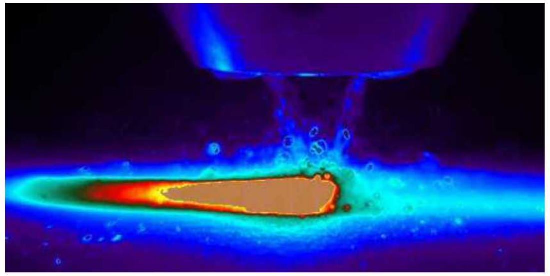
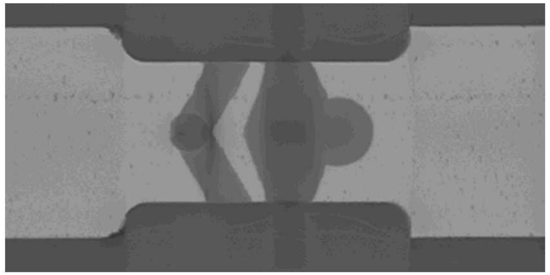
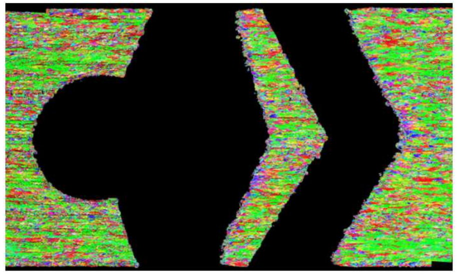
SAND2019-7028C

Multiscale Stochastic Modeling for Additive Manufacturing Part Qualification







PRESENTED BY

Kyle Johnson[1], John Emery[1], Mircea Grigoriu[2], Jay Carroll[1], Joe Bishop[1], Kyle Karlson[1], Guy Bergel, Chris Hammetter[1], Spencer Grange[1], Kurtis Ford[1], and Judy Brown[1]

Engineering Mechanics Institute Conference 2019
June 20, 2019

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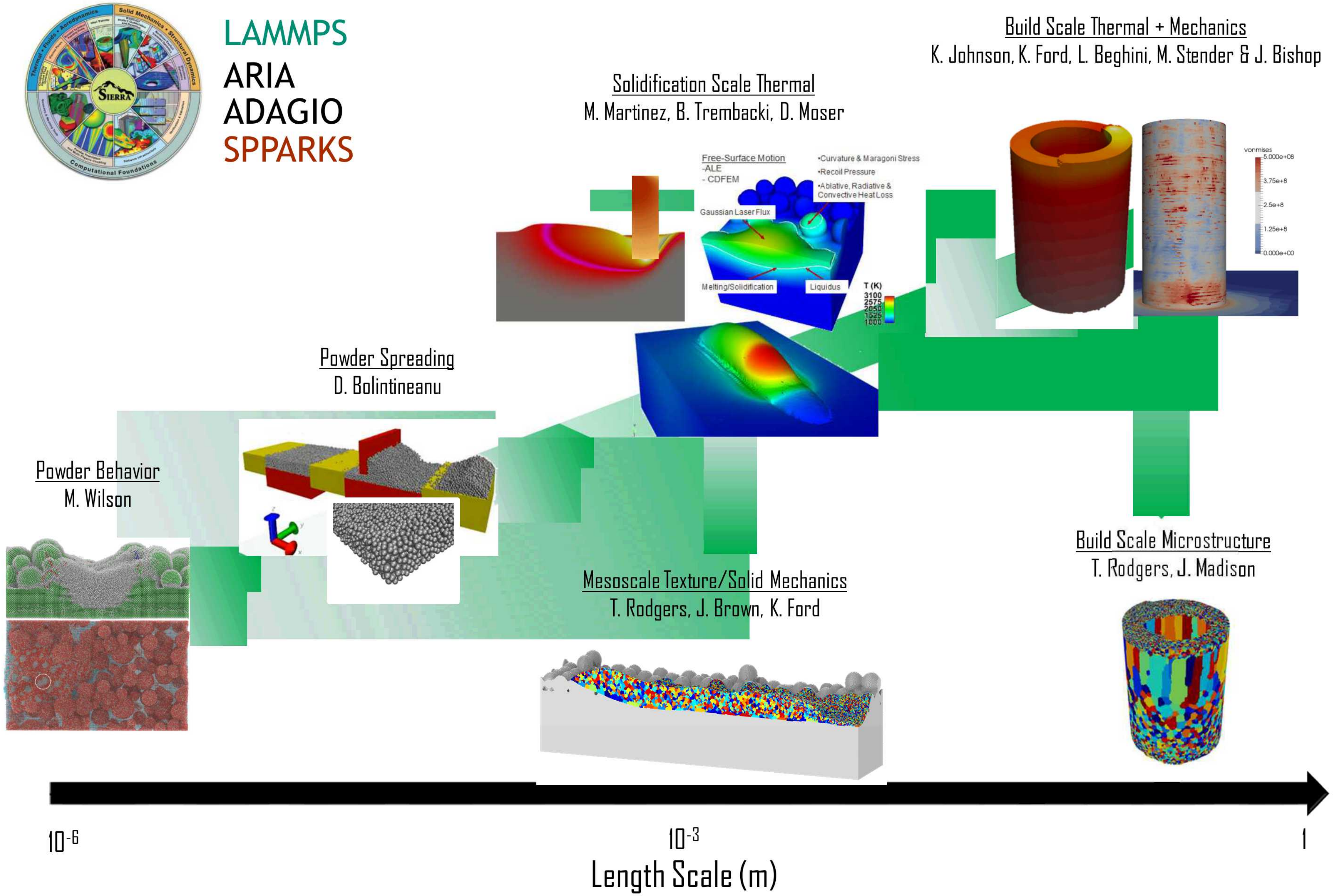
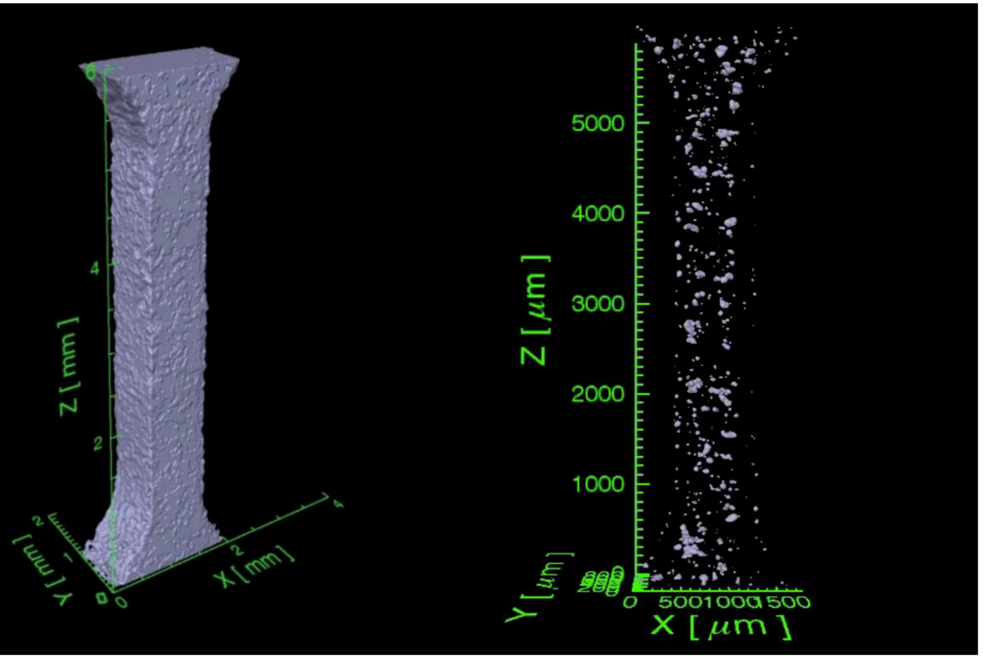
Models Bridging Length Scales



