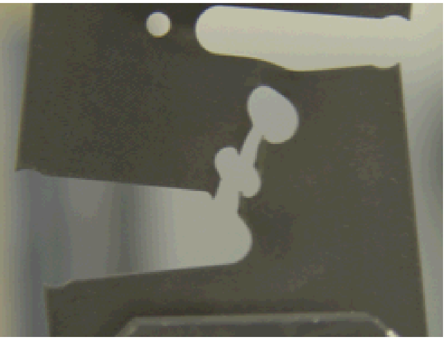
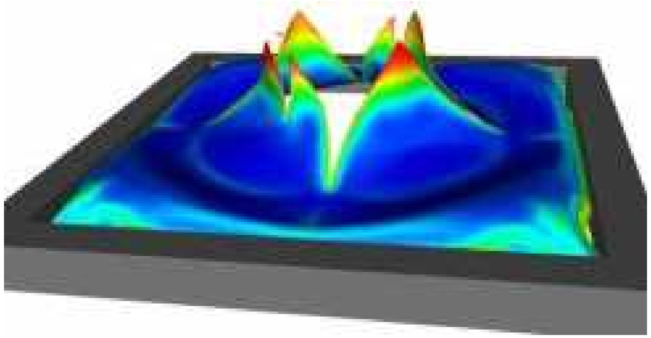
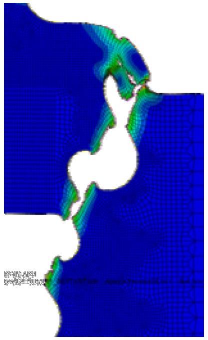
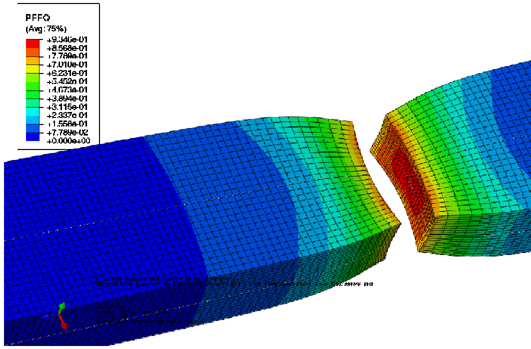
SAND2017-6281C

Assessing ductile rupture predictions through the Sandia Fracture Challenges

Brad Boyce
Materials Science and Engineering Center
Sandia National Laboratories

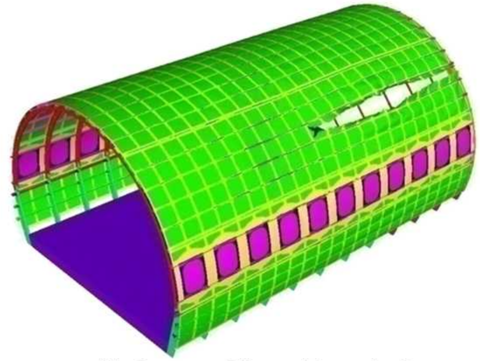
June, 2017

Int. Conf. on Fracture

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and 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-NA-0003525.

Ductile failure is a pervasive problem…

Sandia National Laboratories



Airframe Shoe-Bomb Scenario

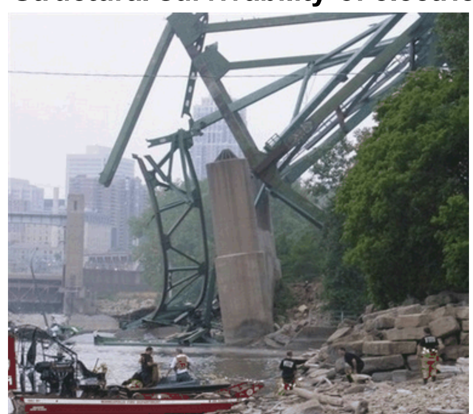
Nuclear safety: operational and threat environments.

Cargoship Rena (2011)

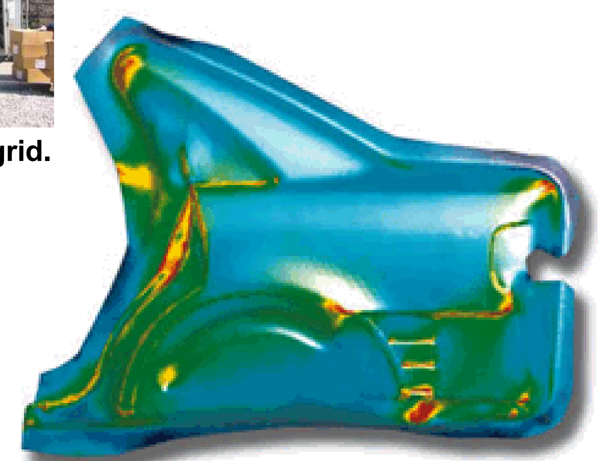
Structural survivability of electric grid.

Hydrogen storage in GM fuel cell vehicles

.

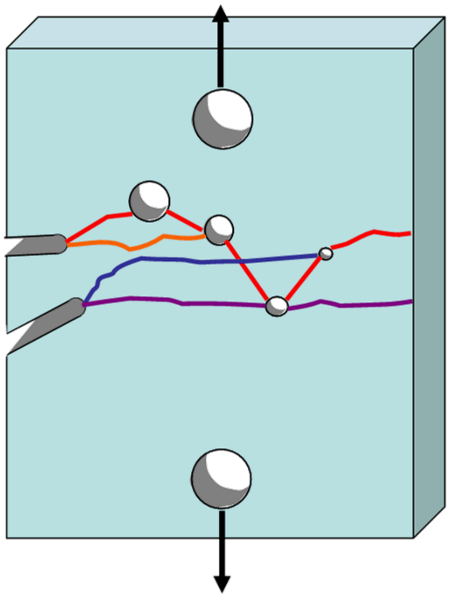


Minnesota I-35W Bridge Collapse..



Metal Forming

OBJECTIVE: *Assess how well we can blindly predict metallic fracture of an unfamiliar geometry*

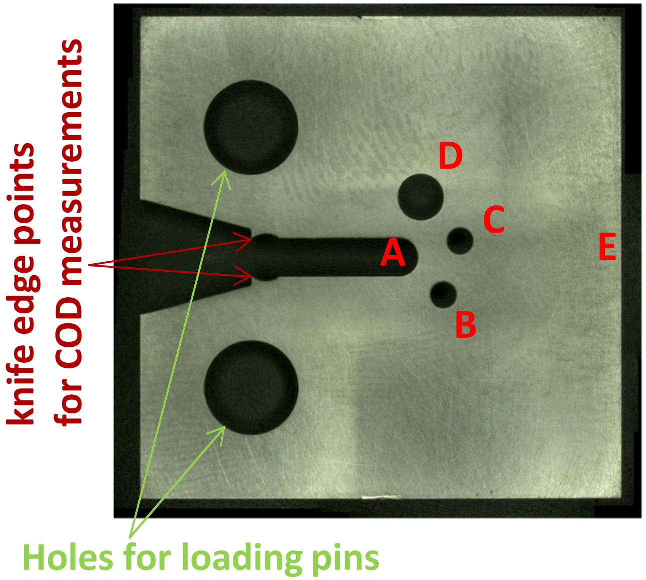


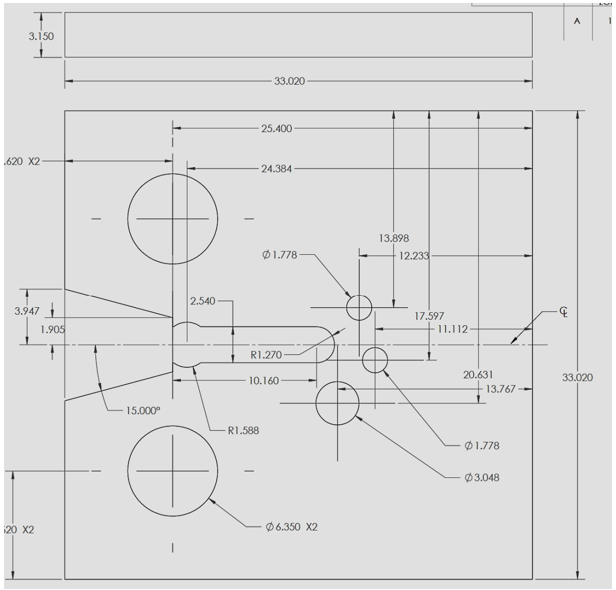
"Crack-in-a-maze" Concept

PHILOSOPHY:

- Replicate real-world engineering constraints (time, budget, information)
- **Blind** predictions are reported before confirmation experiments are available
- 'Toy Problem' is geometrically simple but captures salient difficulties of real-world problems
- Assess the whole prediction stream: (physics, numerical methods, code, calibration & people)
- Do not specify the models/tools/methods to be used: let the engineers use their judgement & strengths
- Verify the experimental outcome in multiple labs, and disseminate results *after* blind predictions are reported
- Use the assessment to inspire improvements
- **COMPETITION DRIVES INNOVATION**

The SFC1 Challenge





Alloy: 15-5PH H1100

The challenge. When loaded at room temperature at a loading rate of 0.0005 inches/sec,

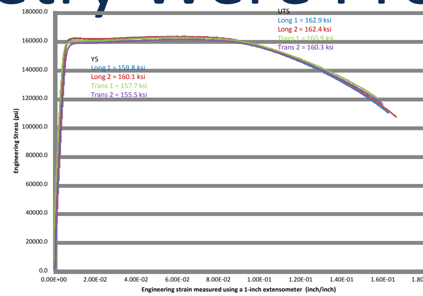
(Q1) What is the force and COD displacement[1] at which a crack first initiates[2]?

