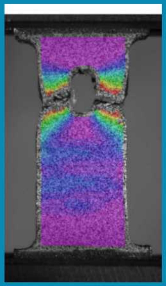
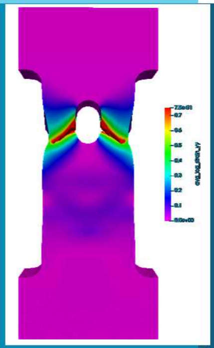
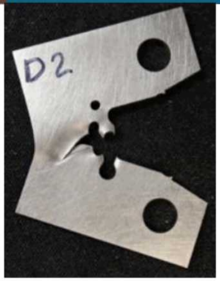
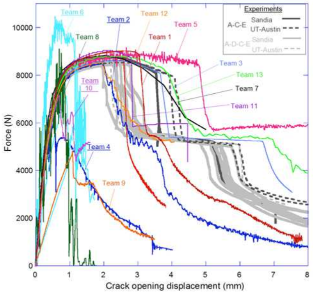
SAND2019-6519C

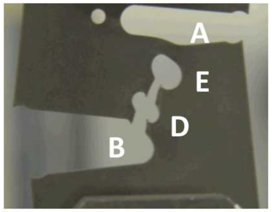
The Third Sandia Fracture Challenge: A Deep Dive into the Experimental Results

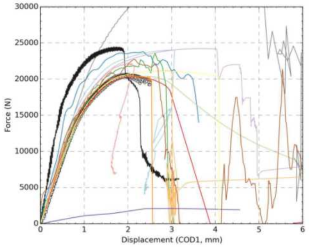


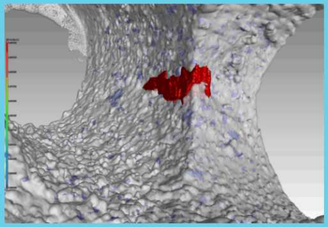












Sharlotte Kramer, Brad Boyce, **Amanda Jones,**
Jhana Gearhart, Brad Salzbrenner, Thomas Ivanoff,
Jonathan Madison, and Andrew Lentfer

12 June 2019

CFRAC 2019- Braunschweig, Germany

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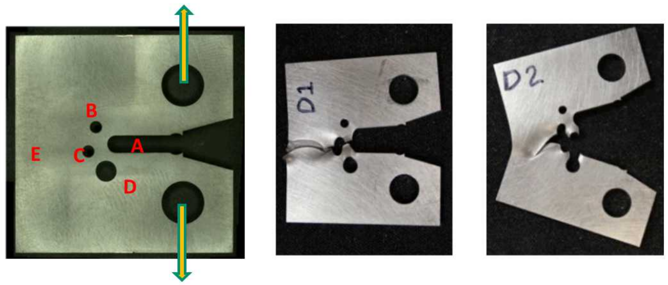
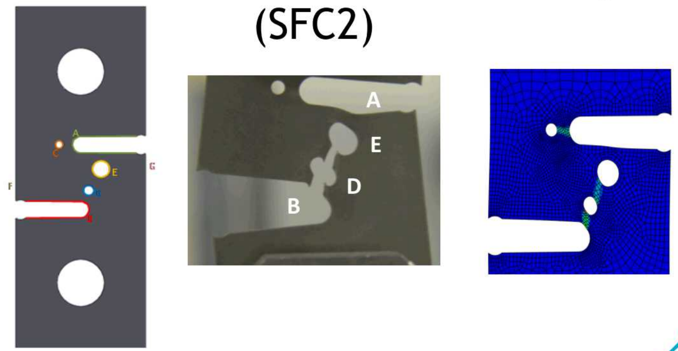
Presentation Organization

What is the Sandia Fracture Challenge?

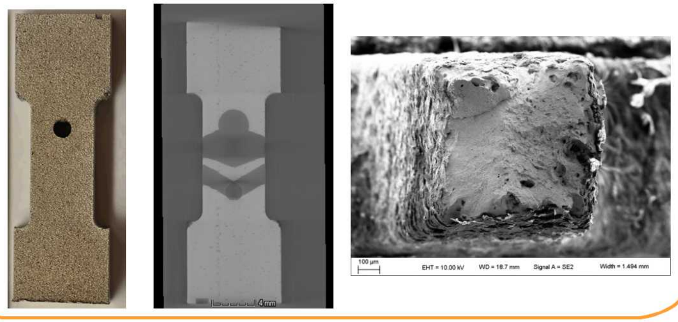
First Sandia Fracture Challenge
(SFC1)



Second Sandia Fracture Challenge
(SFC2)



Third Sandia Fracture Challenge
(SFC3)

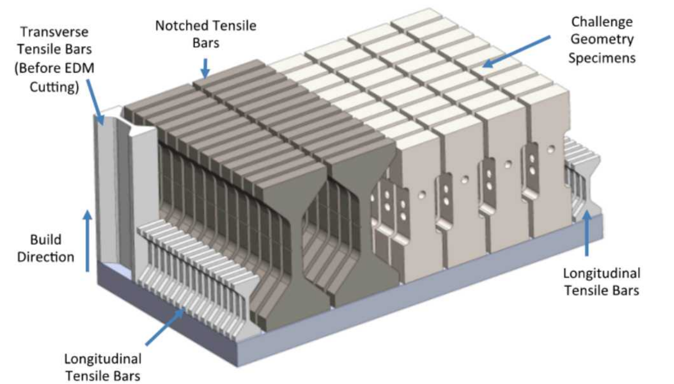


Structural Reliability Partnership
(SRP)

SFC3: Failure in an AM Metal

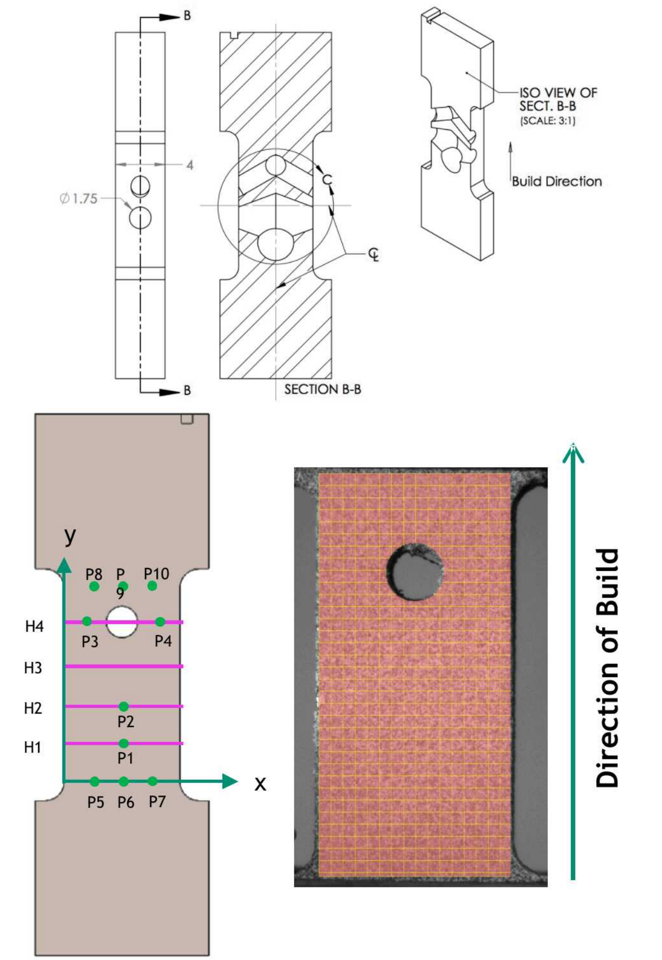
The Third Sandia Fracture Challenge explores the experiments and model methods required to predict ductile failure in AM metal parts.

SFC3 AM Build Plate



Description of Challenge

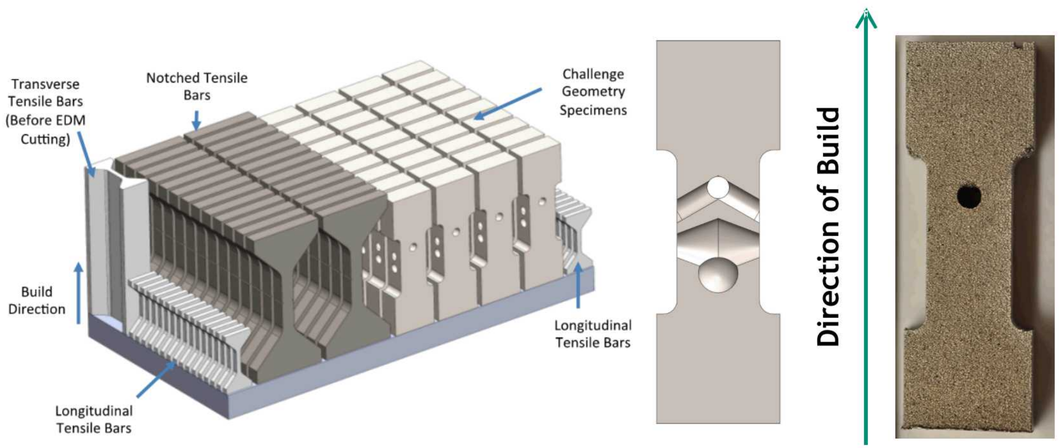
- **Material:** Additively manufactured 316L stainless steel
- **Extensive material property information**
- **Six Questions of global and local measures** based on load and DIC measurements
  - Required nominal response and requested 20^{th} and 80^{th} percentile bounds as optional
- **Challenge Issuance: December 15^{th}, 2016**
- **Prediction Deadline: July 15^{th}, 2017**

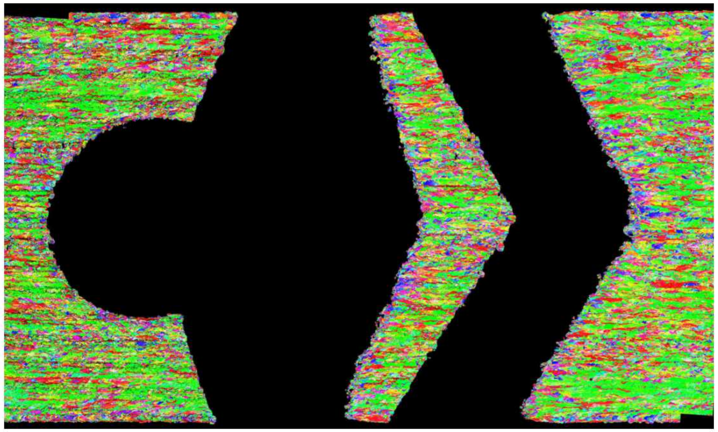


Challenge Geometry: Drawing (Top Image),Front View Schematic of Points and Lines of Interest (Bottom Left Image), and Representative DIC Area of Interest 41-pix Subsets (Bottom Right Image)

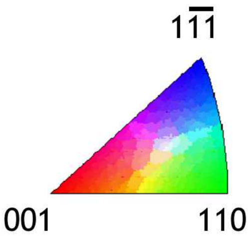
Examples of Provided Data

AM Build of All Test Specimens (Left); Central Cross-Section Schematic (Center) and Front Views of the Challenge Geometry (Right)

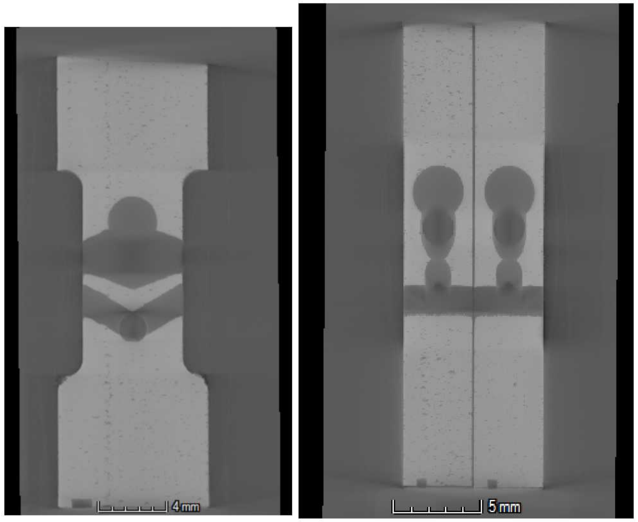




EBSD Inverse Pole Figure (IPF) in Build Direction

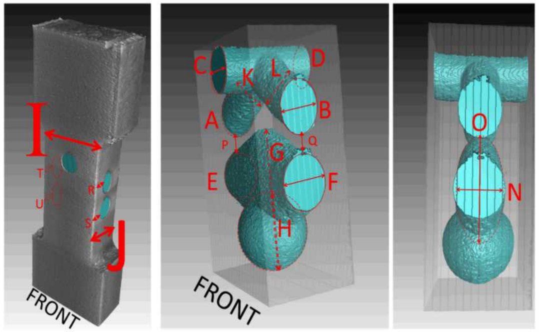


Example of micro-CT Scans of Challenge Geometry



A32 Front View "Thick Slab" Image

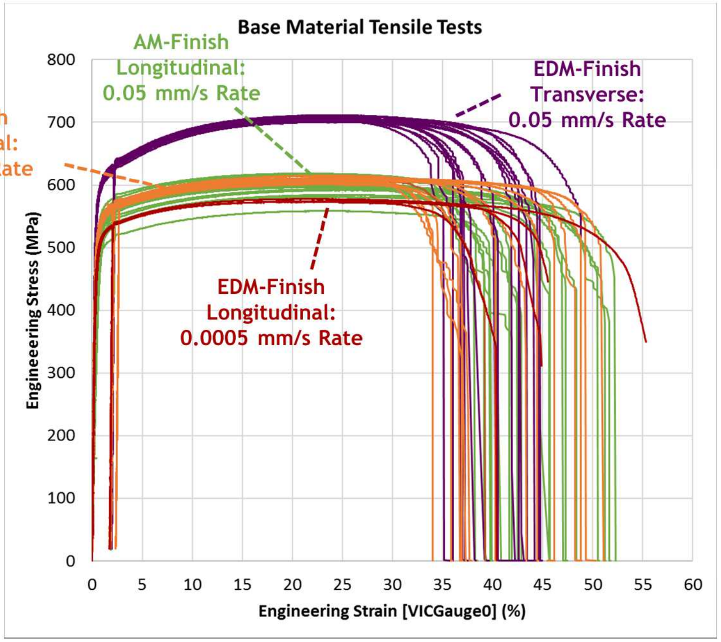
Side View Image of A32 (left) and A15 (Right)

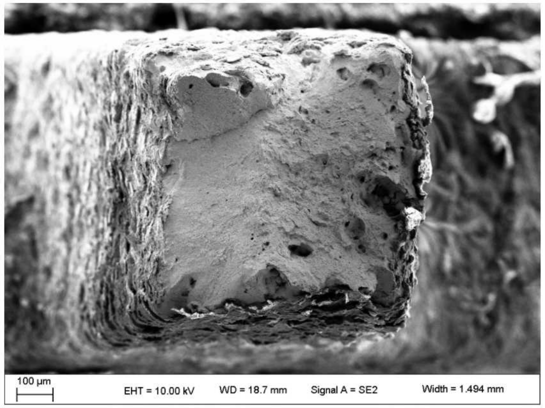


Reconstructed micro-CT Scans with Provided Feature Measurements

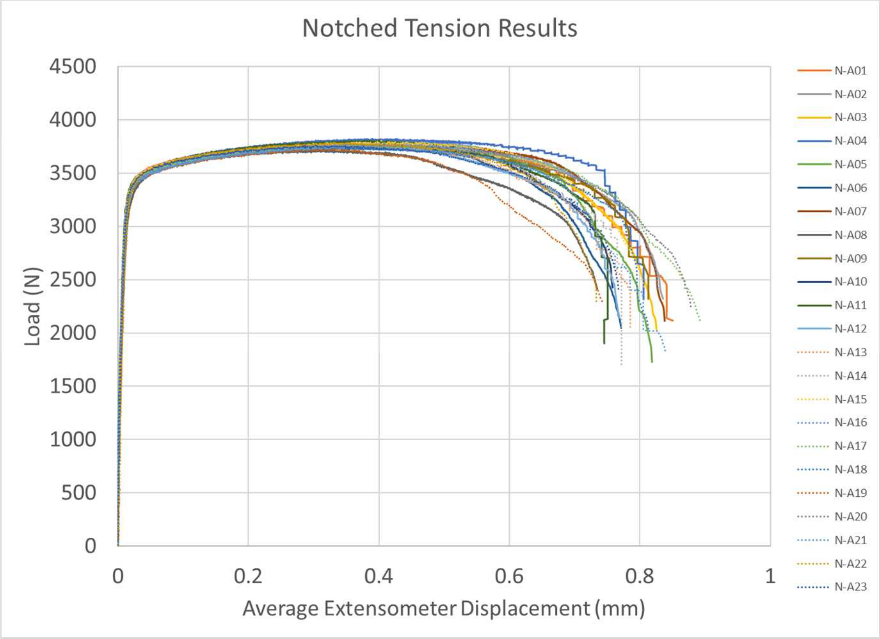
Examples of Provided Data

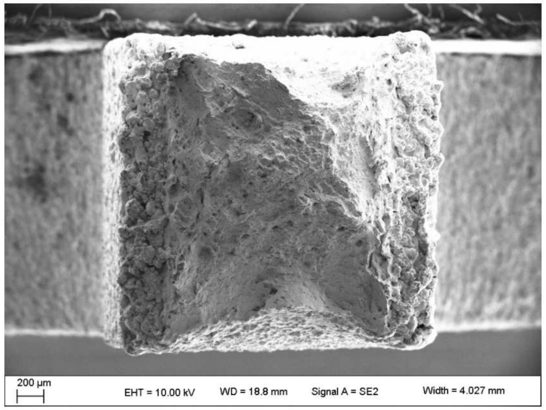
Base Material Test Data (Top); SEM Image of Fracture Surface of Tensile Specimen LTA04 (Bottom)