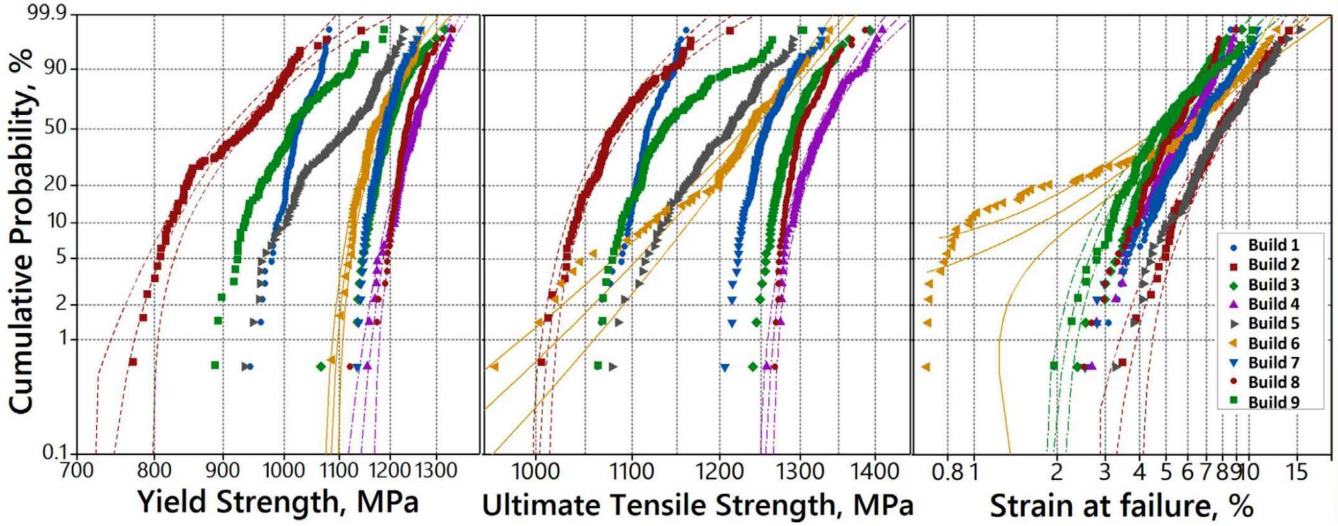
Outline

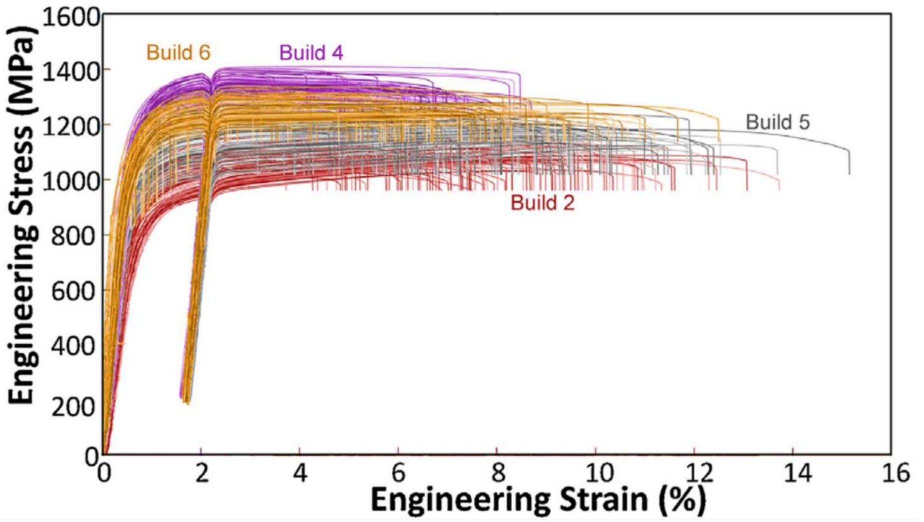
1. Motivation
2. Predicting AM Part Performance in the Sandia Fracture Challenge
3. Ongoing Work
4. Conclusions

Motivation: Additive Manufacturing (AM) Defects Can Lead to Large Performance Variability



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





Boyce et al., Advanced Engineering Materials 2017

Can we predict performance and failure of specific AM parts without explicitly meshing pores?

Sandia Fracture Challenge: Blind Predictions of Ductile Failure

Int J Fract (2014) 186:5–68
DOI 10.1007/s10704-013-9904-6

ORIGINAL PAPER

The Sandia Fracture Challenge: blind round robin predictions of ductile tearing

B. L. Boyce · S. L. B. Kramer · H. E. Fang · T. E. Cordova · M. K. Neilsen · K. Dion · A. K. Kaczmarowski · E. Karasz · L. Xue · A. J. Gross · A. Ghahremaninezhad · K. Ravi-Chandar · S.-P. Lin · S.-W. Chi · J. S. Chen · E. Yreux · M. Rüter · D. Qian · Z. Zhou · S. Bhamare · D. T. O'Connor · S. Tang · K. I. Elkhodary · J. Zhao · J. D. Hochhalter · A. R. Cerrone · A. R. Ingraffea · P. A. Wawrzynek · B. J. Carter · J. M. Emery · M. G. Veilleux · P. Yang · Y. Gan · X. Zhang · Z. Chen · E. Madenci · B. Kilic · T. Zhang · E. Fang · P. Liu · J. Lua · K. Nahshon · M. Miraglia · J. Cruce · R. DeFrese · E. T. Moyer · S. Brinckmann · L. Quinkert · K. Pack · M. Luo · T. Wierzbicki

Int J Fract (2016) 198:5–100
DOI 10.1007/s10704-016-0089-7

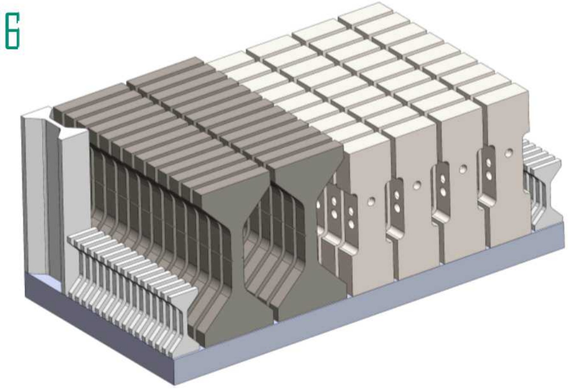
SANDIA FRACTURE CHALLENGE 2014

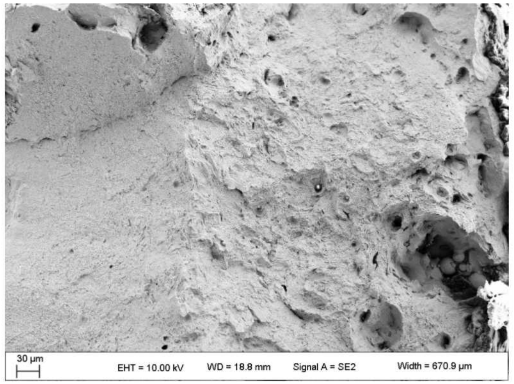
The second Sandia Fracture Challenge: predictions of ductile failure under quasi-static and moderate-rate dynamic loading

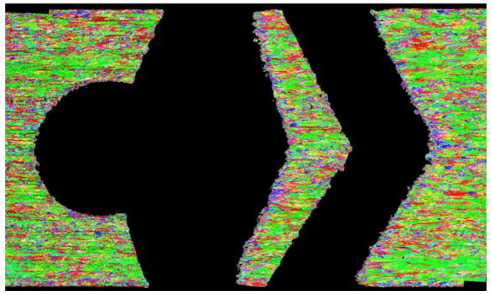
B. L. Boyce · S. L. B. Kramer · T. R. Bosiljevac · E. Corona · J. A. Moore · K. Elkhodary · C. H. M. Simha · B. W. Williams · A. R. Cerrone · A. Nonn · J. D. Hochhalter · G. F. Bomarito · J. E. Warner · B. J. Carter · D. H. Warner · A. R. Ingraffea · T. Zhang · X. Fang · J. Lua · V. Chiaruttini · M. Mazière · S. Feld-Payet · V. A. Yastrebov · J. Besson · J.-L. Chaboche · J. Lian · Y. Di · B. Wu · D. Novokshanov · N. Vajragupta · P. Kucharczyk · V. Brinnel · B. Döbereiner · S. Münstermann · M. K. Neilsen · K. Dion · K. N. Karlson · J. W. Foulk III · A. A. Brown · M. G. Veilleux · J. L. Bignell · S. E. Sanborn · C. A. Jones · P. D. Mattie · K. Pack · T. Wierzbicki · S.-W. Chi · S.-P. Lin · A. Mahdavi · J. Predan · J. Zadravec · A. J. Gross · K. Ravi-Chandar · L. Xue

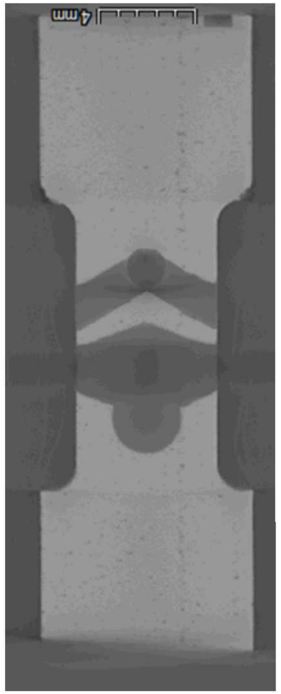
The Third Sandia Fracture Challenge – 2016

