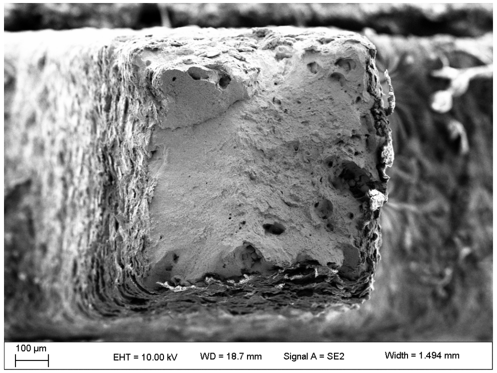
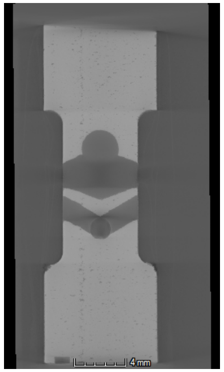
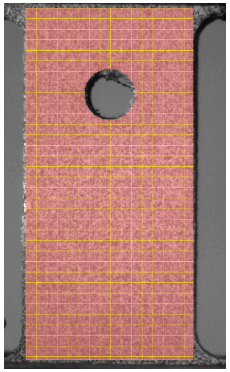
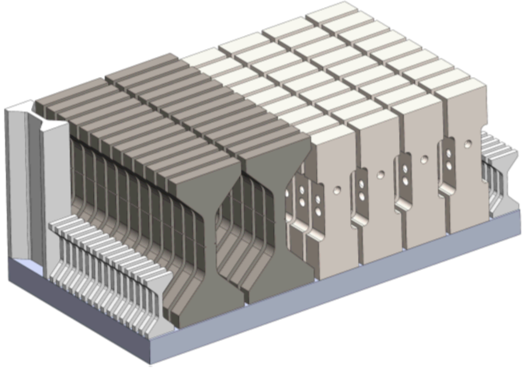
SAND2017-9167PE









Preliminary Results from the Third Sandia Fracture Challenge (SFC3)

Sharlotte Kramer

Team: Brad Boyce, Amanda Jones, Brad Salzbrenner, and Jhana Gearhart

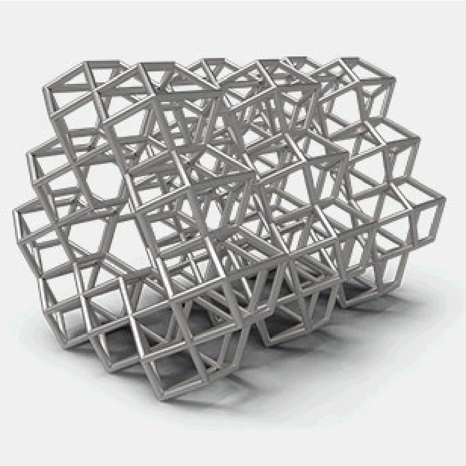
30 August 2017

Structural Reliability Partnership Kickoff Meeting

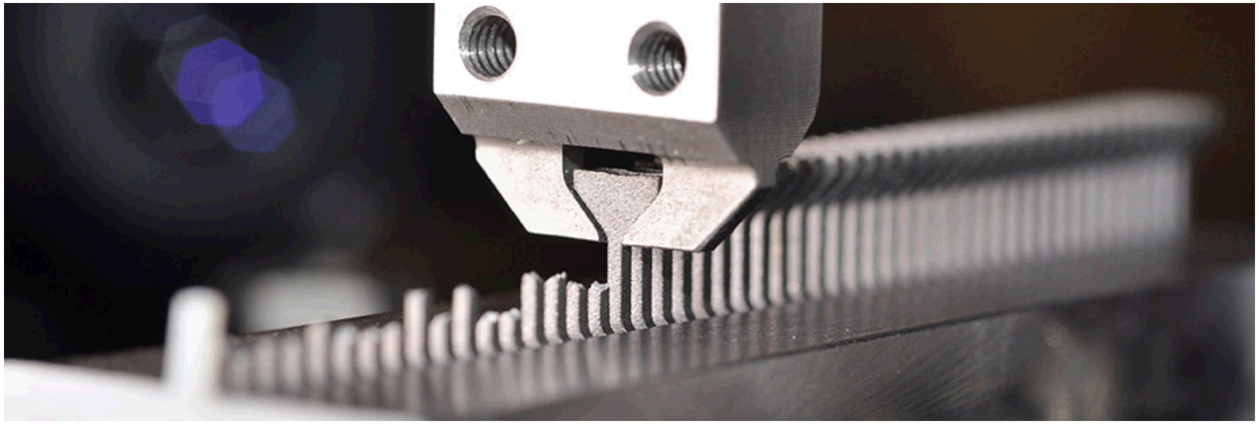
Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Origins of the SFC3

Additive manufacturing (AM) capability poses not only great potential for revolutionizing design and fabrication of parts, but also many questions as to how these parts will perform and how we test and model their mechanical behavior.



Example of AM metal part with an organic structure*



High-throughput testing capability in Material Mechanics Laboratory at Sandia for tensile testing of AM dogbones

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

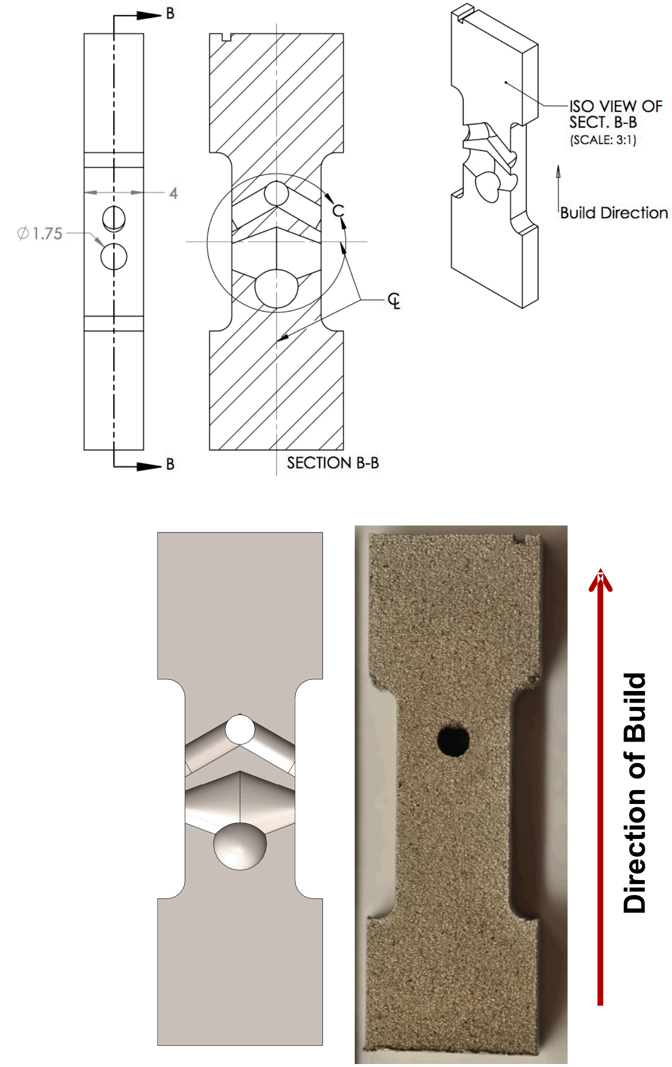
*(https://www.protolabs.com/resources/white-papers/rapid-manufacturing-for-metal-prototypes-and-production-parts/#hard-metals)

SFC3 Problem Definition

Sandia National Laboratories

Predict the deformation and failure of the geometry shown on the right

- **Material:** Additively manufactured 316L stainless steel from a commercial vendor; Laser Powder Bed Fusion also known as Direct Metal Laser Sintering (DMLS) method with 20-micron layers
- **Loading Rate:** 0.0127 mm/s
- **Extensive material property information available**
    - Base material tensile tests Notched tensile tests for fracture properties
    - Micro-computed tomography (CT) of all Challenge geometry specimens to quantify the void content
    - Cross-sections of undeformed specimens
        - Characterization of void content using optical microscopy with higher resolution than micro-CT
        - Electron backscattter diffraction (EBSD) for grain structure characterization of the Challenge geometry
    - SEM imaging of tensile test and notched tensile test fracture surfaces
- **Challenge Issuance: December 15th, 2016**
- **Prediction Deadline: July 15th, 2017**



Drawing (Top Image), Central Cross-Section Schematic (Bottom Left Image), and Front (Bottom Right Image) Views of the Challenge Geometry

Challenge Questions

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

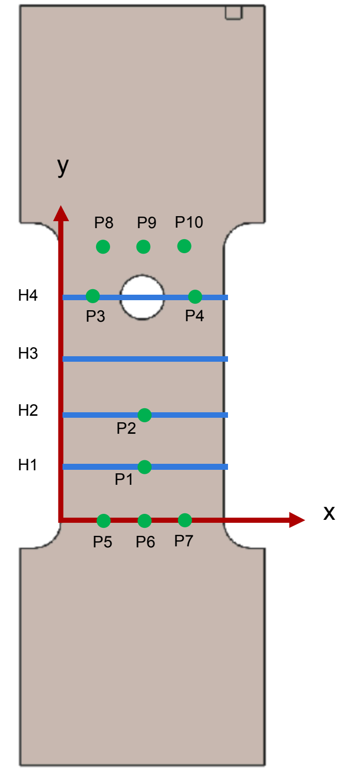
Question 2: Report force and Hencky (logarithmic) strain in the vertical direction (ε_{yy}) at four points, P1, P2, P3, and P4, on the surface at 75% of peak load before peak load (F1), 90% of peak load before peak load (F2), at peak load (F3), and at 90% of peak load after peak load (F4).