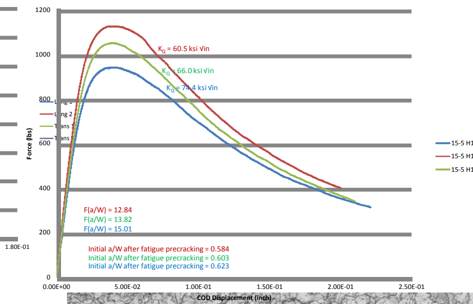
(Q2) What is the path of crack propagation? (Use feature labels A-E to describe path)

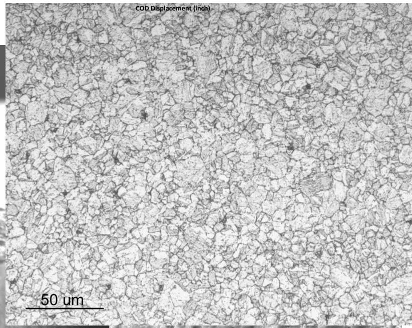
(Q3) If the crack does propagate to either holes B,C, or D, at what force and COD displacement does the crack re-initiate out of the first hole?

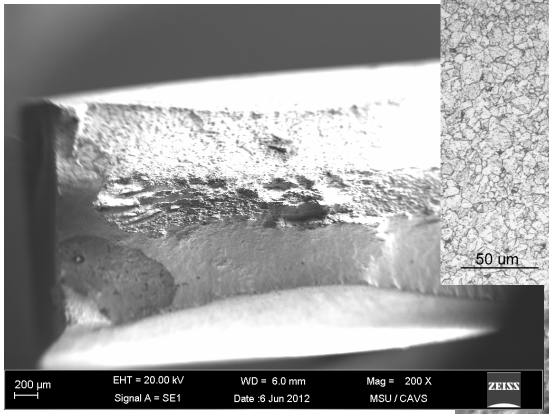
Details of the Material & Geometry Were Provided

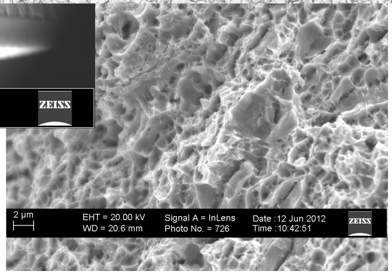
- Multiple tensile stress-strain curves for both longitudinal and transverse deformation
- Multiple Sharp-crack 'fracture toughness' force-displacement curves on sheet of same thickness as challenge
- Images of the fracture surface, side view of the necking region
- Material certification, including material chemistry and mechanical properties
- Detailed heat treatment records
- Measured hardness values
- Engineering drawings that were also sent to machinists for specimen manufacture



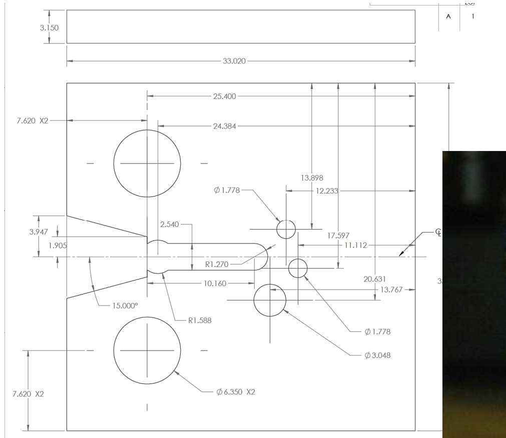








Mississippi State (Horstemeyer et al)



Boyce, et al., *Int. J. Fracture*, 2014

Leverage the external mechanics community

Sandia National Laboratories

Sandia National Laboratories

The University of Texas at Austin

NASA

MINES ParisTech

MIT Massachusetts Institute of Technology

Cornell University Founded A.D. 1865

Northwestern University 1851

GE

Univerza v Mariboru

UIC University of Illinois at Chicago

Natural Resources Canada Ressources naturelles Canada

CanmetÉNERGIE
Leadership en écoInnovation

الجامعة الأمريكية بالقاهرة
The American University in Cairo

RWTH AACHEN UNIVERSITY

ONERA
THE FRENCH AEROSPACE LAB

UCLA Bruins

GLOBAL ENGINEERING & MATERIALS, INC.
Engineering and Innovative Solutions

University of Miami

UT Dallas

Chongqing University 1929

Tsinghua University 1911

Zhejiang University 1897

University of Cincinnati

Missouri

Dalian University of Technology 1949

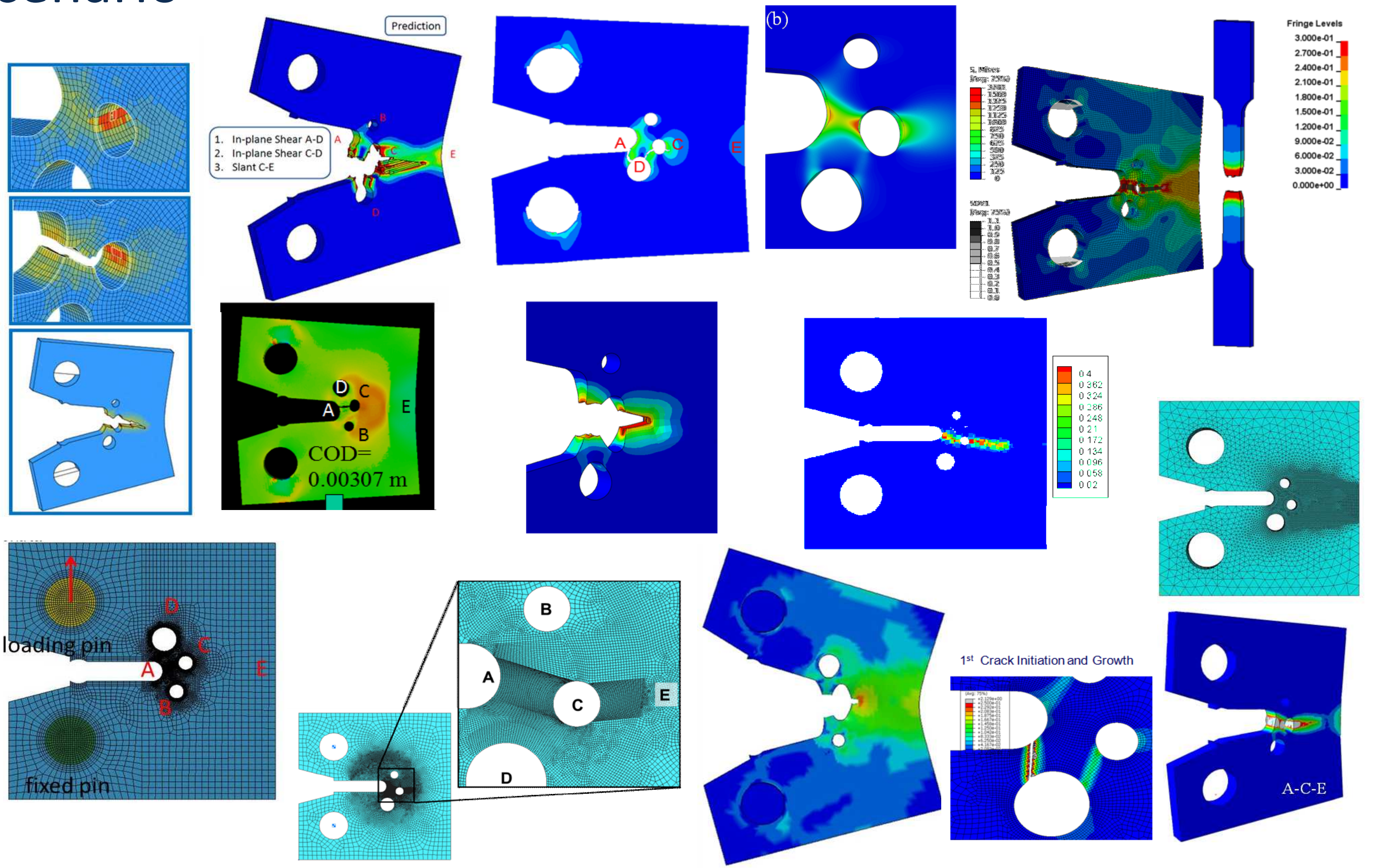
NSWC Naval Surface Warfare Center
A Tradition of Excellence