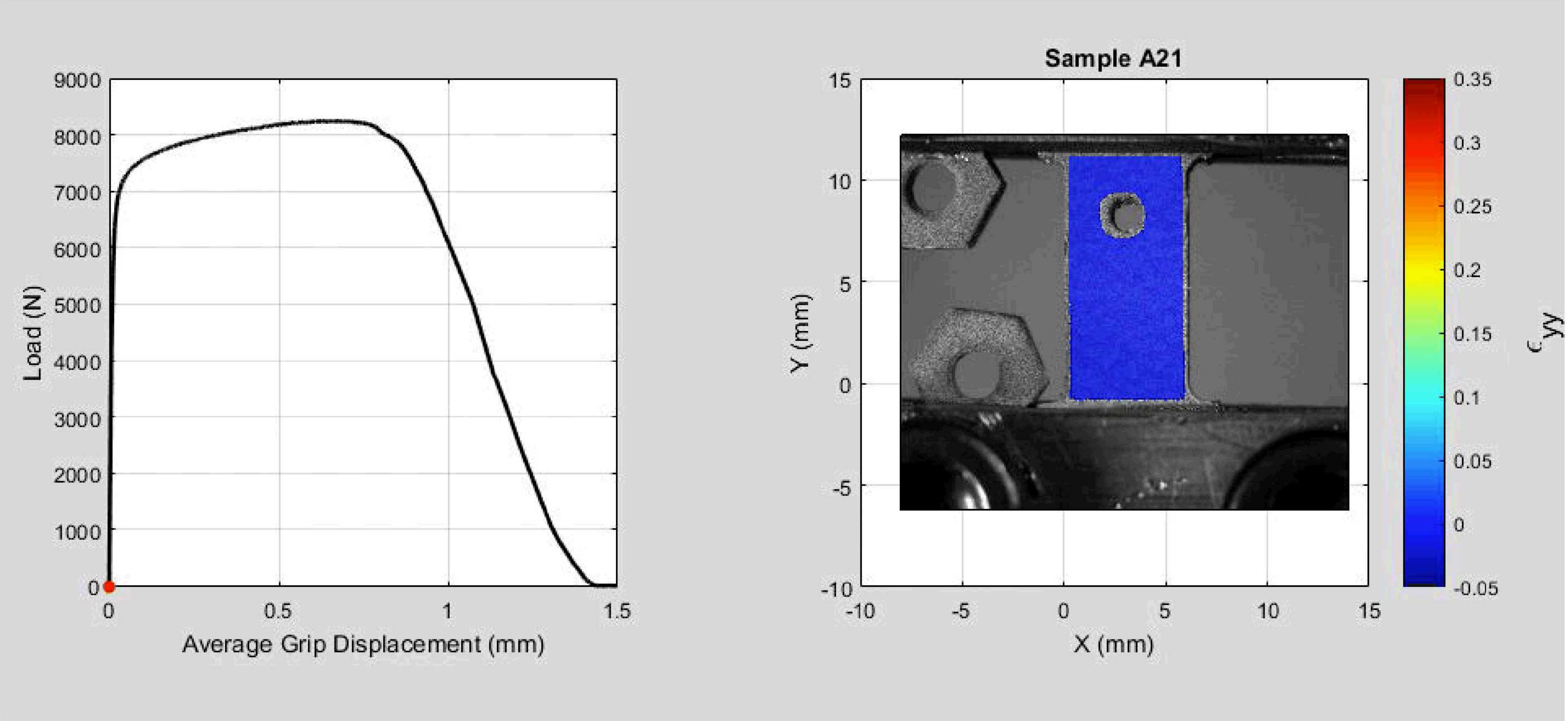


Notched Tensile Test Data (Top); SEM Image of Fracture Surface of Notched Tensile Specimen NA05 (Bottom)





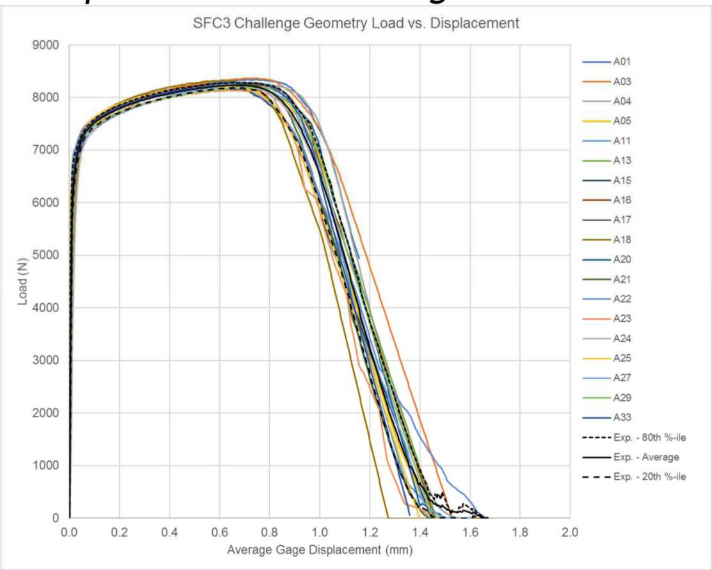
Challenge Geometry Experimental Result



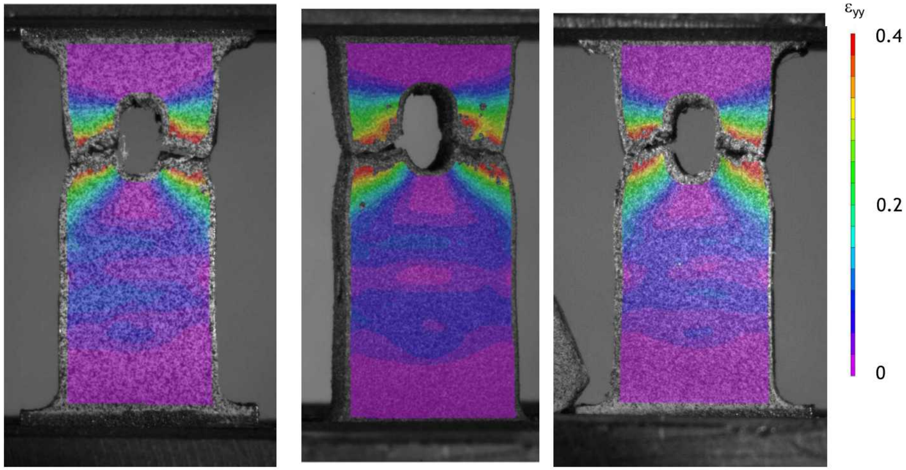
Experiments: Question 3 & 6

Force vs. Gage Displacement D

19 Specimens with Average and Bounds



Hencky Tensile Strain Fields at Failure



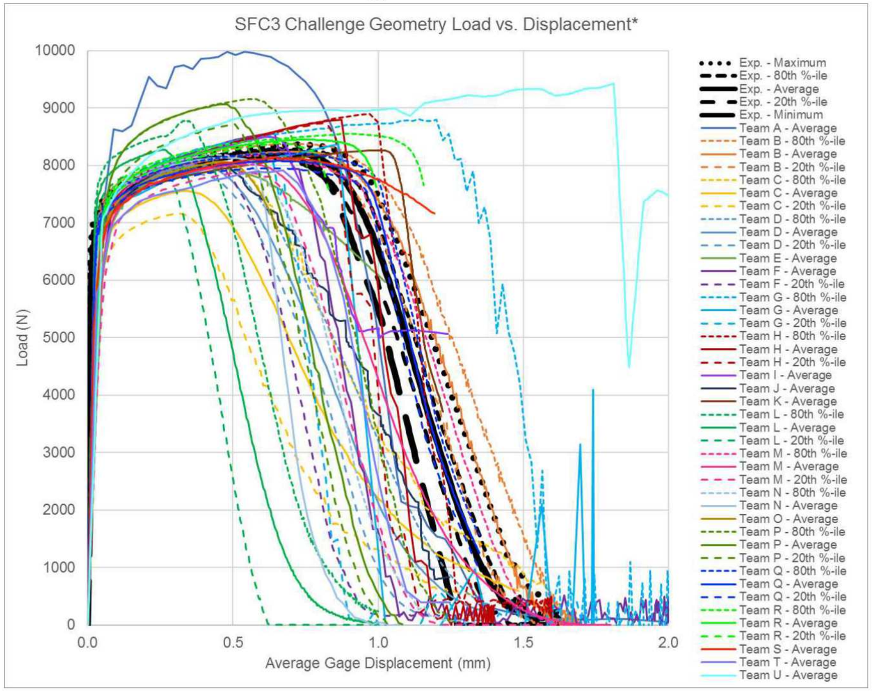
A04 A05 A21

- Relatively repeatable experimental data set with all specimen failing in nominally the same location
- Experimental data from two testing laboratories overlap
- Crack path is similar for each specimen, but not necessarily following the angled channels

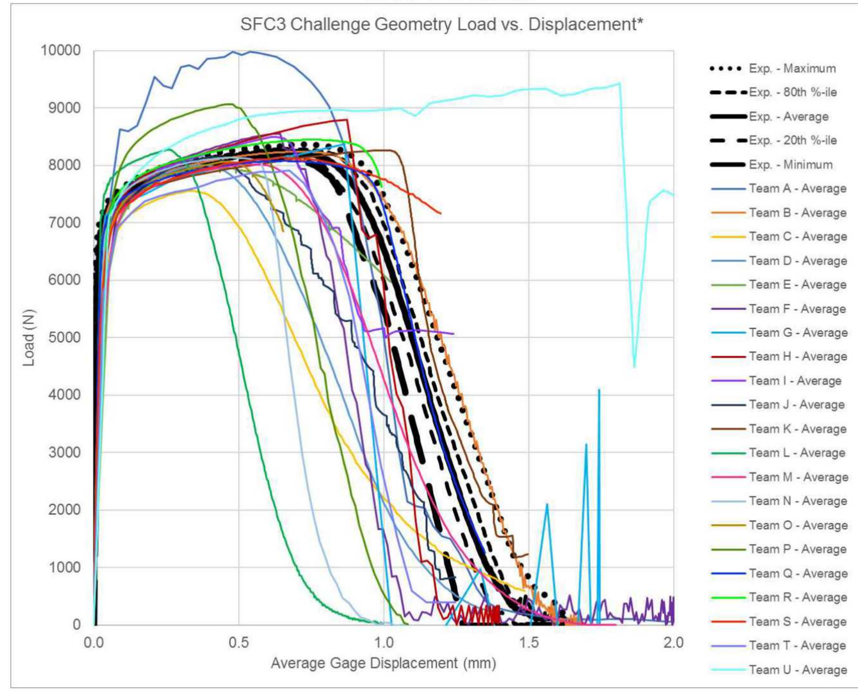
Digital Image Correlation Parameters		
Subset	41 pixel x 41 pixel	0.368 mm x 0.368 mm
Step	7 pixels	0.063 mm
Strain Window	9 step	--
Virtual Strain Gage	57 pixel	0.512 mm

Predictions: Global Measures

21 Predictions and Bounds with Exp. Average and Bounds

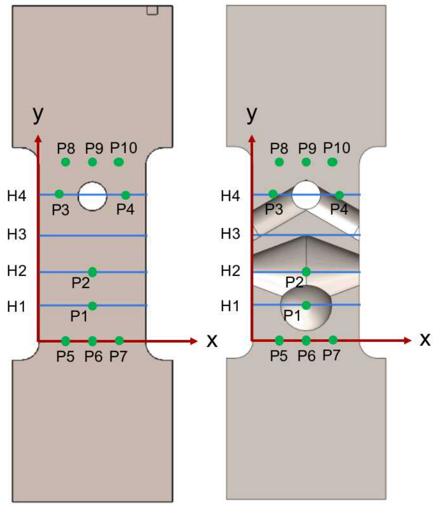


21 Nominal Predictions with Exp. Average and Bounds



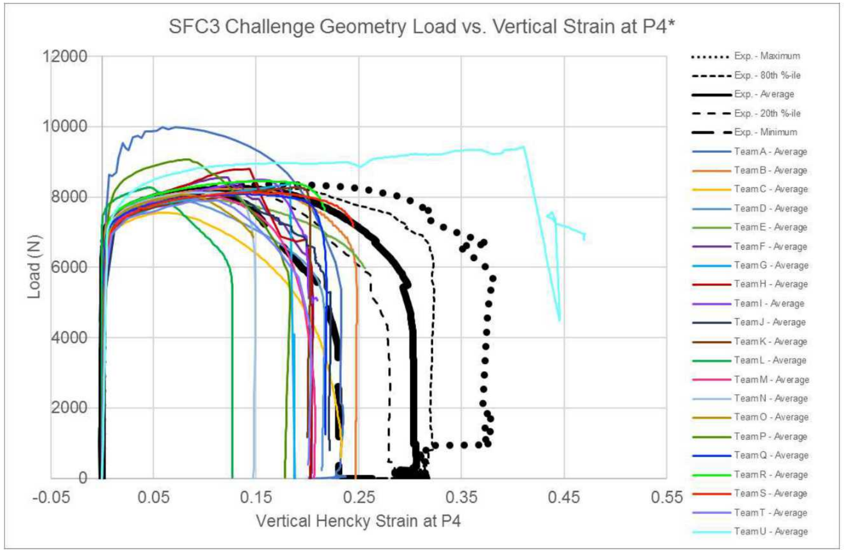
- **All 21 predictions correctly identified the nominal crack path with initiation at the through-thickness hole**
- More teams under-predicted the failure displacement than over-predicted.
- There were only two teams whose nominal prediction fell within the bounds of the experimental data (Teams B and Q)
- The uncertainty bounds on predictions ranged from too small to too large

Predictions: Local Measures



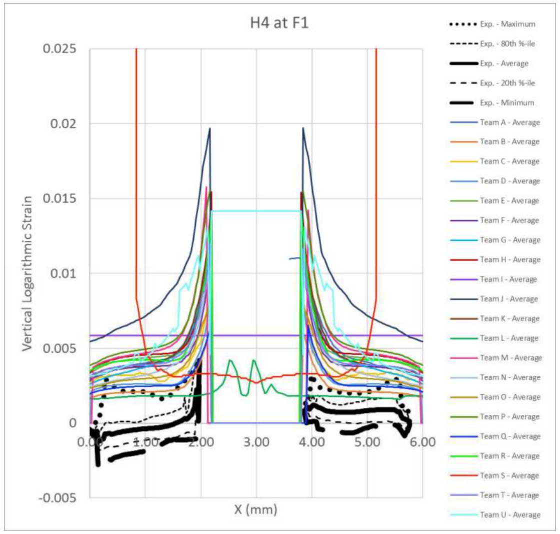
Challenge Geometry (Surface - Left, Cutaway - Right)

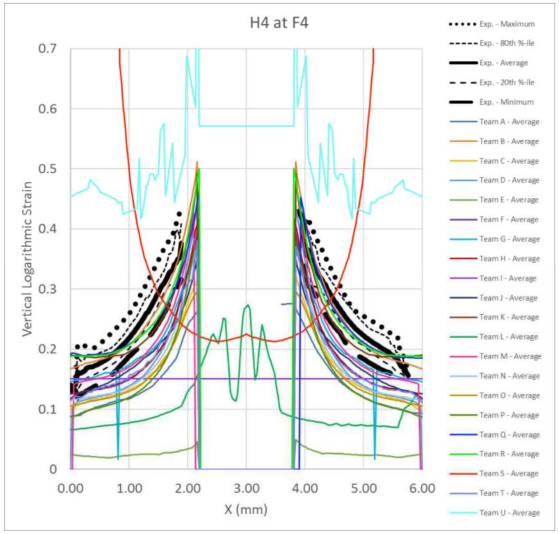
Question 4: Report force vs. Hencky strain in the vertical direction (ε_{yy}) at P4.



Strain predictions close to failure were generally too low.