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

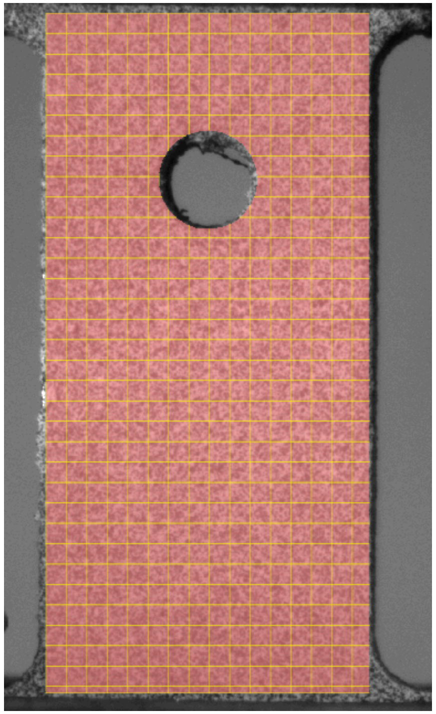
Question 4: Report force vs. Hencky (logarithmic) strain in the vertical direction (ε_{yy}) at four points, P1, P2, P3, and P4, on the surface for the test.

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

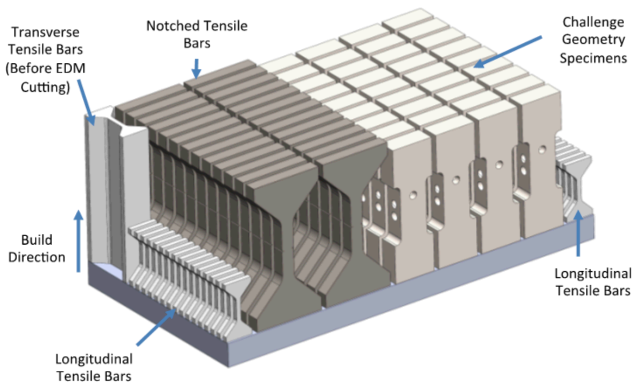


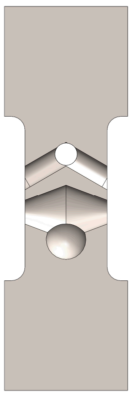
Representative DIC Area of Interest Showing a Grid of 41 pixel x 41 pixel Subsets

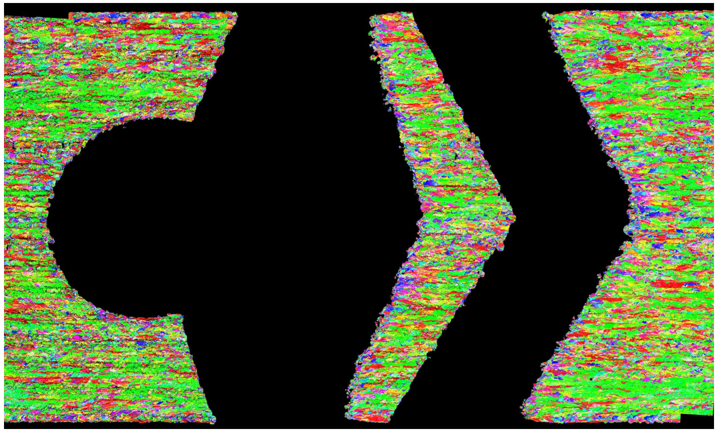
***For Questions 1-4, please report nominal (average) value and optionally report the 80-percentile upper bound and 20-percentile lower bound values to compare to a population of 19 experimental observations.**

Examples of Provided Data

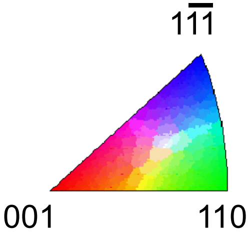
AM Build of All Test Specimens (Left); Central Cross-Section Schematic (Center) and Front Views of the Challenge Geometry (Right)



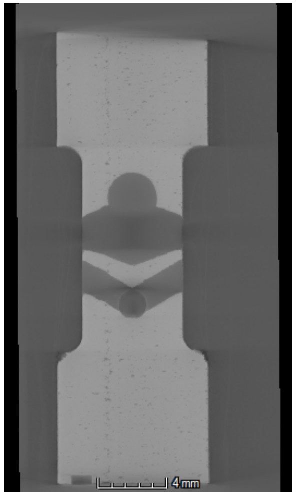




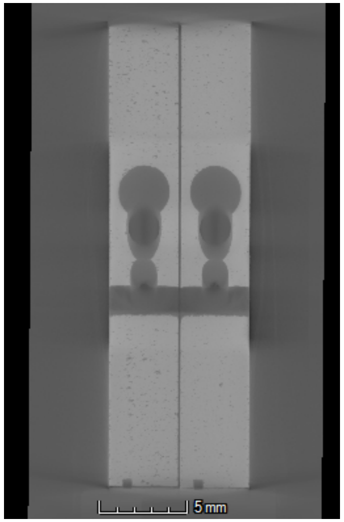
EBSD Inverse Pole Figure (IPF) in Build Direction



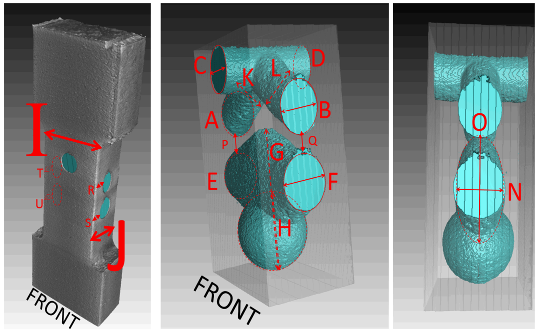
Example of micro-CT Scans of Challenge Geometry



A32 Front View "Thick Slab" Image



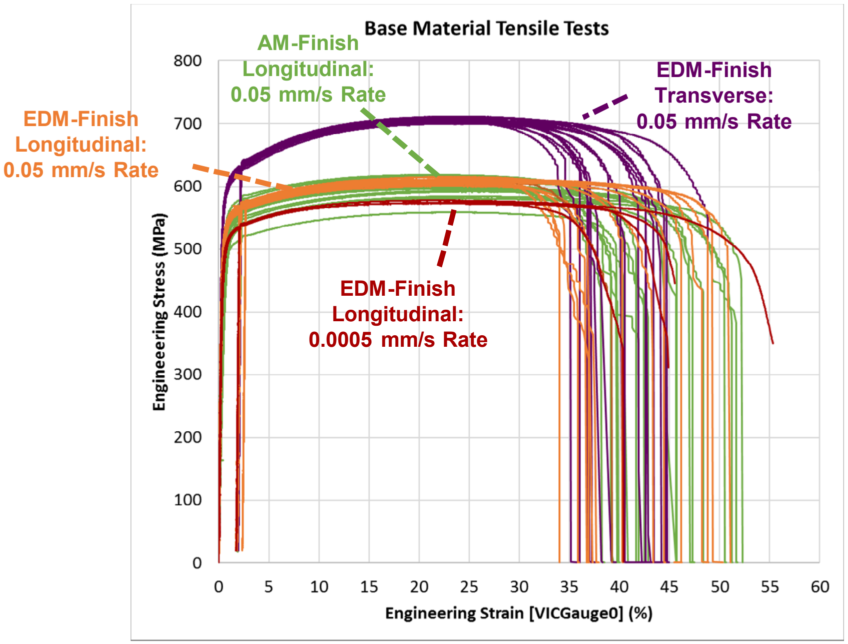
Side View Image of A32 (left) and A15 (Right)