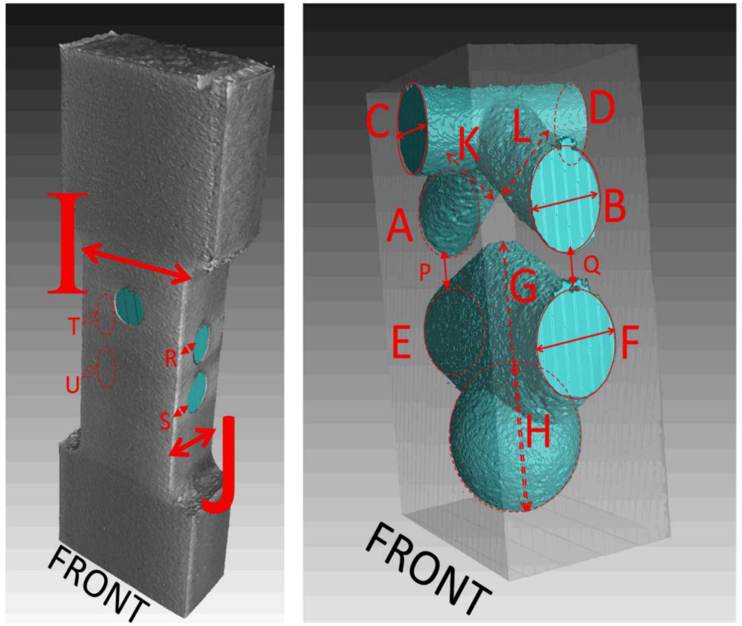
- 316L AM Part
- Goal: Predict Tensile Failure
- 21 Participant Teams











Bammann-Chiesa-Johnson (BCJ) Constitutive Model for Plasticity

- Based on work by Bammann et al. 1993, Brown and Bammann 2012
- History-dependent viscoplastic internal state variable model
- Stress is dependent on damage ϕ and evolves according to

$$\dot{\sigma}_{ij} = \left(\frac{\dot{E}}{E} - \frac{\dot{\phi}}{1-\phi}\right)\sigma_{ij} + E(1-\phi)\left(\dot{\epsilon}_{ij} - \dot{\epsilon}_{ij}^{p}\right)$$

- Flow rule includes yield stress and internal state variable for hardening

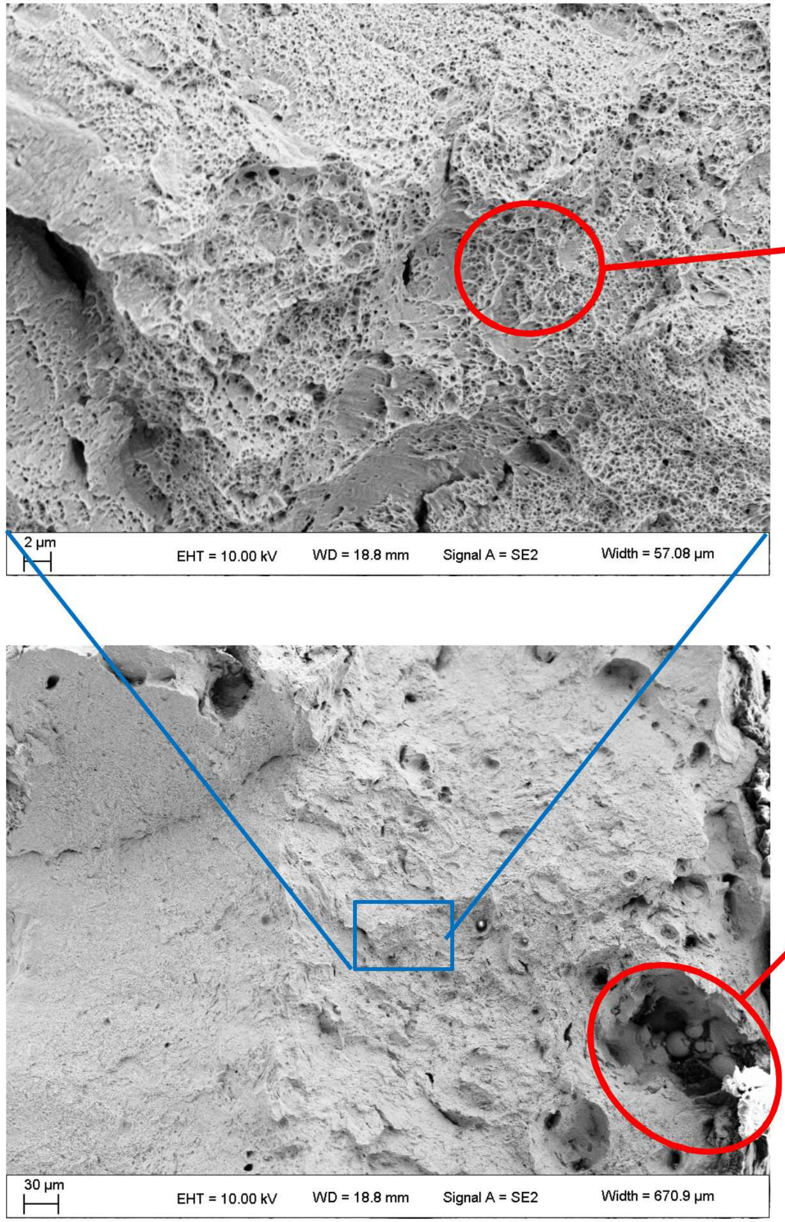
$$\dot{\epsilon}_p = \sinh\langle\frac{\sigma_e}{Y+\kappa} - 1\rangle$$

- The isotropic hardening variable κ evolves in a hardening minus recovery form.

$$\dot{\kappa} = \kappa\frac{\dot{\mu}}{\mu} + (H - R_d\kappa)\dot{\epsilon}_p$$

Johnson et al. IJF (Accepted)

Fracture Surfaces Indicated Both Existing Pores and Pore Nucleation



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

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

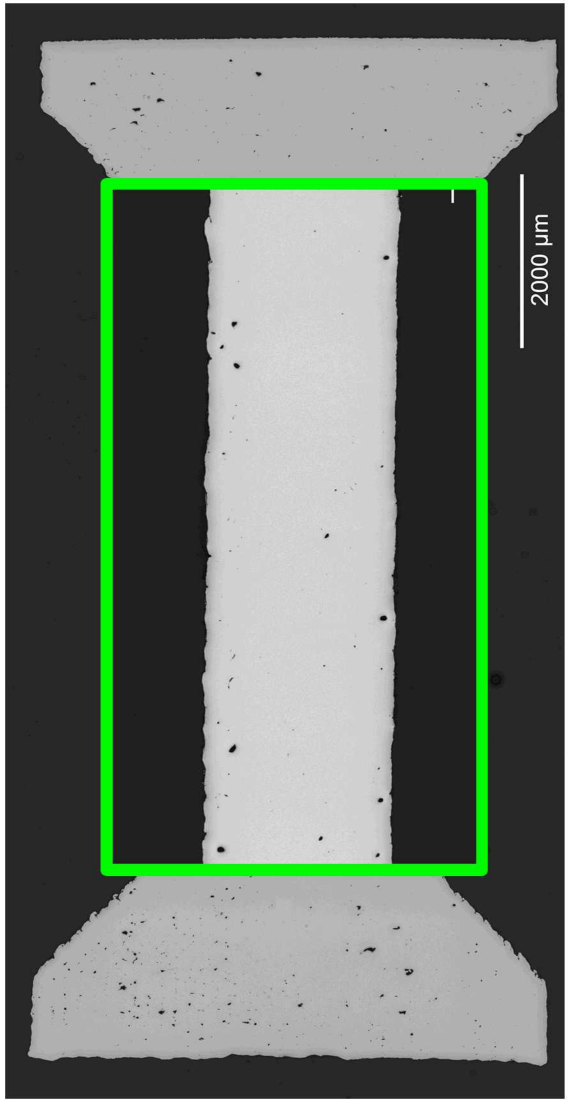
Total Damage

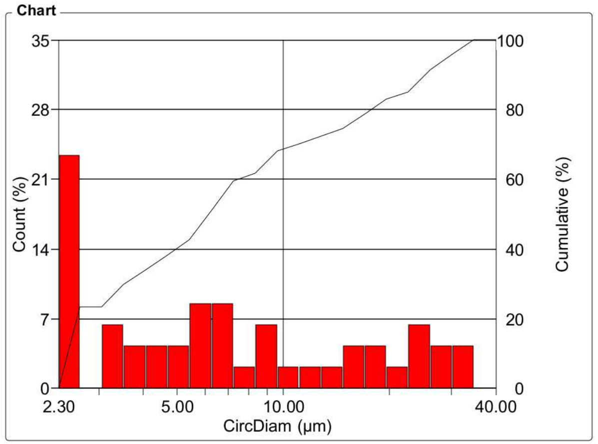
$$\phi = \frac{\eta v_v}{1 + \eta v_v}$$

(Horstemeyer & Gokhale 1999)

Johnson et al. IJF (Accepted)