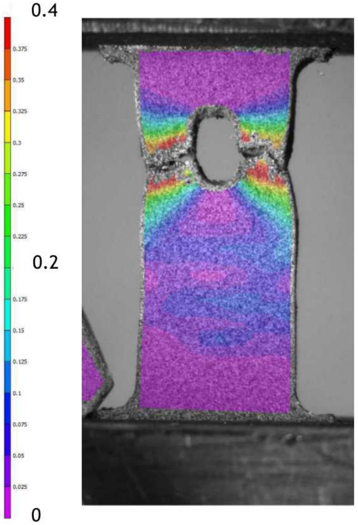
Question 5: Report force and Hencky strain in the vertical direction (ε_{yy}) along horizontal line H4 on the surface at forces F1, F2, F3, and F4.



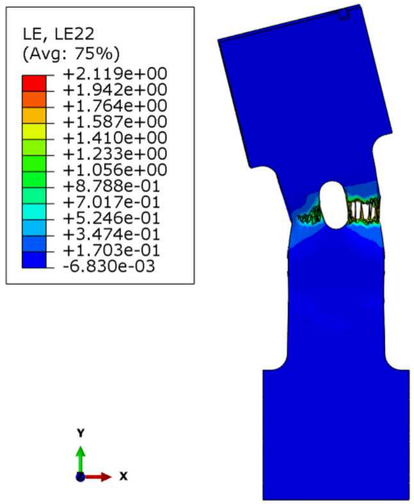


Most teams over-predicted the nominal strain at F1, but many teams' predictions improved for higher forces.

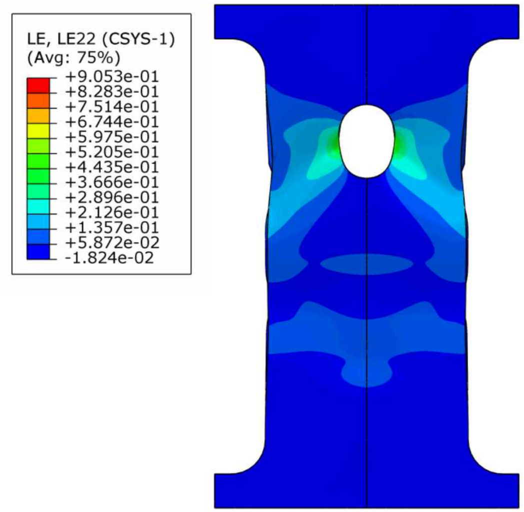
Example Predictions: Question 6 Failure - Strain



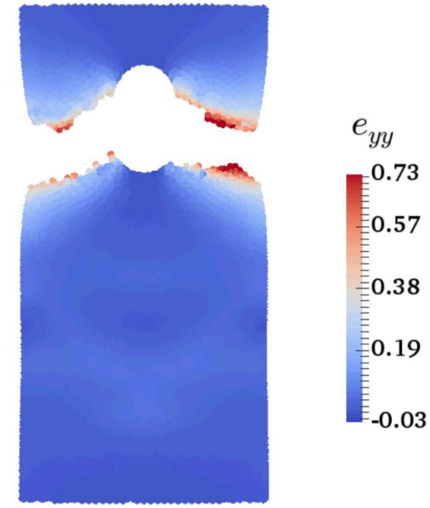
A13



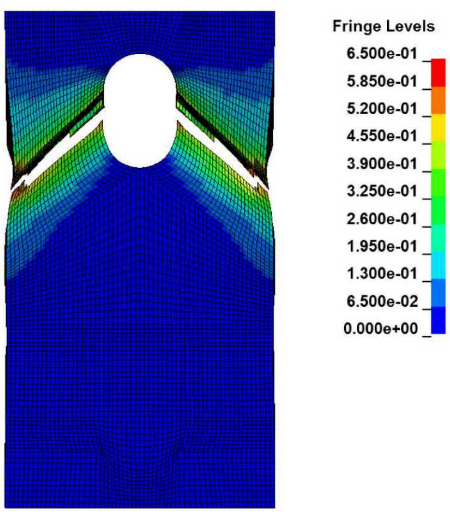
Team A



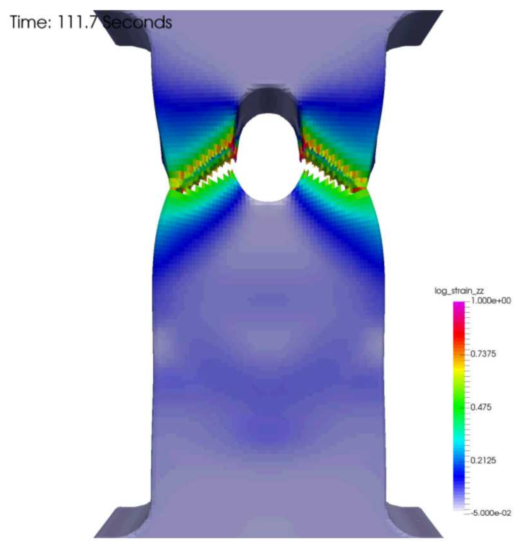
Team B



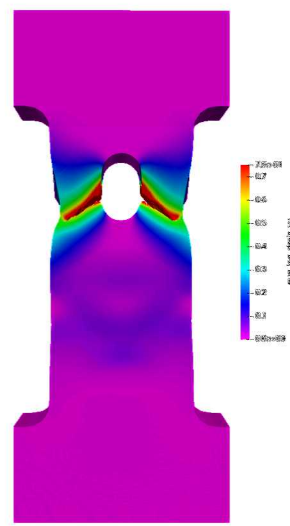
Team C



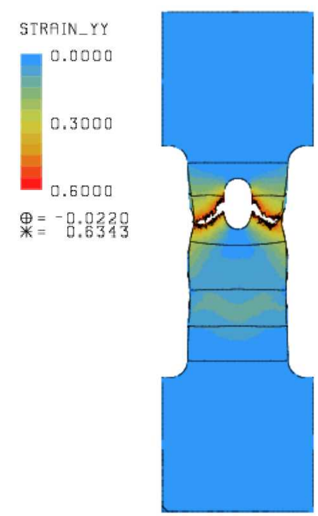
Team L



Team M



Team Q

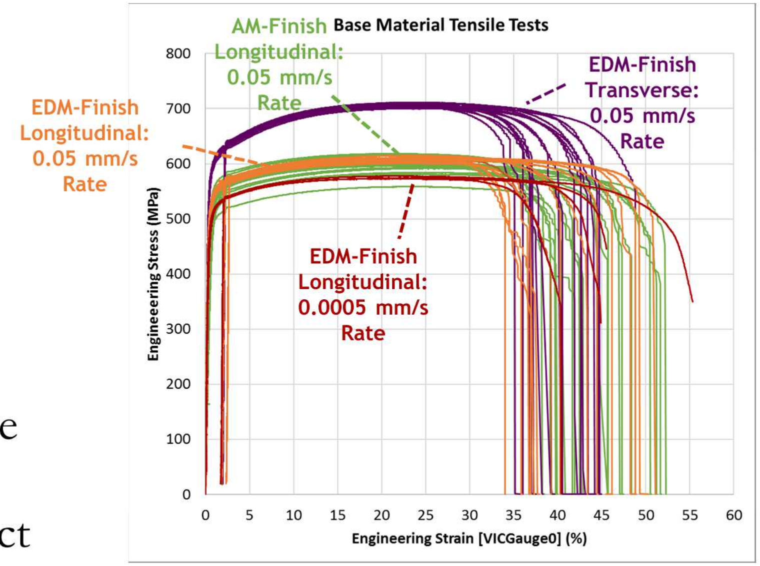


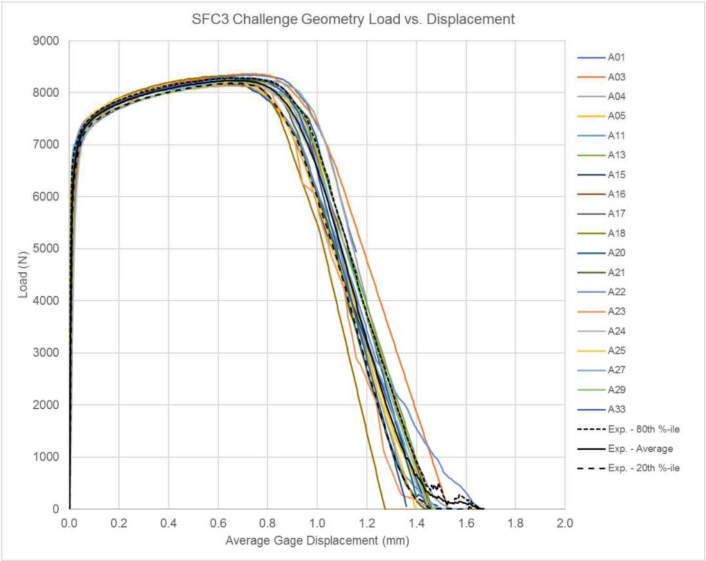
Team T

SFC3 Observations

Predictions

- **All teams predicted the correct crack path**
- Two teams predicted a nominal load-displacement behavior within experimental bounds
- All teams used provided **tensile data of AM-manufactured specimens** with similar void structure as the Challenge geometry
- Predictions of **surface strains** (local measures) were generally different than in experiments
- The teams took vastly different approaches to predict **uncertainty bounds** in their models
- Few teams considered the geometric variation and pore structures characteristic of AM metals, despite considerable data provided to aid that effort
- The post-blind assessment revealed several **clerical errors** in the predictions





Overall

- **Large features in the AM part overwhelmed the overall response** of the structure compared to the unintentional voids, a hope to use of AM parts
- **We need further research to understand the role of the voids of the local fracture processes**

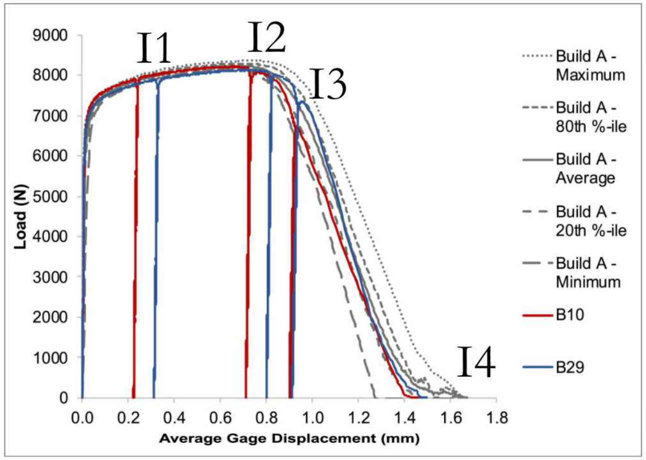
SFC3 Experimental Reinvestigation

Question: What is the effect of pre-existing voids on deformation, damage, and failure in AM metallic structures like the SFC3-geometry specimens?

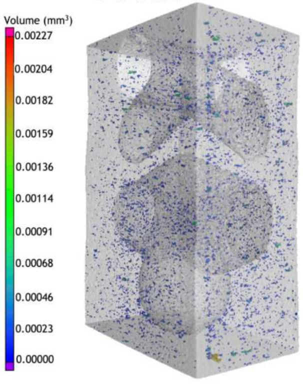
We will look at the global behavior and local crack initiation and growth relative to pre-test void population and the evolution of void growth and crack evolution via interrupted testing with ex situ micro-CT imaging.

- Tested 6 "Build B" specimens to failure to see overlap with original "Build A" specimens
- Interrupted test intervals for six specimens:
  - I1 – To middle of hardening
  - I2 – Peak load
  - I3 – Visible crack
  - I4 - Failure
- All interrupted test specimens had the same failure mode as tests to complete failure

Example of Interrupted Response



Pre-test μ-CT Data Showing Voids

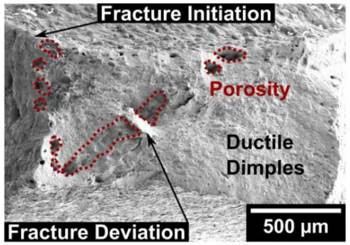


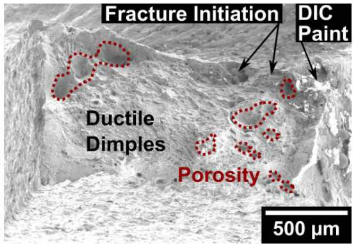
Geometry Dominates Global Behavior in SFC3 Specimens:
Metrics of the pre-existing void population do not correlate with the global mechanical behavior of the SFC3 specimens, but rather the large stress concentrations from the geometry overwhelmingly dominate the global behavior.

SFC3: Effect of AM Voids

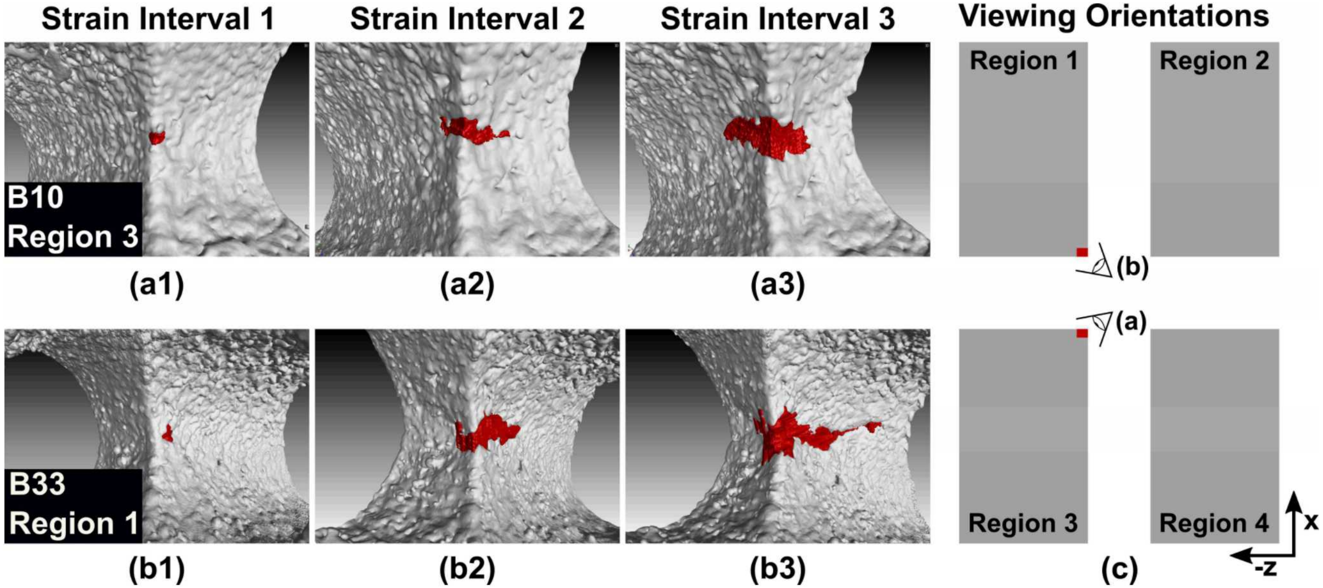
Voids Influence Local Crack Initiation and Growth:
Voids and surface defects influence local crack initiation and growth by introducing variation in crack initiation site in some cases and deviation from initial crack path to intersect voids.