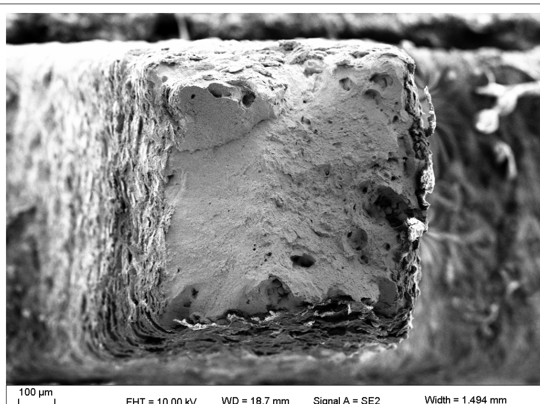


Reconstructed micro-CT Scans with Provided Feature Measurements

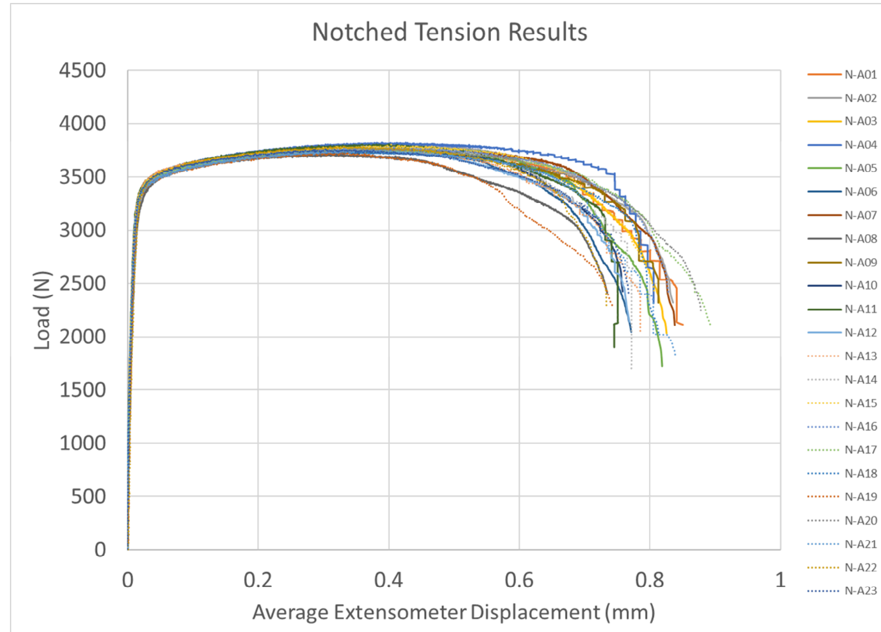
Examples of Provided Data

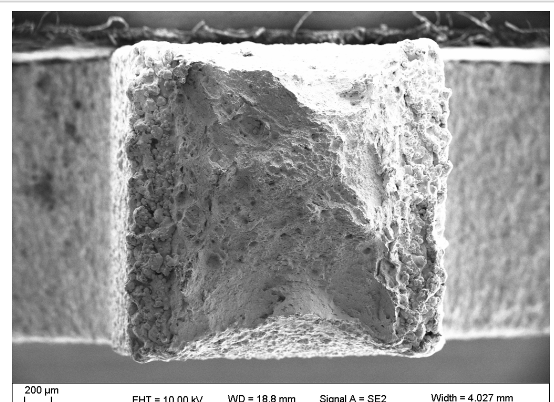
Base Material Test Data (Top); SEM Image of Fracture Surface of Tensile Specimen LTA04 (Bottom)



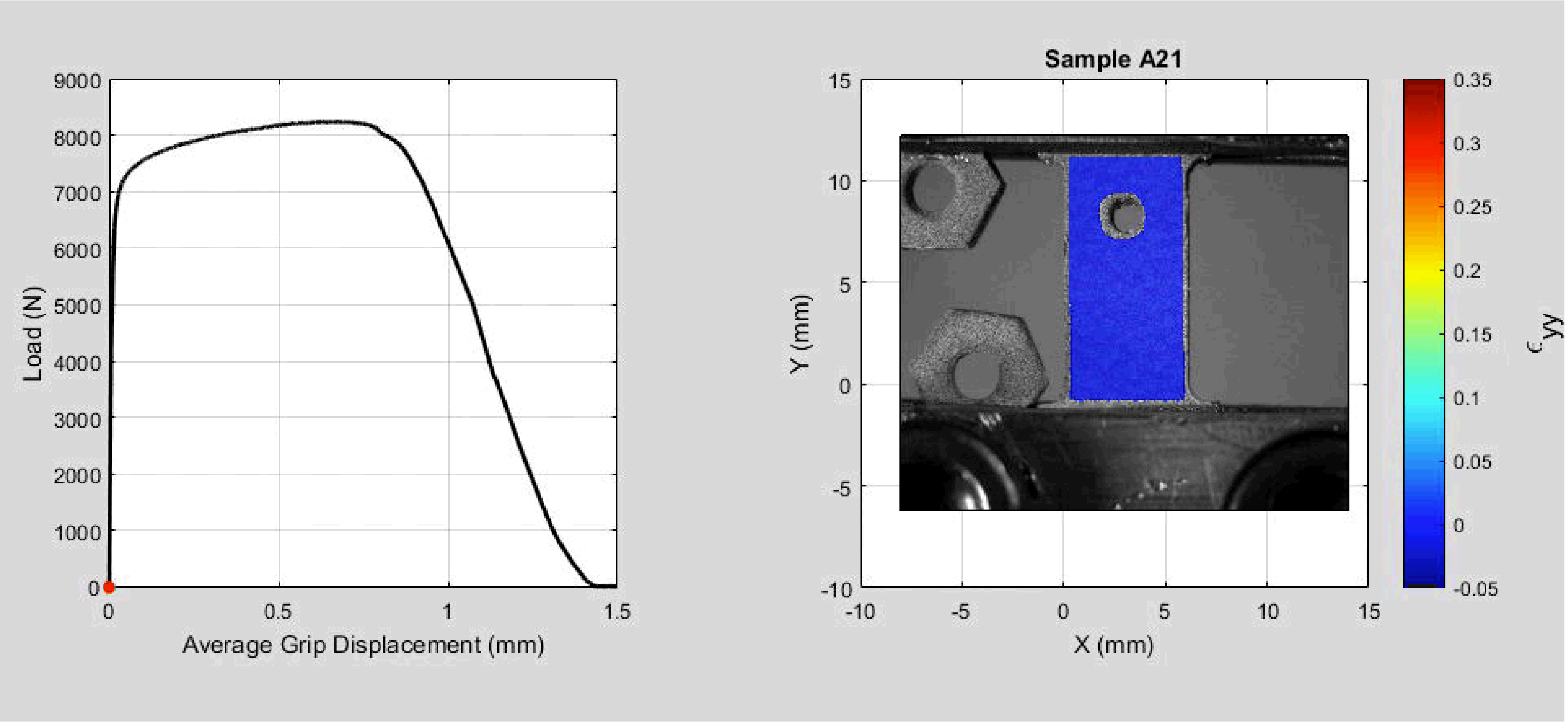


Notched Tensile Test Data (Top); SEM Image of Fracture Surface of Notched Tensile Specimen NA05 (Bottom)





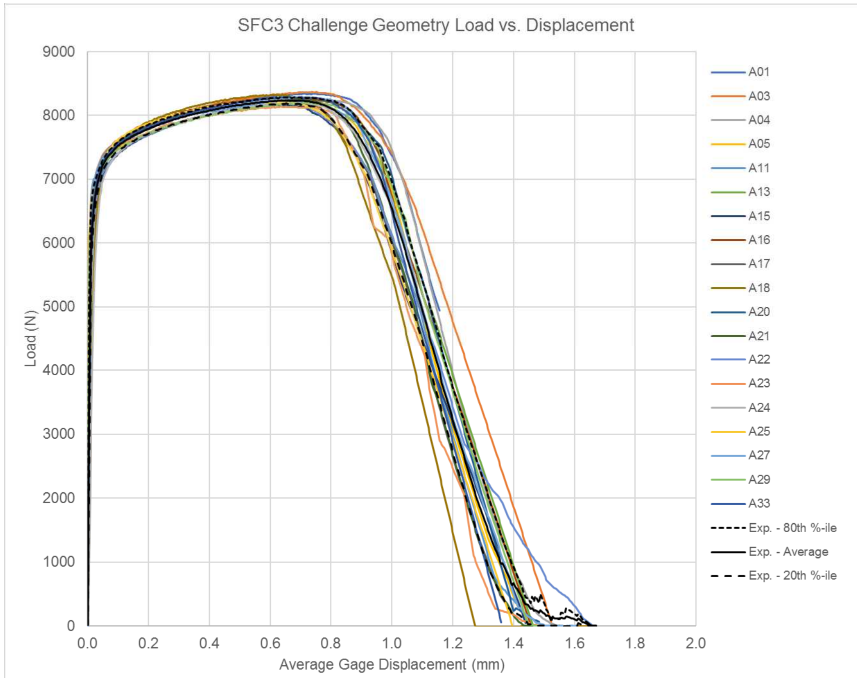
Challenge Geometry Experimental Result



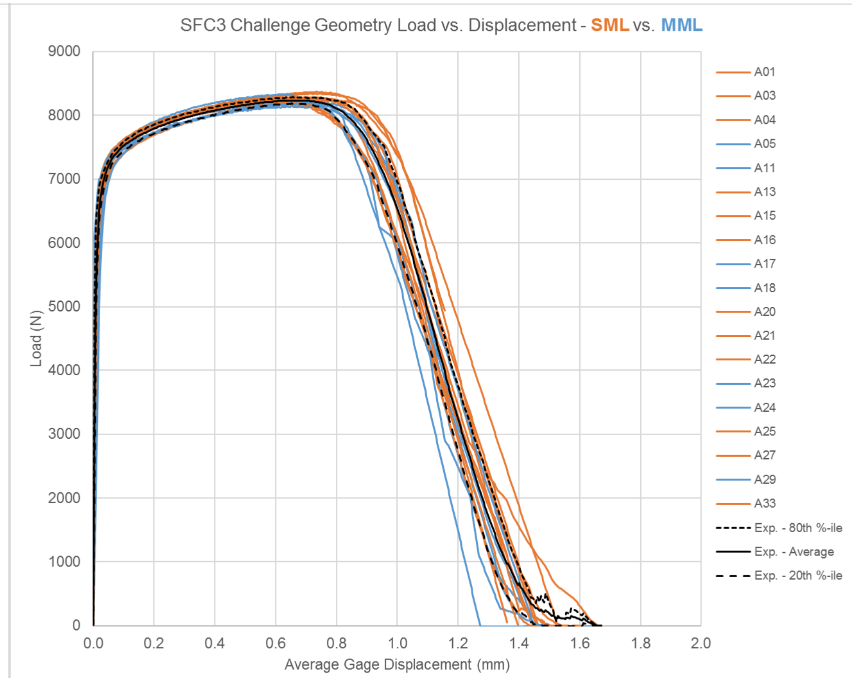
Experiments: Question 3

Report the force vs. gage displacement D for the test.

