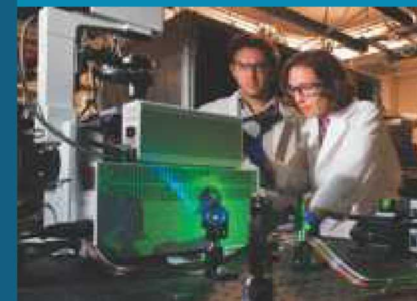
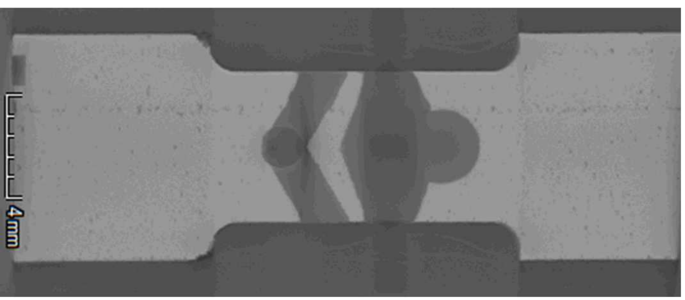
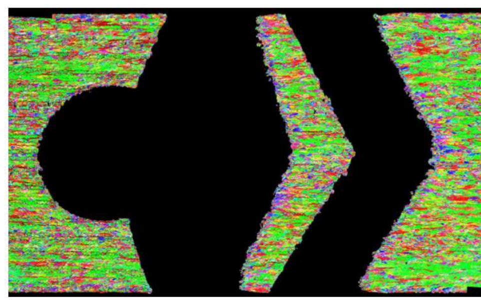
SAND2018-13036C

# Predicting Performance and Failure in Additively Manufactured Stainless Steel Parts





PRESENTED BY

**Kyle Johnson**, John Emery, Chris Hammetter, Judy Brown, Spencer Grange, Kurtis Ford, and Joseph Bishop

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# Outline

- Background on Sandia Fracture Challenge
- Modeling Approach
- Implementing Voids and Damage
- Blind Predictions
- Residual Stress Effects
- Summary

# Sandia Fracture Challenge

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

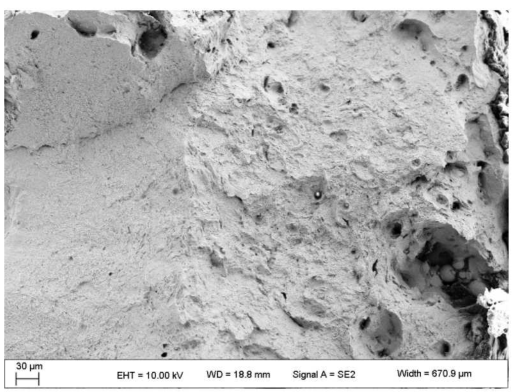
SANDIA FRACTURE CHALLENGE 2014

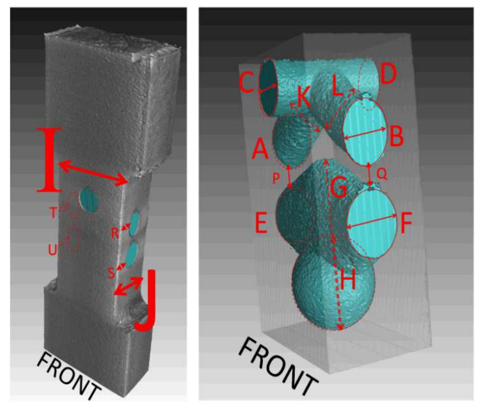
## The second Sandia Fracture Challenge: predictions of ductile failure under quasi-static and moderate-rate dynamic loading

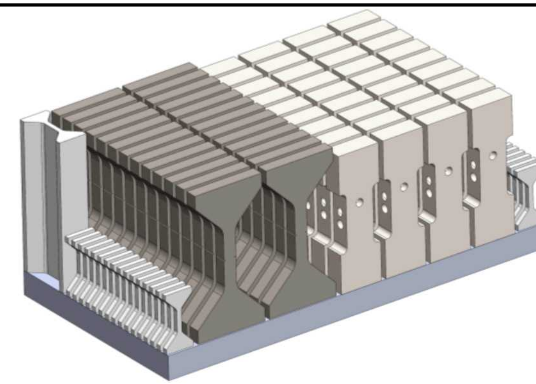
B. L. Boyce · S. L. B. Kramer · T. R. Bosiljevac · E. Corona · J. A. Moore · K. Elkhodary · C. H. M. Simha · B. W. Williams · A. R. Cerrone · A. Nonn · J. D. Hochhalter · G. F. Bomarito · J. E. Warner · B. J. Carter · D. H. Warner · A. R. Ingraffea · T. Zhang · X. Fang · J. Lua · V. Chiaruttini · M. 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

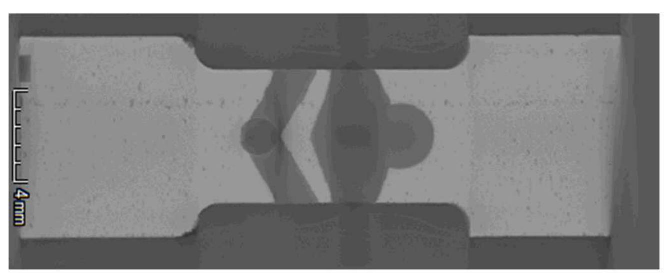
## The Third Sandia Fracture Challenge – 2016-2017

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






# Sandia/NM Predictive Approach

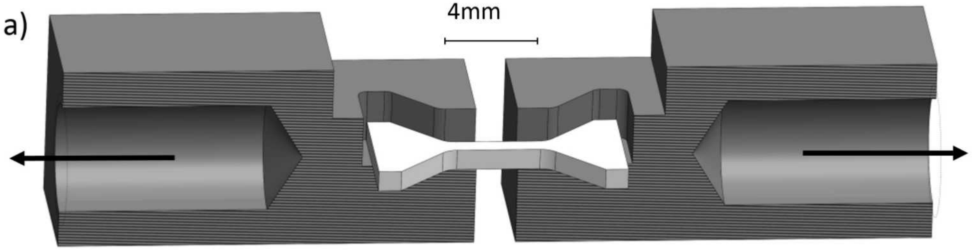
1. Fit robust plasticity model to calibration test data with porosity distributions as initial damage
2. Run many iterations of challenge geometry with many porosity distributions
3. Perform statistical analysis on results to enrich result distributions

SNL/NM Team Members: Kyle Johnson, John Emery, Kurtis Ford, Joe Bishop, Judy Brown, Chris Hammetter, Spencer Grange

Additional help from Kyle Karlson (SNL/CA)

# Tension Data Was Taken Using High Throughput Test Method

a)