Fracture Surfaces





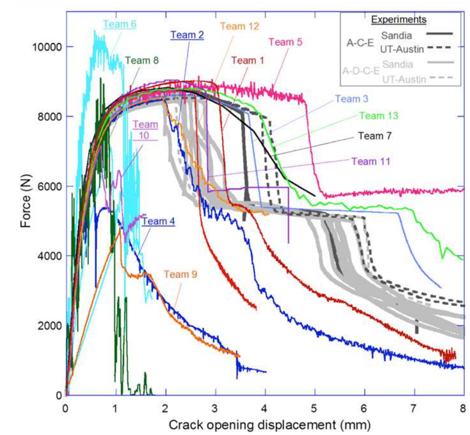
3D Reconstructions Highlighting Crack Volume

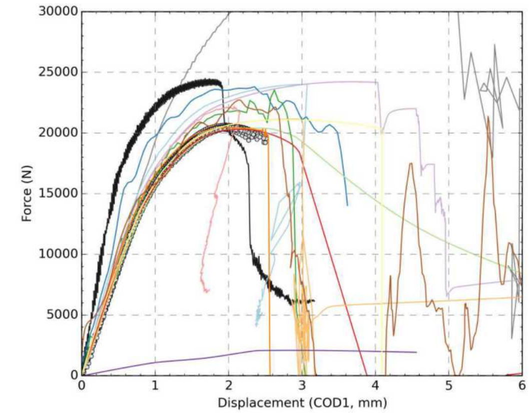


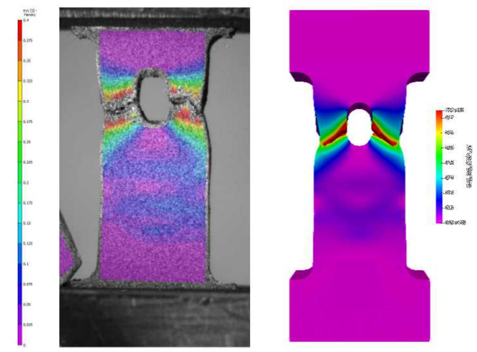
- Fracture at high-stress intersection point or at large surface defect
- Crack initiation at a surface defect occurs in I1, while otherwise can happen at I1-I3
- Cracks deviate to intersect voids
- Cracks initiating at surface defects grow faster, but total specimen crack volume growth does not vary much

SFC: What We Have Learned So Far

- A **good calibration of plasticity** is a prerequisite for predicting ductile failure
- **No single numerical method, constitutive model, or failure criterion** dominates amongst the more successful predictions
- **Experience and peer review** matter
- We need considerable **research on ductile failure** including:
  - **Stochastic and local nature of ductile failure**
  - Accepted **shear-dominated experiments** for model calibration
  - Theoretical and experimental work on **thermomechanical coupling**
  - Effect of material **anisotropy** on failure
  - **Efficient constitutive and failure models** for large structures
  - **Quantitative comparison** of full-field experimental and computational data
  - Methods for **uncertainty quantification** on engineering time-scales







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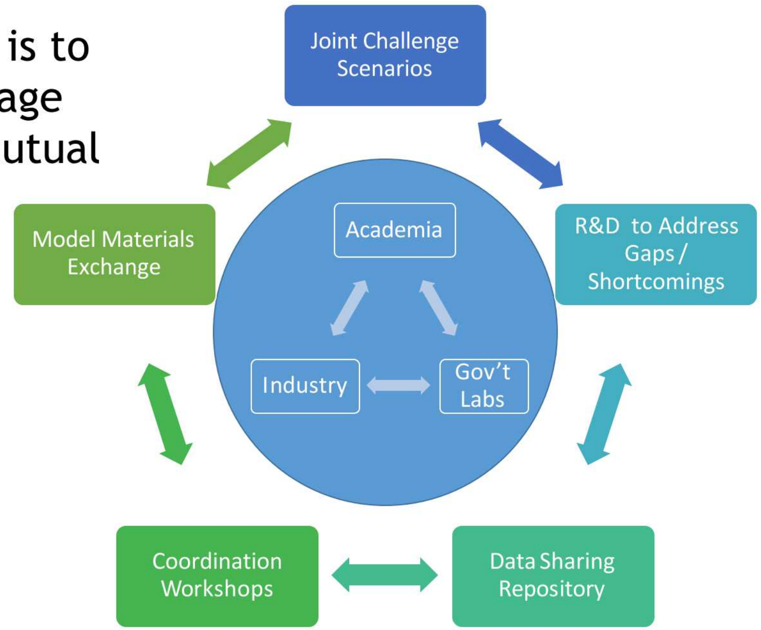
STRUCTURAL RELIABILITY PARTNERSHIP

The purpose of the Structural Reliability Partnership is to coordinate research, share best practices, and leverage investments from multiple institutions on areas of mutual interest in the domain of structural reliability.



PILOT PARTNERS:

Sandia National Laboratories

ExxonMobil

THE UNIVERSITY OF TEXAS AT AUSTIN

Initial Participant Institutions:

Lawrence Livermore National Lab
University of Utah
Purdue University
National Science Foundation
Pratt & Whitney
Pacific Northwest National Lab
NIST
University of Illinois
Georgia Tech University
Boeing
Mississippi State University
Oak Ridge National Lab
Naval Research Labs
Johns Hopkins University
University of California at Davis
Michigan State University

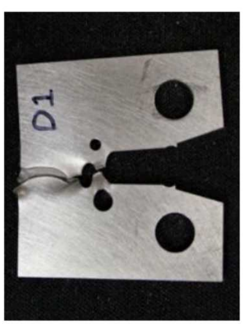
As a result of the August 2017 Workshop, the Partnership launched two initial focus areas:
(1) Reliability in additive manufacturing, and
(2) Hydrogen-assisted fracture in pipeline welds

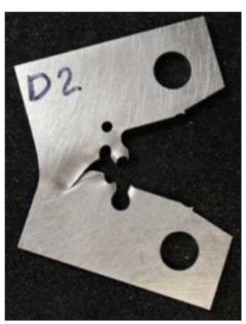
Summary

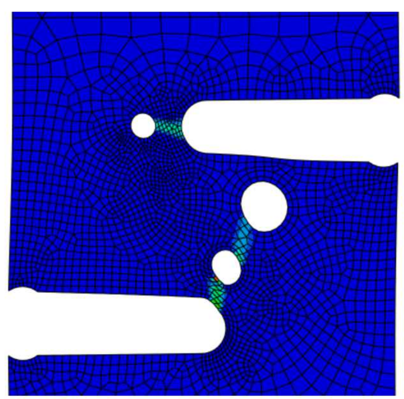
Sandia Fracture Challenge:

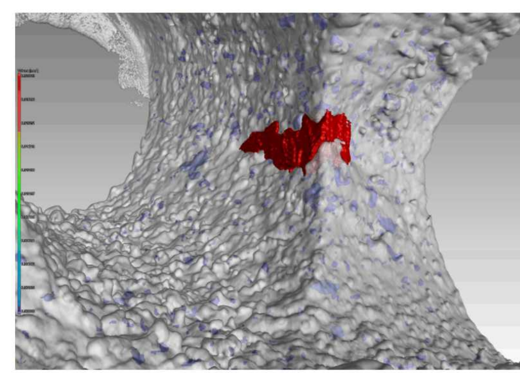
- Provides a **collaborative environment** for capability assessments
- Provides documentation of **'state-of-the-art'** in ductile failure predictions
- Illustrates **key deficiencies** in ductile failure predictions
- Raises international **awareness on the need for improved simulation capabilities**

Structural Reliability Partnership is a new paradigm of **cooperative research** using the "Challenge scenario" as the medium to research capabilities in experiments and computations **in structural mechanics**.









Questions

Boyce, B.L., Kramer, S.L.B., *et al.*, "The Sandia Fracture Challenge: blind round robin predictions of ductile tearing," *International Journal of Fracture,* vol. 186, pp. 5-68, 2014.

Boyce, B.L., Kramer, S.L.B., *et al.*, "The second Sandia Fracture Challenge: predictions of ductile failure under quasi-static and moderate-rate dynamic loading," *International Journal of Fracture,* vol. 198, pp. 5-100, 2016.

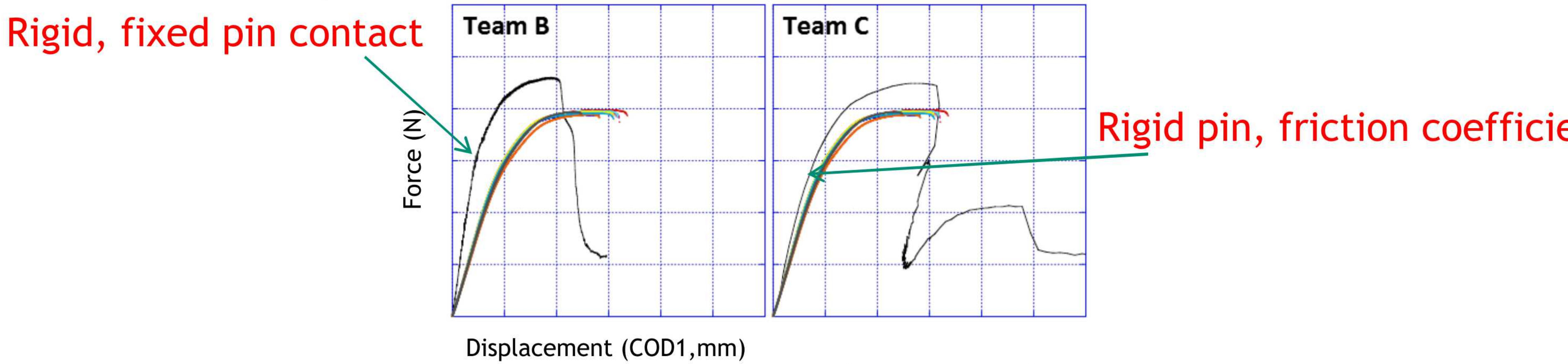
More details on SFC3 will be available in the summer in a special volume of the *International Journal of Fracture.*

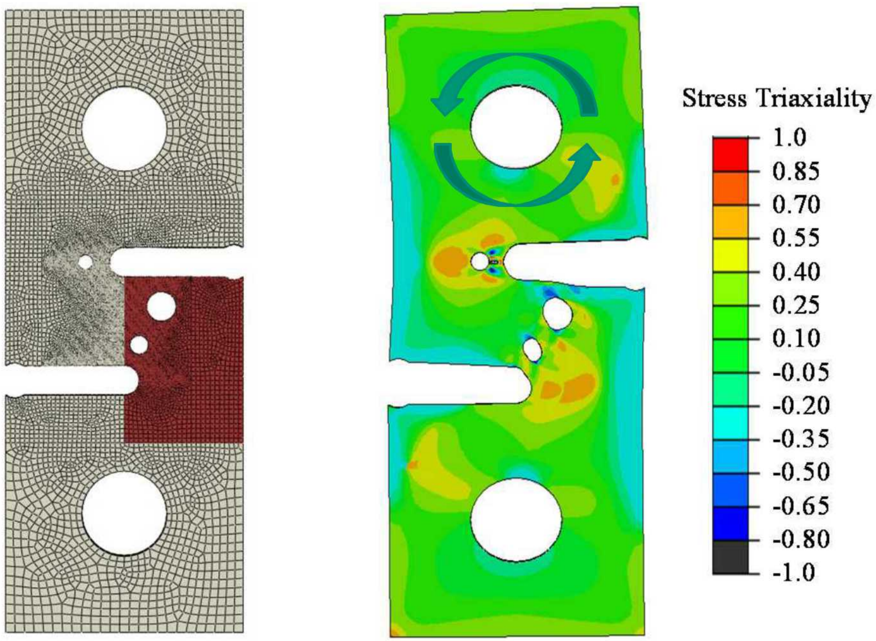
Kramer, S.L.B. *et al.,* "The third Sandia Fracture Challenge: predictions of ductile fracture in additively manufactured metal" (DOI: 10.1007/s10704-019-00361-1), (in press).

Kramer, S.L.B. *et al.*, "Evolution of Damage and Failure in an Additively Manufactured 316L SS Structure: Experimental Reinvestigation of the Third Sandia Fracture Challenge" (DOI: 10.1007/s10704-019-00357-x), Published Online March 2019.

Backup Slides

SFC2 Gap 1: Representing surface contact and friction



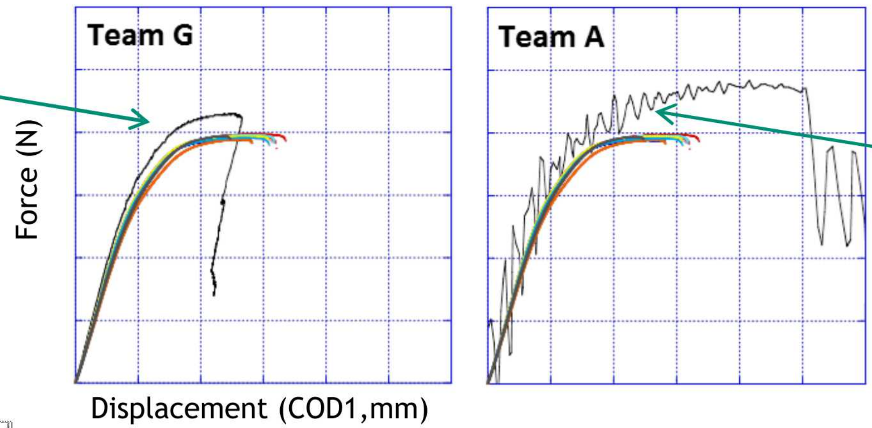


Model From Team C

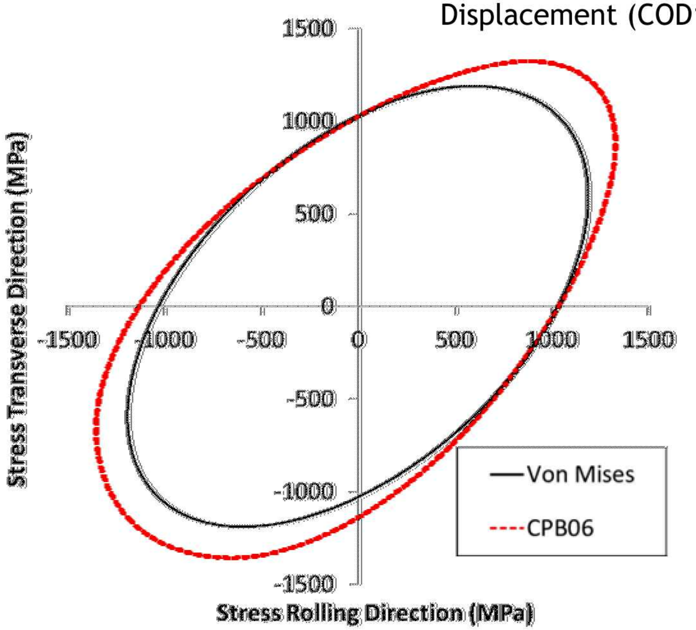
- Apparent stiffness was overpredicted by ~1/2 the teams. In some cases the predicted stiffness was 2X the experimental result!
- Teams that chose fully constrained non-sliding pin contact tended to overpredict stiffness and peak forces.
- Frictionless or free-rotating pin contact appeared to mimic experiments most closely.

SFC2 Gap 2: Accounting for sheet anisotropy and Lode Angle dependence

No anisotropy or lode angle dependence



J_2 plasticity law, No calibration to shear data



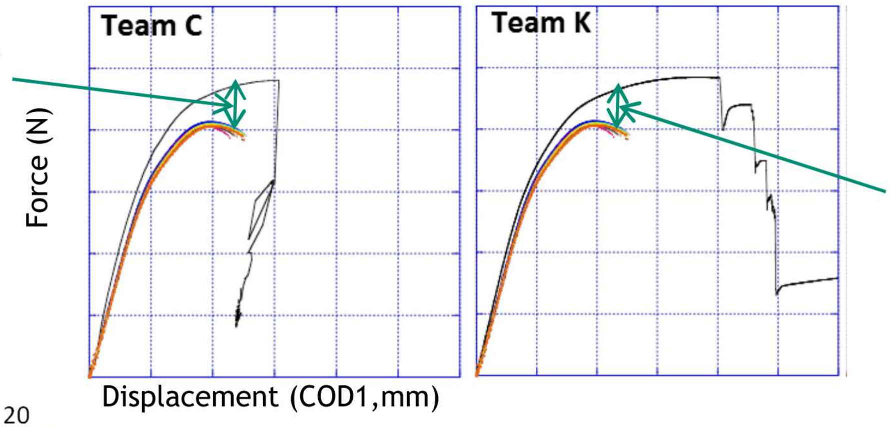
Team B: Comparison of yield surfaces at zero plastic strain

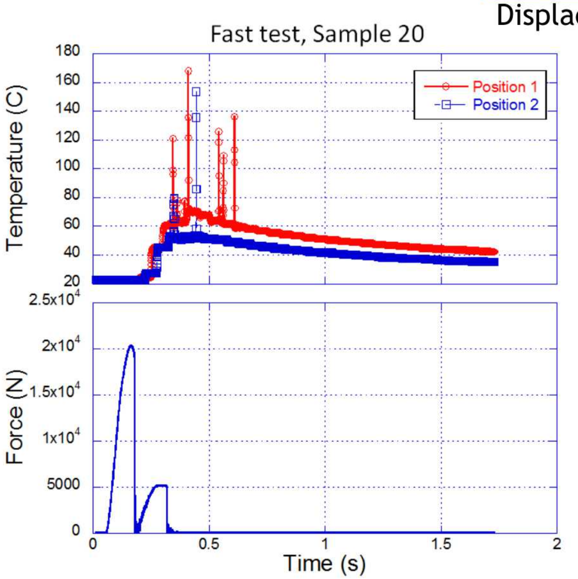
ld in shear was 0.88X the value of predicted by on Mises yield surface.

s effect was only observable by comparing the sile yield points to the yield point of the non- ndard shear test.

ms that used a simple J_2 (von Mises) plasticity del tended to overpredict yield/hardening avior since the yield in shear was softer than in tension.

SFC2 Gap 3: Estimating thermal work coupling factor





- There was a >60ºC temperature rise in the necking ligament under the faster loading condition.
- Many teams ignored the plastic-work induced thermal softening that occurs under modest dynamic loading.
- Teams that chose either an adiabatic condition or some coupling parameter tended to capture some degree of extended necking behavior.
- There is little data (and even contradictory data from the same group) on the plastic work thermal coupling parameter (Taylor-Quinney coefficient).