19 Specimens with Average and Bounds



Comparison of Tests From Two Laboratories



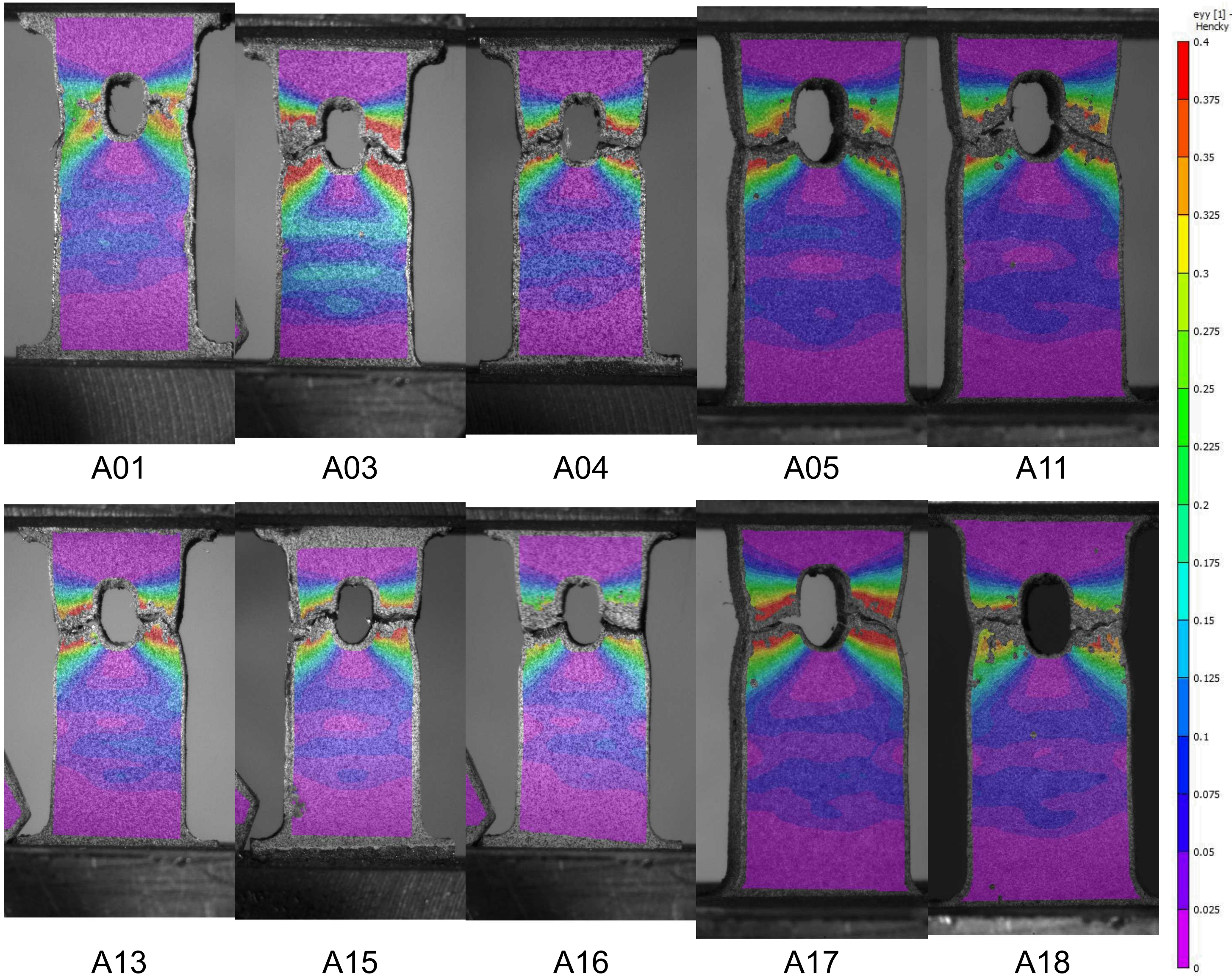
- Relatively repeatable experimental data set with all specimen failing in nominally the same location
- Experimental data from two testing laboratories (12 specimens for the Structural Mechanics Laboratory and 7 specimens from the Material Mechanics Laboratory) overlap
- 20th percentile, average, 80th percentile forces were determined from the population of 19 specimens where data was available at each value of displacement

Experiments: Question 6 Failure - Strain

The image shown for A01 is immediately before complete failure, where DIC correlation was lost.

Crack path is similar for each specimen, but are not necessarily following the angled channels in every specimen.

Note: SML DIC setup had the left camera perpendicular to the specimen face, while the MML DIC setup had the left camera at an angle relative to the specimen face.



21 Teams of Challenge Participants

Sandia National Laboratories

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

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

Government Laboratories

Sandia National Laboratories

US Army Corps of Engineers

Natural Resources Canada / Ressources naturelles Canada

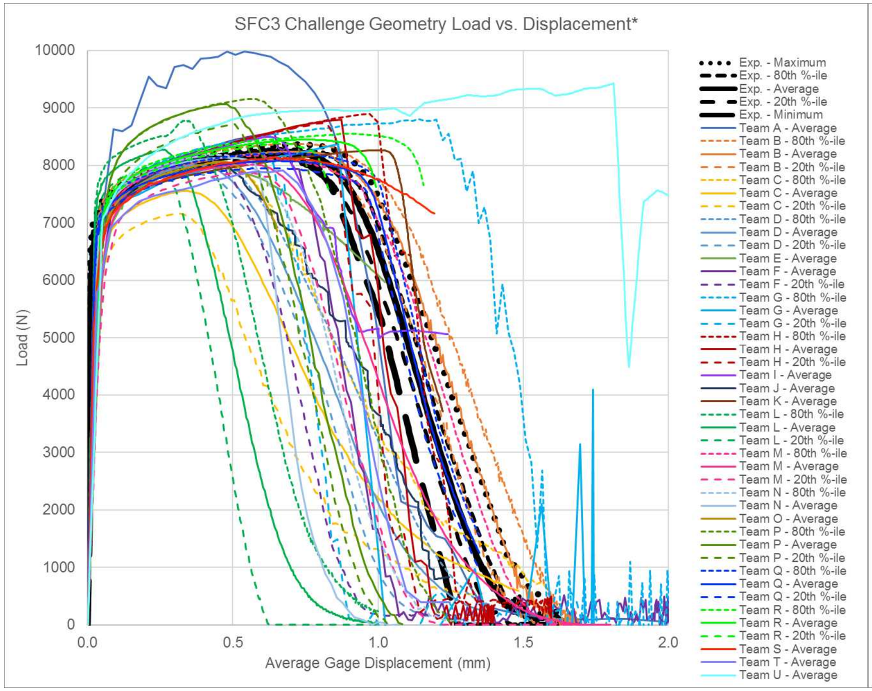
CanmetÉNERGIE

Leadership en écoInnovation

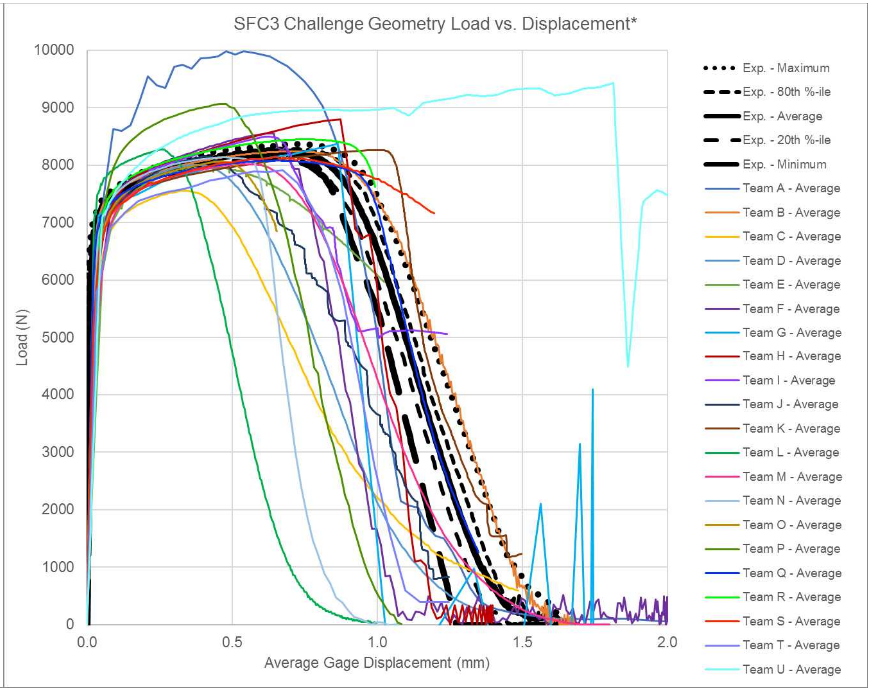
Predictions: Question 3

Report the force vs. gage displacement D for the test.