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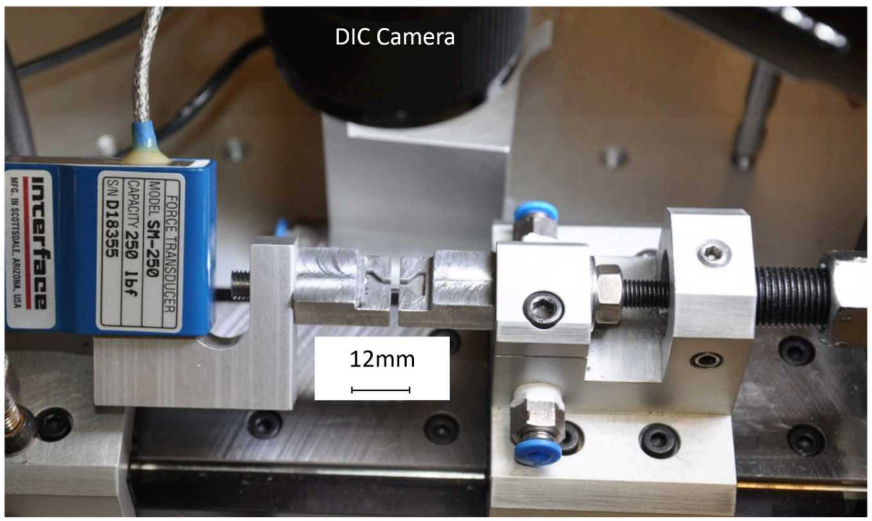
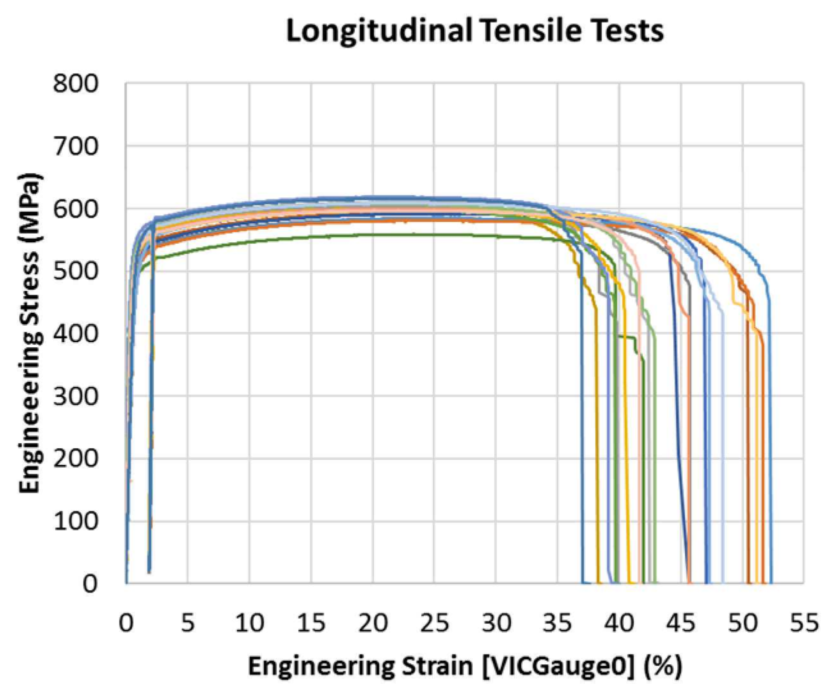
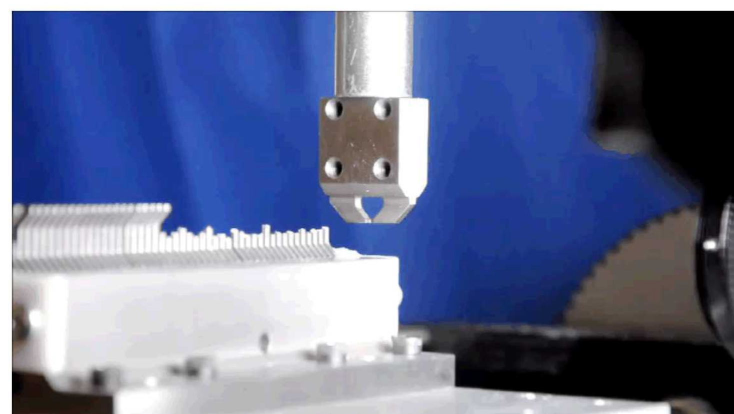


- B.L. Boyce *et al.*, “Extreme-value statistics reveal rare failure-critical defects in additive manufacturing”, *Advanced Engineering Materials*, 2017.
- B.C. Salzbrenner *et al.*, “High-throughput stochastic tensile performance of additively manufactured stainless steel”, *Journal of Materials Processing Technology*, 2017.

# BCJ Material Model

- Temperature and history-dependent viscoplastic internal state variable model
- Stress is dependent on damage $\phi$ and evolves according to

$$\dot{\sigma} = \left(\frac{\dot{E}}{E} - \frac{\dot{\phi}}{1-\phi}\right)\sigma + E(1-\phi)(\dot{\epsilon} - \dot{\epsilon_p})$$

- Flow rule includes yield stress and internal state variables for hardening and damage

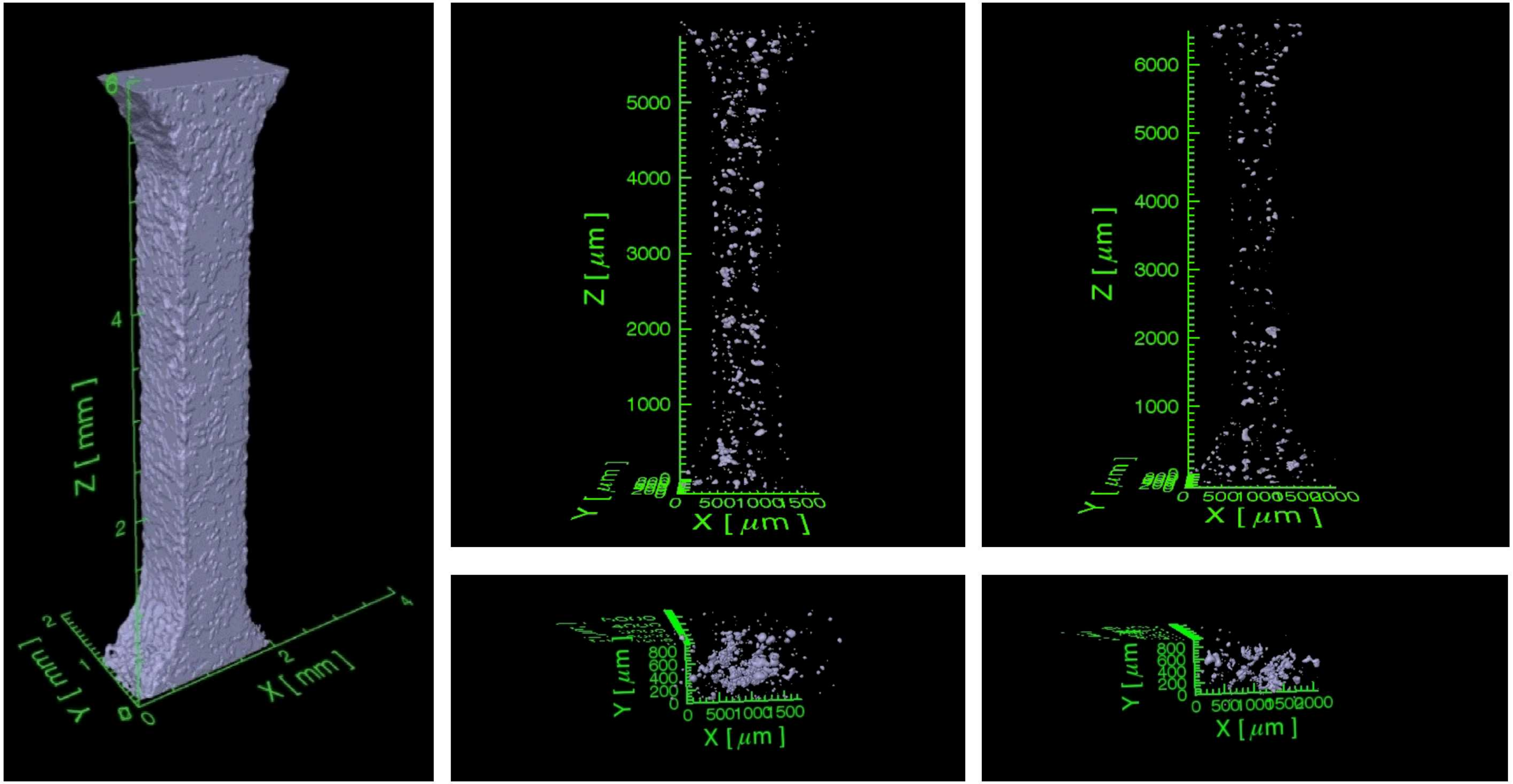
$$\dot{\epsilon}_p = f\,sinh^n\left(\frac{\frac{\sigma_e}{1-\phi} - \kappa}{Y} - 1\right)$$