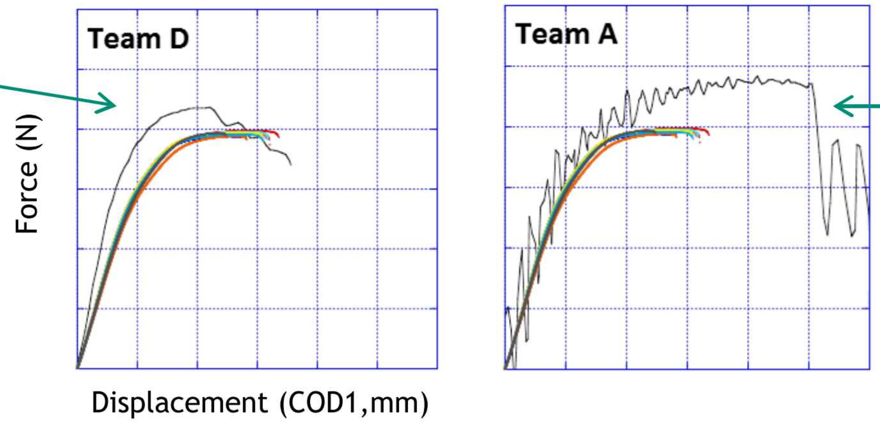
Volumetric heating rate

$$\dot{Q} = \eta \dot{W}^p = \eta \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}^{in}$$

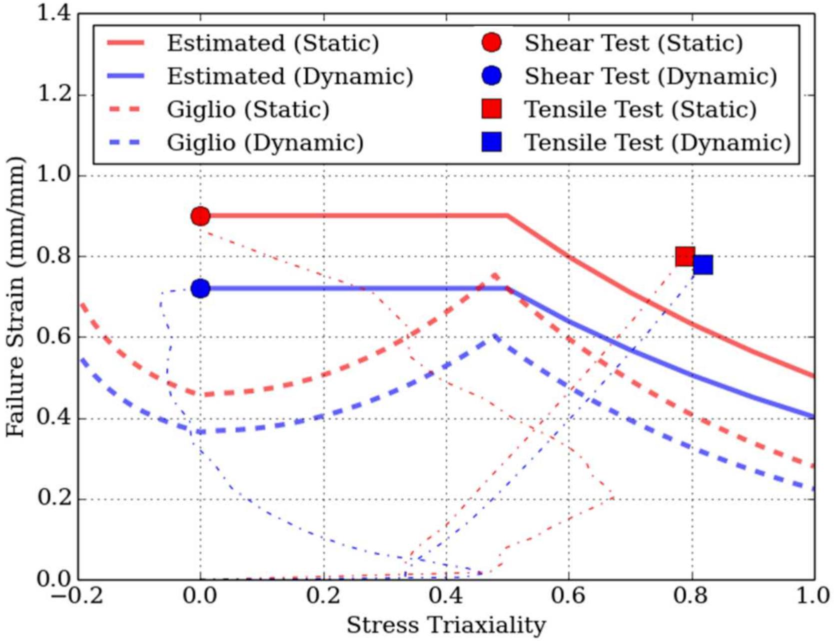
Taylor-Quinney coefficient

SFC2 Gap 4: Choosing a realistic failure parameter

Plastic strain criterion does not account for triaxiality / shear



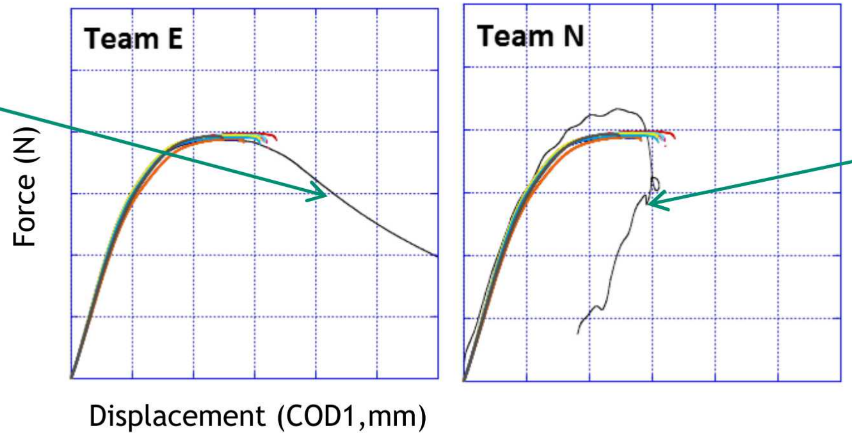
Failure parameter calibration only used tension data, not shear data.



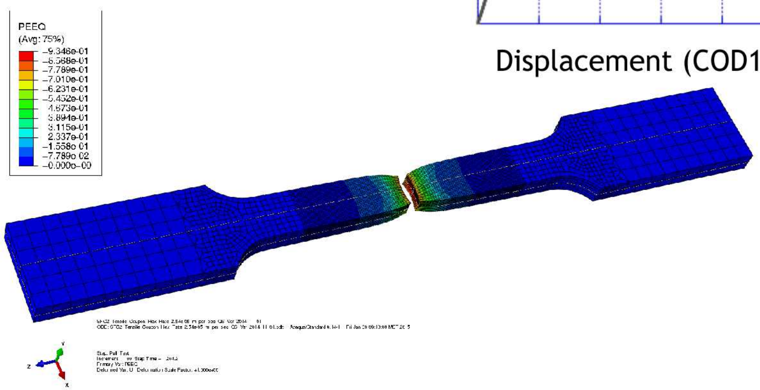
- There is no consensus on a realistic model for crack initiation. **(Gurson is not sufficient)**
- Predictions tended to be more accurate if they used shear data and calibrated a triaxiality-dependent failure model.
- While a suite of various loading paths and triaxiality conditions is needed, there are no standards for such material testing. **(A tension test is not sufficient)**

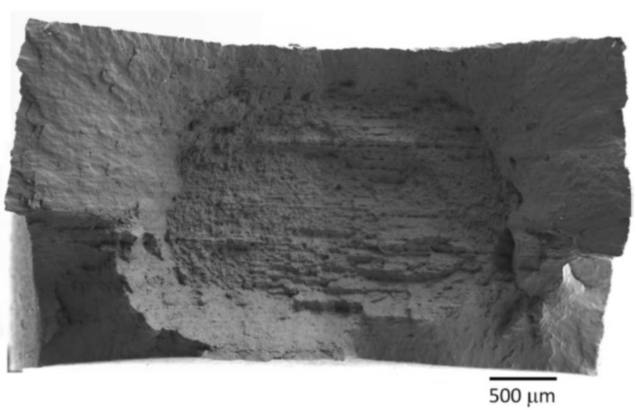
SFC2 Gap 5: Damage progression / fracture morphology

Quasi-static cohesive zone law did not predict unstable fracture



Incorrect crack path





- Some approaches have difficulty capturing the unstable nature of crack propagation.
- Some approaches do not properly characterize the resistance of the material to crack growth (and hence crack path).
- None of the approaches accurately capture the macroscopic 3D profile of a real fracture surface, such as shear lips vs flat fracture seen in the calibration fracture surfaces.

Challenge Questions

Questions regarding point measures and for the entire test, utilizing load and DIC measurements with uncertainty bounds.

Question 1: Report the **force at the following displacements D**: 0.25 mm, 0.5 mm, 0.75 mm, and 1.0 mm.

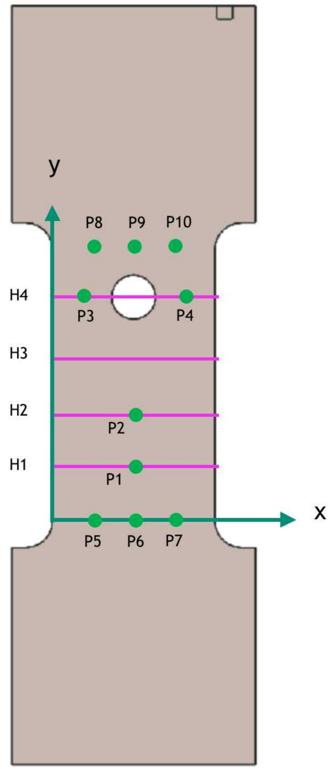
Question 2: Report **force and Hencky (logarithmic) strain in the vertical direction (ε_{yy}) at four points**, P1, P2, P3, and P4, on the surface at 75% of peak load before peak load (F1), 90% of peak load before peak load (F2), at peak load (F3), and at 90% of peak load after peak load (F4).

Question 3: Report the **force vs. gage displacement D** for the test.

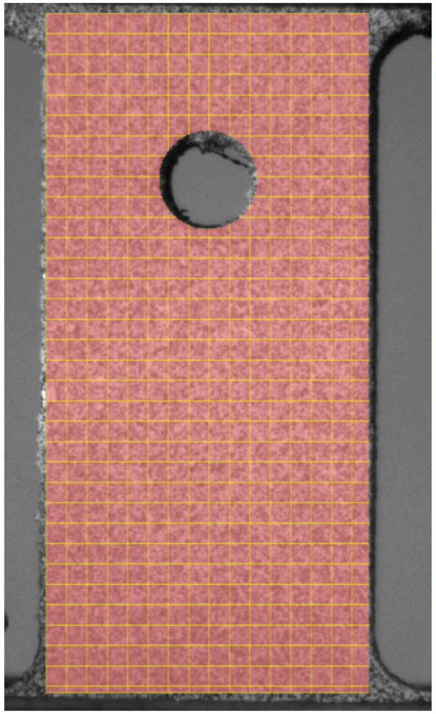
Question 4: Report **force vs. Hencky (logarithmic) strain in the vertical direction (ε_{yy}) at four points,** P1, P2, P3, and P4, on the surface **for the test**.

Question 5: Report **force and Hencky (logarithmic) strain in the vertical direction (ε_{yy}) along four horizontal lines**, H1, H2, H3, and H4 on the surface at forces F1, F2, F3, and F4. Line scan data should be provided with a data spacing of Δx=0.030 mm.

Question 6: Provide images of the model directly viewing the front surface (same as the side for DIC) at crack initiation and at complete failure, showing **contours of Hencky (logarithmic) strain**.



Front View of Challenge Geometry



Representative DIC Area of Interest Showing a Grid of 41 pixel x 41 pixel Subsets

***For Questions 1-4, please report nominal (average) value and optionally report the 80-percentile upper bound and 20-percentile lower bound values to compare to a population of 19 experimental observations.**

21 Teams of Challenge Participants

Universities

UTSA

Massachusetts Institute of Technology

Cornell University Founded A.D. 1865

OTH Ostbayerische Technische Hochschule Regensburg

The University of Texas at Austin

Uniwersytet Kazimierza Wielkiego w Bydgoszczy

Industry

SwRI Southwest Research Institute

Exponent

COCAS

100 Jahre 1917–2017 Max-Planck-Institut für Eisenforschung

Government Laboratories

Sandia National Laboratories

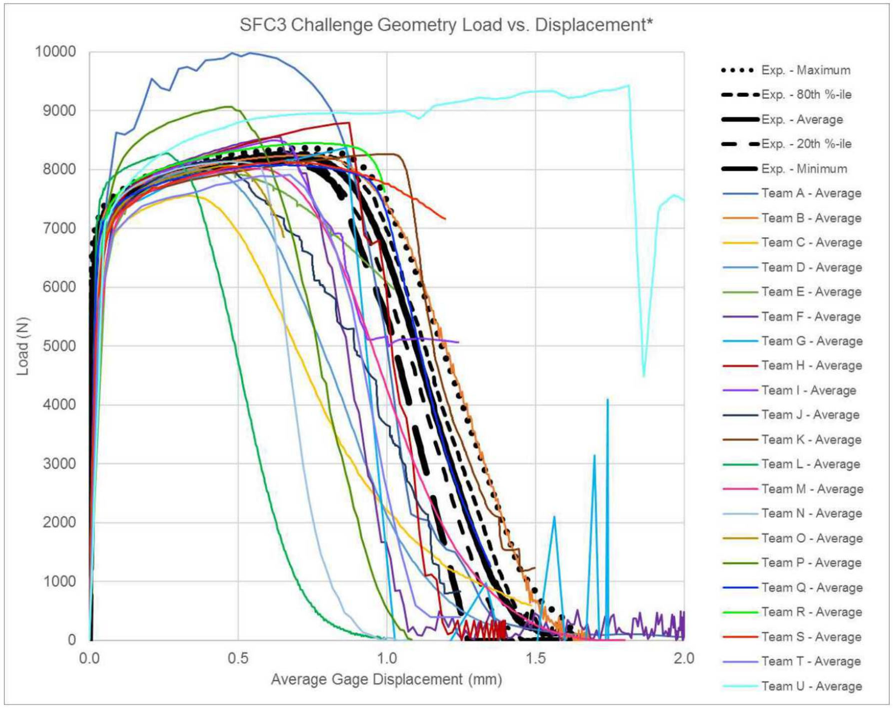
US Army Corps of Engineers

Natural Resources Canada / Ressources naturelles Canada

CanmetÉNERGIE

Leadership en écoInnovation

Prediction Methods



The 21 predictions were obtained from a variety of methods, for example:

- **Solvers**: Explicit vs. Implicit; Quasi-statics vs. Dynamics
- **Fracture Method**: Element deletion, Peridynamics with bond damage, XFEM, Damage (stiffness degradation), and Adaptive remeshing
- **Uncertainty**: Material and geometric
- **Plasticity**: J2 plasticity or Hill yield with Isotropic hardening, mixed Swift-Voce hardening, kinematic hardening, or custom hardening curves
- **Fracture Criteria**: GTN model, Hosford-Coulomb, triaxiality-dependent strain, critical fracture energy, damage-based model, critical void volume fraction, and Johnson-Cook model
- **Damage Evolution**: Damage accumulation / evolution, crack band model, fracture energy, displacement value threshold, incremental stress triaxiality, Cocks-Ashby void growth, and void nucleation / growth / coalescence
- **Calibration Data**: Various combinations of the tensile specimens, the notched tensile specimens, and literature data

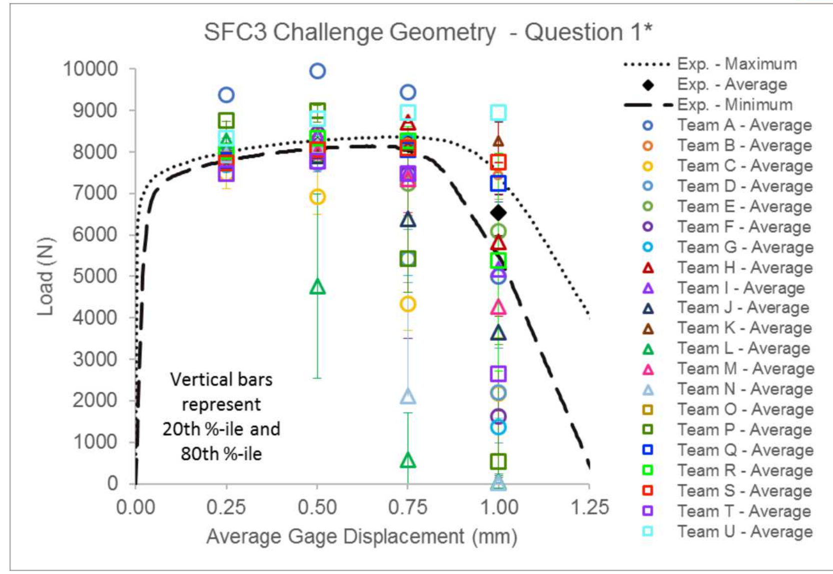
All 21 predictions correctly identified the nominal crack path with initiation at the through-thickness hole

13 teams offered uncertainty bounds on their predictions

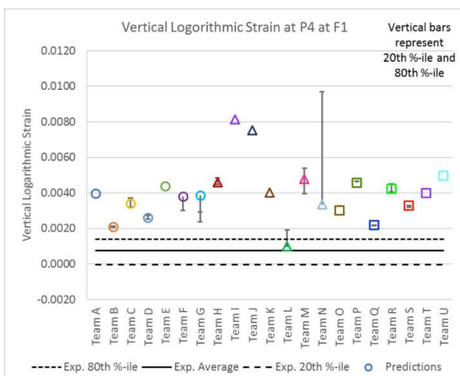
SFC3 Predictions: Question 1 & 2

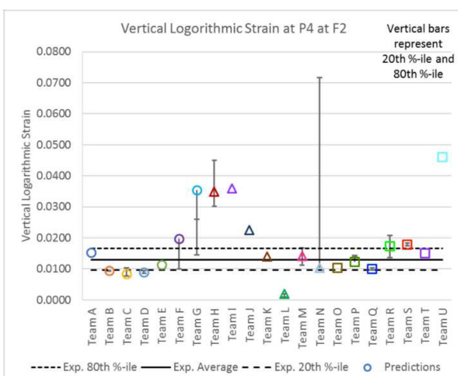
Question 1: Report the force at the following displacements D: 0.25 mm, 0.5 mm, 0.75 mm, and 1.0 mm.

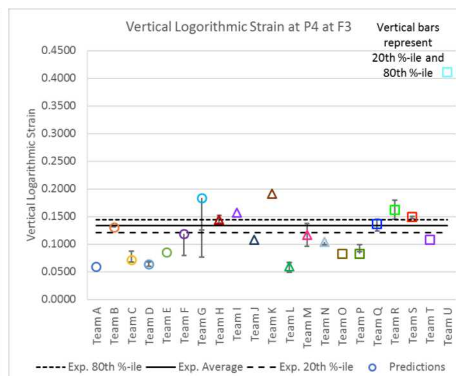
Several teams predicted the initial structural yield, but the variation broadened with increasing displacement.