The University of Arizona

RUHR UNIVERSITÄT BOCHUM

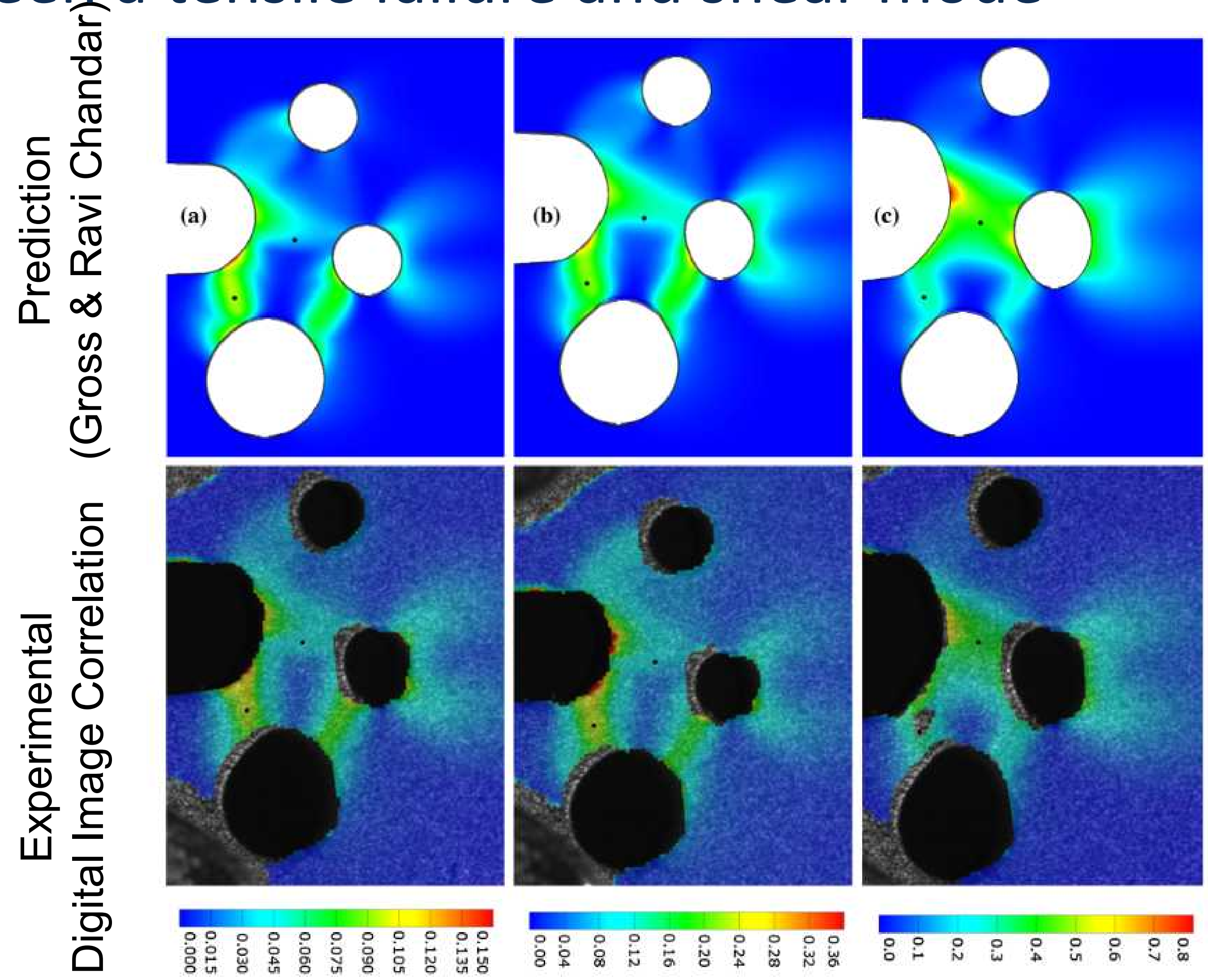
RUB

Each team attempted to blindly predict the failure scenario

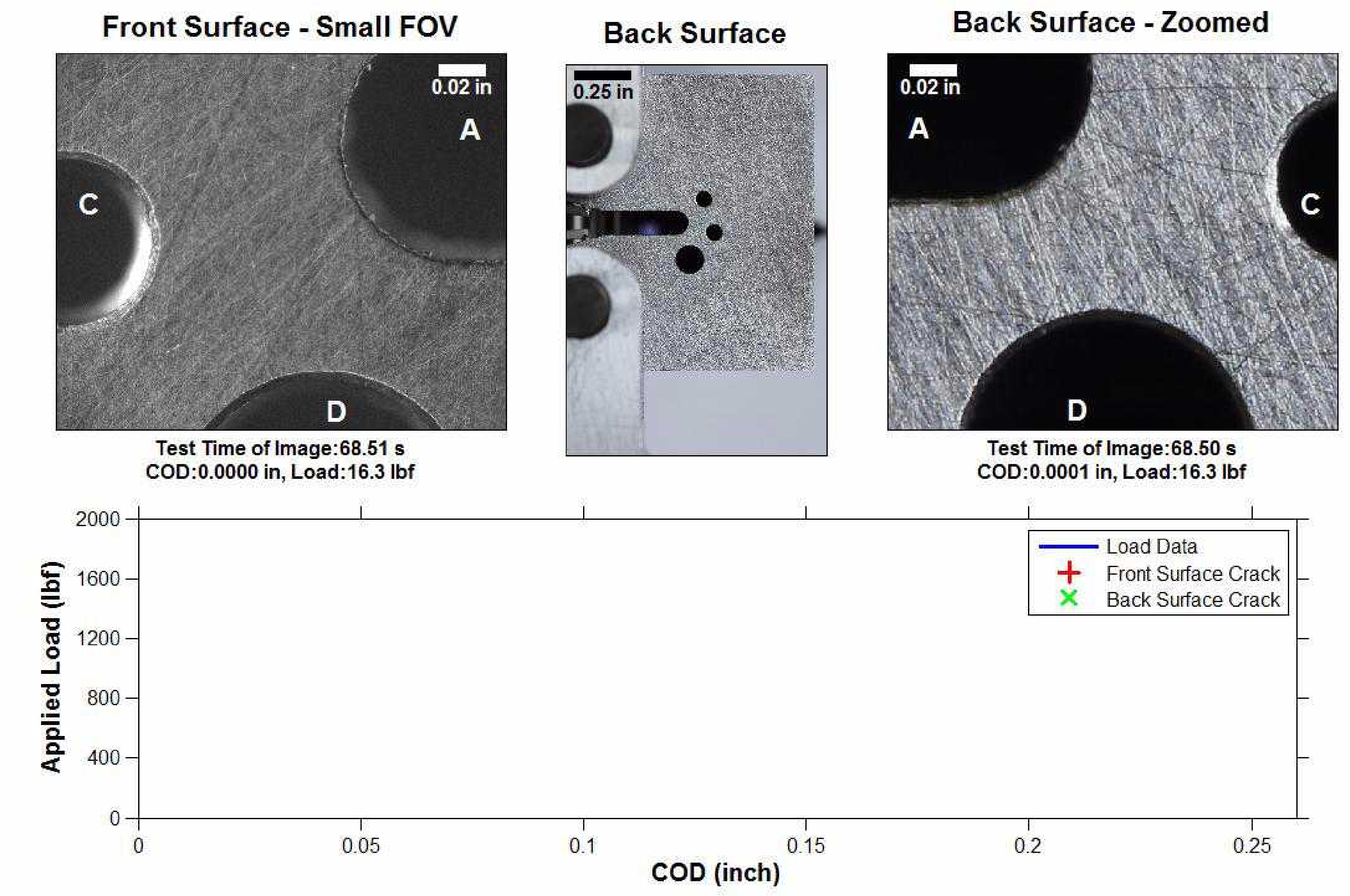


Boyce, et al., *Int. J. Fracture*, 2014

The challenge geometry creates a competition between a tensile failure and shear mode