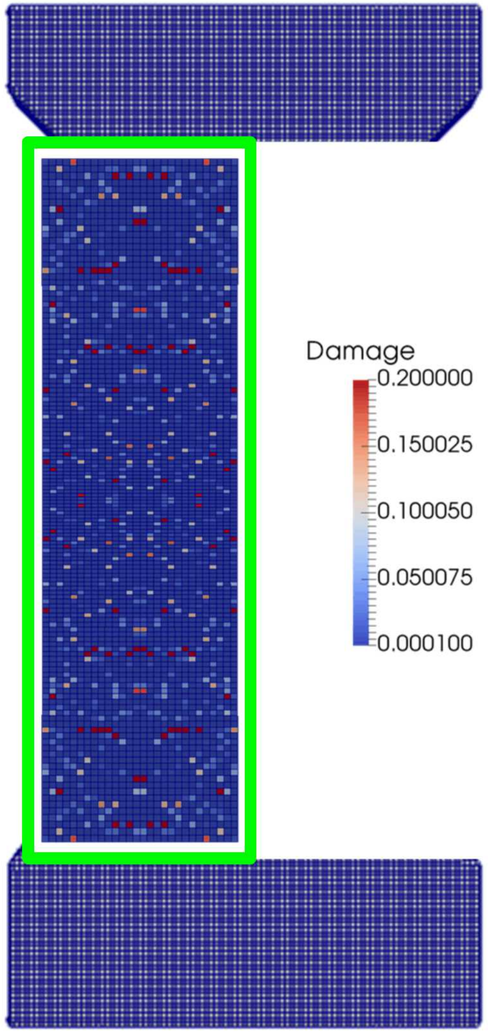
Incorporating Porosity as Initial Damage





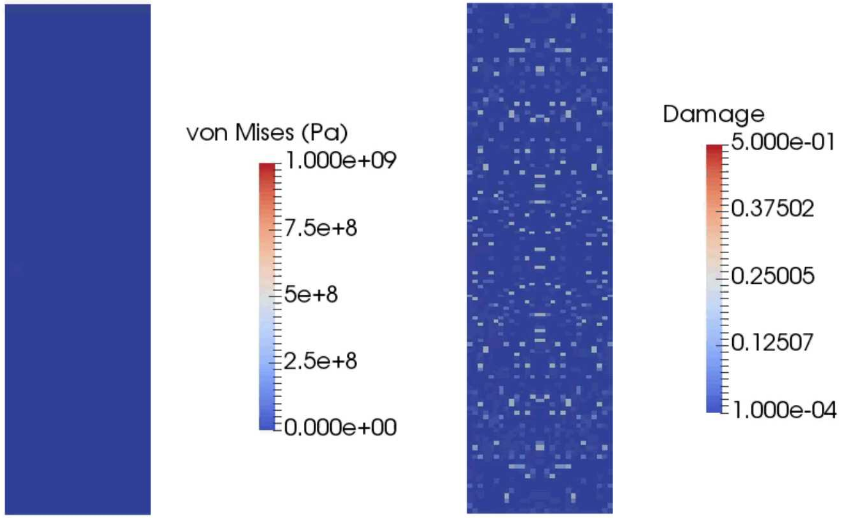
Porosity Mapping

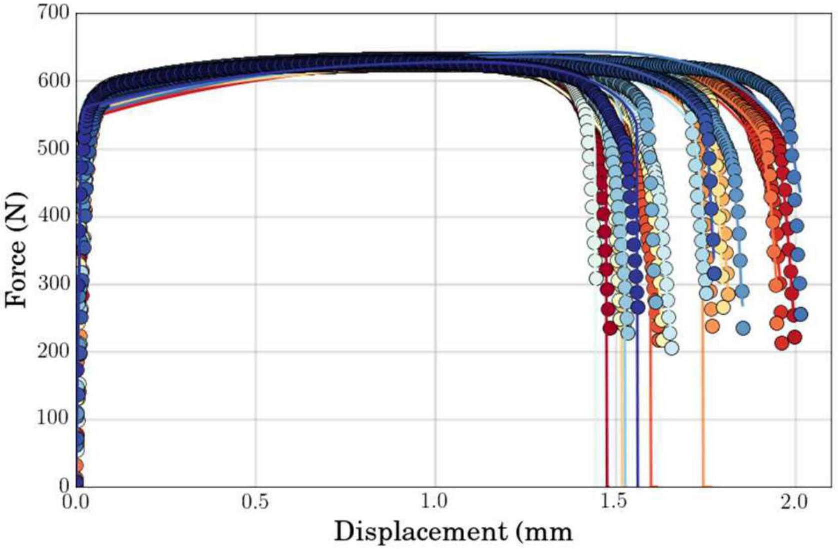
x, y, z, r_{pore}

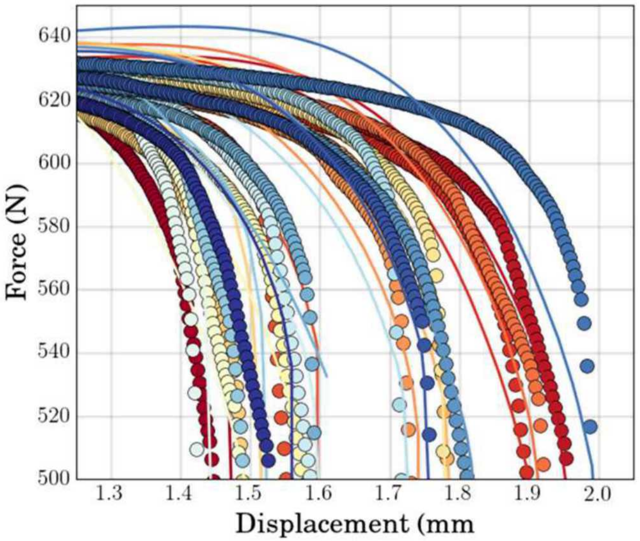


Johnson et al. IJF (Accepted)

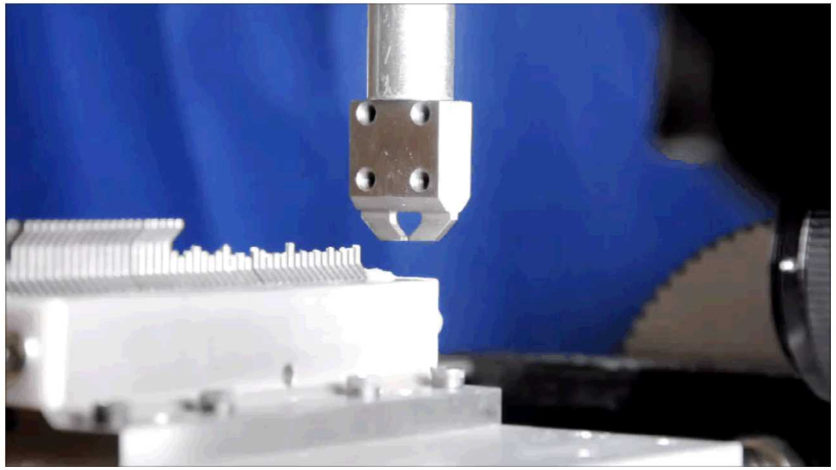
Calibration Results for High Throughput Tensile Testing







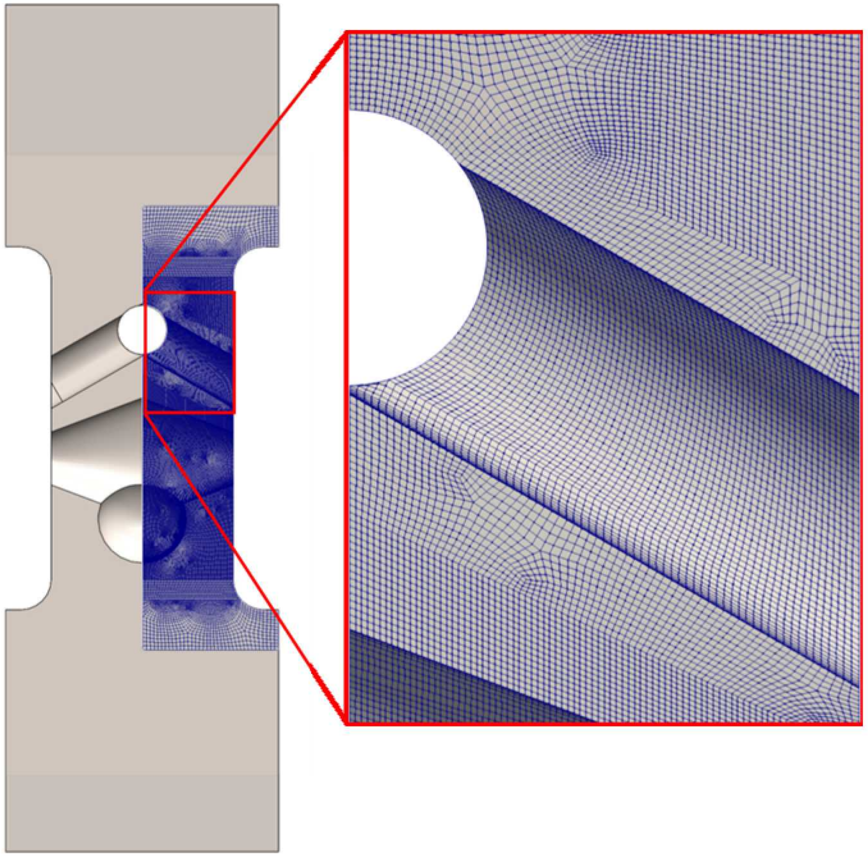
- A parameter set was calibrated for each longitudinal tension test
- Transverse and notched tensile data were not used due to time constraints
- FEA performed in Sierra/SM
- Calibration performed using Dakota and MatCal (Kyle Karlson)