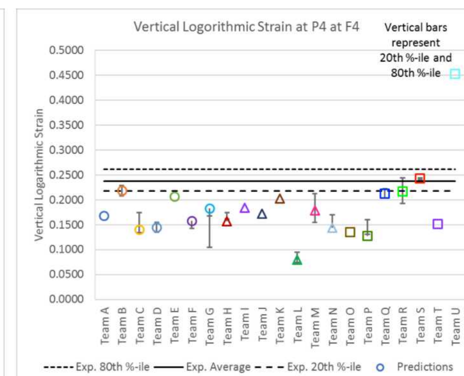


Question 2: Report force and Hencky (logarithmic) strain in the vertical direction (ε_{yy}) at four points, P1, P2, P3, and **P4**, on the surface at 75% of peak load before peak load (F1), 90% of peak load before peak load (F2), at peak load (F3), and at 90% of peak load after peak load (F4).







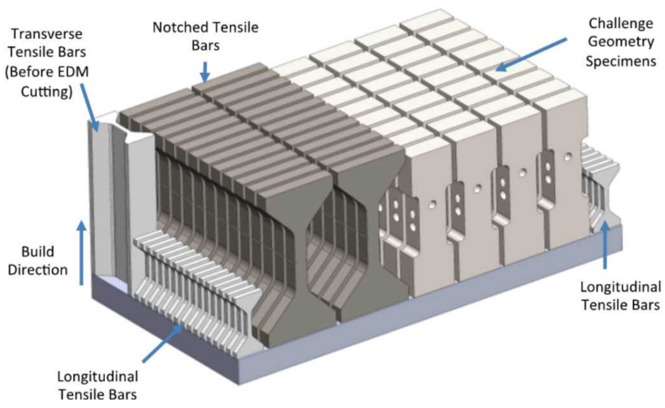


Generally, the predictions were initially too high, particularly for F1, and then were under-predicting by F4.

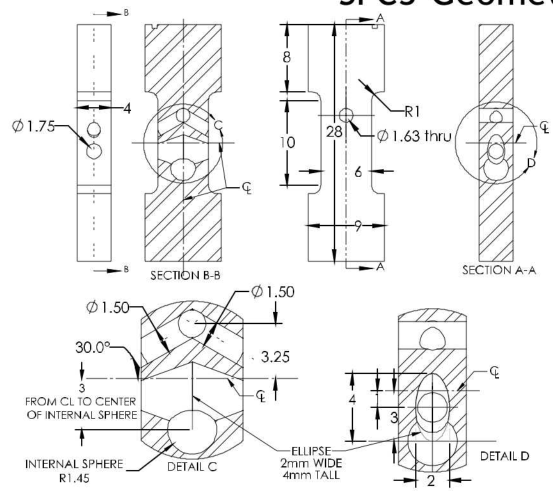
Motivation: Understanding Failure in AM Metal Structures and The Third Sandia Fracture Challenge

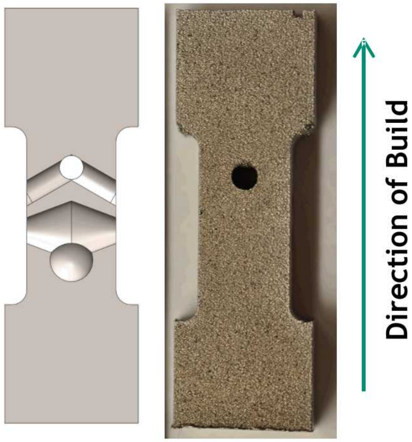
The Third Sandia Fracture Challenge explores the experiments and model methods required to predict ductile failure in AM metal parts.

AM 316L SS Build Plate: Laser Powder Bed Fusion

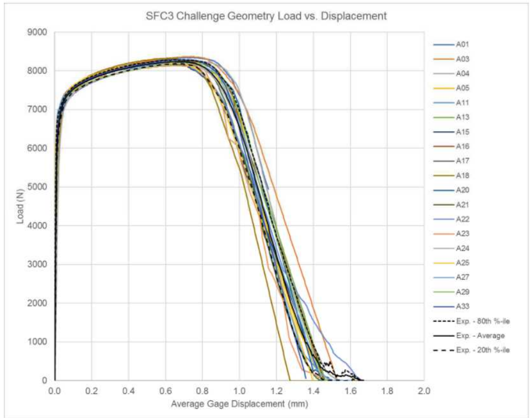


SFC3-Geometry Specimens

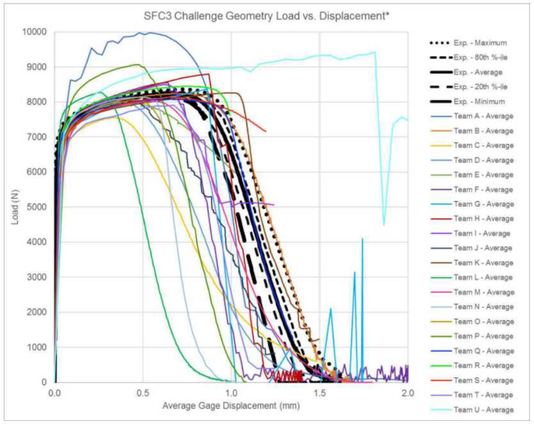




Load-Displacement Response of SFC3-Geometry Specimens



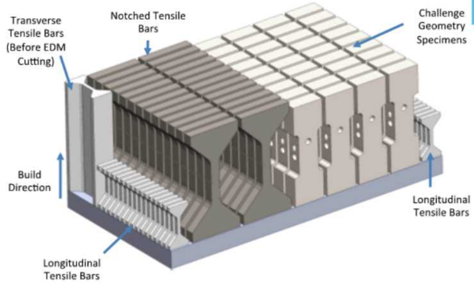
21 Nominal Predictions with Exp. Average and Bounds



Most predictions did not consider the AM porosity, but yet did reasonably well in predicting the global response. This implies that geometry, not porosity, dominates global behavior.

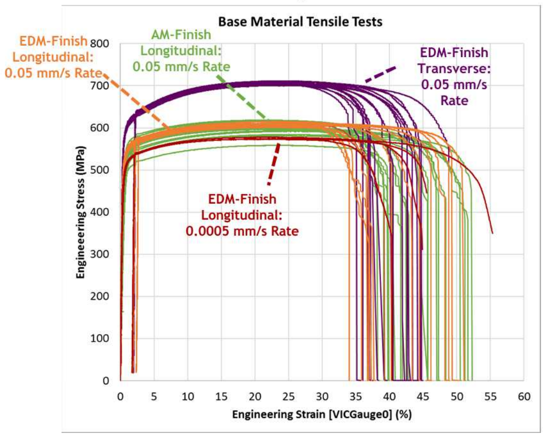
Motivation: Understanding Failure in AM Metal Structures and The Third Sandia Fracture Challenge

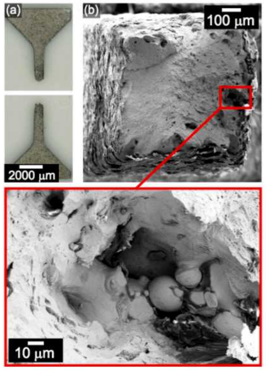
Question: What is the effect of pre-existing voids on deformation, damage, and failure in AM metallic structures like the SFC3-geometry specimens?



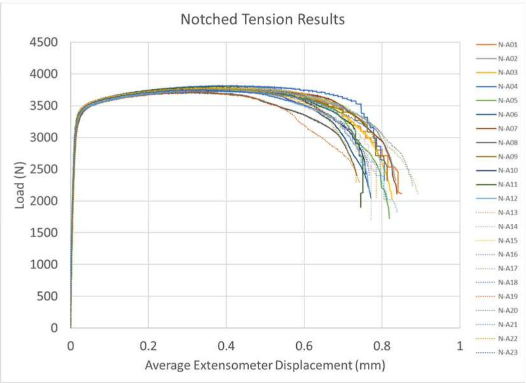
AM 316L SS Build Plate

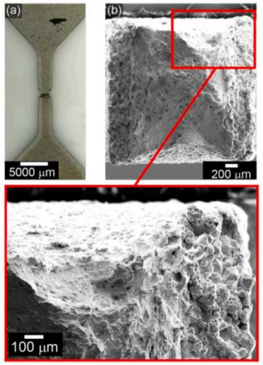
Tensile Specimens



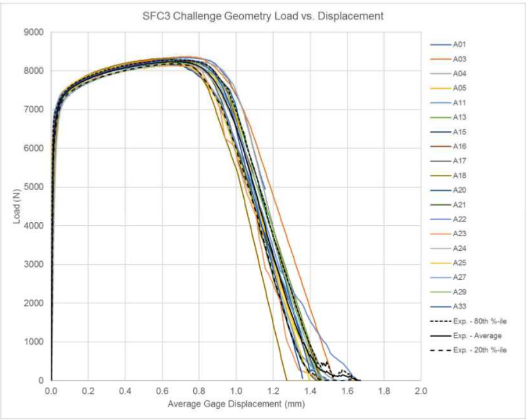


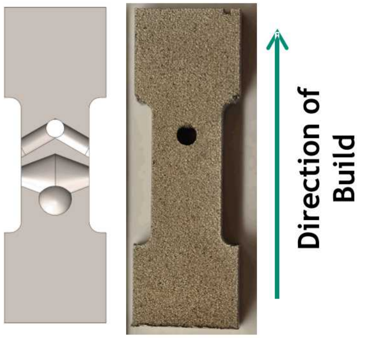
Notched Tensile Specimens





SFC3-Geometry Specimens



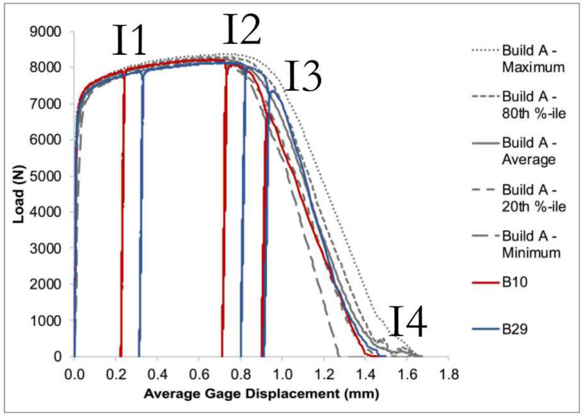


We will look at the global behavior and local crack initiation and growth relative to pre-test void population and the evolution of void growth and crack evolution.

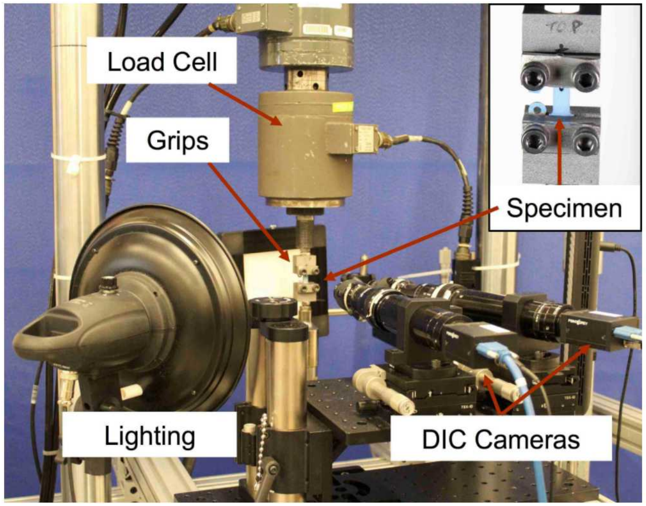
Experimental Approach: Interrupted Testing with Micro-CT

- Tested 6 "Build B" specimens to failure to see overlap with original "Build A" specimens
- Interrupted test intervals for six specimens:
  - I1 – To middle of hardening
  - I2 – Peak load
  - I3 – Visible crack
  - I4 - Failure
- All interrupted test specimens had the same failure mode as tests to complete failure

Interrupted Response

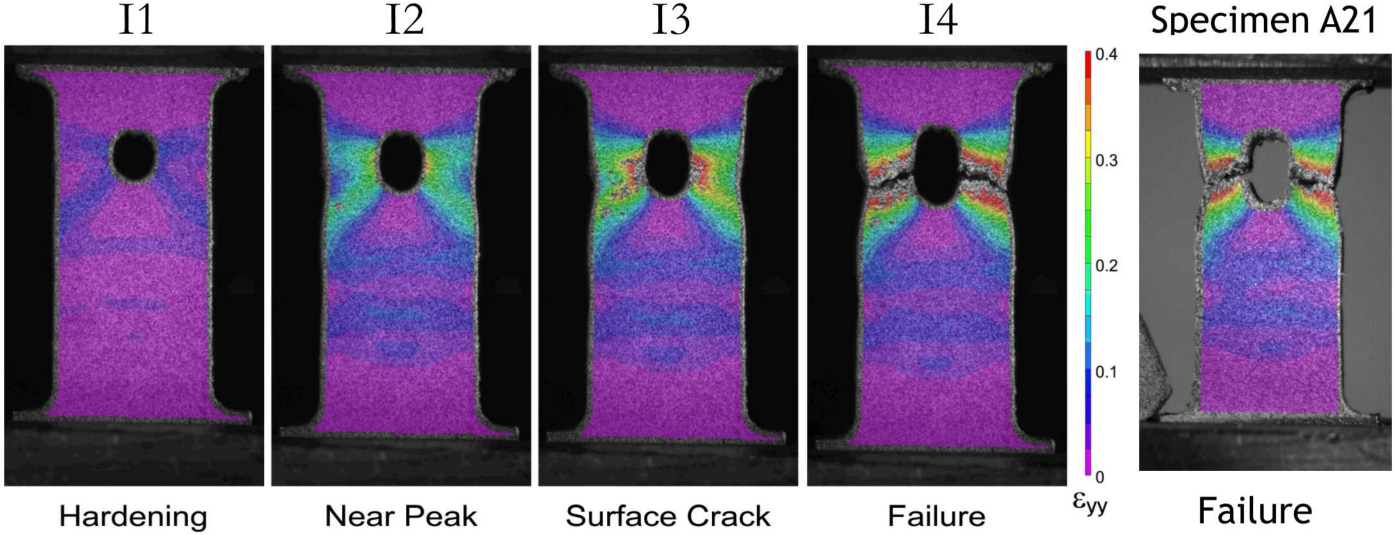


MTS 100-kN load frame with custom AM grips and Correlated Solutions Stereo DIC system (VIC3D)



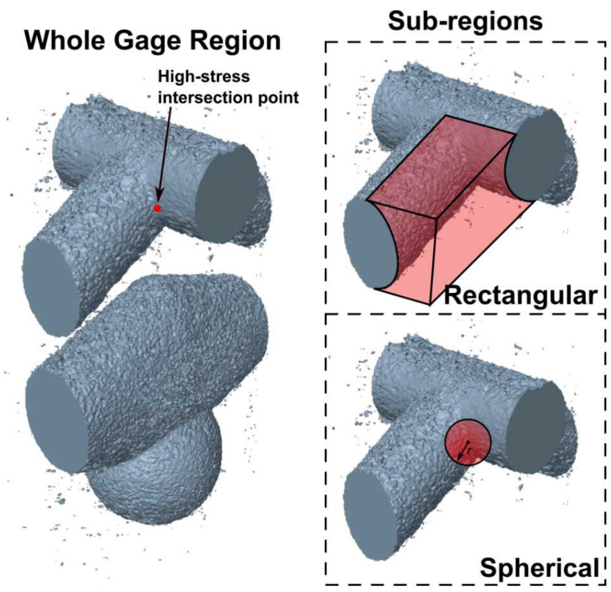
Hencky Tensile Strain Fields for B28

Subset Size (pix)	41
Step Size (pix)	8
Strain Window (pix)	9
Virtual Strain Gage (pix)	65
Virtual Strain Gage (mm)	0.517
Pixel to Length Ratio (pix/mm)	125.8



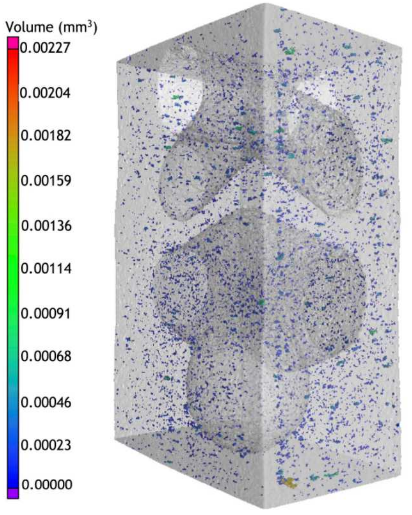
Micro-CT and Void Analysis Methods

- X-Ray Worx 225kV tubehead with a Varian cesium iodide 2520DX detector using North Star Imaging software
- **Voxel resolution of 6.2+/-0.6 μm**
- 16-bit tiff images reconstructed with Volume Graphics 3.2 Max software
- Image processing in FIJI and MATLAB
- Void analysis performed using IDL software with a requirement of **at least 8-connected voxels to count as a void with a minimum Equivalent Spherical Diameter (ESD) of 13-9-16.9 μm**

