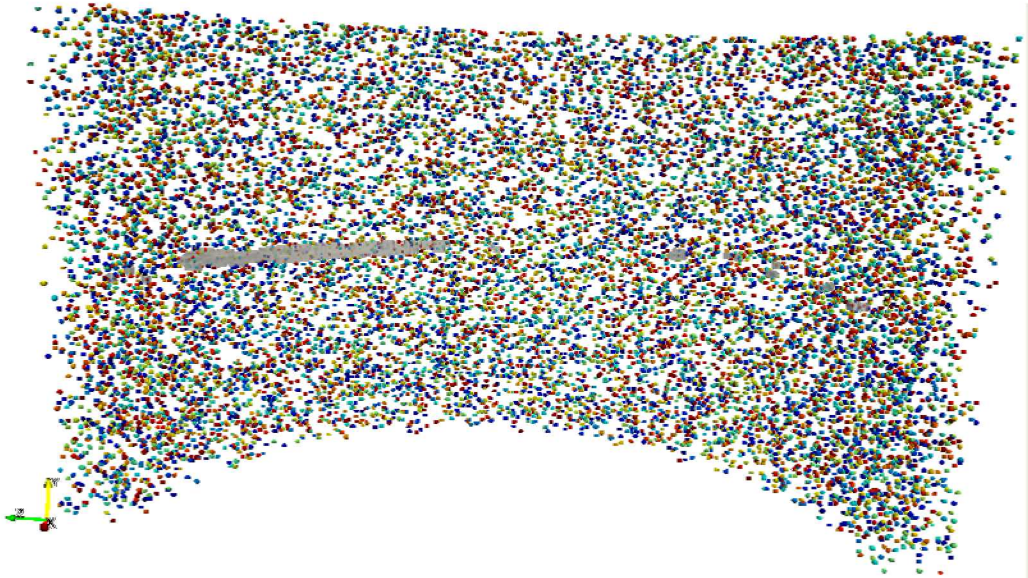


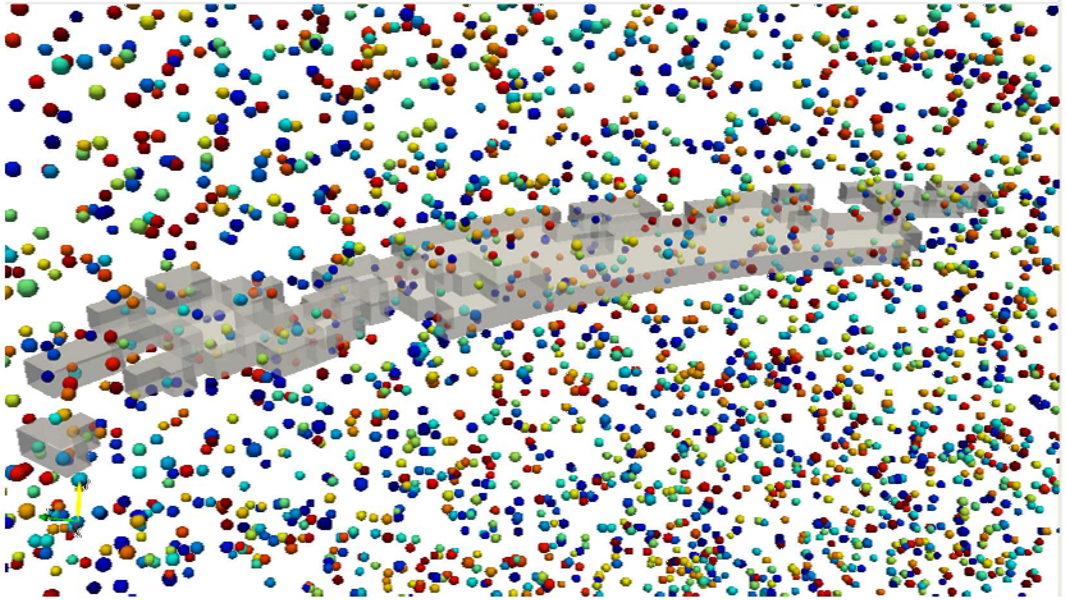
Pore Distributions on Low Fidelity Tube Mesh