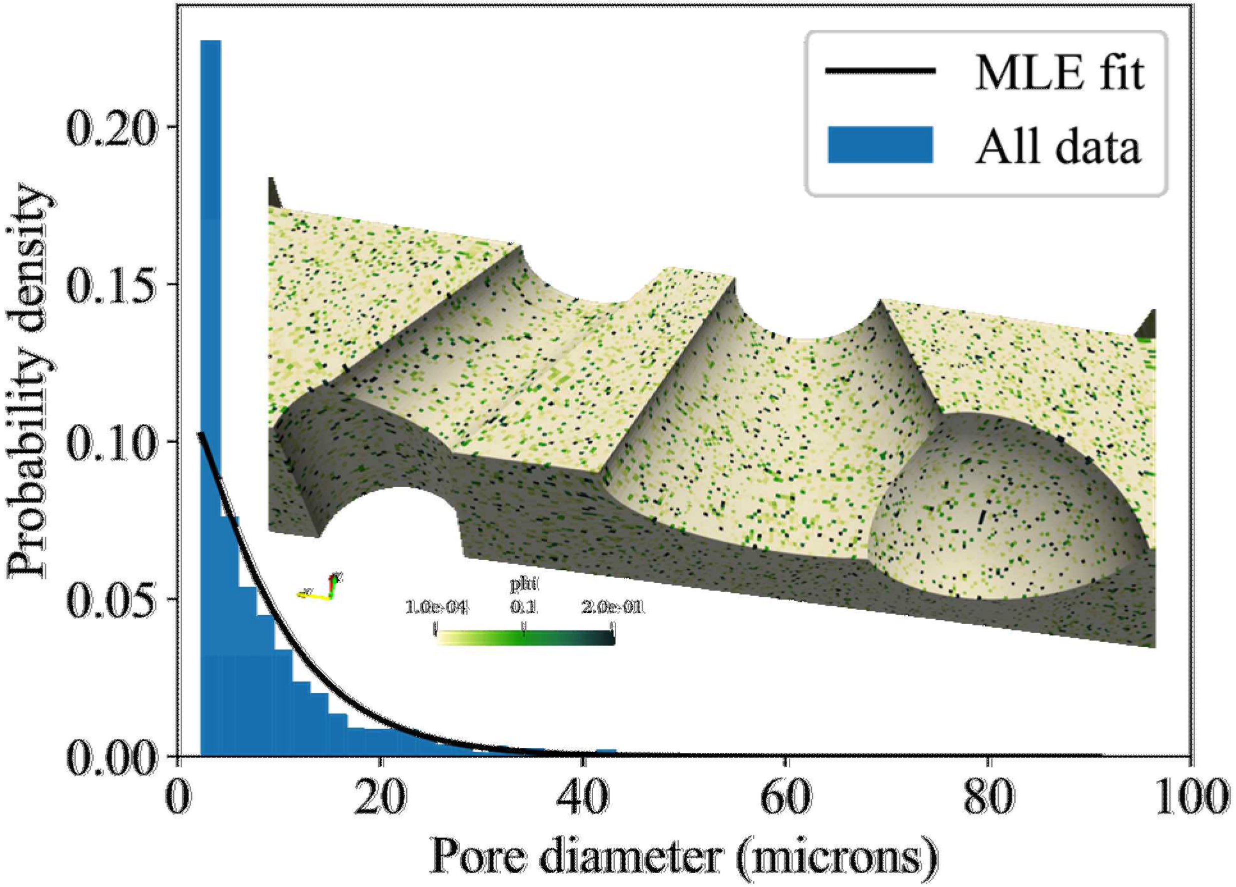


Boyce et al., Adv Eng Mat 2017, Salzbrenner et al. JMPT 2017

Johnson et al. IJF (Accepted)

Porosity Overlaid on Quarter-Symmetry Challenge Geometry

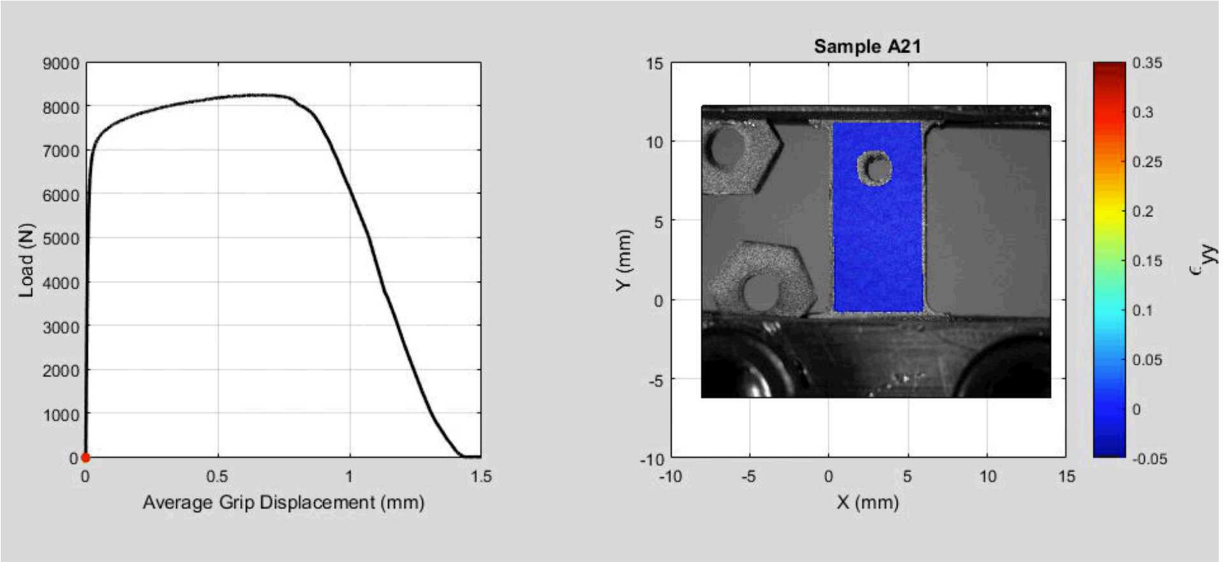


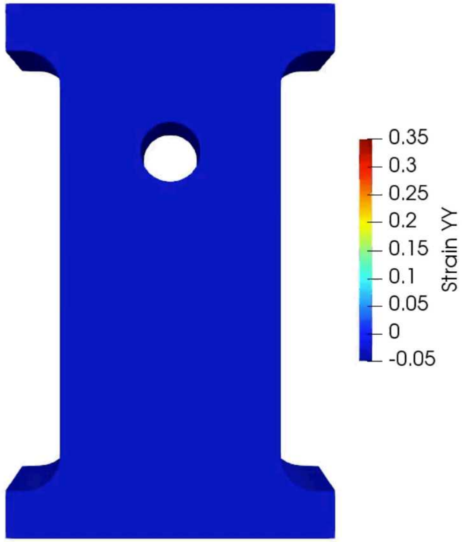


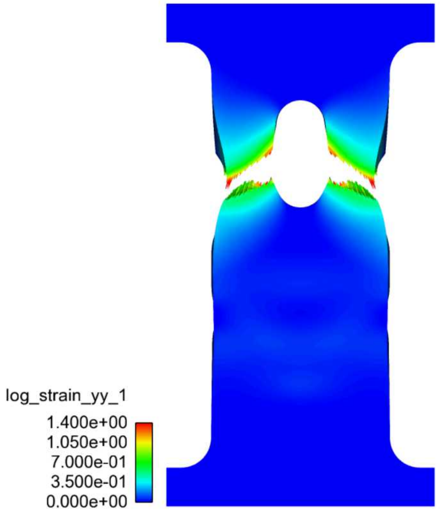
- Multiple porosity initializations were used to capture uncertainty in performance