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

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

(Bammann *et al*. 1993, Brown and Bammann 2012)

# AM Parts Can Contain Many Pores

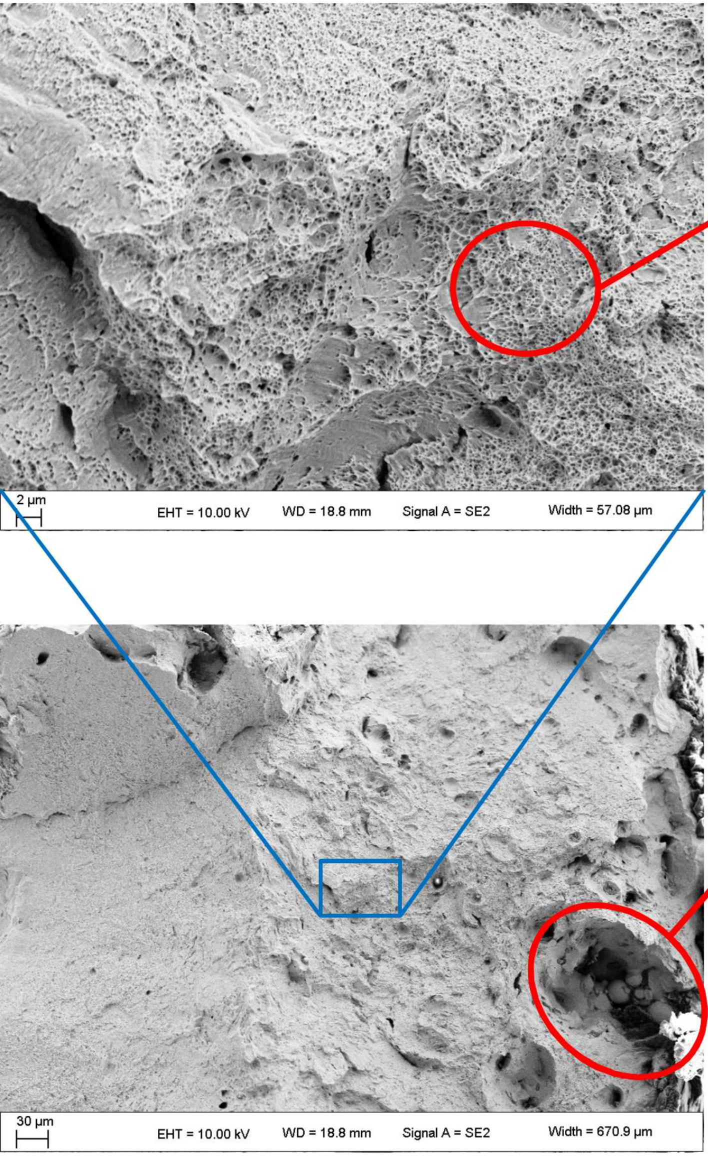



*3D μCT surface render* *3D μCT internal porosity*

Tremendous variation in pore content from sample to sample
Pore locations reminiscent of AM laser raster pattern

*J. Madison, T. Ivanoff, O. Underwood*

# Incorporating porosity as initial damage




## Void Nucleation

Fine scale voids (< 1$\mu$m) indicate nucleation

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

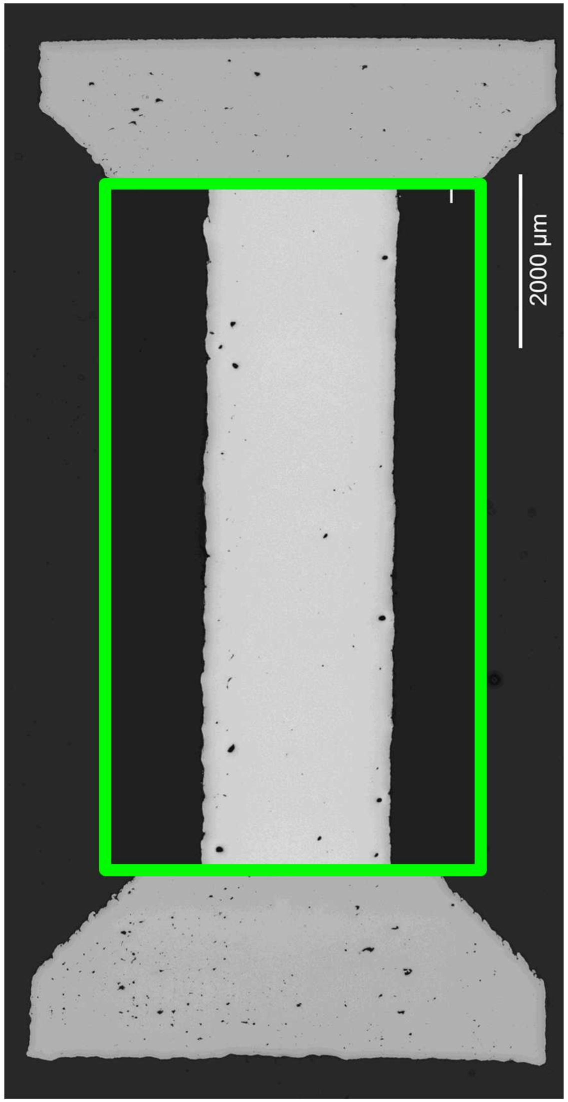
## Void Growth

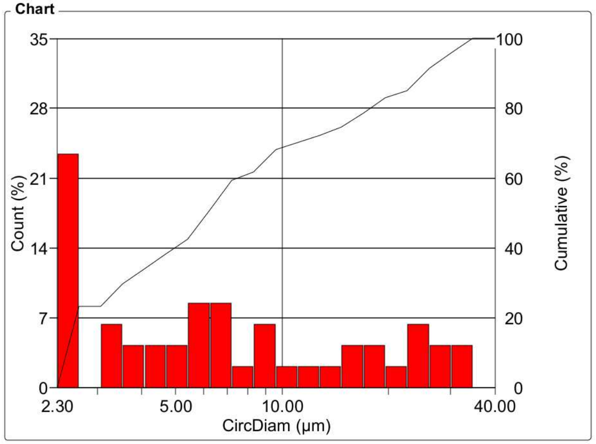
Pre-existing voids captured by void growth