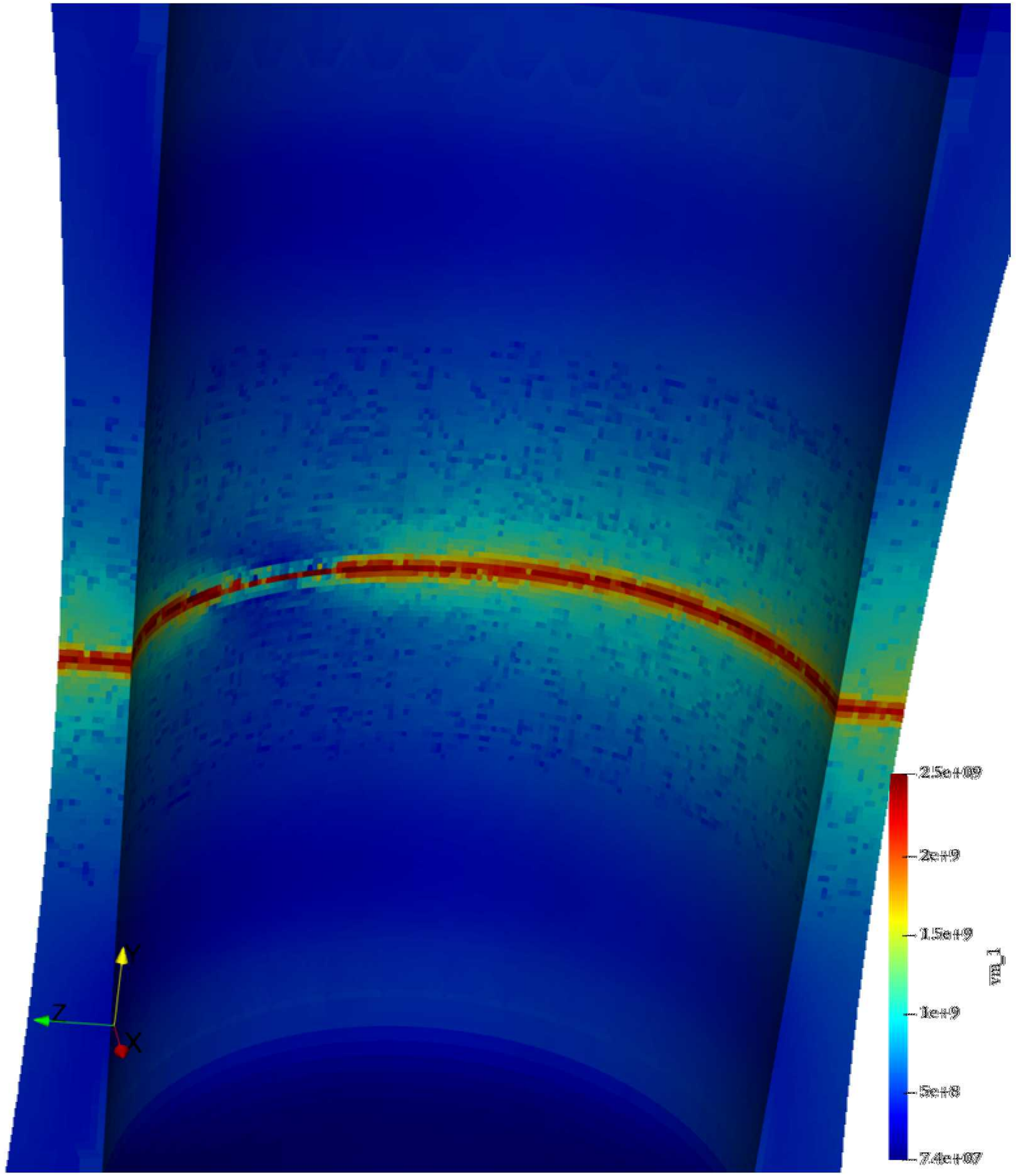




Pore Distributions on Low Fidelity Tube Mesh Lead to Crack Initiation







Conclusions

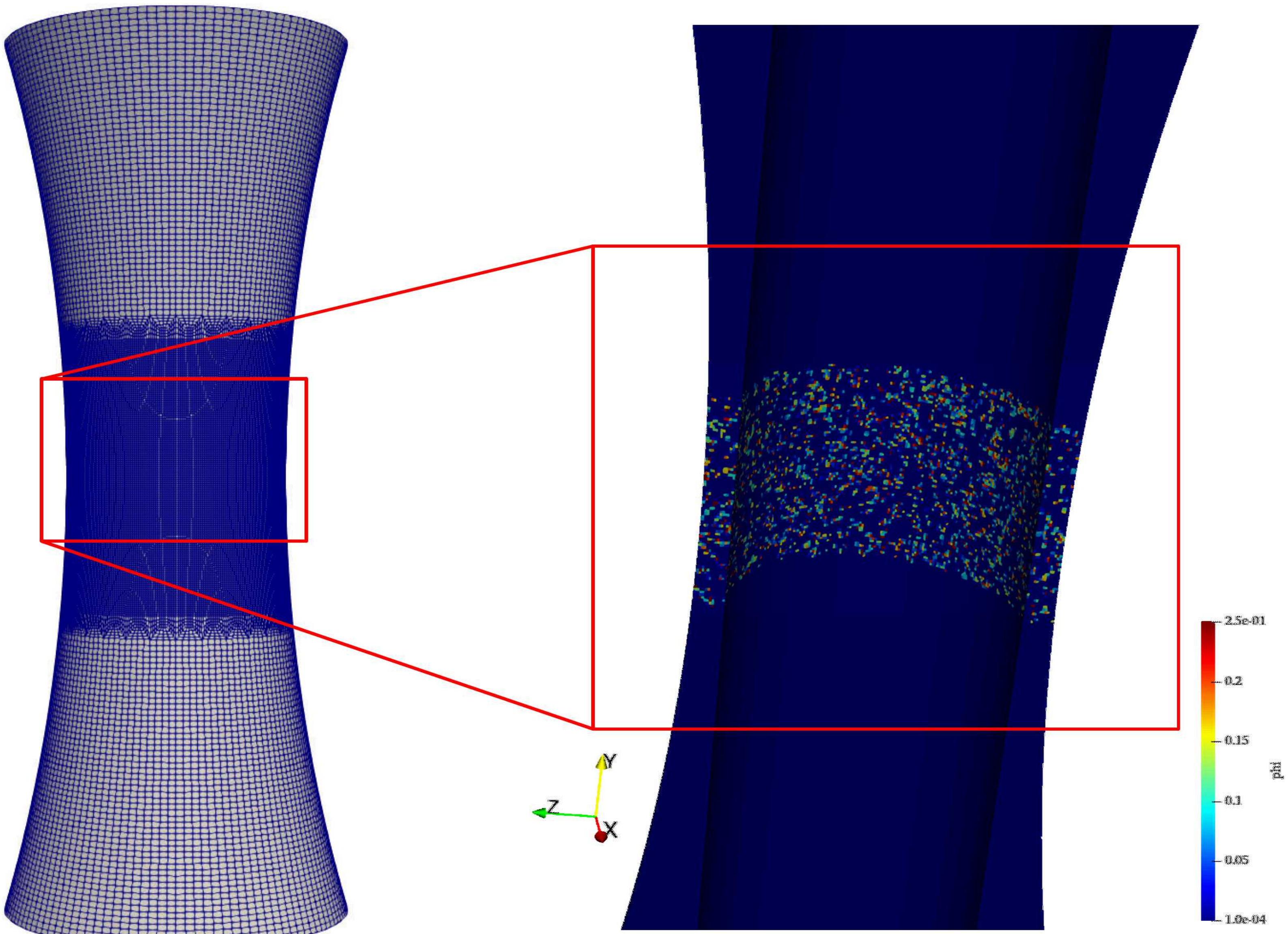
- AM Materials often have significant material variability
- Different defect structures affect crack initiation and propagation
- Low fidelity model is fast and accurate in initial simulations
- High fidelity model more accurately reflects pore geometry
- Hierarchical approach has potential to be efficient simulation method for qualification modeling