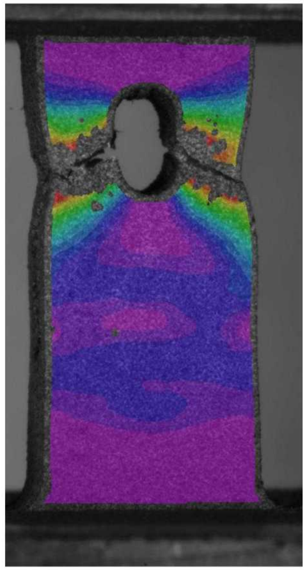
Johnson et al. IJF (Accepted)

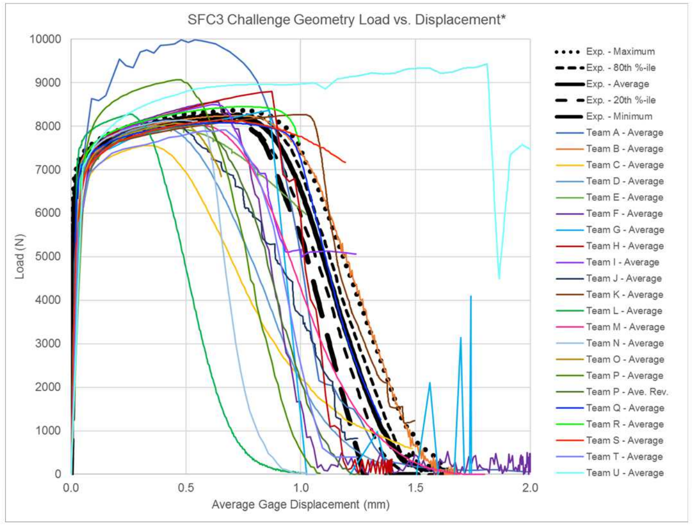
Blind Performance Prediction



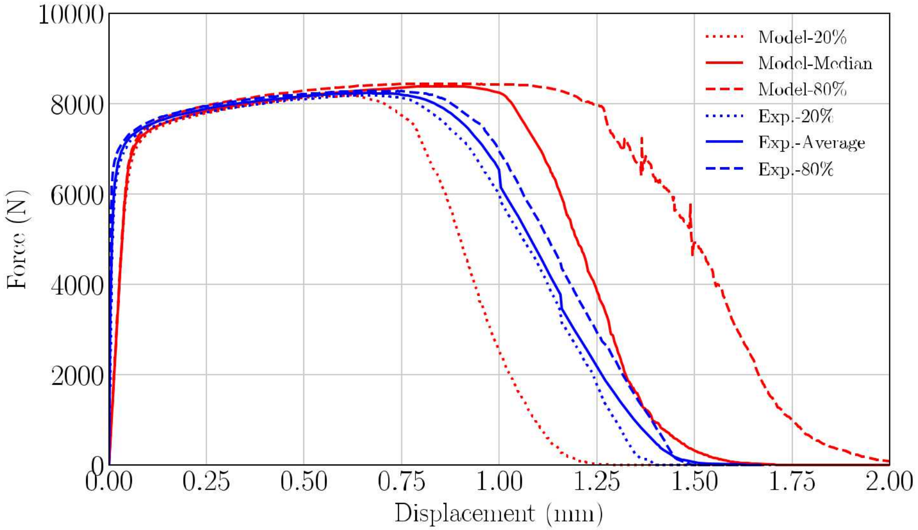








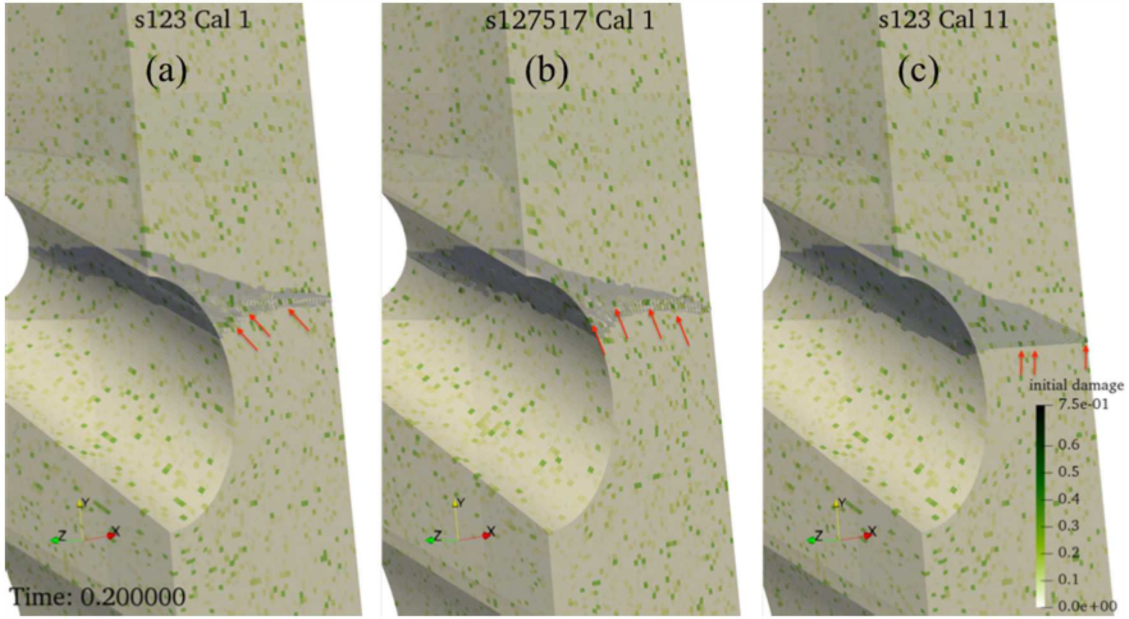
All Participant Predictions with Experimental in Black

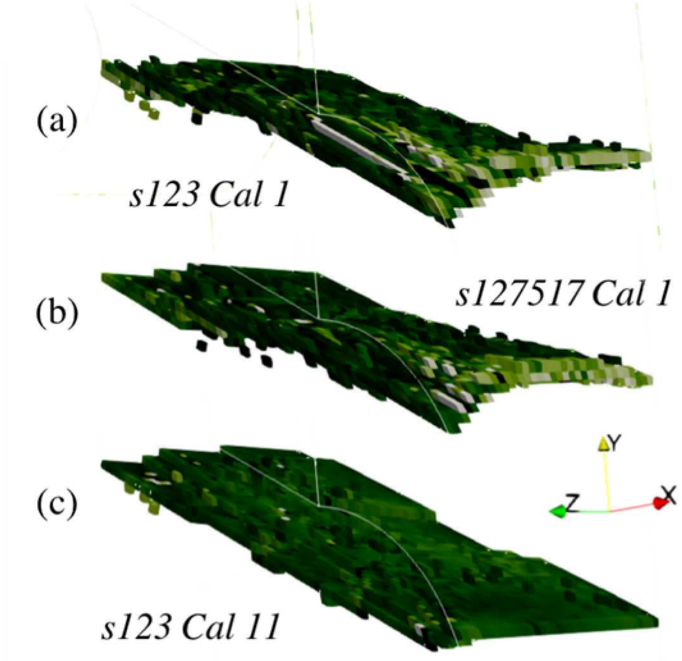


SNL/NM Prediction

Johnson et al. IJF (Accepted), Kramer, Boyce et al., IJF (Accepted)