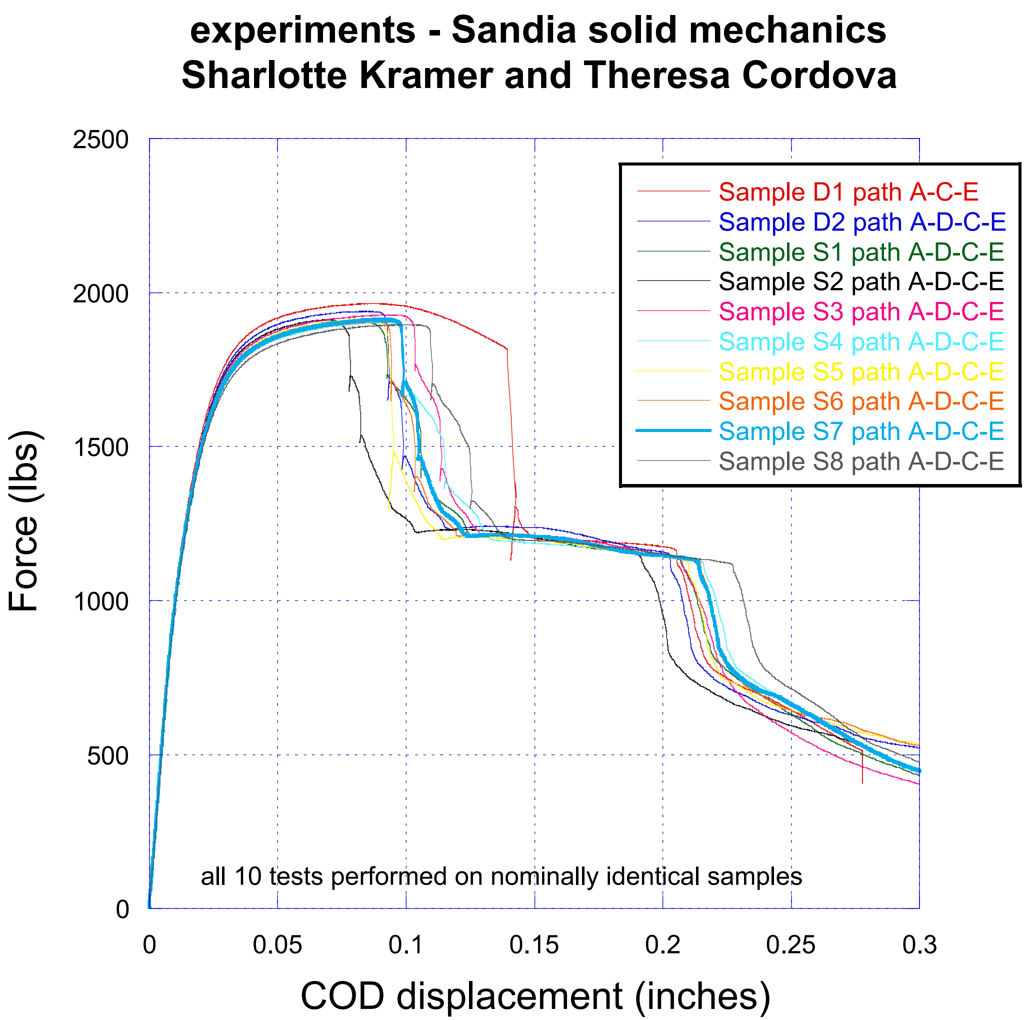


The deformation and fracture behavior is determined experimentally

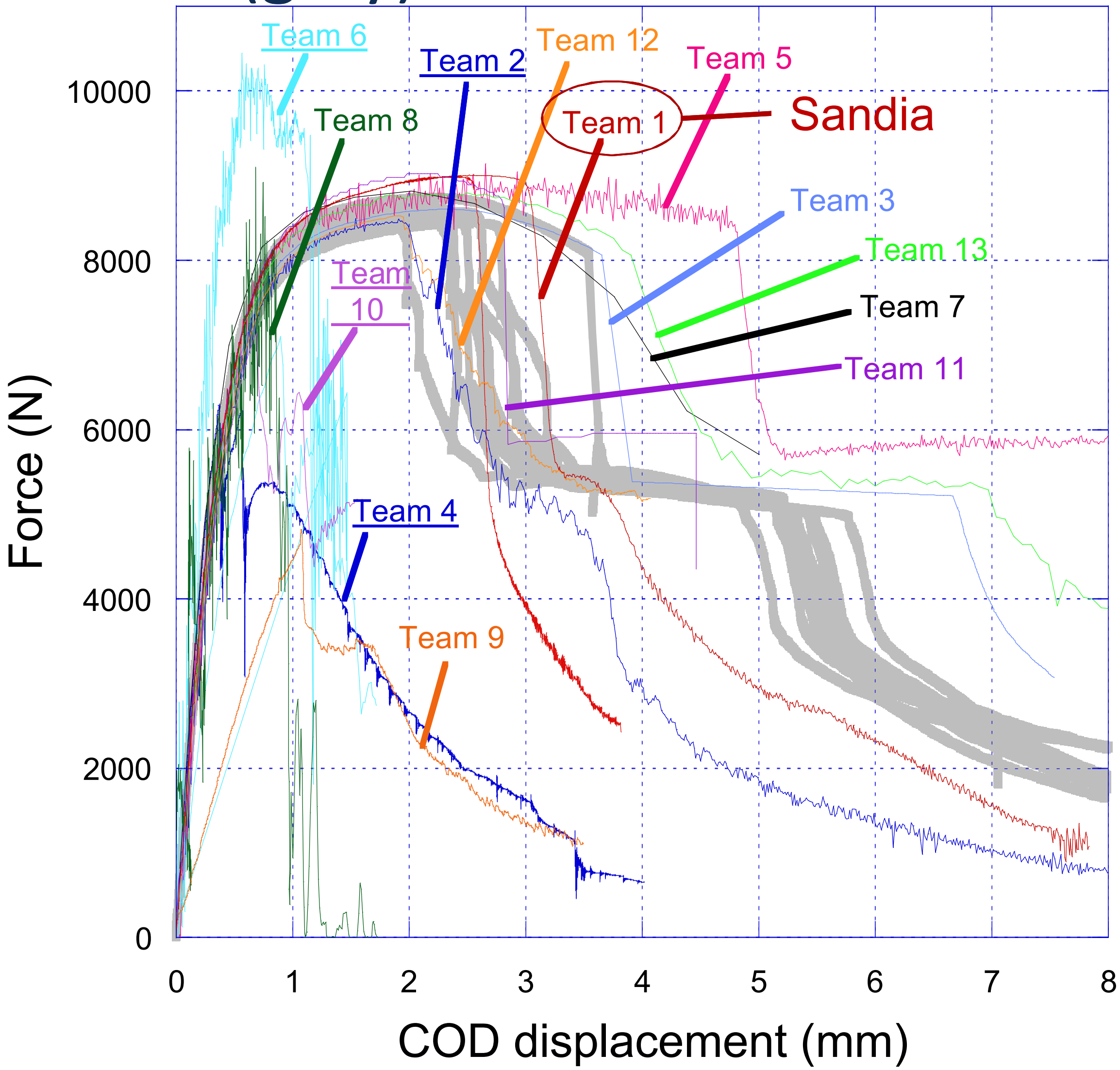


Boyce, et al., *Int. J. Fracture*, 2014

This time, more scatter in the experimental response

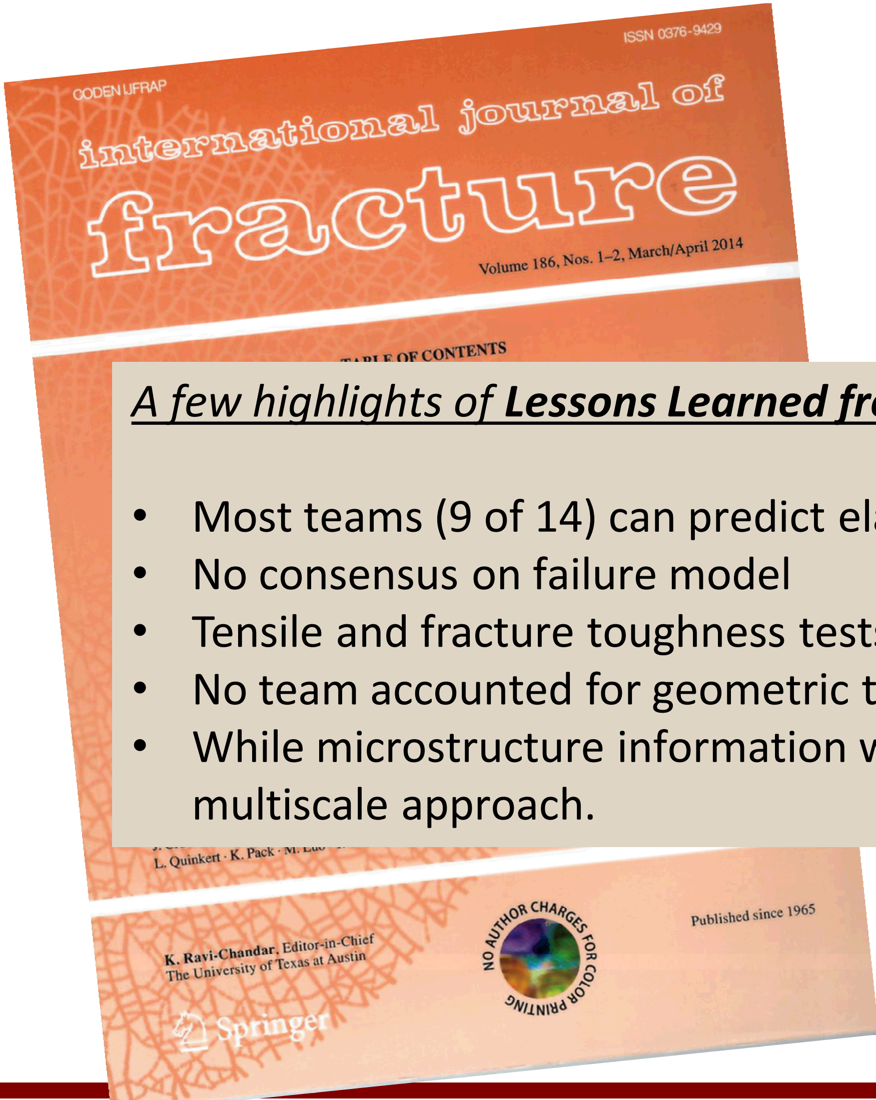


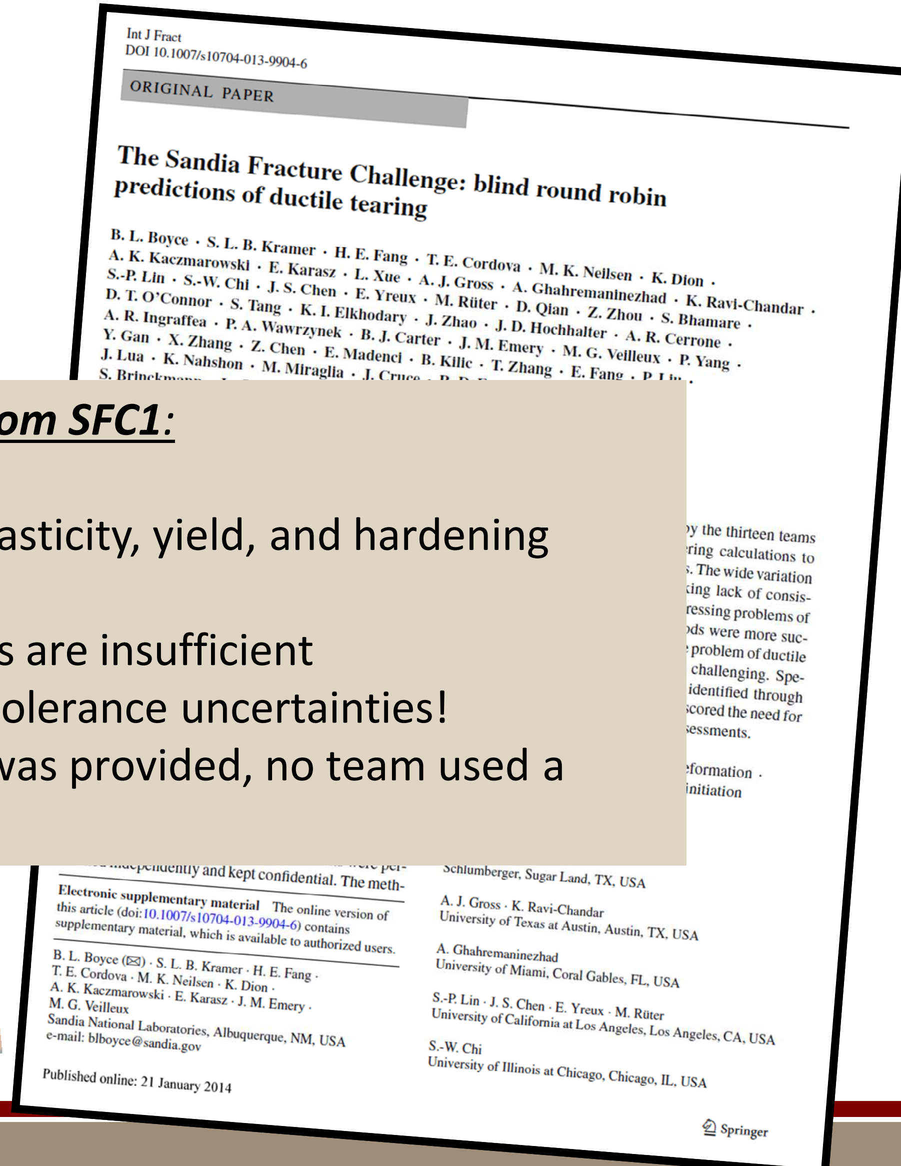
Overlay: Predictions (colors) compared to experiments (gray)



Note: Crack path 'A-C-E' represents both scenarios where the crack initiated in hole A growing towards hole C and scenarios where the crack initiated in hole C and grew back to hole A; similarly for crack path A-D-C-E.