Future Work

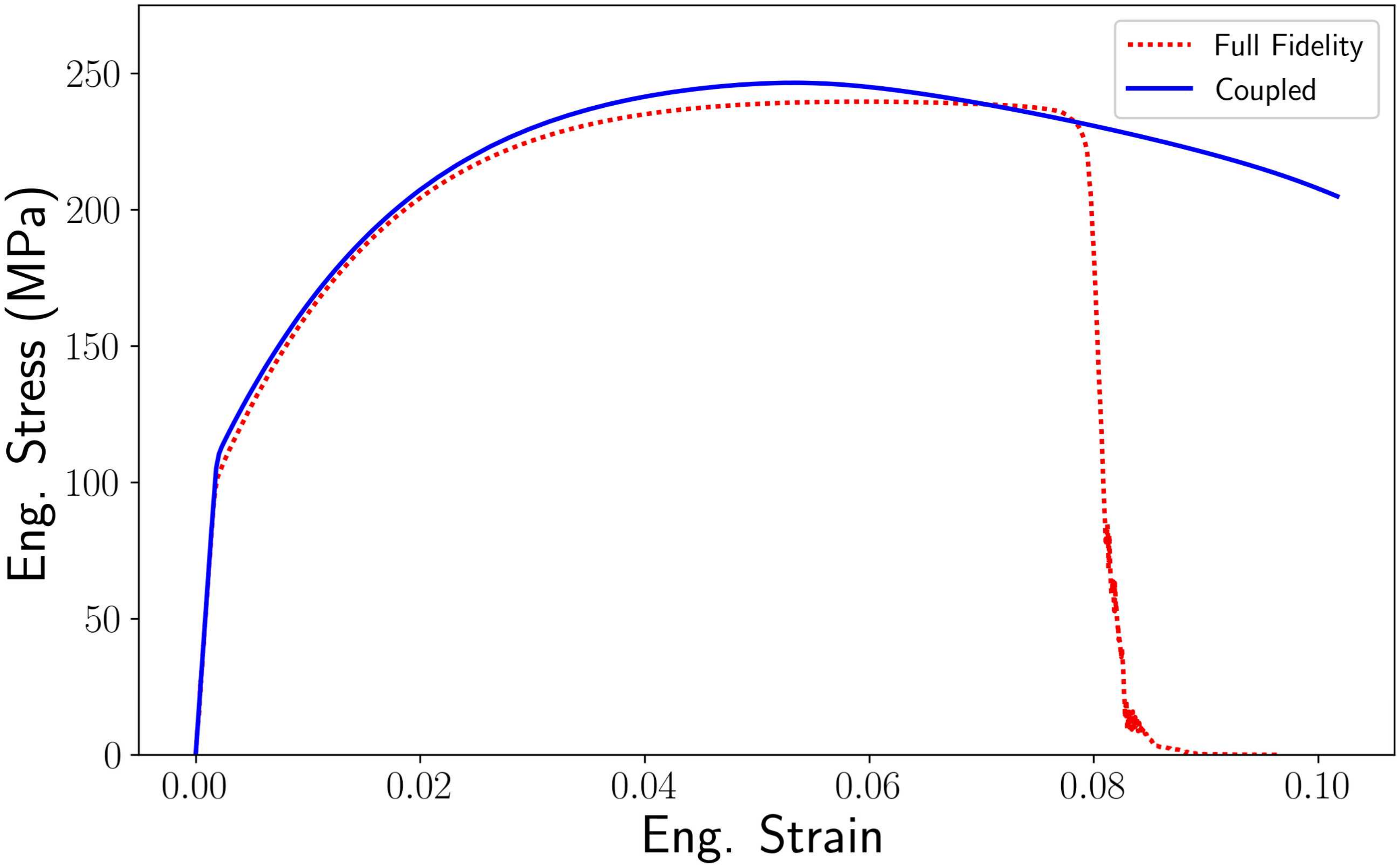
- Perform coupled multiscale simulations on tube geometries
- Apply residual stress predictions as initial conditions