Different Porosity Distributions Affect Crack Path

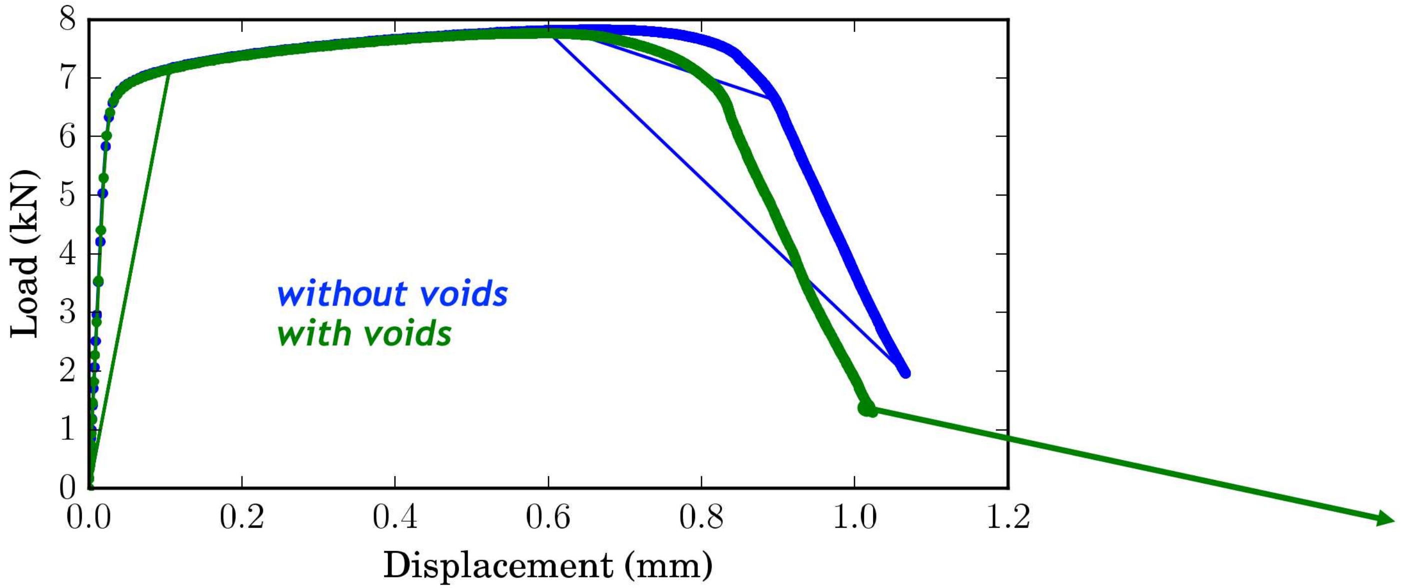


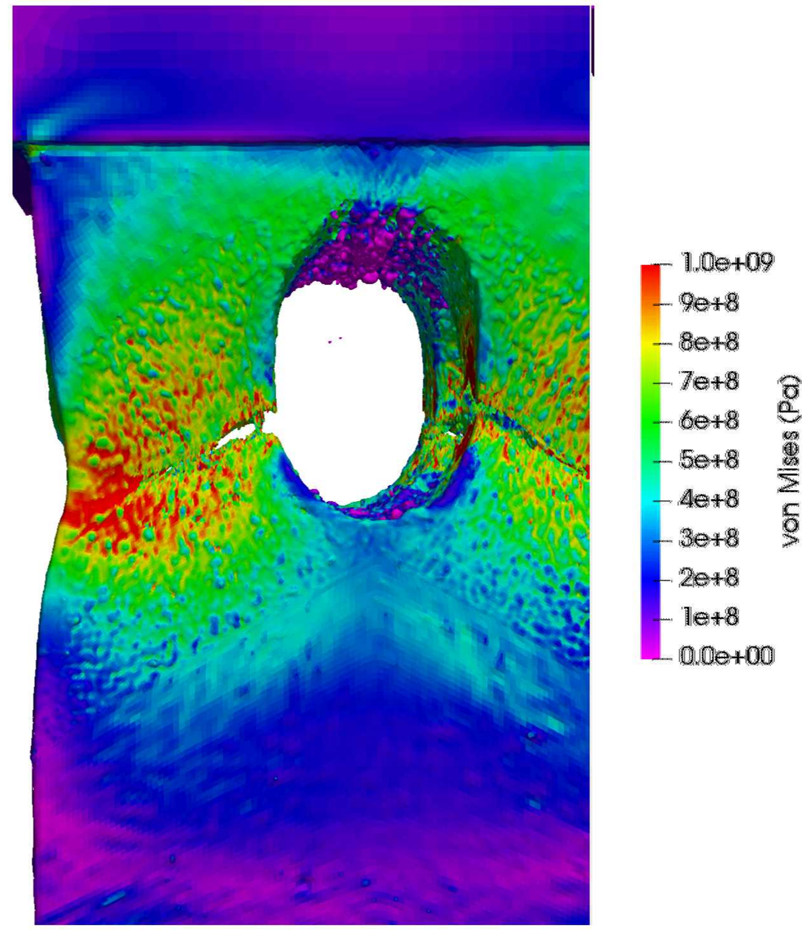


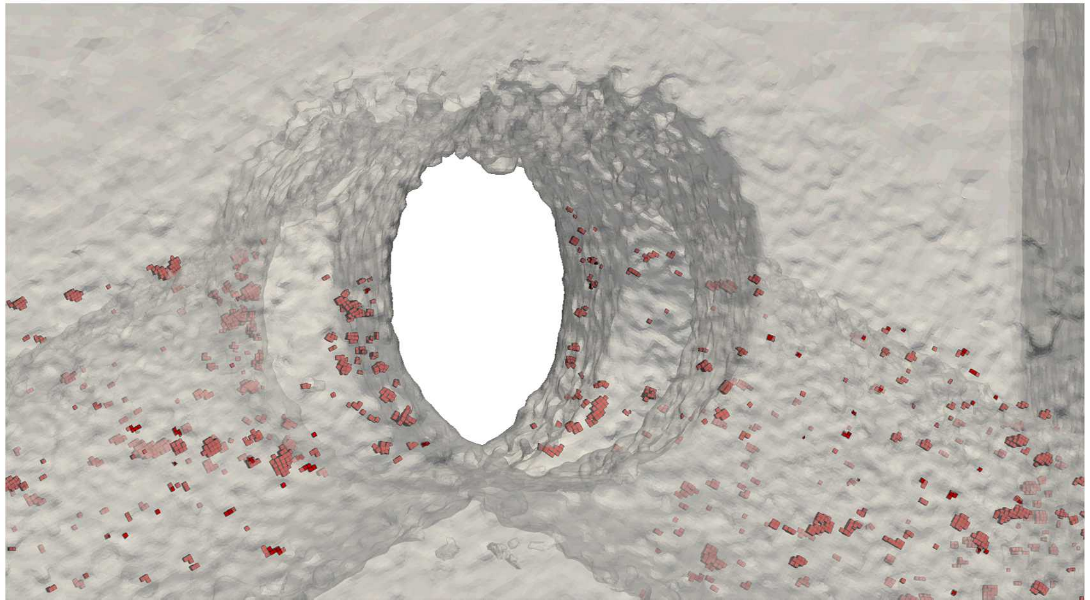
- Porosity seed indicated by *s* number, i.e. s123 is a different realization than s127517
- For the same calibration number (Cal 1), a different porosity seed yields a different crack path

Johnson et al. IJF (Accepted)

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







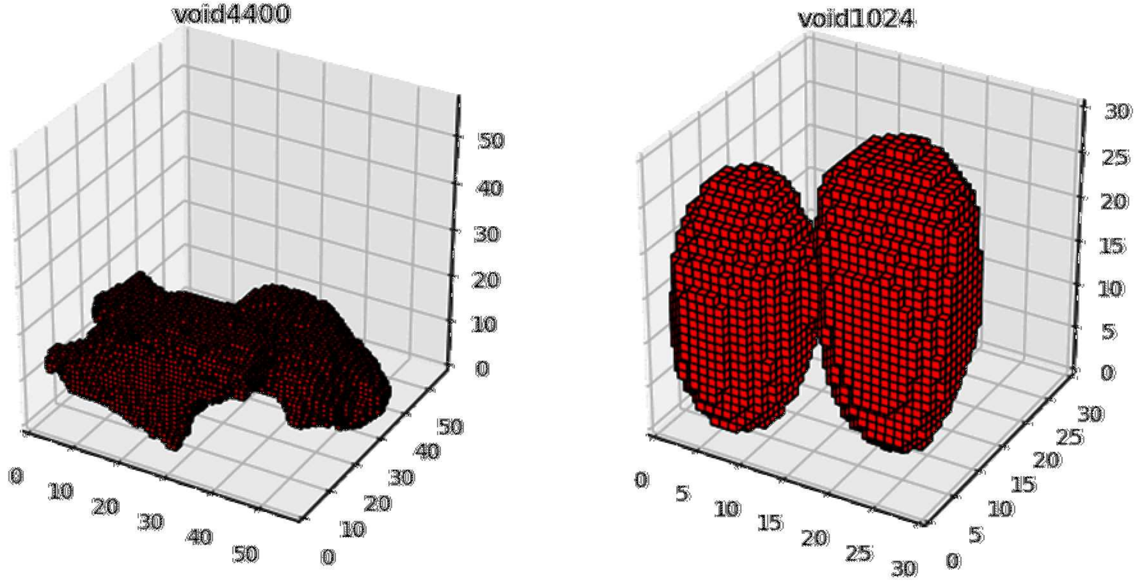
Simulation results from ~13 million element meshes generated from CT scans.