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

(Horstemeyer & Gokhale 1999)

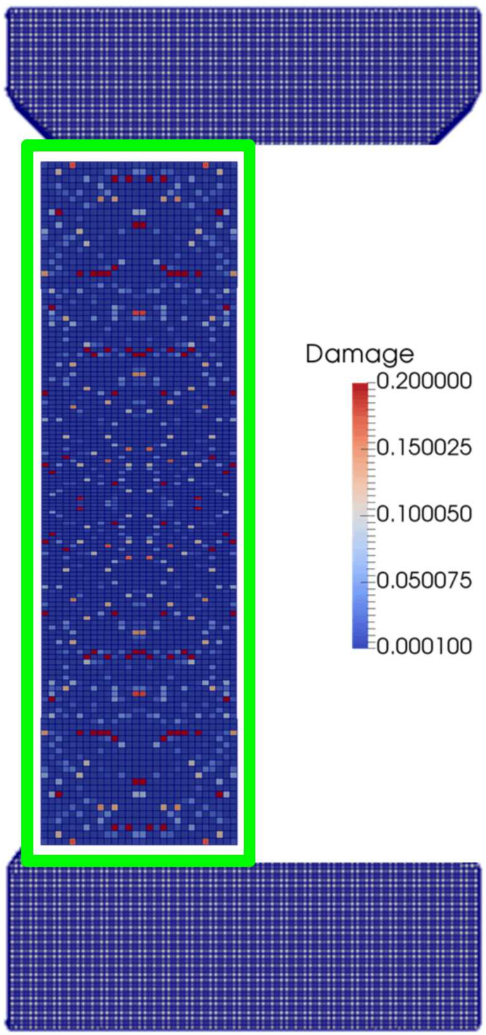
# Porosity Distribution Directly Mapped to Mesh