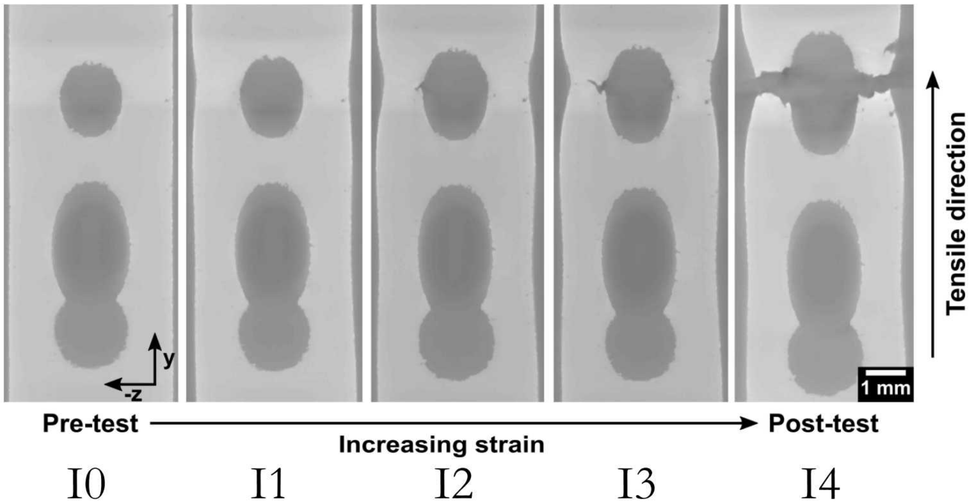


Isolation of voids with high-stress intersection point identified and different volumes for pre-test void analysis

Pre-test data showing voids



Ex situ micro-CT internal slices for Specimen B33



Mechanical Response

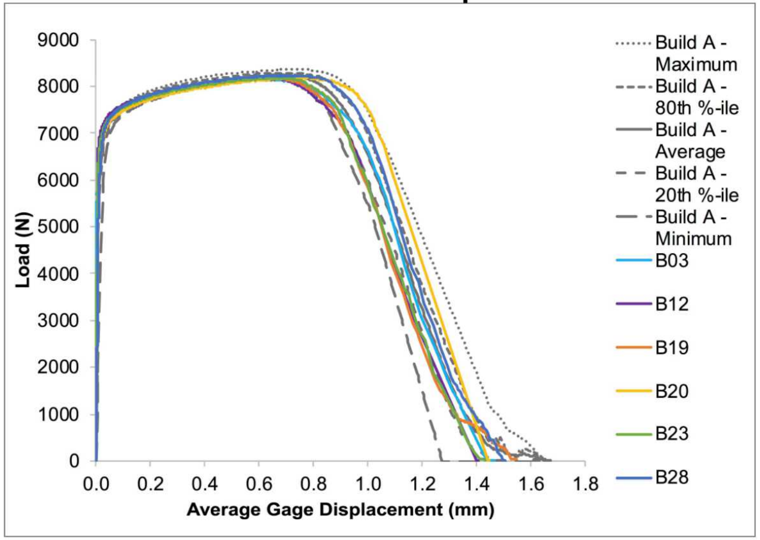
SFC3-Geometry specimens from "Build B" behaved similarly to those from "Build A", so analysis of "Build B" specimens is assumed represent that of all SFC3 specimens.

Global measures considered:

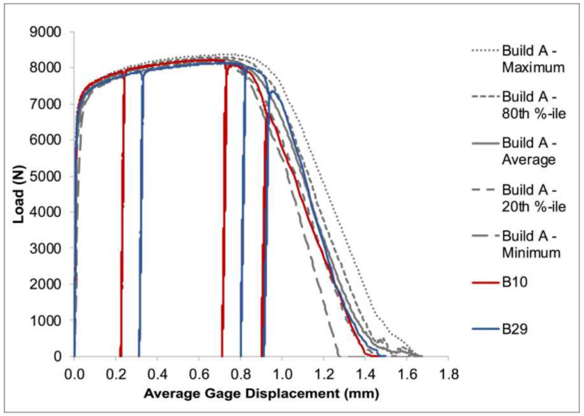
- Peak load
- Displacement at peak load
- Displacement at failure
- Maximum unloading rate

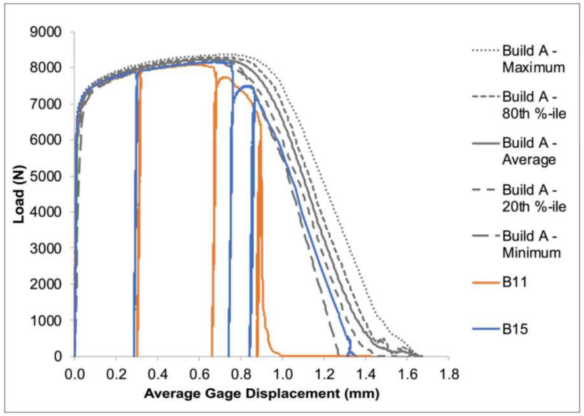
All measures for monotonic and interrupted "Build B" specimens were similar to that of the monotonic "Build A" specimens.

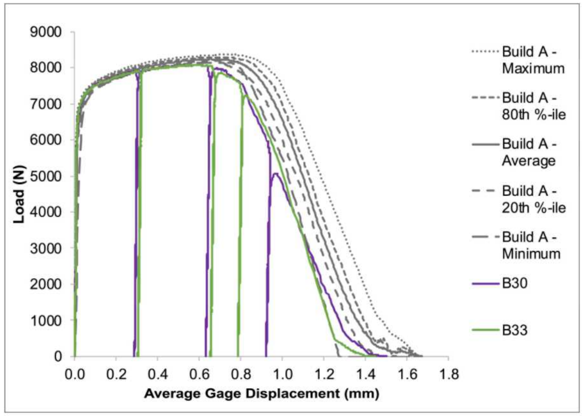
Monotonic Response



Interrupted Response







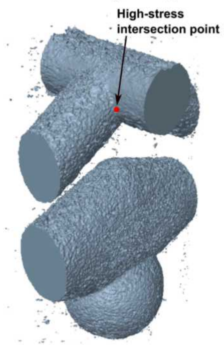
Influence of Aggregate Void Metrics on Mechanical Response

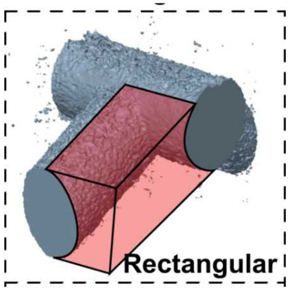
Original Hypothesis:
Metrics of aggregate pre-test void population will correspond to mechanical behavior

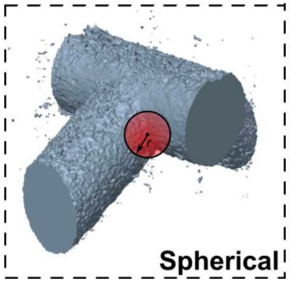
Finding:
Metrics of pre-test void population do not strongly correspond to variations seen in mechanical performance

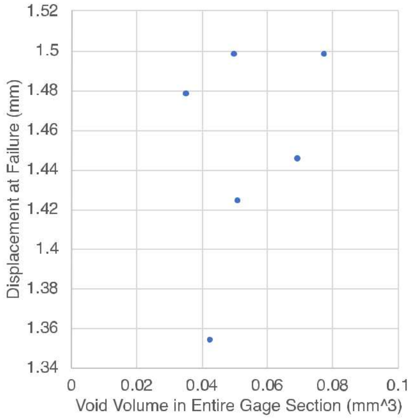
Example: Displacement to Failure Versus Void Volume Over Different Regions

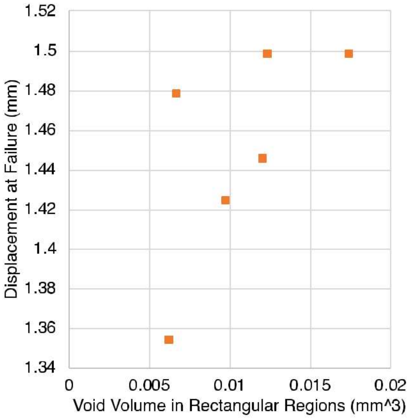
Whole Gage Region

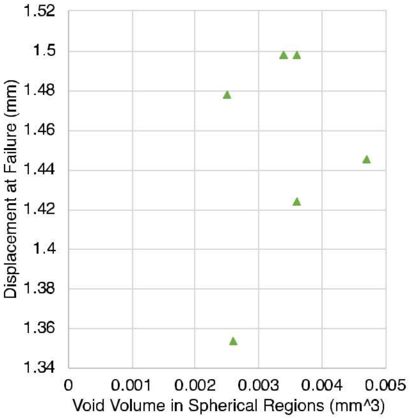






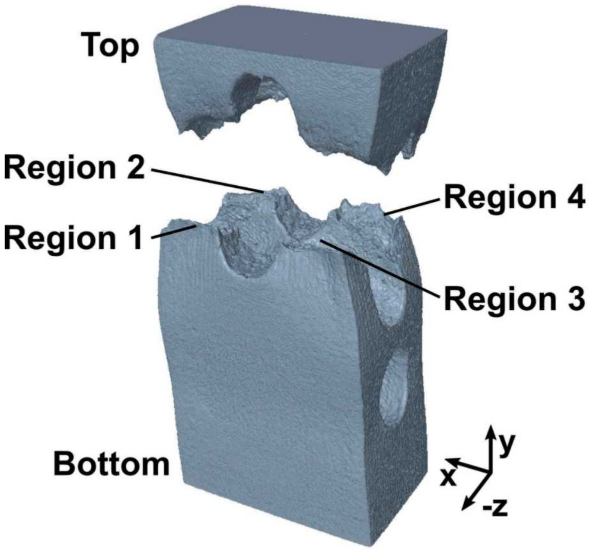


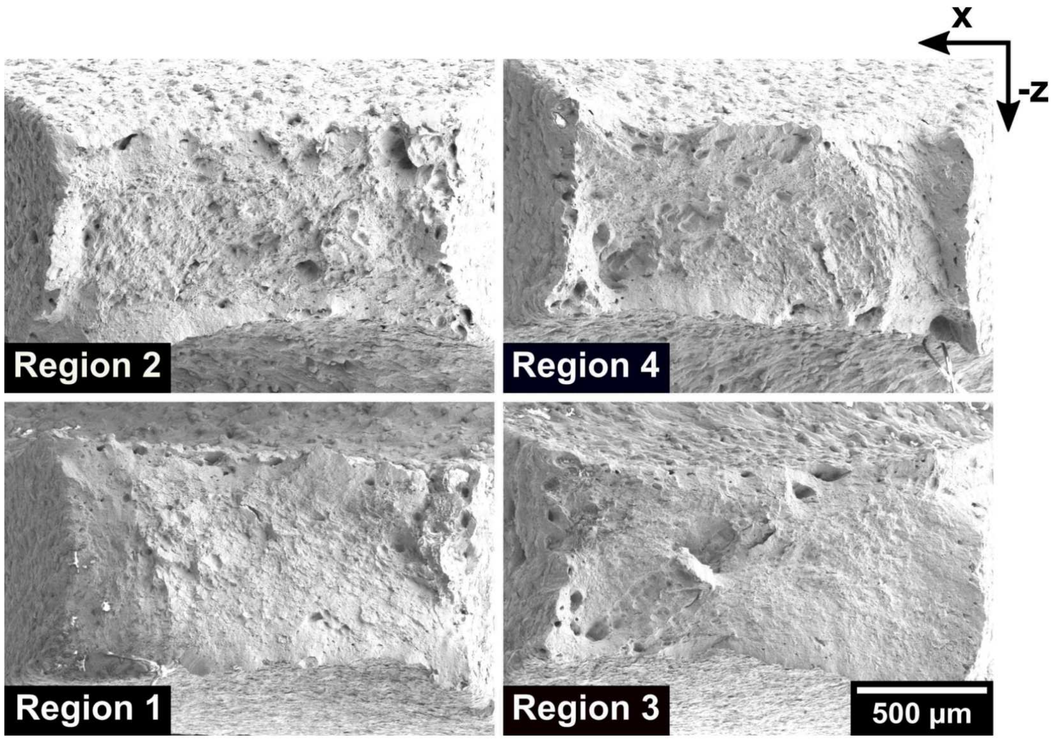




Influence of Void Presence on Fracture

Specimen B10

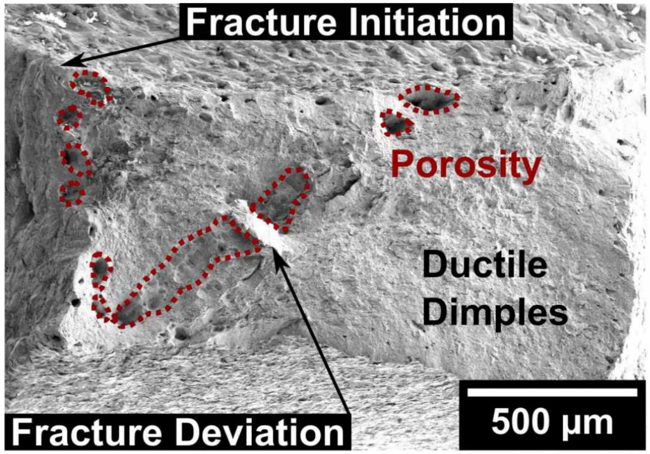




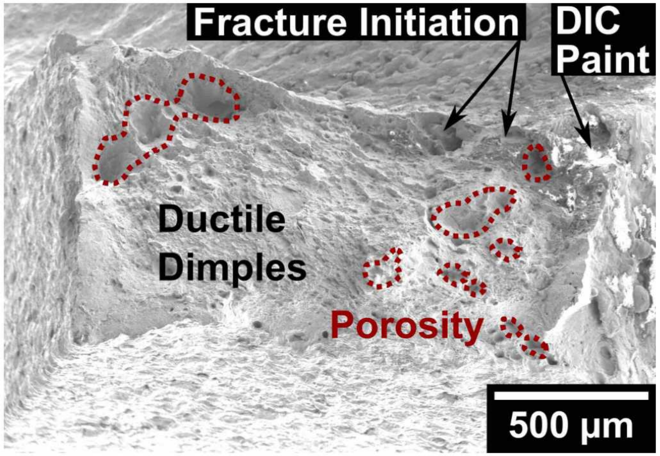
- Ductile dimples
- Intersected voids

Influence of Void Presence on Fracture

Specimen B10 Region 3

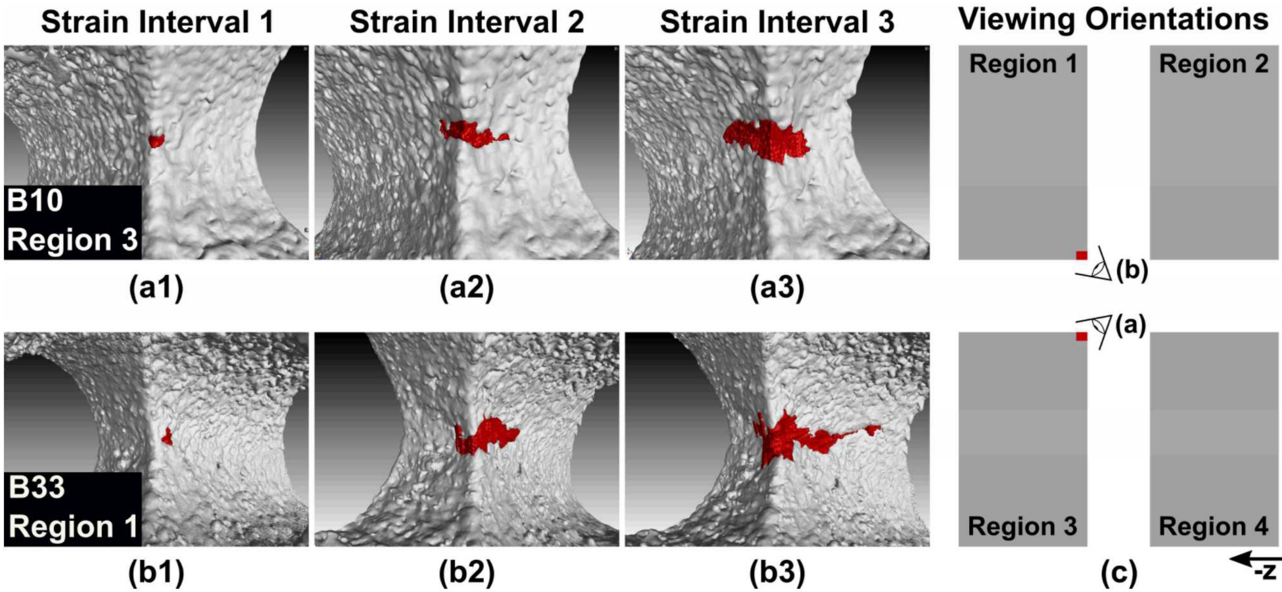


Specimen B33 Region 1



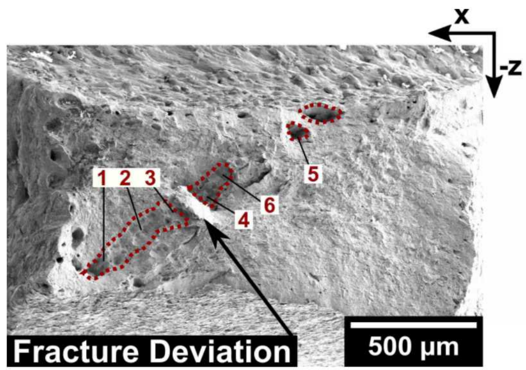
- Ductile dimples
- Intersected voids
- Fracture deviation
- Different crack initiation locations (Surface defect or geometric intersection point)