More details available in Special Issue of International Journal of Fracture (2014)




Int J Fract
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 · J. Lua · K. Nahshon · M. Miraglia

independently and kept confidential. The meth-

Electronic supplementary material The online version of this article (doi:10.1007/s10704-013-9904-6) contains supplementary material, which is available to authorized users.

B. L. Boyce (✉) · S. L. B. Kramer · H. E. Fang · T. E. Cordova · M. K. Neilsen · K. Dion · A. K. Kaczmarowski · E. Karasz · J. M. Emery · M. G. Veilleux
Sandia National Laboratories, Albuquerque, NM, USA
e-mail: blboyce@sandia.gov

Schlumberger, Sugar Land, TX, USA

A. J. Gross · K. Ravi-Chandar
University of Texas at Austin, Austin, TX, USA

A. Ghahremaninezhad
University of Miami, Coral Gables, FL, USA

S.-P. Lin · J. S. Chen · E. Yreux · M. Rüter
University of California at Los Angeles, Los Angeles, CA, USA

S.-W. Chi
University of Illinois at Chicago, Chicago, IL, USA

Published online: 21 January 2014

Springer

*<u>A few highlights of **Lessons Learned from SFC1**:</u>*

- Most teams (9 of 14) can predict elasticity, yield, and hardening
- No consensus on failure model
- Tensile and fracture toughness tests are insufficient
- No team accounted for geometric tolerance uncertainties!
- While microstructure information was provided, no team used a multiscale approach.

Boyce, et al. (50 authors), *Int. J. Fracture*, 2014

The 2014 Sandia Fracture Challenge (SFC2)

Predict the forces and displacement associated with crack initiation and propagation in the geometry shown on the right.

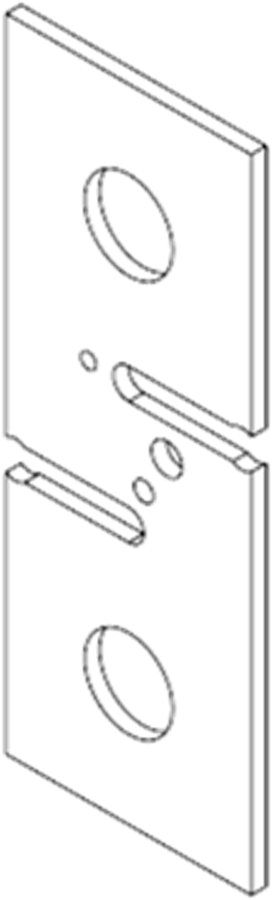
Material: Ti-6Al-4V, 3.15 mm-thick sheet.

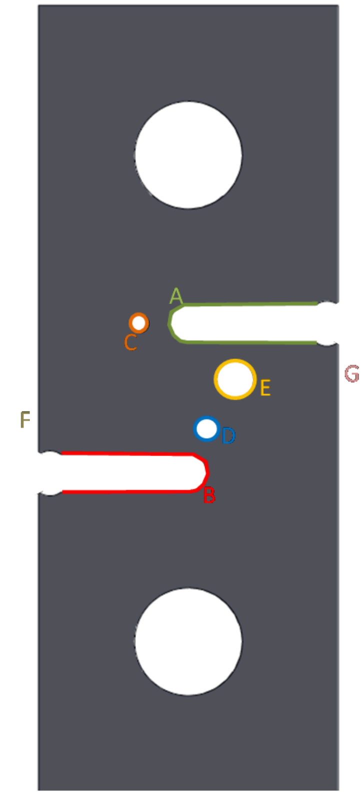
Loading Rate: : 25.4 mm/sec and 0.0254 mm/sec.

Extensive material property information available

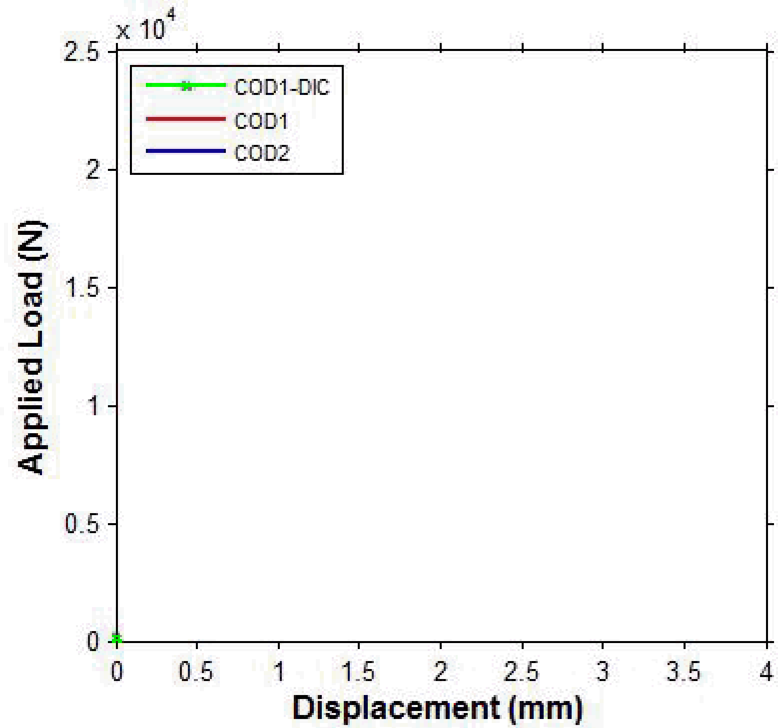
- tensile tests in both sheet axes at 2 rates
- shear failure tests in both axes at 2 rates
- images of all broken samples
- exact measured geometry of each test coupon