21 Predictions and Bounds with Exp. Average and Bounds

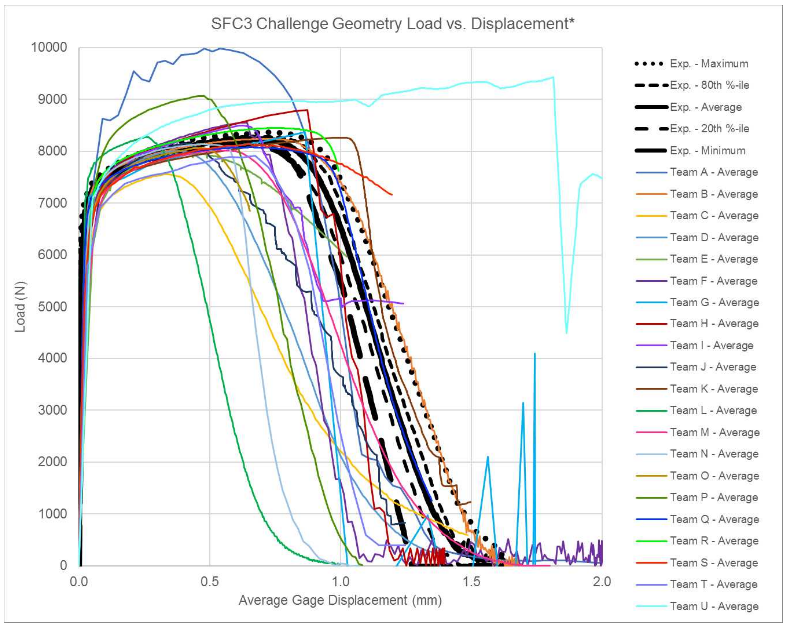


21 Nominal Predictions with Exp. Average and Bounds



- 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 with most unlike the experiments where there was little initial variability with moderate variability after peak load.

Prediction Methods

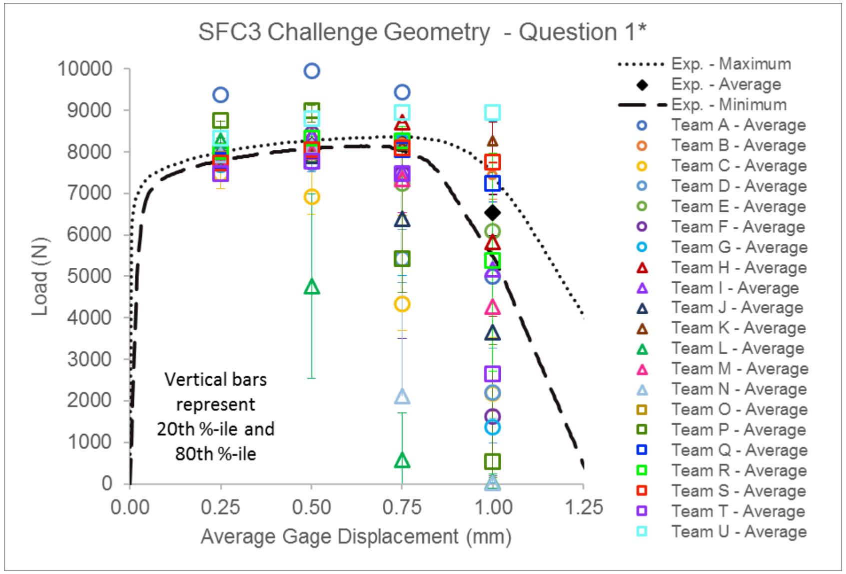


- **The 21 predictions were obtained from a variety of methods**, for example:
  - **Solvers**: Explicit vs. Implicit; Quasi-statics vs. Dynamics
  - **Fracture Method**: Element deletion, Peridynamics with bond damage, XFEM, Damage (stiffness degradation), and Adaptive remeshing
  - **Uncertainty**: 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**
- **12 teams offered uncertainty bounds on their predictions**

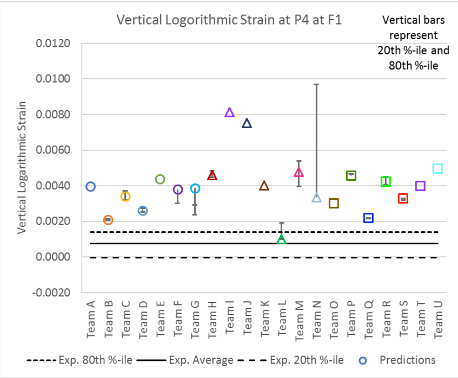
Predictions: Question 1 & 2

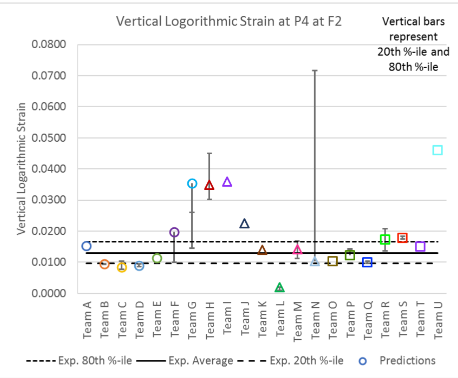
Question 1: Report the force at the following displacements D: 0.25 mm, 0.5 mm, 0.75 mm, and 1.0 mm.

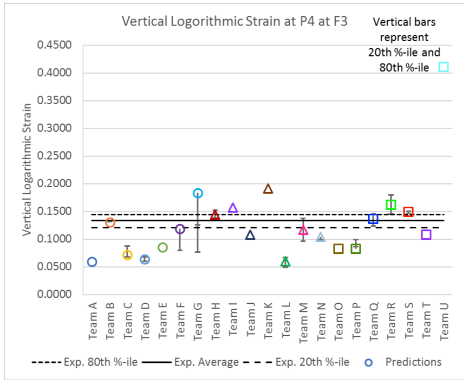
Several teams predicted the initial structural yield, but the variation broadened with increasing displacement.

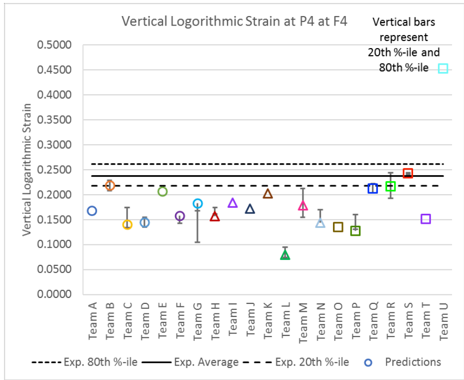


Question 2: Report force and Hencky (logarithmic) strain in the vertical direction (ε_{yy}) at four points, P1, P2, P3, and **P4**, on the surface at 75% of peak load before peak load (F1), 90% of peak load before peak load (F2), at peak load (F3), and at 90% of peak load after peak load (F4).





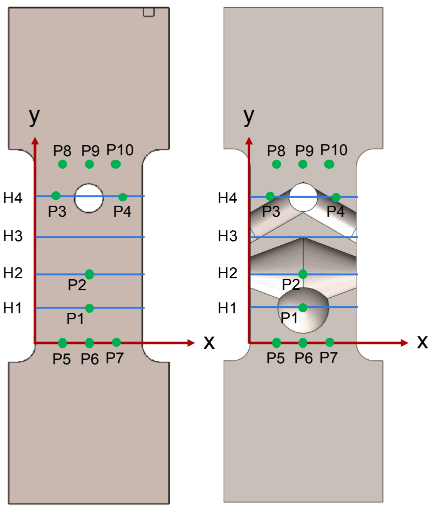




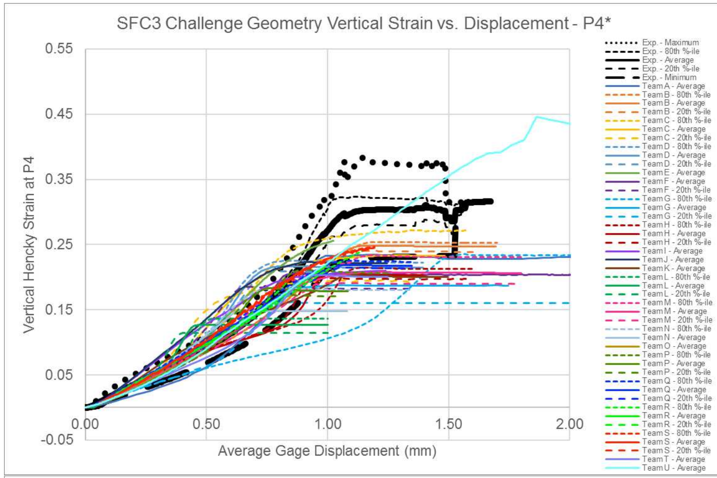
Generally, the predictions were initially too high, particularly for F1, and then were under-predicting by F4.

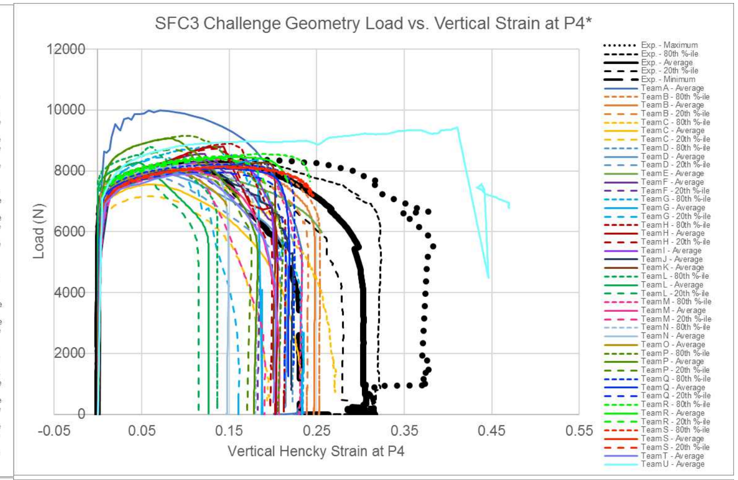
Predictions: Question 4 P4

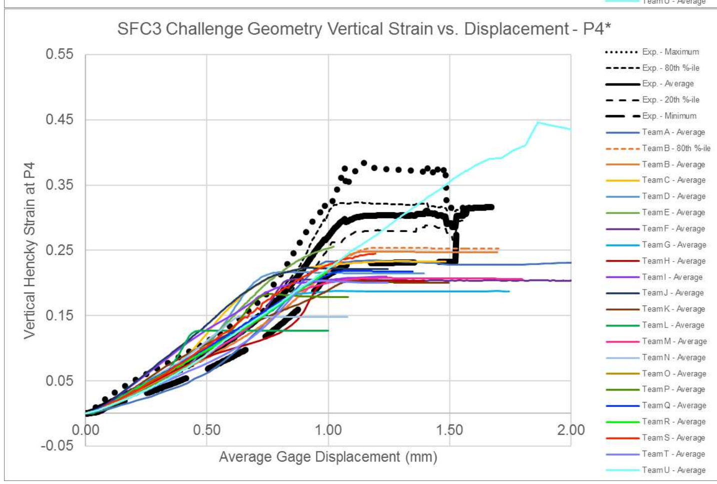
Report force vs. Hencky (logarithmic) strain in the vertical direction (ε_{yy}) at P4.