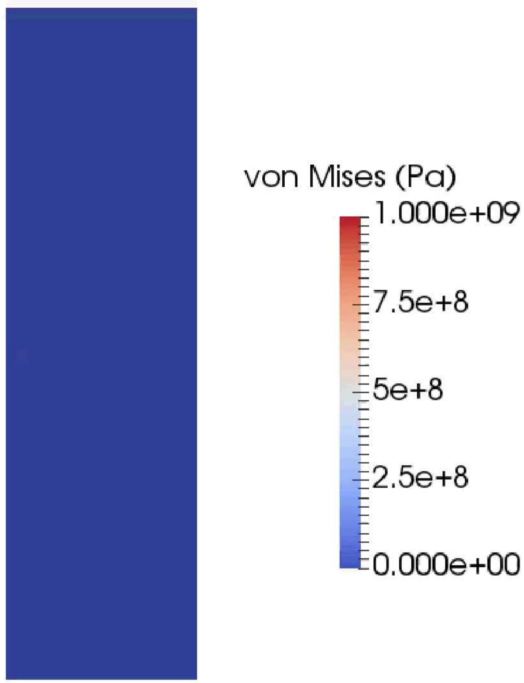



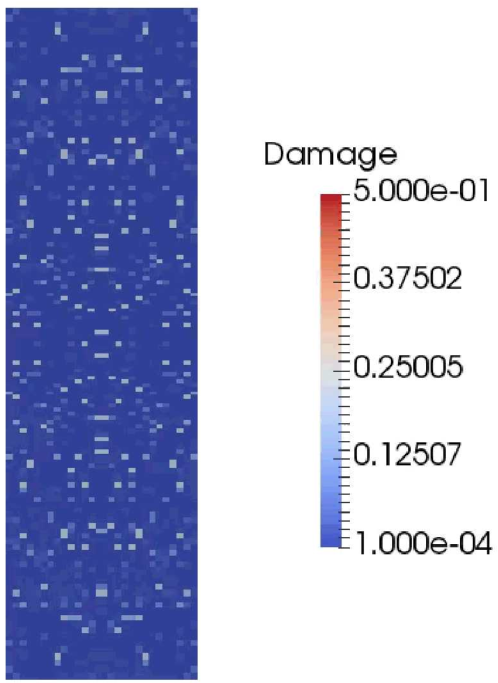

Porosity Mapping

$x,y,z,r_{pore}$

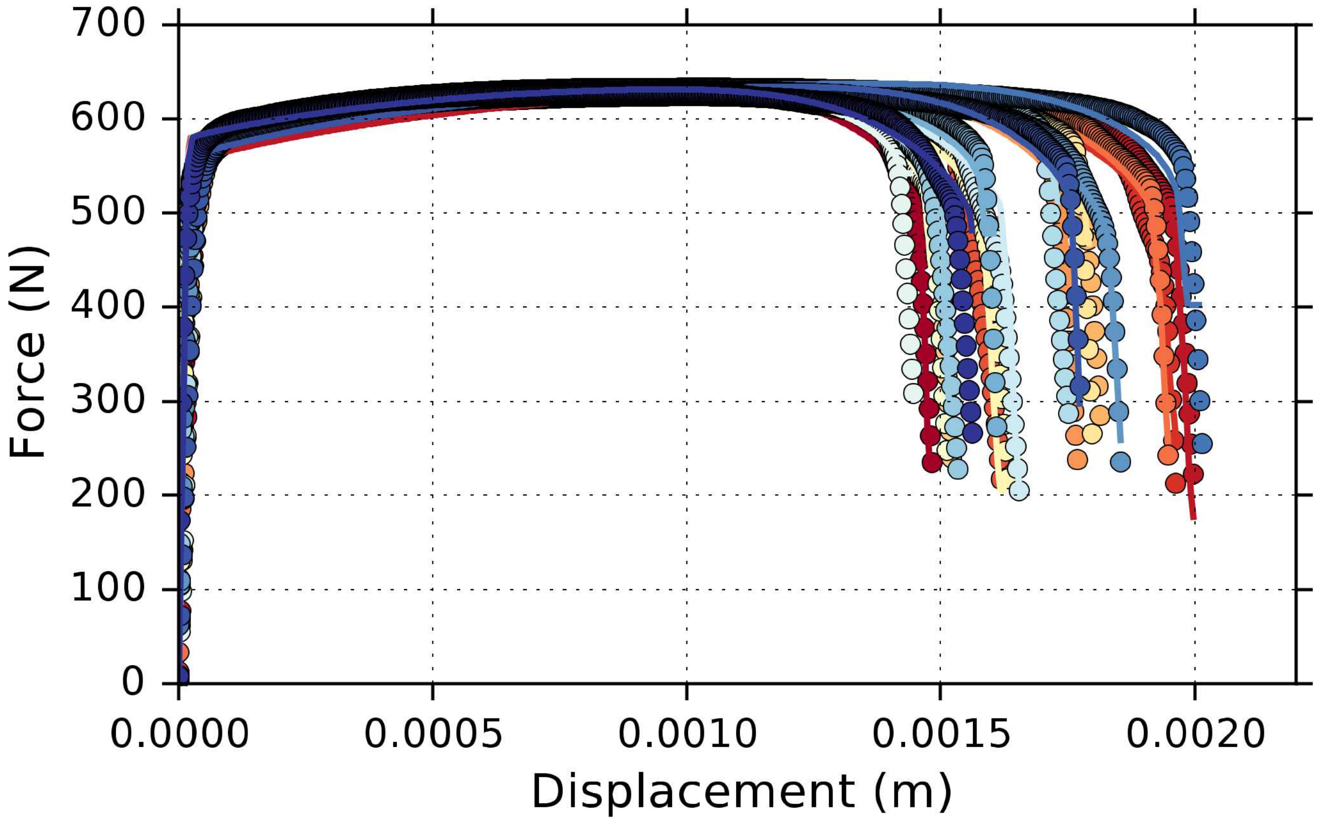


# Tensile Calibration Results



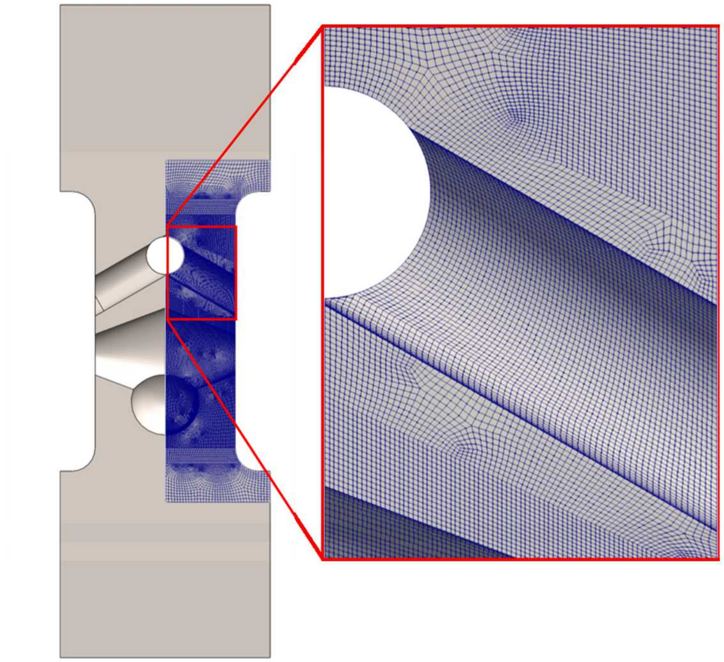



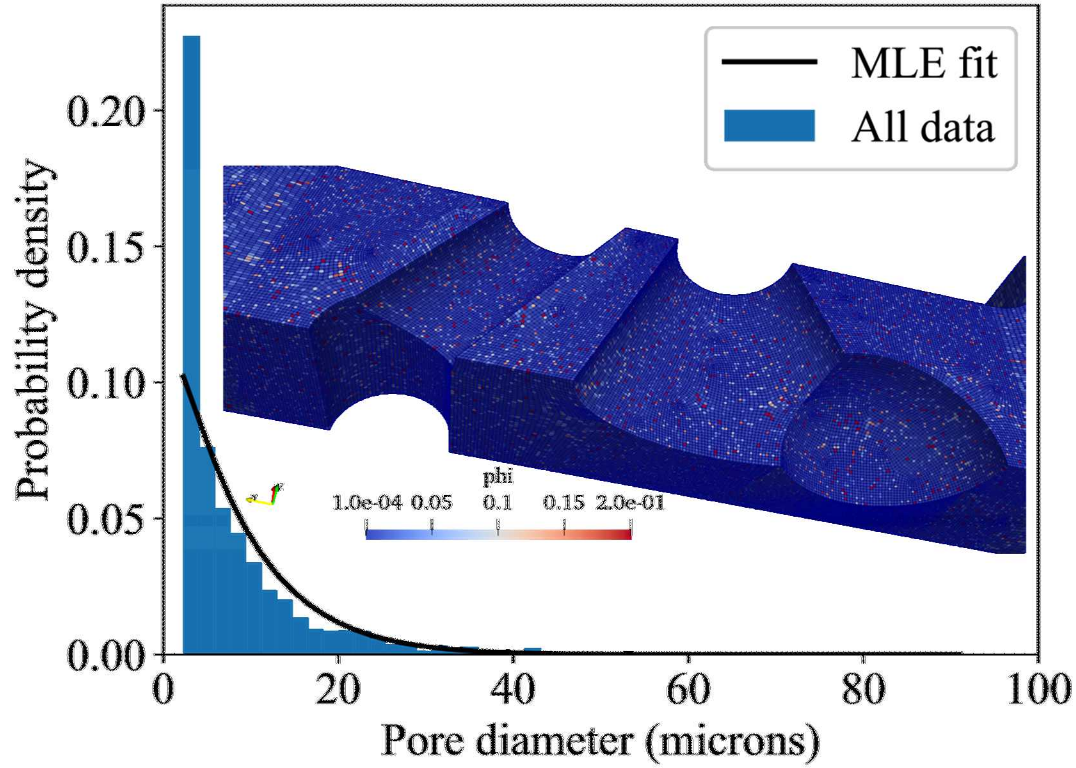
# Calibration Results With Void Growth and Nucleation



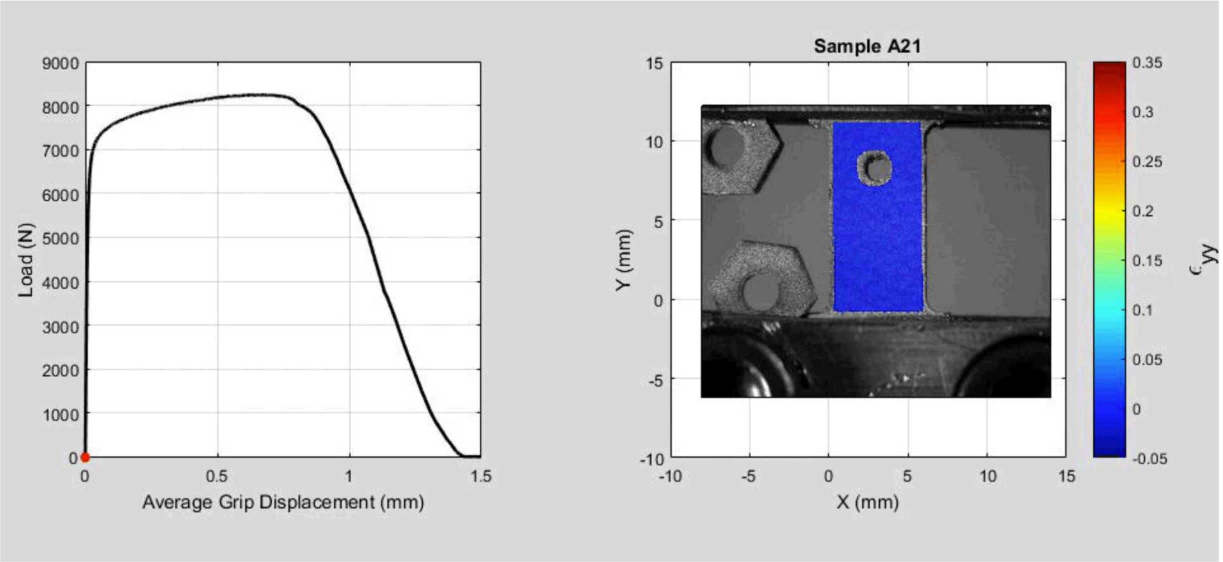

- Each test has unique parameter set
- Challenge geometry was simulated using all 20 parameter sets