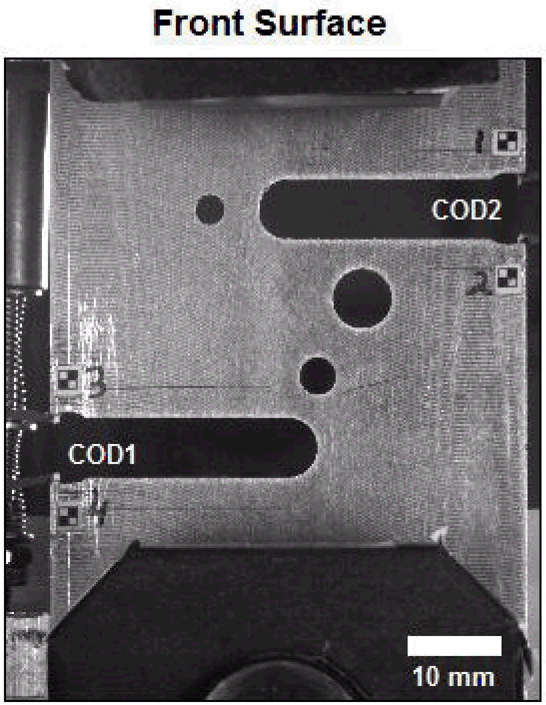
Prediction Deadline: November 1st, 2014



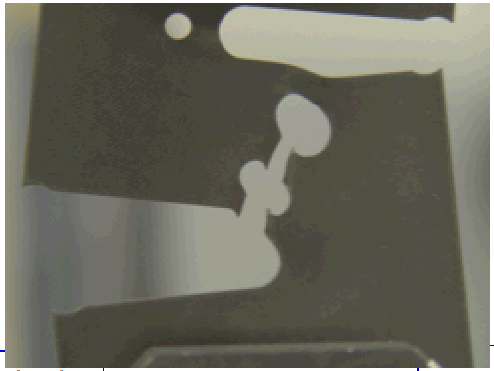


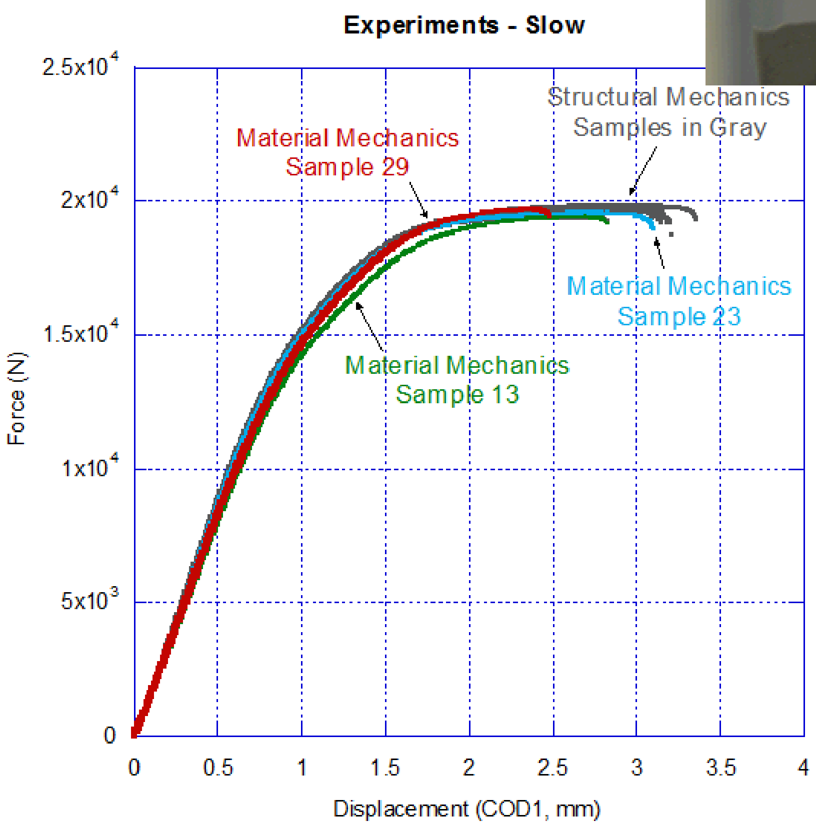
Experimental outcome of SFC2

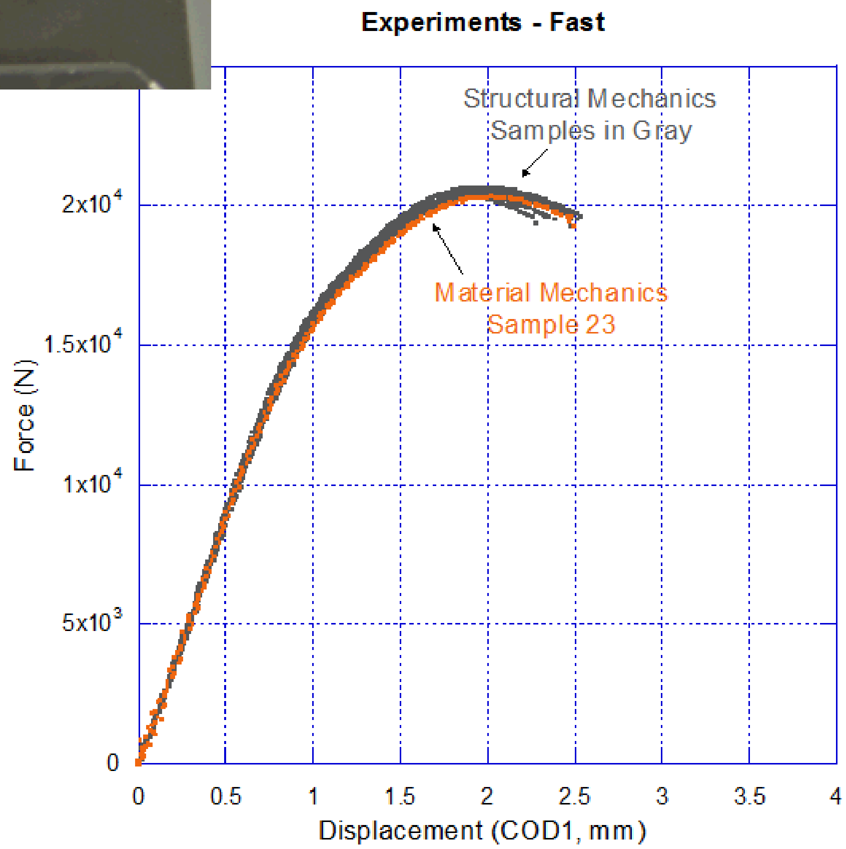




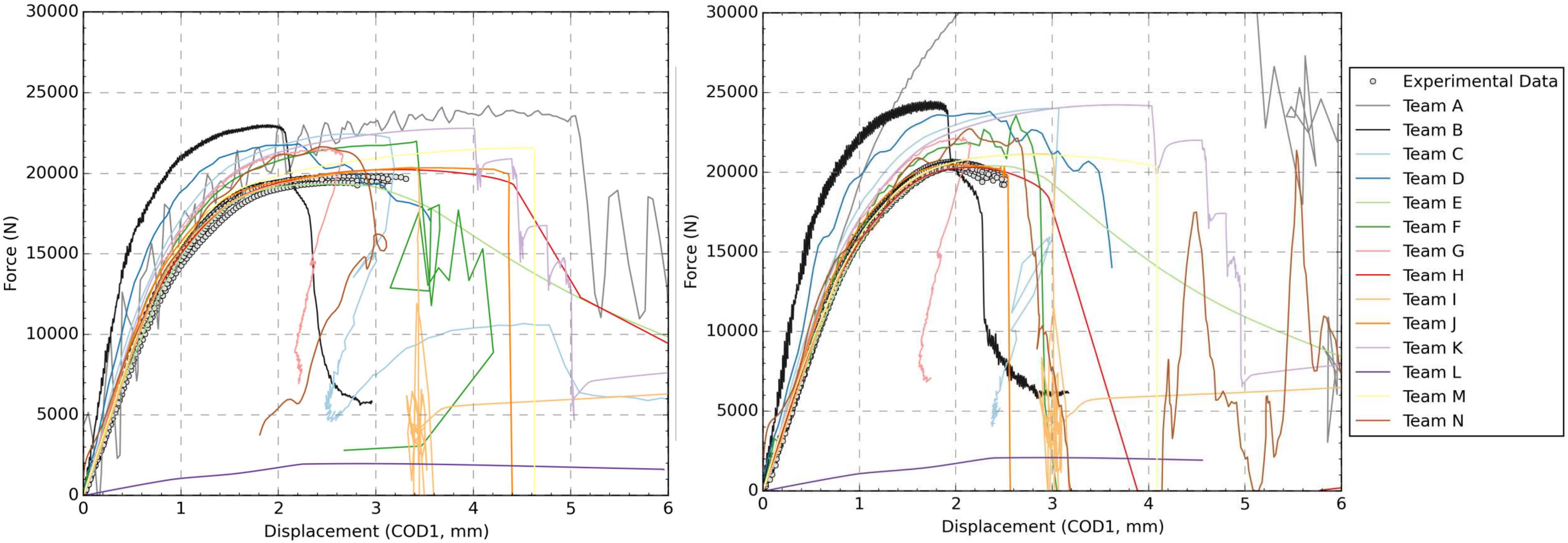
Experimental Force-Displacement Curves up to the point of First Fracture





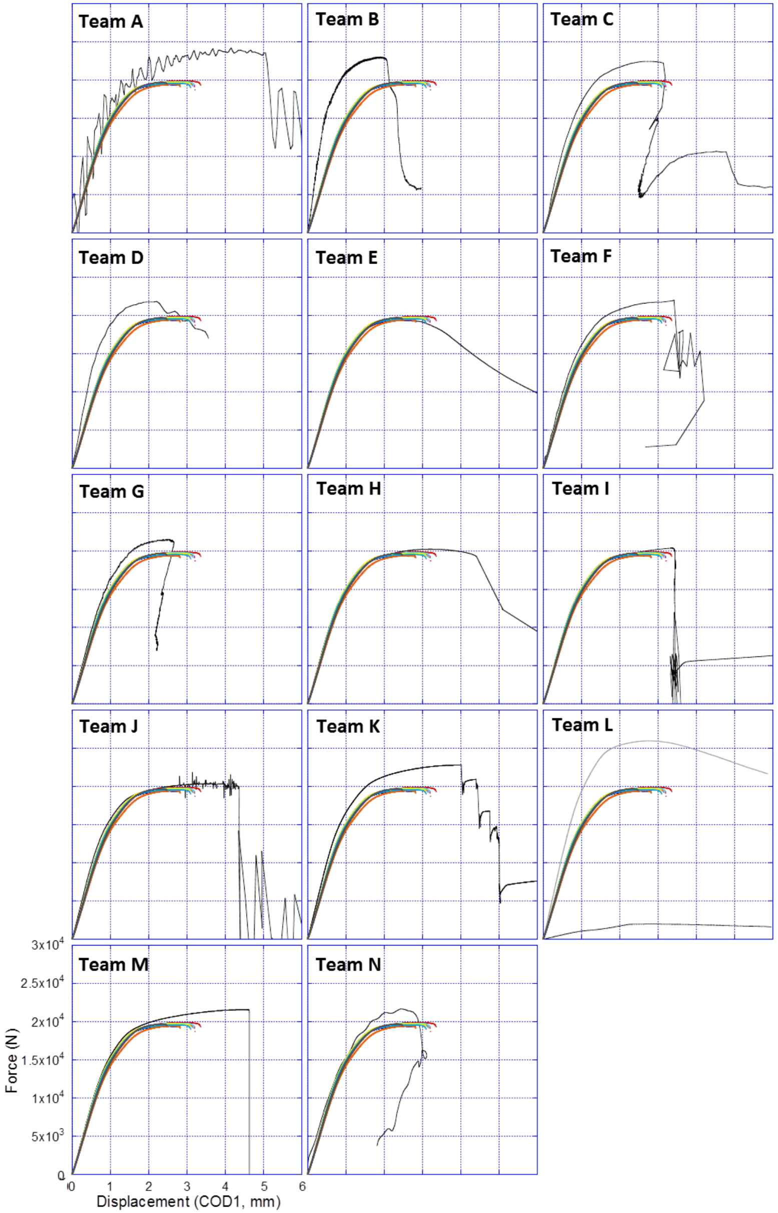


A complex comparison, but general improvement…



- One team (low purple line) made a human error to sum all reaction nodes
- 57% of teams could predict behavior up to peak force within 10% of the expt’l scatter
- Post-necking behavior and crack initiation continue to be a source of significant discrepancy
- Teams tended to systematically <u>overpredict</u> stiffness & yield