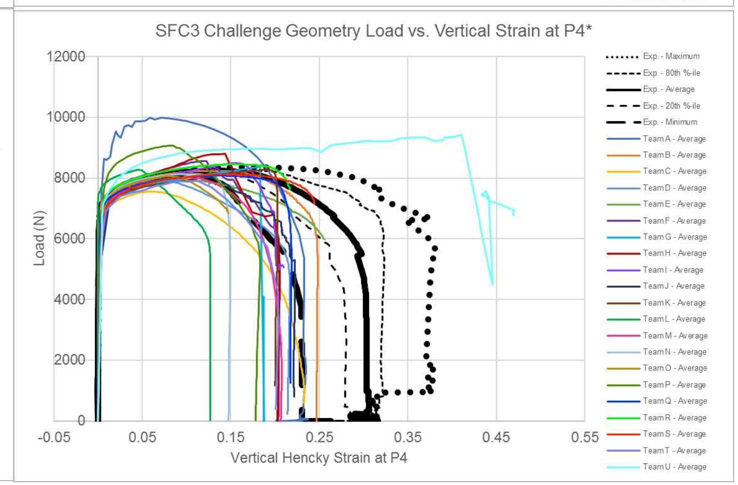


Challenge Geometry (Surface – Left, Cutaway – Right)









Strain predictions close to failure were generally too low.

Predictions: Question 5 H4 F1-F4

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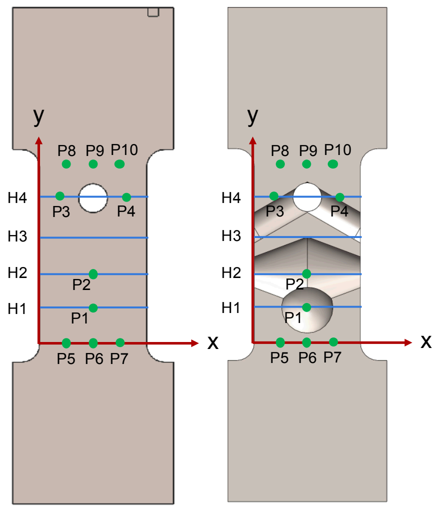
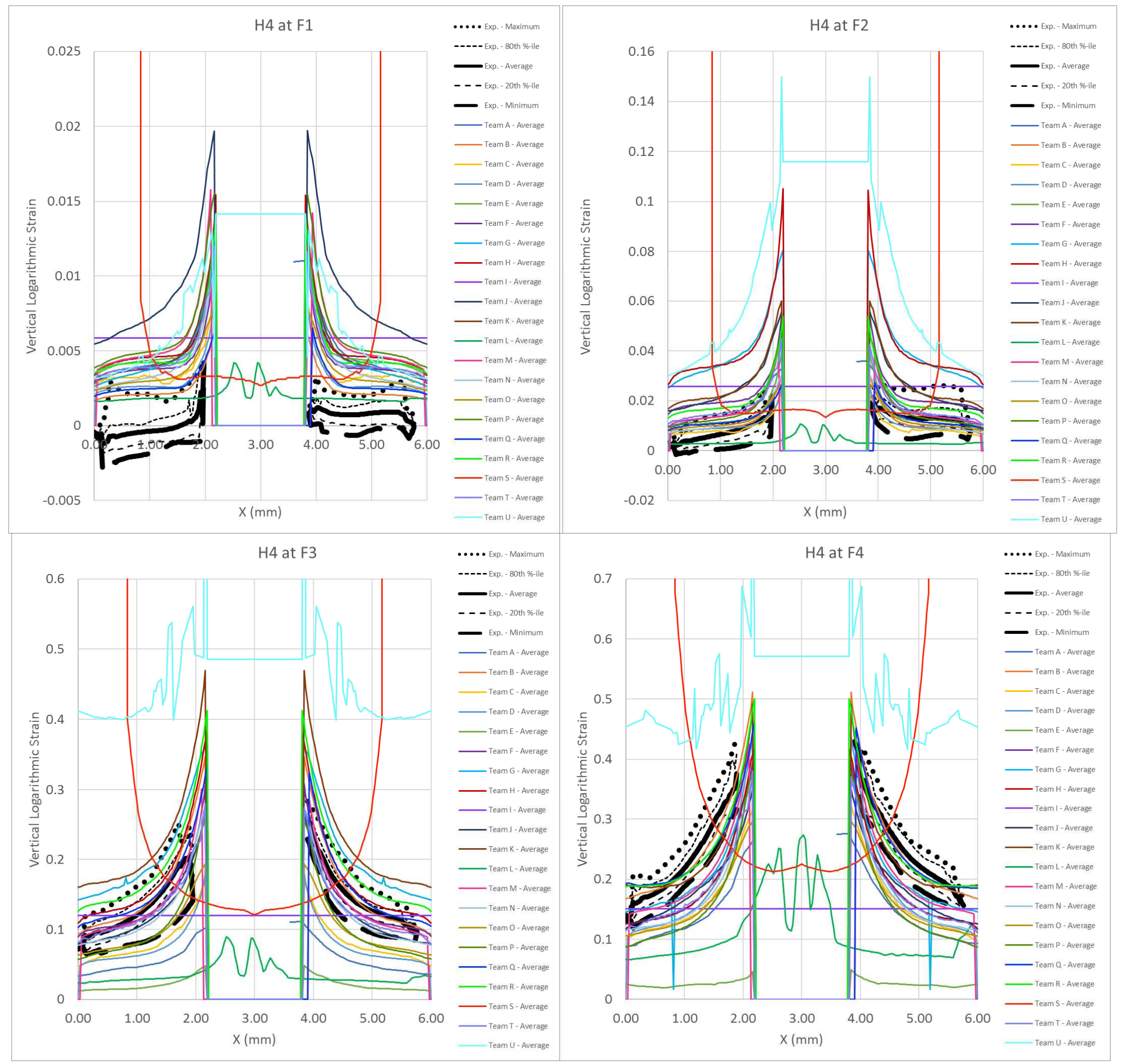
Report force and Hencky (logarithmic) strain in the vertical direction (ε_{yy}) along horizontal line H4 on the surface at forces F1, F2, F3, and F4.

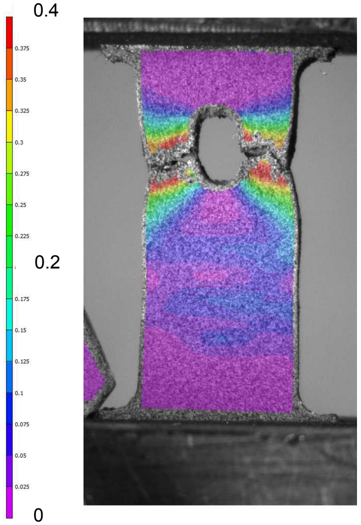


Challenge Geometry (Surface – Left, Cutaway – Right)

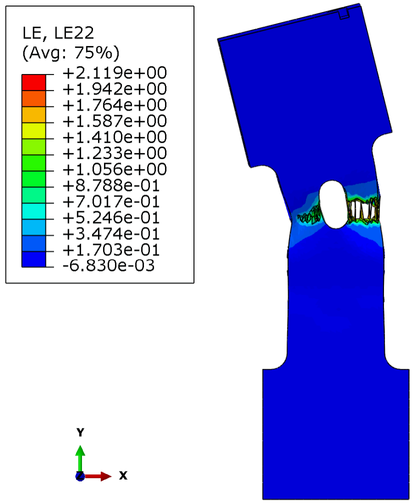


Most teams over-predicted the nominal strain at F1, but many team's predictions improved for higher forces.