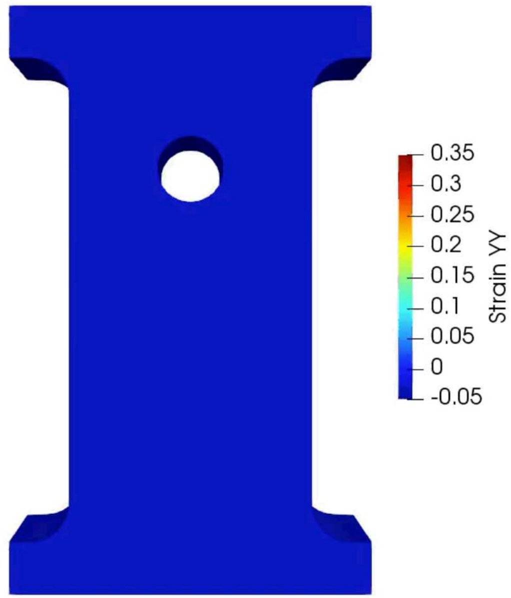
# Porosity Distribution Directly Mapped to Challenge Geometry

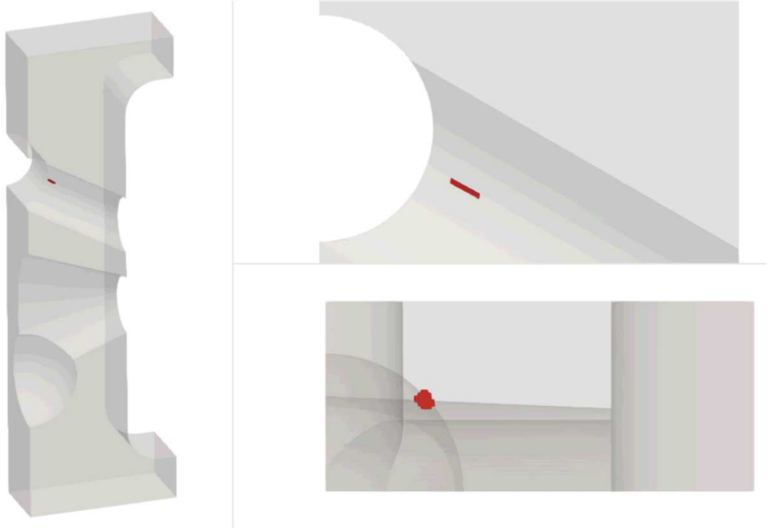


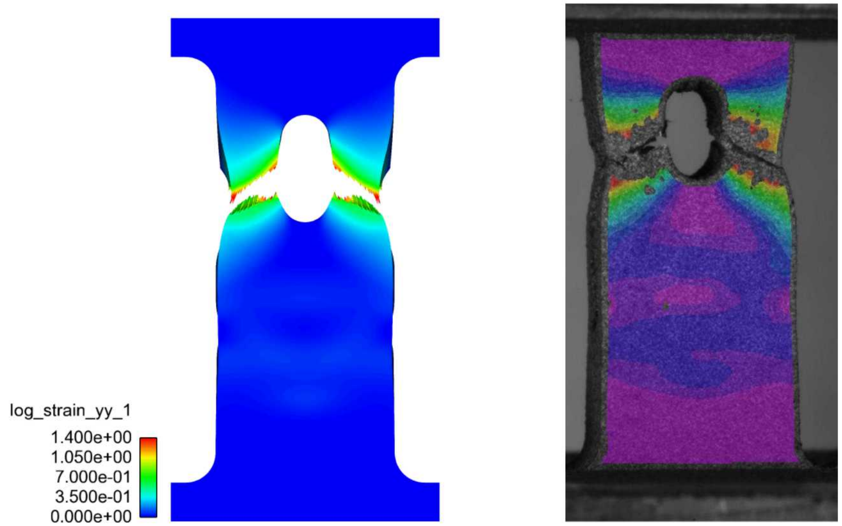


# Performance Prediction and Experiments



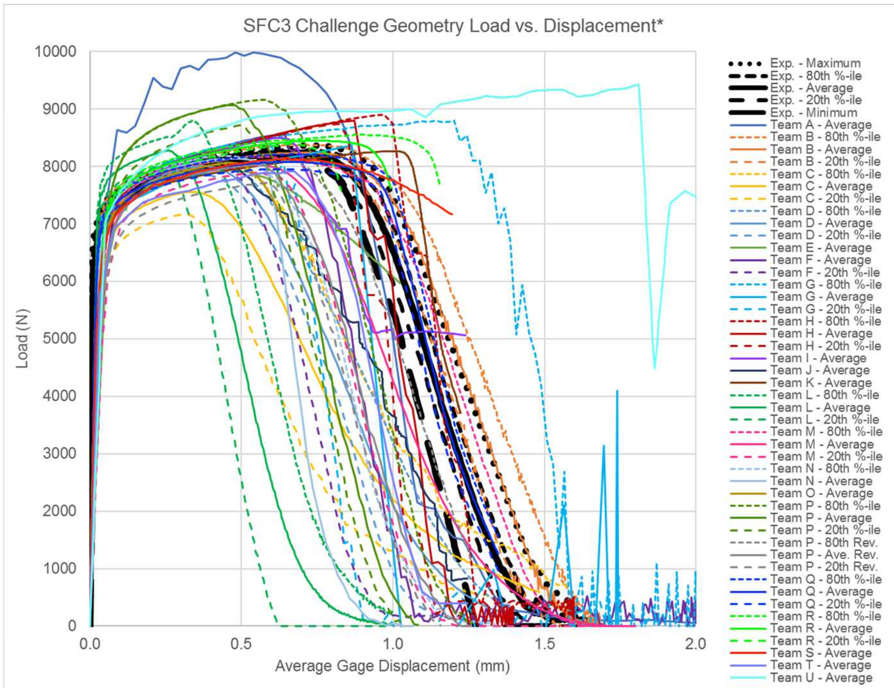



*Kramer, Boyce* et al., *IJF (In preparation), Johnson* et al. *IJF (In preparation)*