Parsing the Individual Team Issues

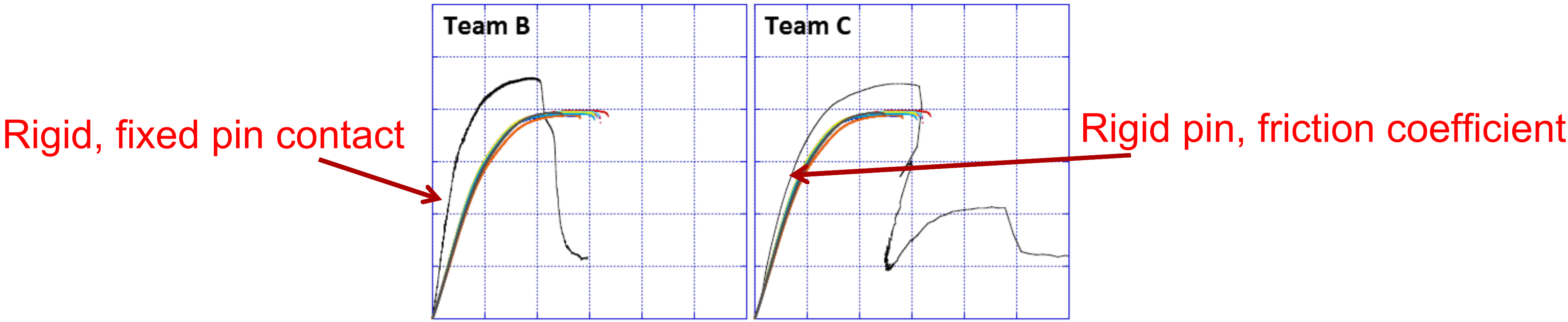


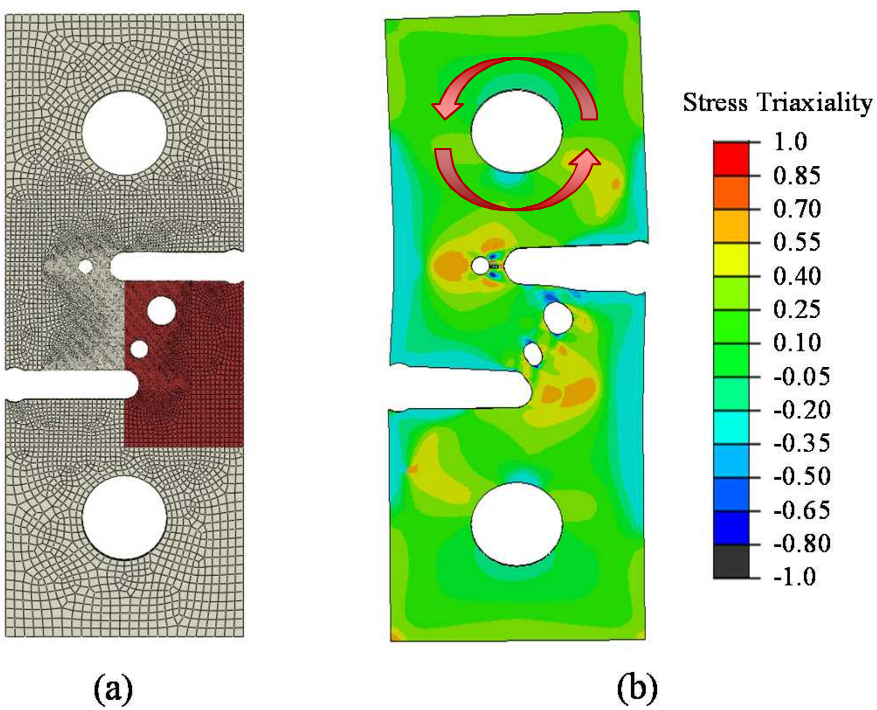
- Explicit vs Implicit Solver
- Thermomechanical Coupling
- Boundary Conditions
- Element Type
- Discretization Level
- Fracture Method (deletion, cohesive surface, etc)
- Uncertainty Method
- Anisotropic Plasticity Model (J2, Hill)
- Hardening Law (Power-law, Swift, Piecewise Linear)
- Failure Criterion (strain parameter, damage law, triaxiality dependence)
- Calibration Data Used

Lessons Learned:

Gaps & Opportunities in Materials Mechanics for Predictive Tearing Fracture

Gap 1: **Representing surface contact and friction**

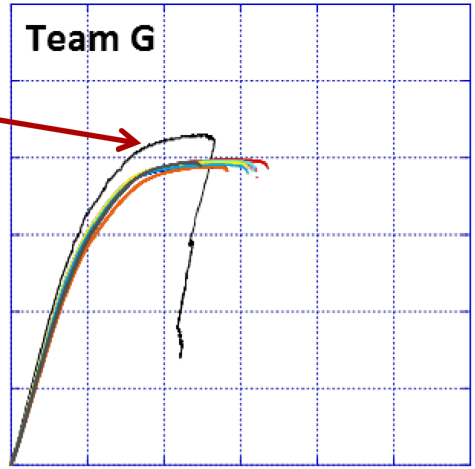


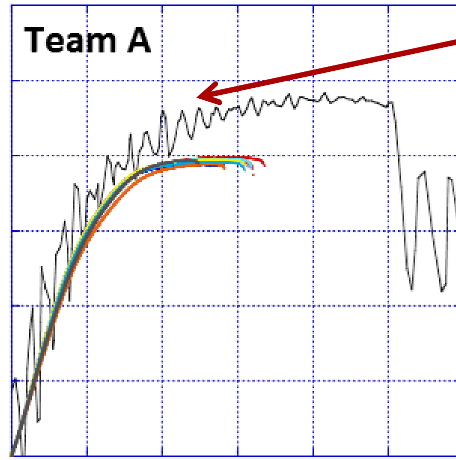


- Apparent stiffness was overpredicted by ~1/2 the teams. In some cases the predicted stiffness was 2X the experimental result!
- Teams that chose fully constrained non-sliding pin contact tended to overpredict stiffness and peak forces.
- Frictionless or free-rotating pin contact appeared to mimic experiments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

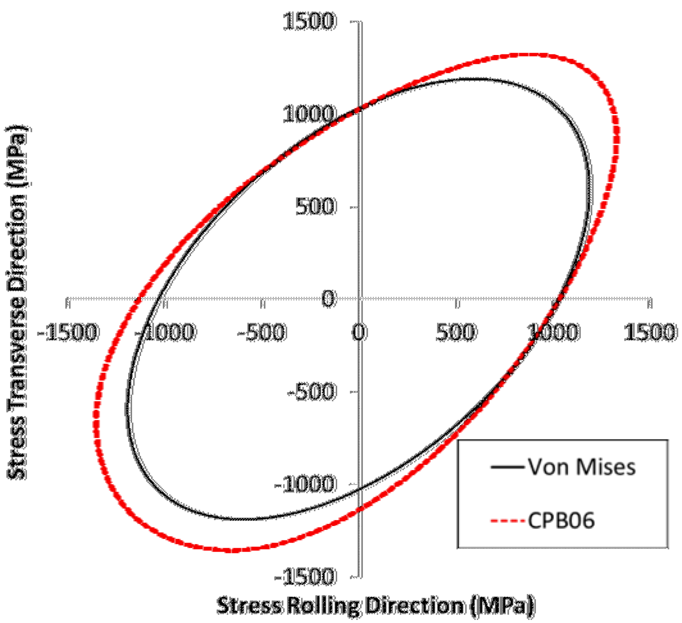
Gap 2: *Accounting for sheet anisotropy*

No anisotropy





J_2 plasticity law,
No calibration to
shear data



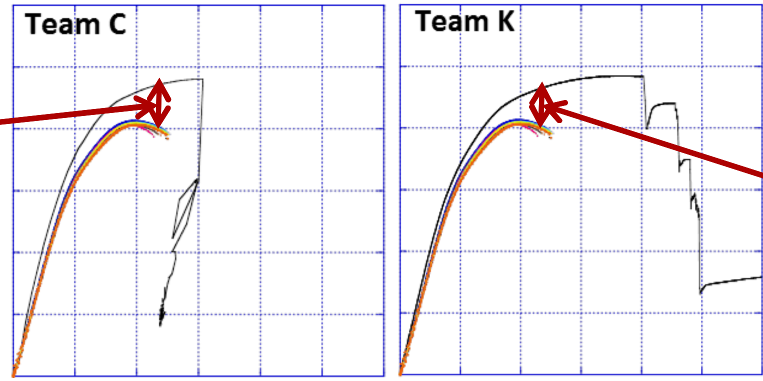
ld in shear was 0.88X the value of predicted by
on Mises yield surface, indicating a response
t is closer to Tresca.

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

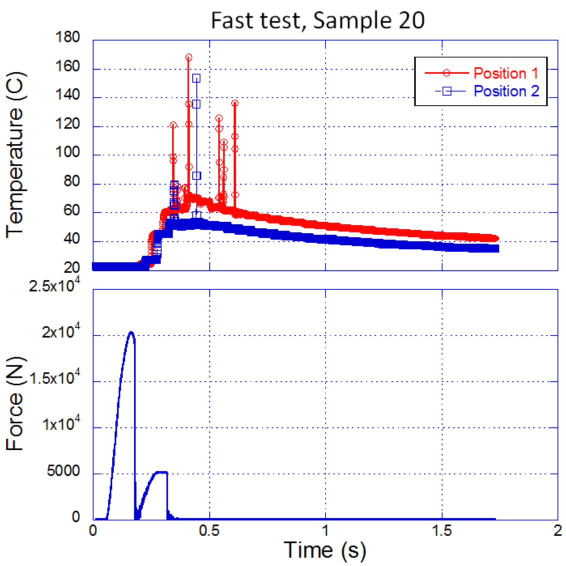
ms that used a simple J_2 (von Mises) plasticity
del tended to overpredict yield/hardening
navior since the yield in shear was softer than
in tension.