Backup Slides

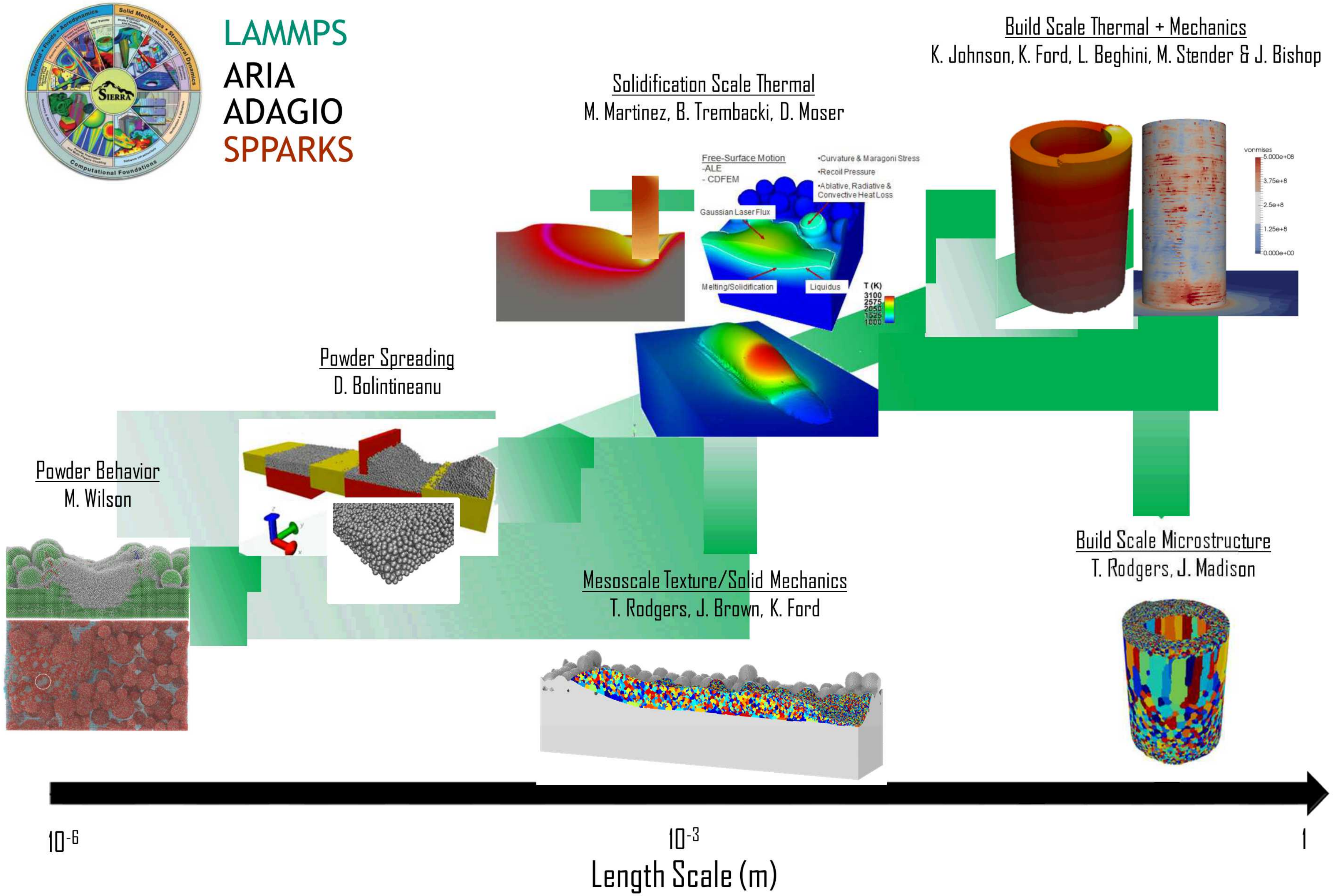
Pore Distributions Are Mapped to Low Fidelity Tube Mesh