Slide Courtesy: Kyle Karlson, Guy Bergel

Ongoing Work: Further Examining Validity of Initializing Local Damage Model Based on Void Overlay

RVE Simulations Investigating Pore Effects

A Tale of Two CT's

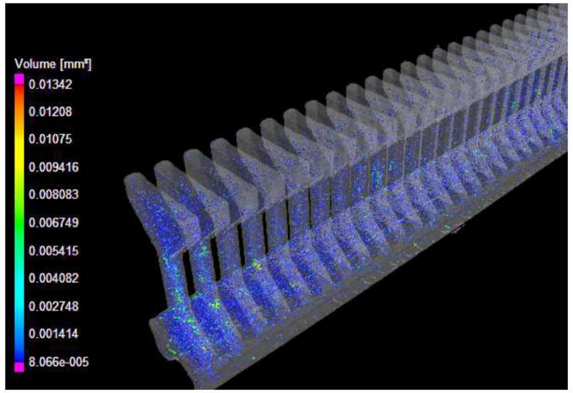


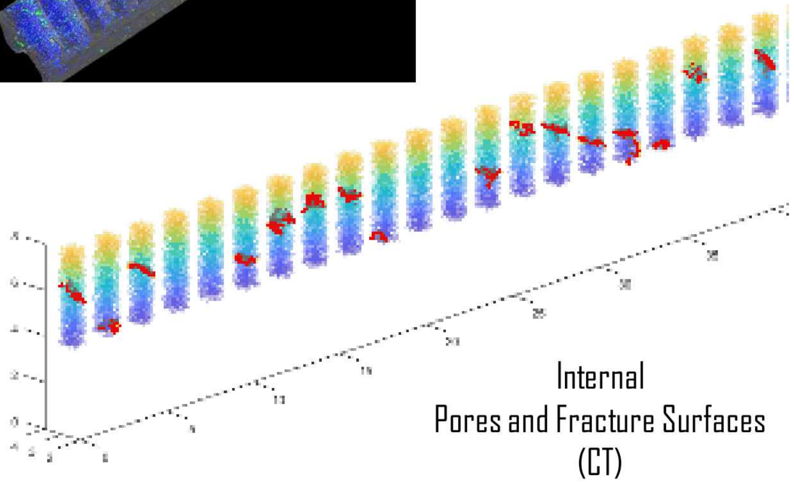
29 um resolution
1.9 um voxel size

15.6 um resolution
2.5 um voxel size

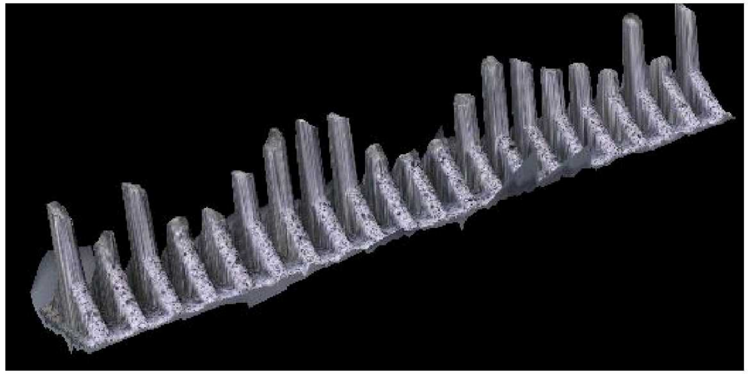
- Approach: Refine mesh of parts from high resolution CT scans to approach limit of explicitly meshed pores (many elements within a pore)
- Where does populating high local damage for pore locations break down?

Reproducing Tension Specimen Failure



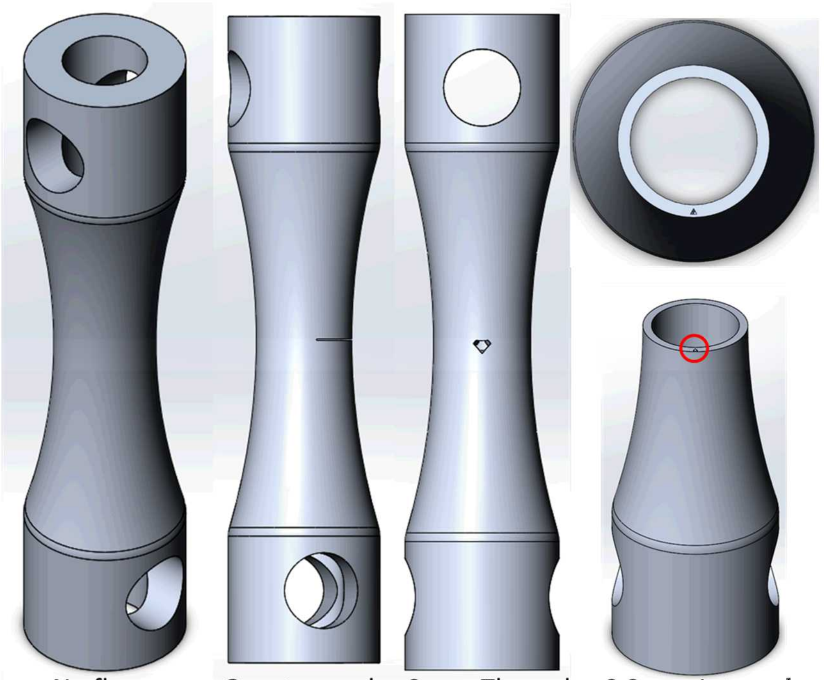


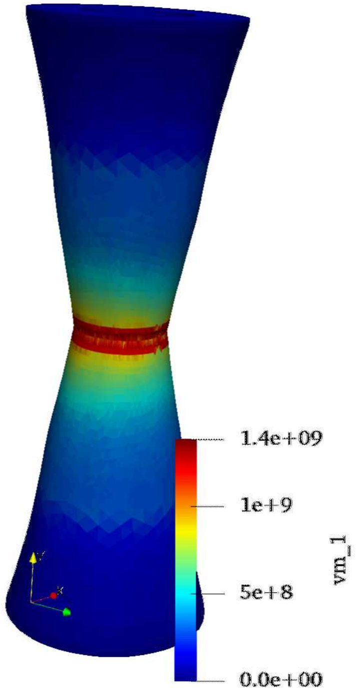
Internal
Pores and Fracture Surfaces
(CT)

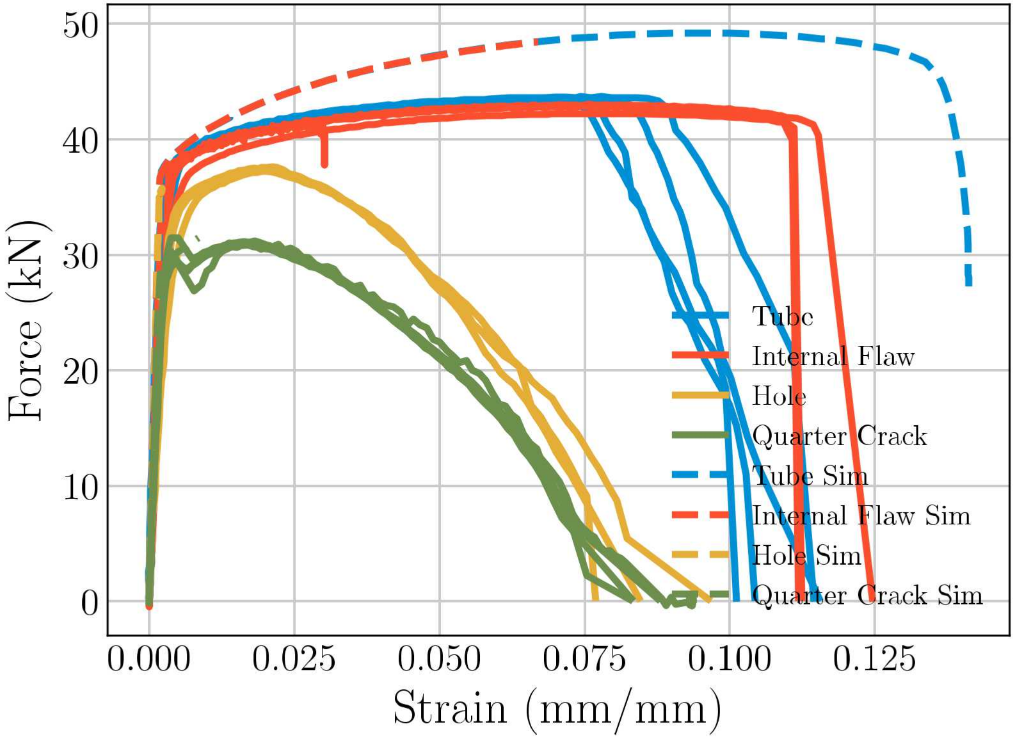


T. Ivanoff, D. Moore, J. Carroll , J. Madison

Ongoing Work: Investigating Design Effects on Performance







- Hollow LPBF 316L stainless steel tubes have different "defects" designed into wall thickness:
  - 1/4 diameter crack
  - 2mm cube through-hole
  - 0.2 mm cubic internal void
- Internal void design has greater ductility than tube with no flaw > design can control performance

Conclusions

- AM Materials often have significant material variability
- Part performance and failure can be predicted using existing tools
  - Part geometry can be used as a tool for flaw tolerance
- Significant scatter in tension data may not translate to scatter in part performance
- Porosity can possibly be accounted for using a damage formulation
- Different defect structures affect crack initiation and propagation

Future Directions

- Further examining using local damage model to represent spatial porosity
- Investigating effects of surface roughness
- What can be done with coarse CT scans?

Backup Slides