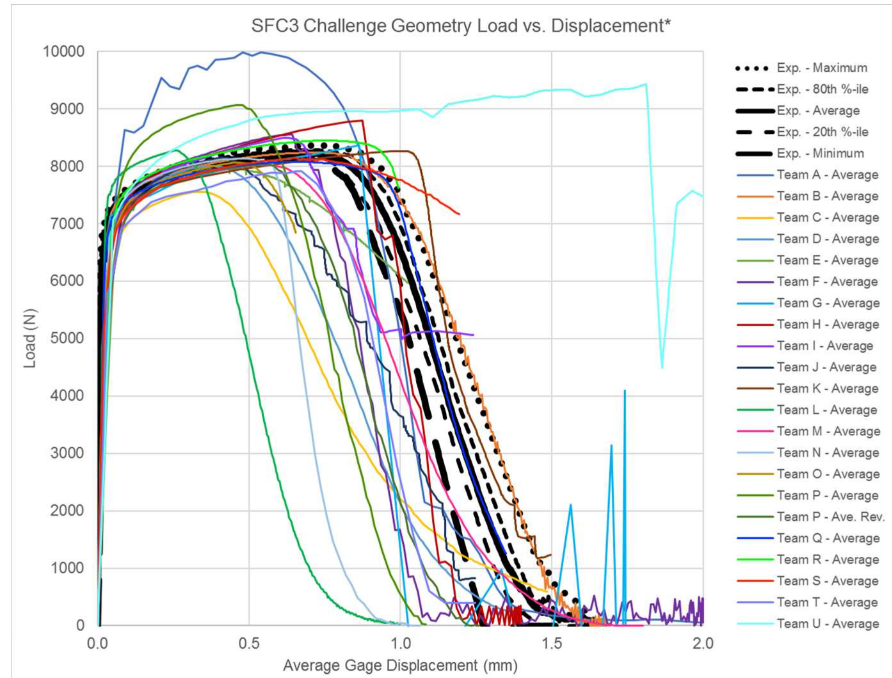
# 21 Participant Predictions Covered A Wide Range of Responses



### 21 Predictions and Bounds with Exp. Average and Bounds

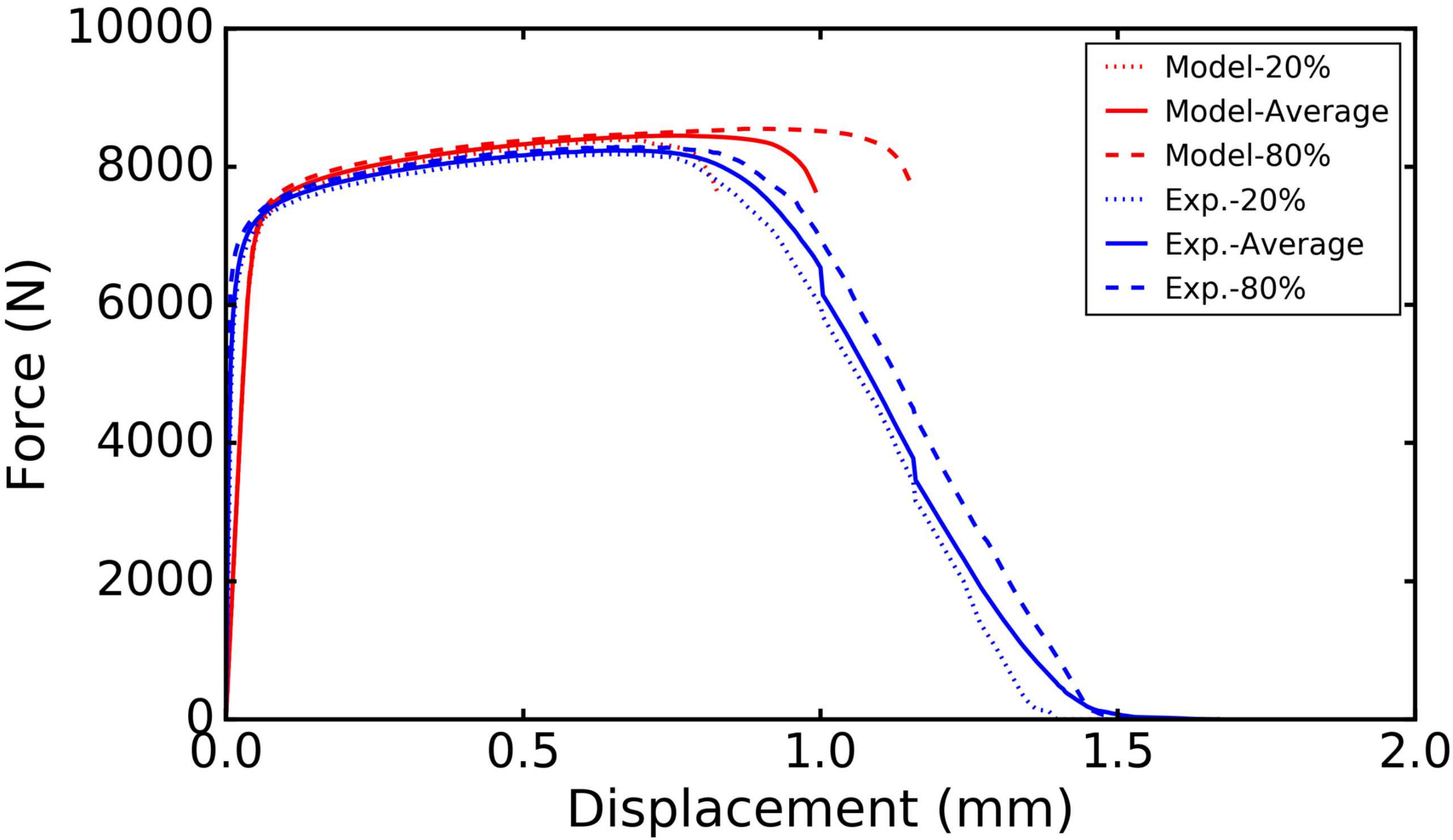



### 21 Nominal Predictions with Exp. Average and Bounds




*Kramer, Boyce* et al., *IJF (In preparation), Johnson* et al. *IJF (In preparation)*