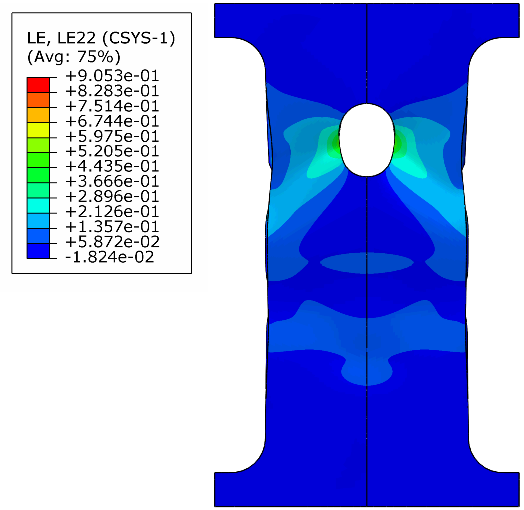
Predictions: Question 6 Failure - Strain



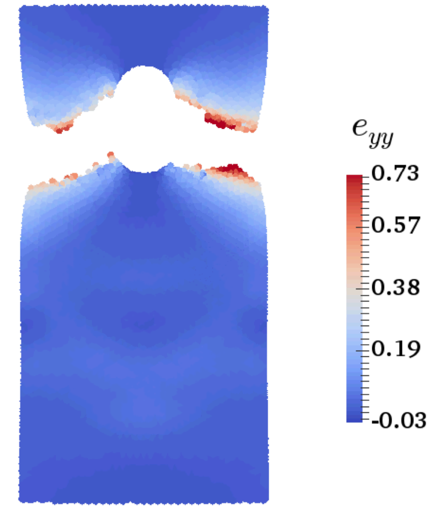
A13



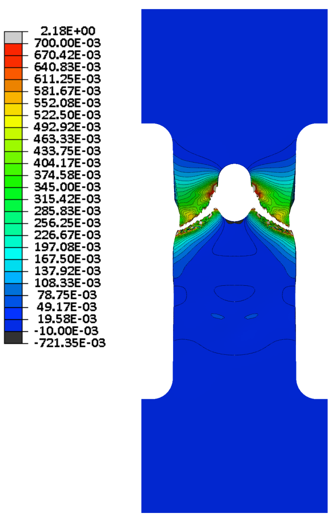
Team A



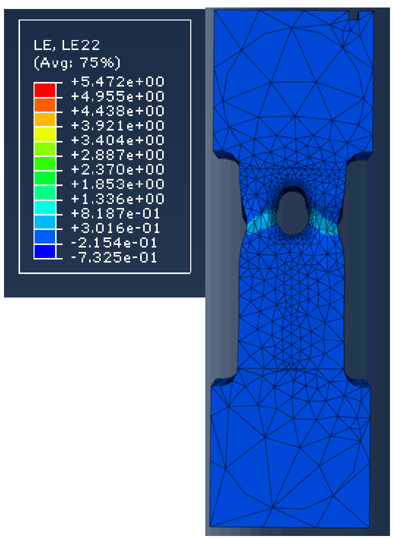
Team B



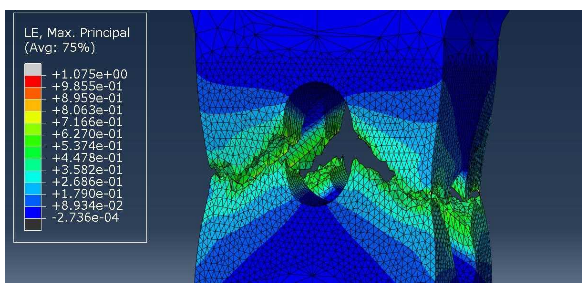
Team C



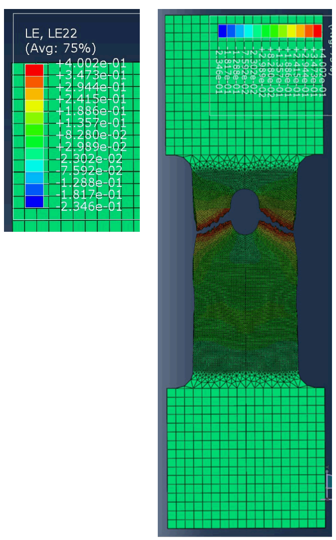
Team D



Team E



Team F



Team G

Predictions: Question 6 Failure- Strain

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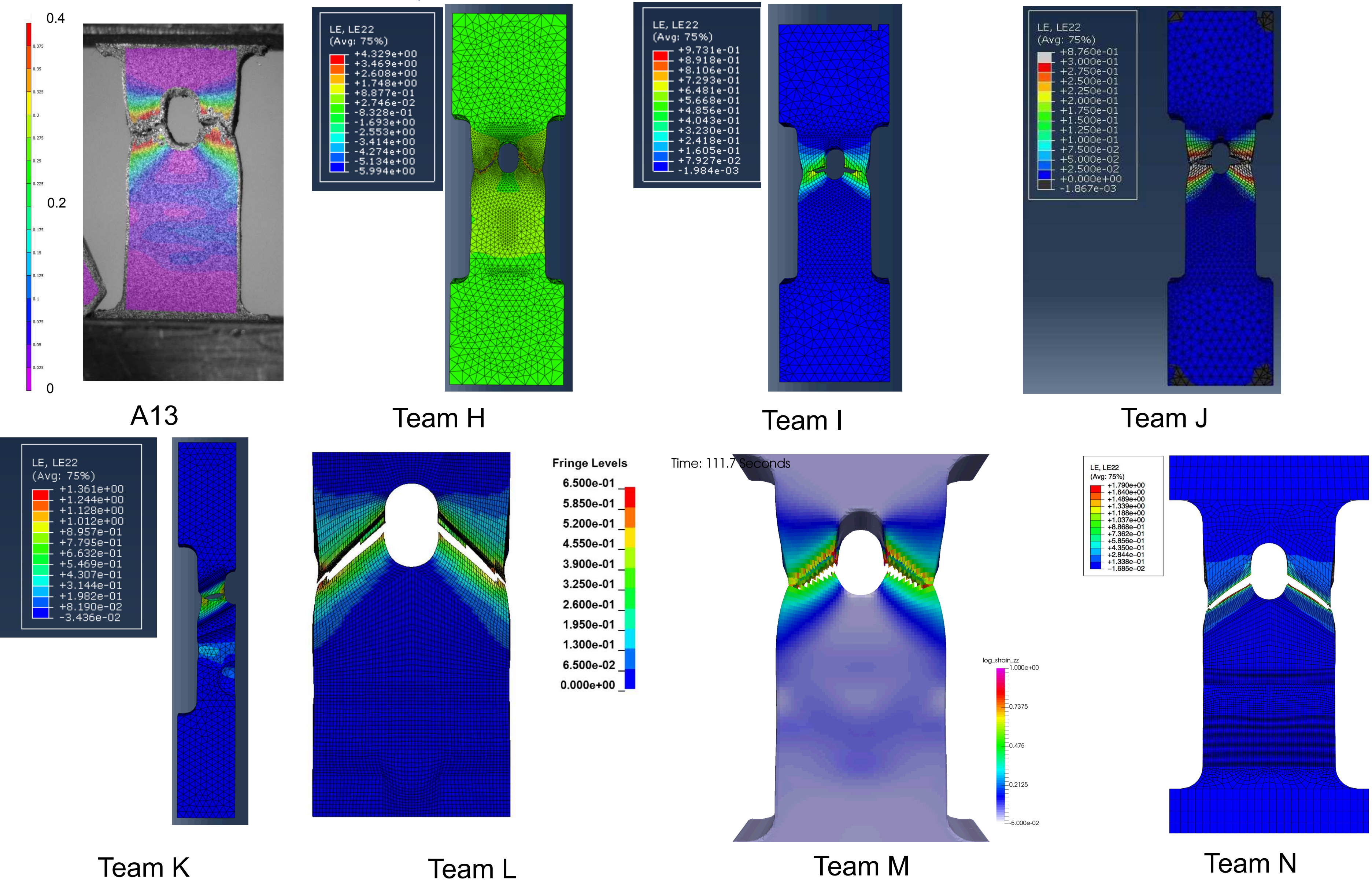
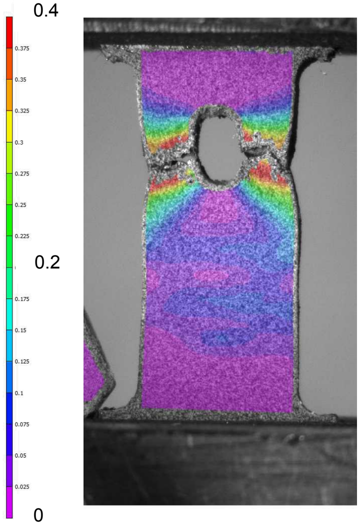
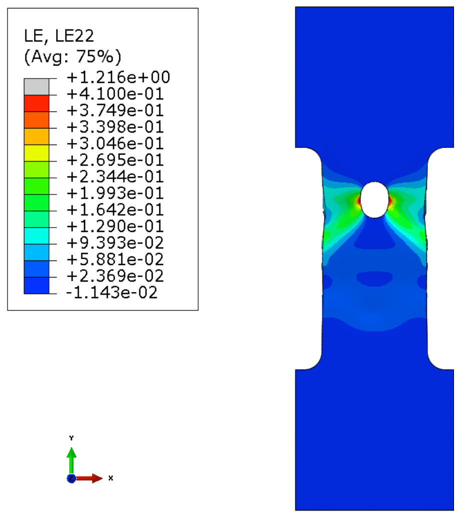


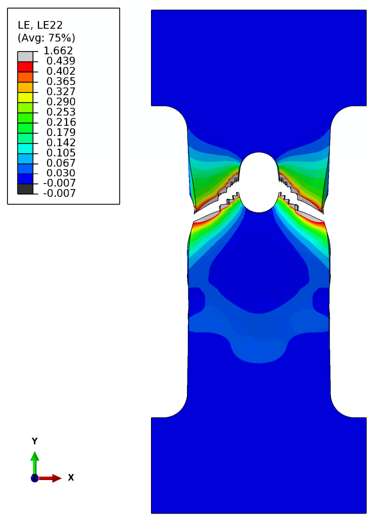
Predictions: Question 6 Failure - Strain