3D Reconstructions Highlighting Crack Volume

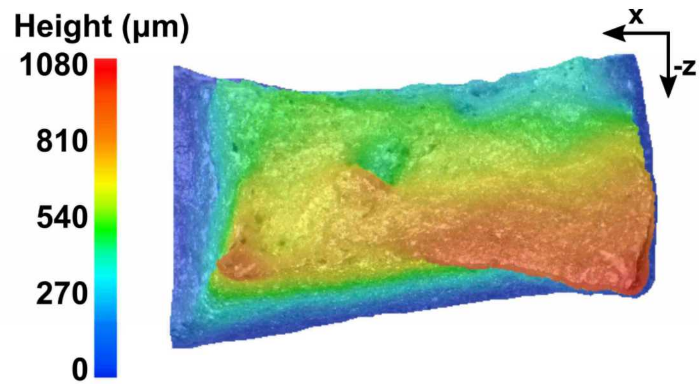


Void Evolution Under Increasing Plastic Strain

Specimen B10
Region 3

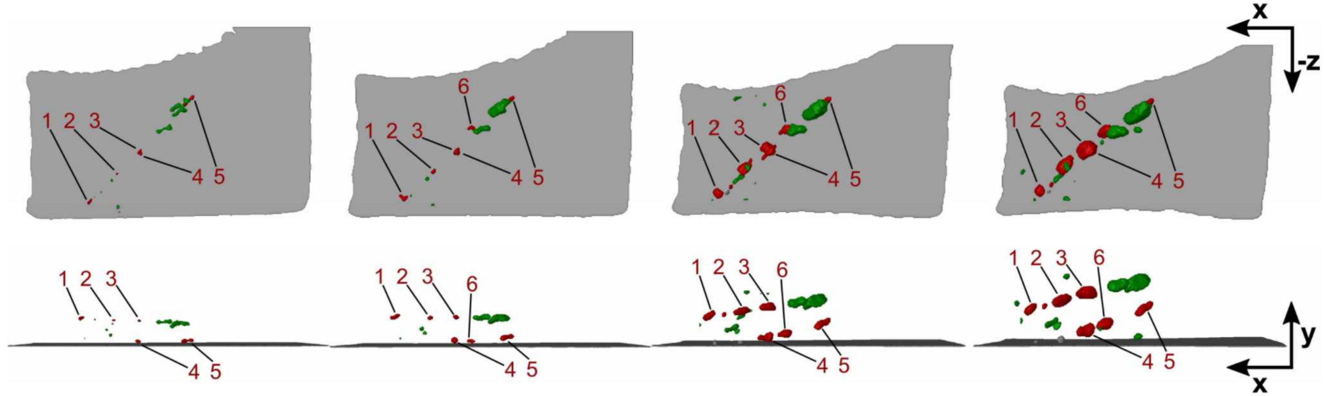


Fracture Surface with Voids Highlighted



Fracture Surface Height Map

Void Evolution: 3D Reconstruction of Voids Near the Fracture Surface (Red Voids Intersected Fracture Surface)



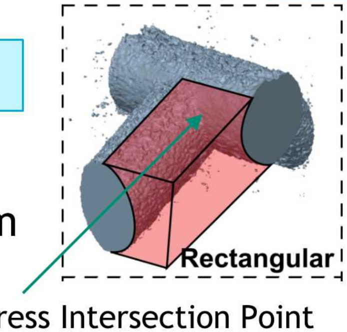
Pre-Test I1 I2 I3

- **All voids grew** regardless of their involvement with the fracture surface.
- **New voids** (or voids too small to be resolved in pre-test scan) such as void 6 **appeared due to deformation** and grew larger than many voids observed in pre-test.
- **The fracture surface did not intersect some of the largest pre-test voids** in this region (see green).
- During I4, **the crack deviated** from the plane of voids 1-3 down to voids 4-6 (or from void 4-6 up to voids 1-3), avoiding the large green voids nearby.

Influence of Local Porosity on Fracture Initiation

Local porosity can change the fracture initiation location and timing.

- **Surface Defect:** Depressions with depths >50 μm
- **Surface Roughness:** Smooth depressions with depths between 11-33 μm



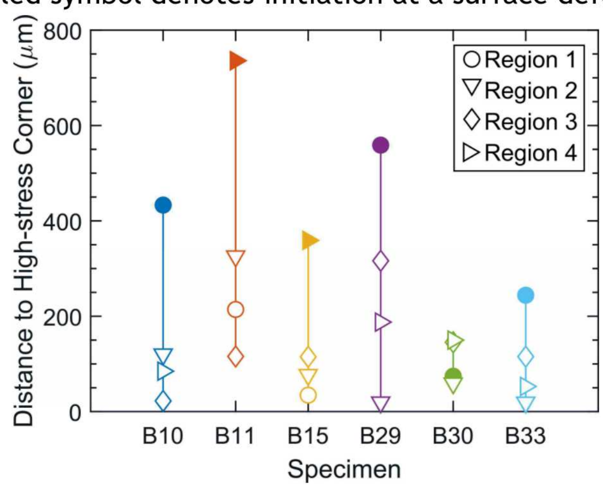
Loading Interval of Fracture Initiation

Specimen	Region 1	Region 2	Region 3	Region 4
B10	1*	2	1	2
B11	2	2	1	1*
B15	2	3	2	1*
B29	1*	1	3	2
B30	1*	2	3	3
B33	1*	1	2	2

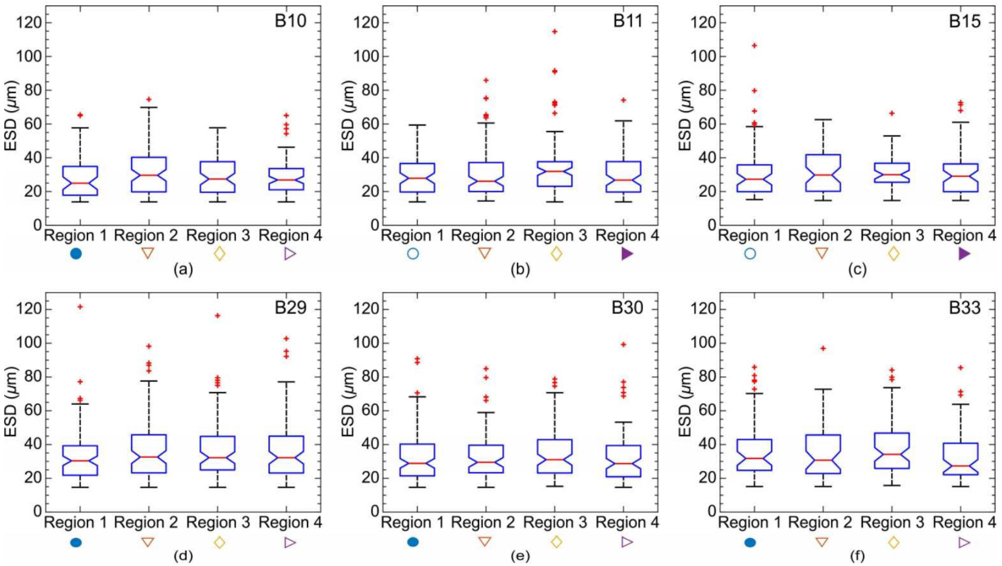
* denotes fracture initiation at a surface defect

Distance of Fracture Initiation Site to High-Stress Intersection Point

(Filled symbol denotes initiation at a surface defect)



Box and Whisker Plots of Equivalent Spherical Diameter (ESD) of Pre-Test Void Population in Rectangular Sub Regions and Table of Pre-test Size of Surface Defects Initiating Fracture



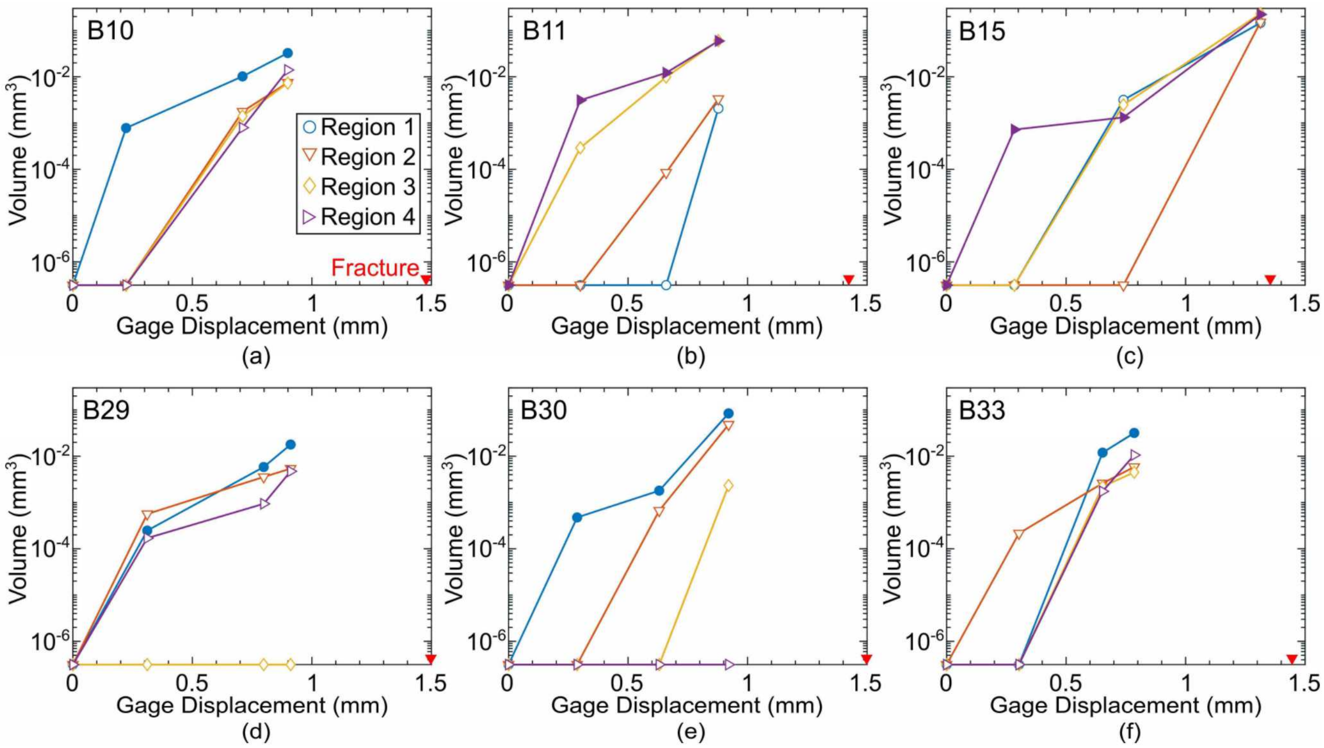
Specimen	B10	B11	B15	B29	B30	B33
Surface Defect ESD (μm)	102	169	80	57	73	113
Region	1	4	4	1	1	1

Influence of Local Porosity on Fracture Growth

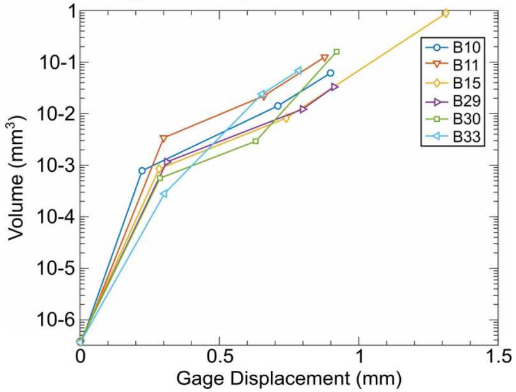
Cracks that initiated at a surface defect tend to grow faster than those that initiated at the high-stress intersection point.

Unloaded Crack Volume After Each Interval for Each Region Versus Unloaded Gage Displacement

(Filled symbol denotes initiation at a surface defect)



Total Unloaded Crack Volume Versus Unloaded Gage Displacement



Despite variation in crack volume evolution between regions, agglomerate volume evolution does not greatly vary between specimens, much like mechanical response.

Future Work

Goal:

Deconvolve influence of several variables including void size, void location, void population, surface roughness, and geometric features on overall part performance.

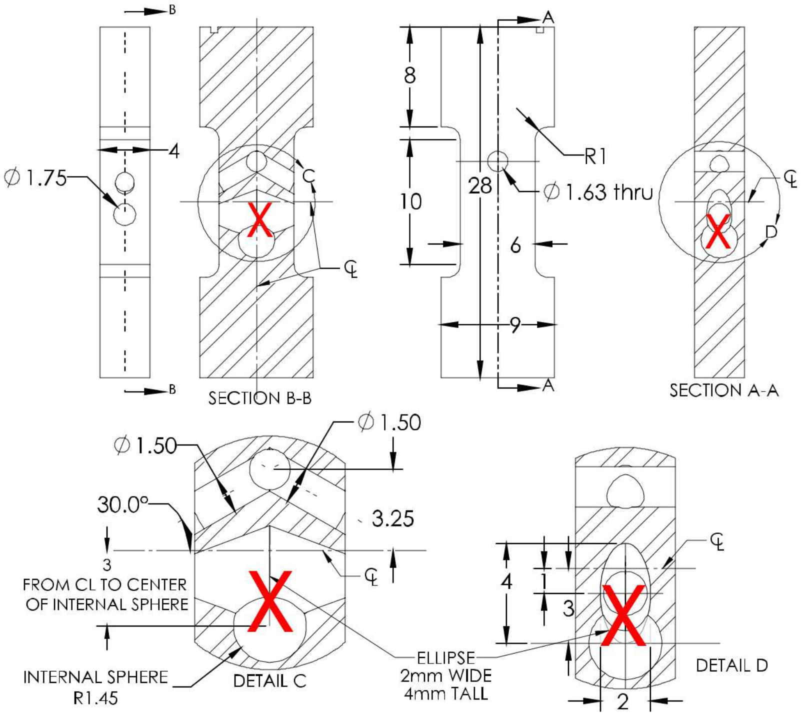
Various SFC3 Cases to Experimentally Study:

- Case 1: AM-built structure with only the through-hole and angled channel features;
- Case 2: AM-built tensile bar with surface roughness removed and the through-hole and angled channel features machined into the part;
- Case 3: a wrought-metal tensile bar with the through-hole and angled channel features machined into the part;
- Case 4: Case 1 that has undergone Hot Isostatic Pressing (HIP); and
- Case 5: Case 2 that has undergone HIP.

Additional Cases:

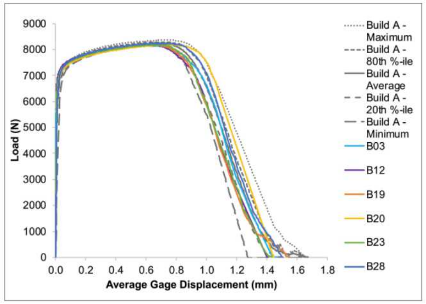
- Different geometric feature sizes relative to void sizes;
- Geometries with only one or two feature; and
- Many more!

SFC3 Geometry Denoted Features To Be Removed

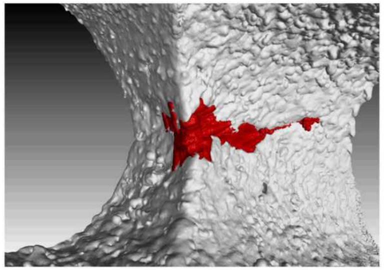


Conclusions

Geometry Dominates Global Behavior in SFC3 Specimens:
Metrics of the pre-existing void population do not correlate with the global mechanical behavior of the SFC3 specimens, but rather the large stress concentrations from the geometry overwhelmingly dominate the global behavior.



Voids Influence Local Crack Initiation and Growth:
Voids and surface defects influence local crack initiation and growth by introducing variation in crack initiation site in some cases and deviation from initial crack path to intersect voids.



Open Question: When Do Voids or Geometry Dominate?
Future work is required to deconvolve influence of several variables including void size, void location, void population, surface roughness, and geometric features on overall part performance.