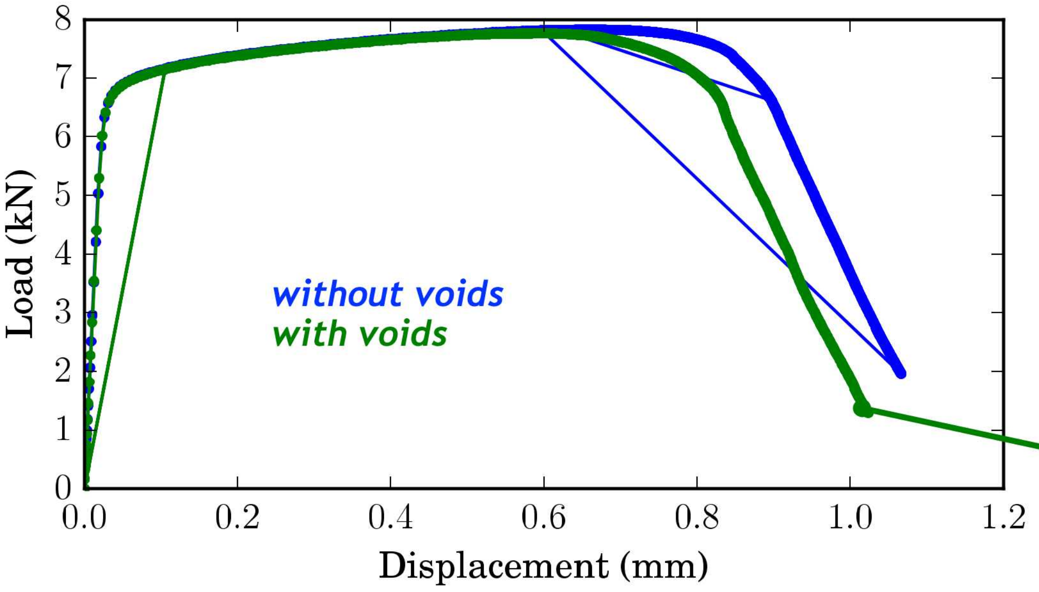
Multiscale Model Response Differs Slightly from Full Fidelity Model