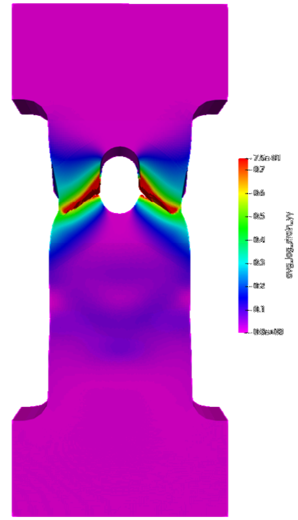
A13



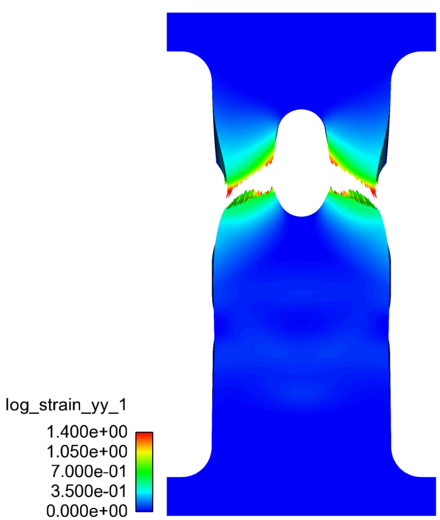
Team O



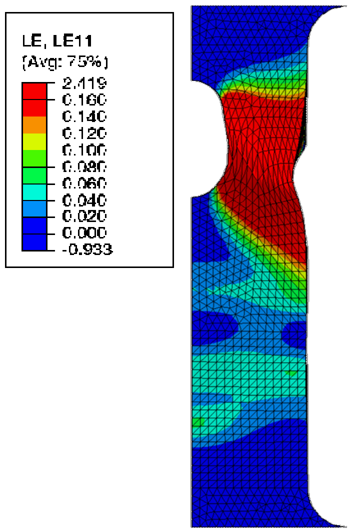
Team P



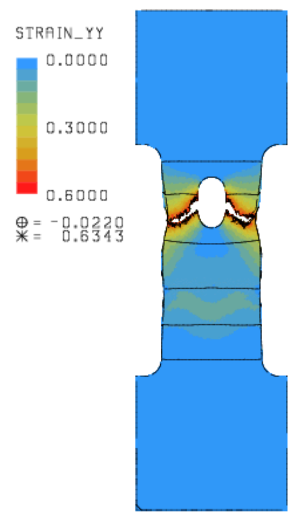
Team Q



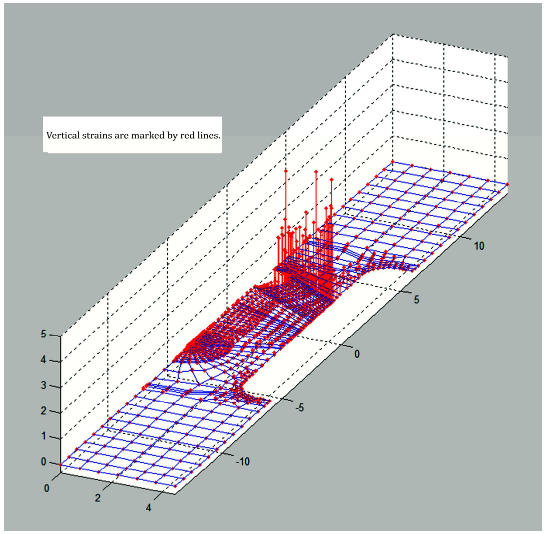
Team R



Team S



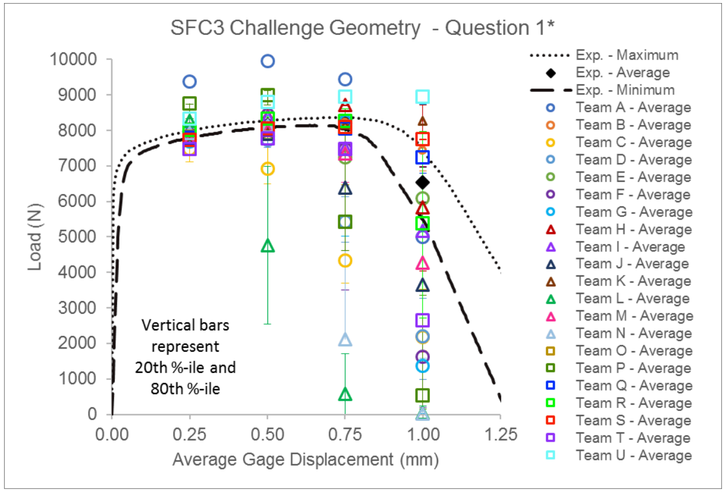
Team T

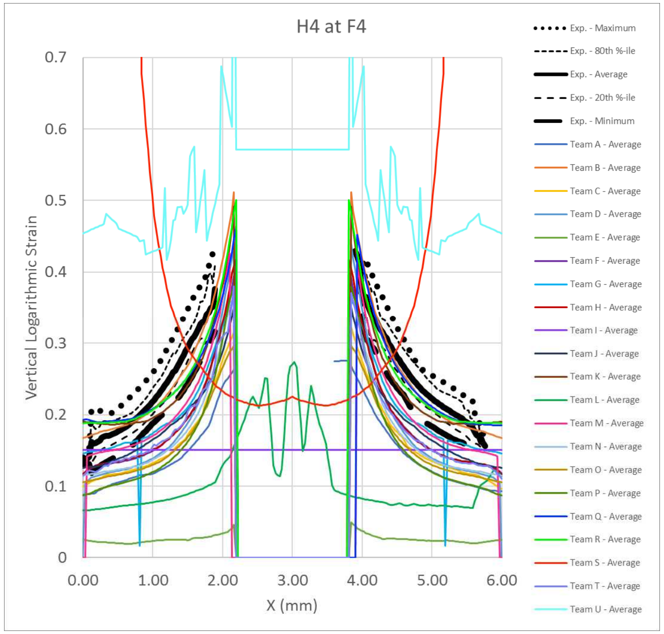


Team U

Initial Impressions of the Predictions

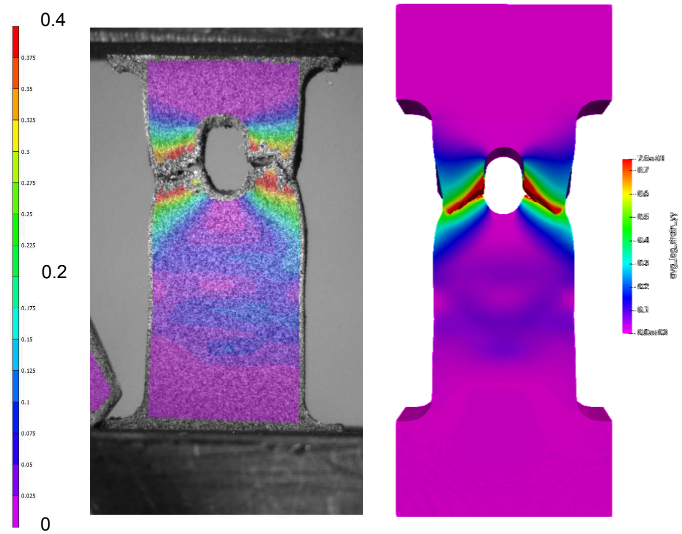
- **All teams predicted the correct crack path**
- Two teams predicted a nominal load-displacement behavior within the bounds of the experimental data
- Experimental strain measurements tended to have larger variation than predicted
- Generally, teams tended to over-predict strains early in the deformation and then under-predict towards failure
- The teams took vastly different approaches to predict uncertainty bounds in their models
- Surprisingly few teams considered the geometric variation and pore structures characteristic of AM metals, despite considerable data provided to aid that effort
- There were examples of clear misinterpretations of the questions

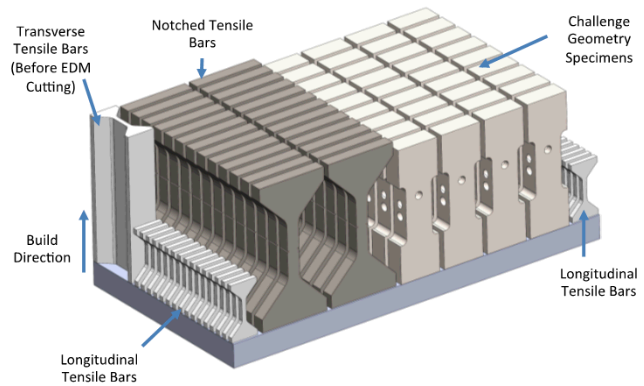




Next Steps in SFC3

- Post-Blind Assessment: Questions to answer
  - What common modeling techniques led to successful predictions?
  - What are common shortcomings, and what are their origins?
  - Why could some teams predict global quantities well, but miss local quantities?
  - How should we compare full-field experimental data and predictions?
  - What methods for uncertainty quantification proved useful? What led to poor estimation of the uncertainty bounds?
- Further Experimental Investigations:
  - Poll teams to ask for calibration experiments or pre-test measurements may have helped their predictions
  - Perform a selection of suggested test measurements to see if they help
- Workshop and Documentation of SFC3





Impact of SFC3

1. Provides a **collaborative environment** for capability assessments
2. Raises questions regarding **how we should tackle testing and modeling additively manufactured parts**
3. Will provide documentation of **'state-of-the-art'**
4. Will illustrate **key deficiencies** in structural mechanics predictions
5. Raises international **awareness on the need for improved simulation capabilities**