# Blind Predictions of Force-Displacement Curves Compare Reasonably Well With Experiments

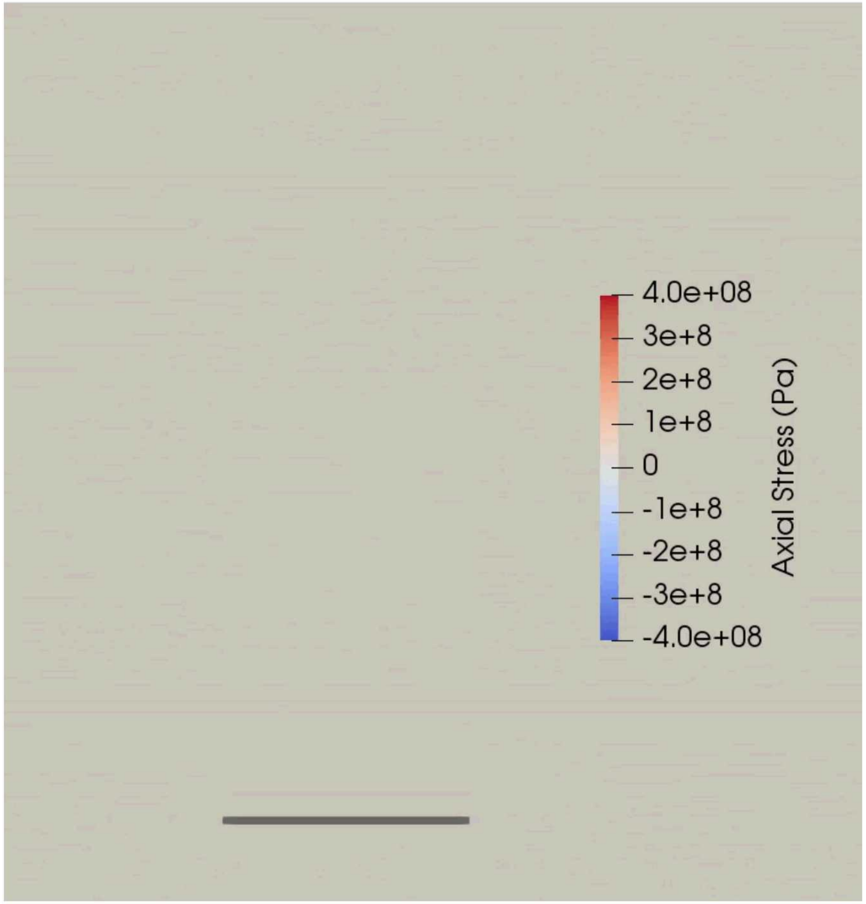


# Inherent Strain Model for Residual Stress Prediction

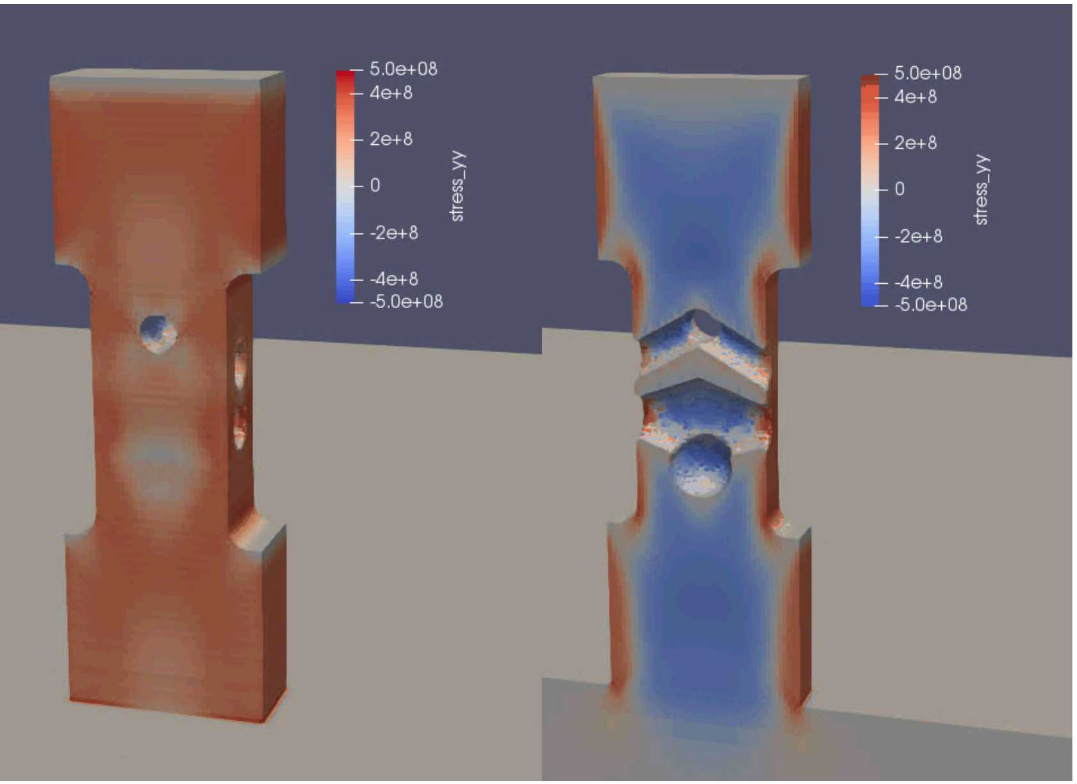
- Part size is challenging for full solution
- Inherent strain method developed for weld stress prediction
    - (Ueda, Fukuda, Tanigawa 1979; Ueda, Kim, Yuan 1980, Hill and Nelson 1995)
- Strain tensor is applied in layers over time
    - Quick approximation for distortion and stress
- Does not capture local variations due to different thermal gradients

$$\varepsilon = \begin{bmatrix} -0.0194 & 0 & 0 \\ 0 & \boxed{0.0255} & 0 \\ 0 & 0 & -0.0194 \end{bmatrix}$$

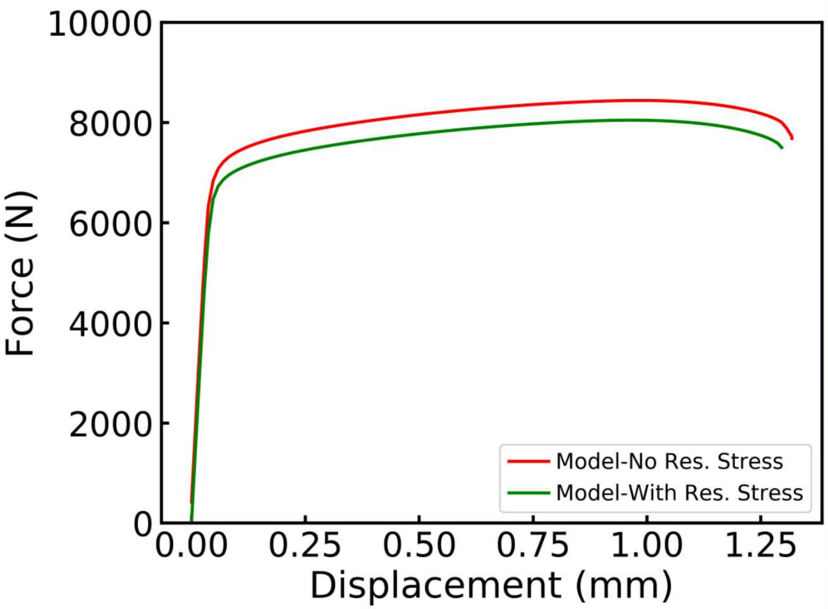
Build Direction



# Residual Stress Decreases Force Prediction




As-built Residual Stress




Residual Stress Effect on Challenge Prediction

# Summary

- Continuum scale modeling of AM part performance compared well in blind predictions
- Significant scatter in tension data may not translate to scatter in part performance
- Crack initiation and propagation was correctly predicted
- Porosity can possibly be accounted for using a damage formulation

# Future Work

- Investigate effects of surface roughness
- Add rate dependence to model