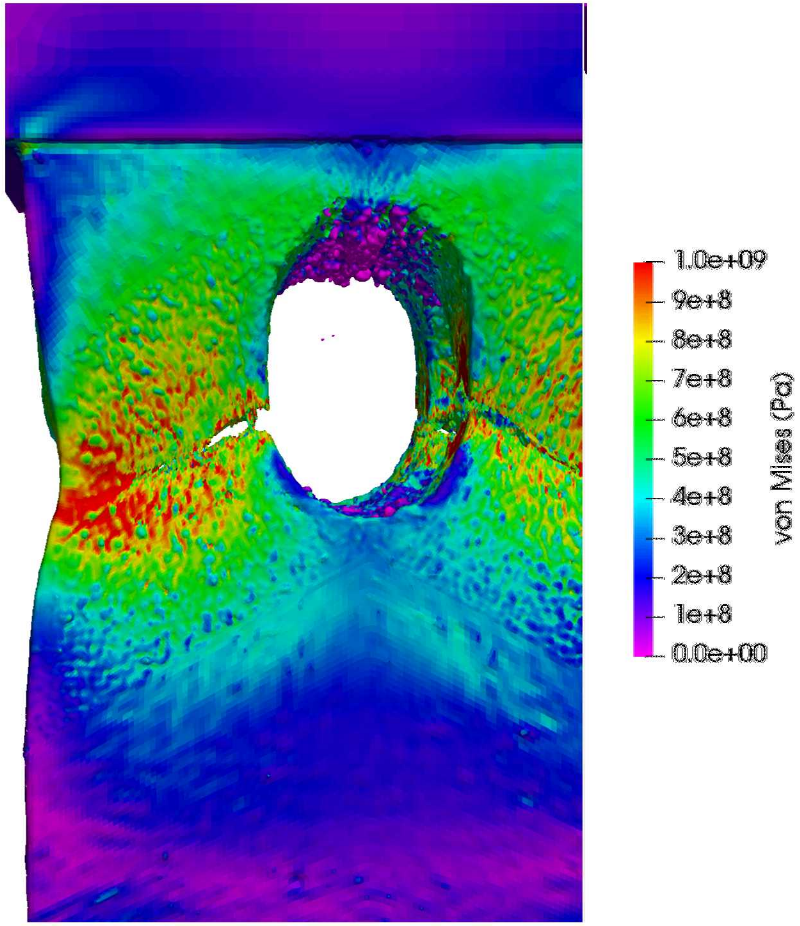


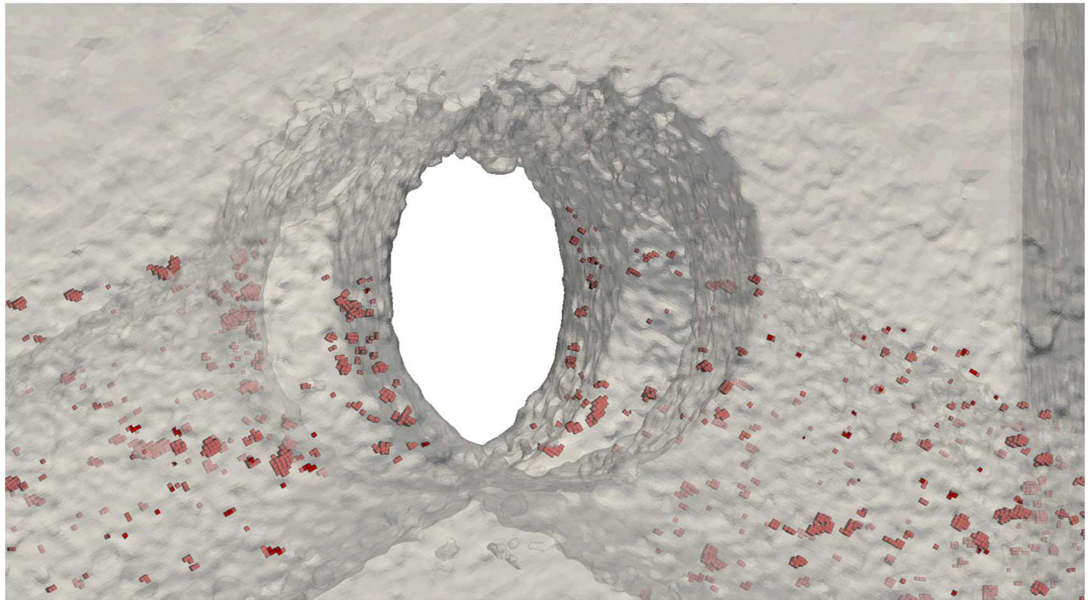
Models Bridging Length Scales



Modeling the Effect of Pores and Surface Roughness From High-Resolution CT Scan in Follow-up Investigation







Simulation results from ~13 million element meshes generated from CT scans.

Slide Courtesy: Kyle Karlson, Guy Bergel