Gap 3: ***Estimating thermal work coupling factor***

No thermal coupling



No thermal coupling



Volumetric heating rate

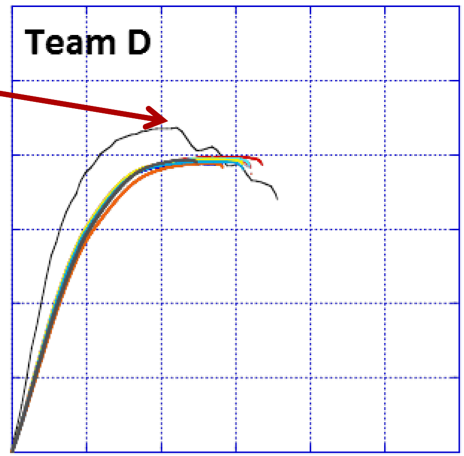
$$\dot{Q} = \eta \dot{W}^p = \eta \boldsymbol{\sigma} : \dot{\boldsymbol{\varepsilon}}^{in}$$

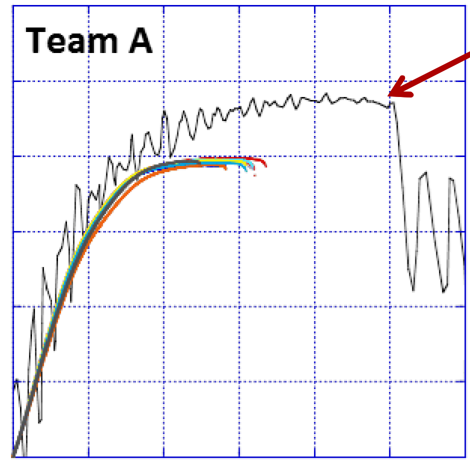
Taylor-Quinney coefficient

- 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)

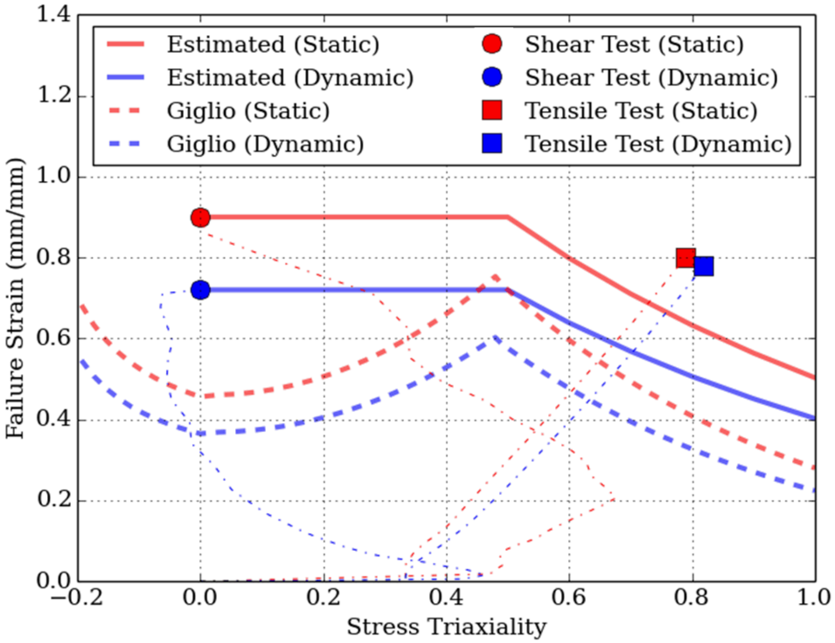
Gap 4: ***Choosing a realistic failure parameter***

Plastic strain criterion does not account for triaxiality / shear





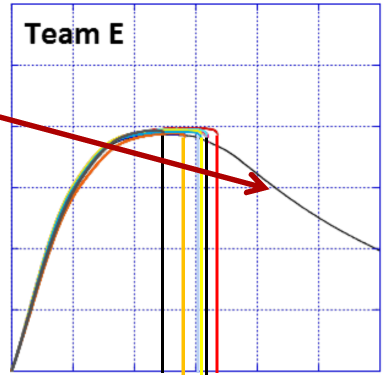
Failure parameter calibration only used tension data, not shear data.

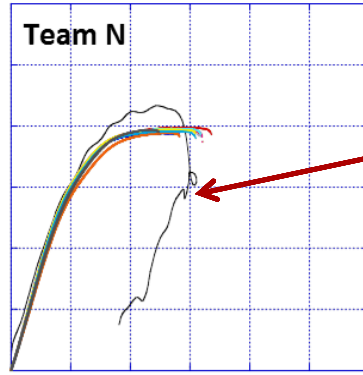


- There is no concensus on a realistic model for crack initiation! **(Gurson is not sufficient)**
- Predictions tended to be more accurate if they used shear data and calibrated a triaxiality-dependent failure model.
- While a suite of various loading paths and triaxiality conditions is needed, there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

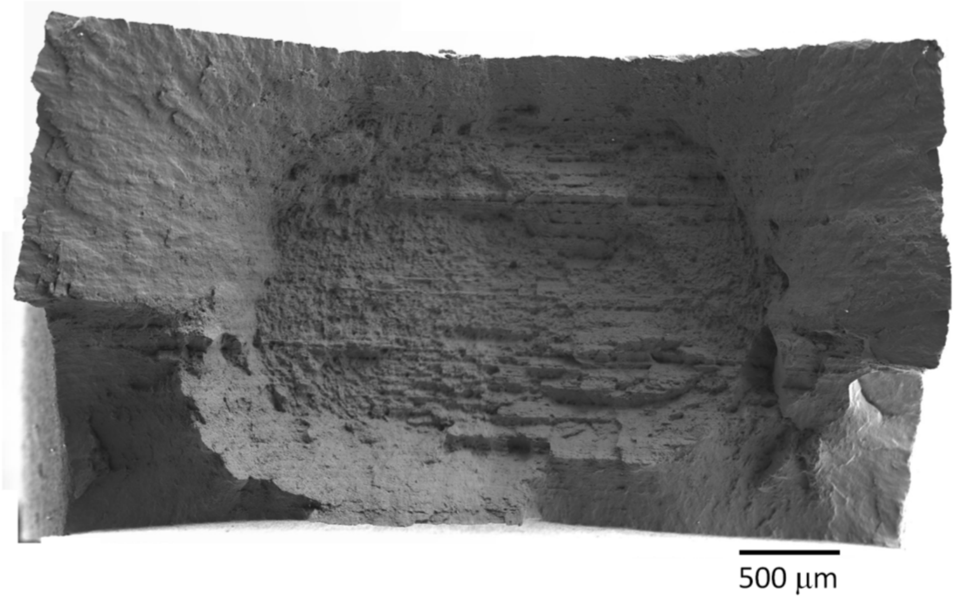
*Gap 5: **Damage progression / fracture morphology***

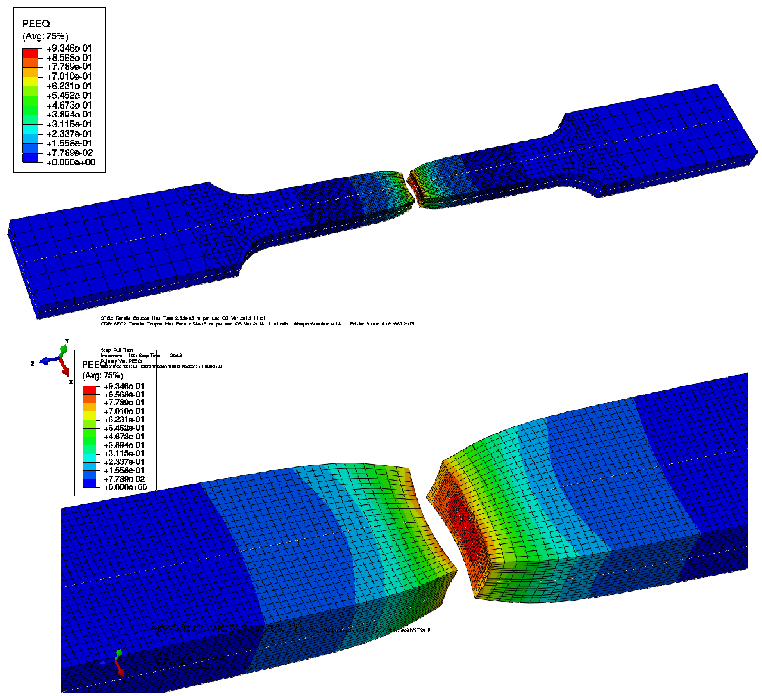
Quasi-static cohesive zone law did not predict unstable fracture



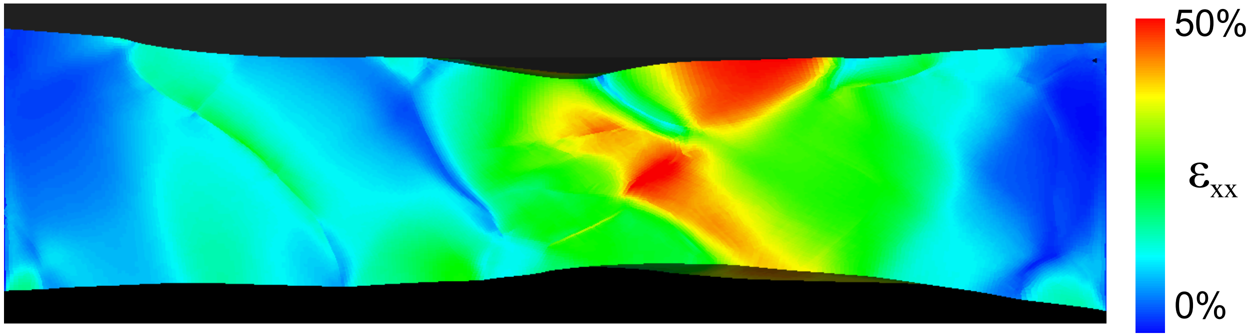


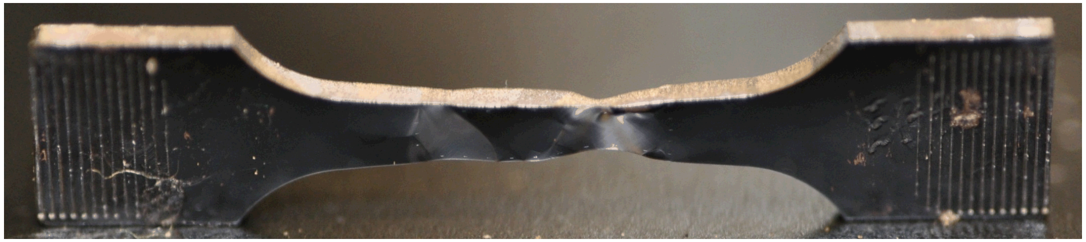
Incorrect crack path





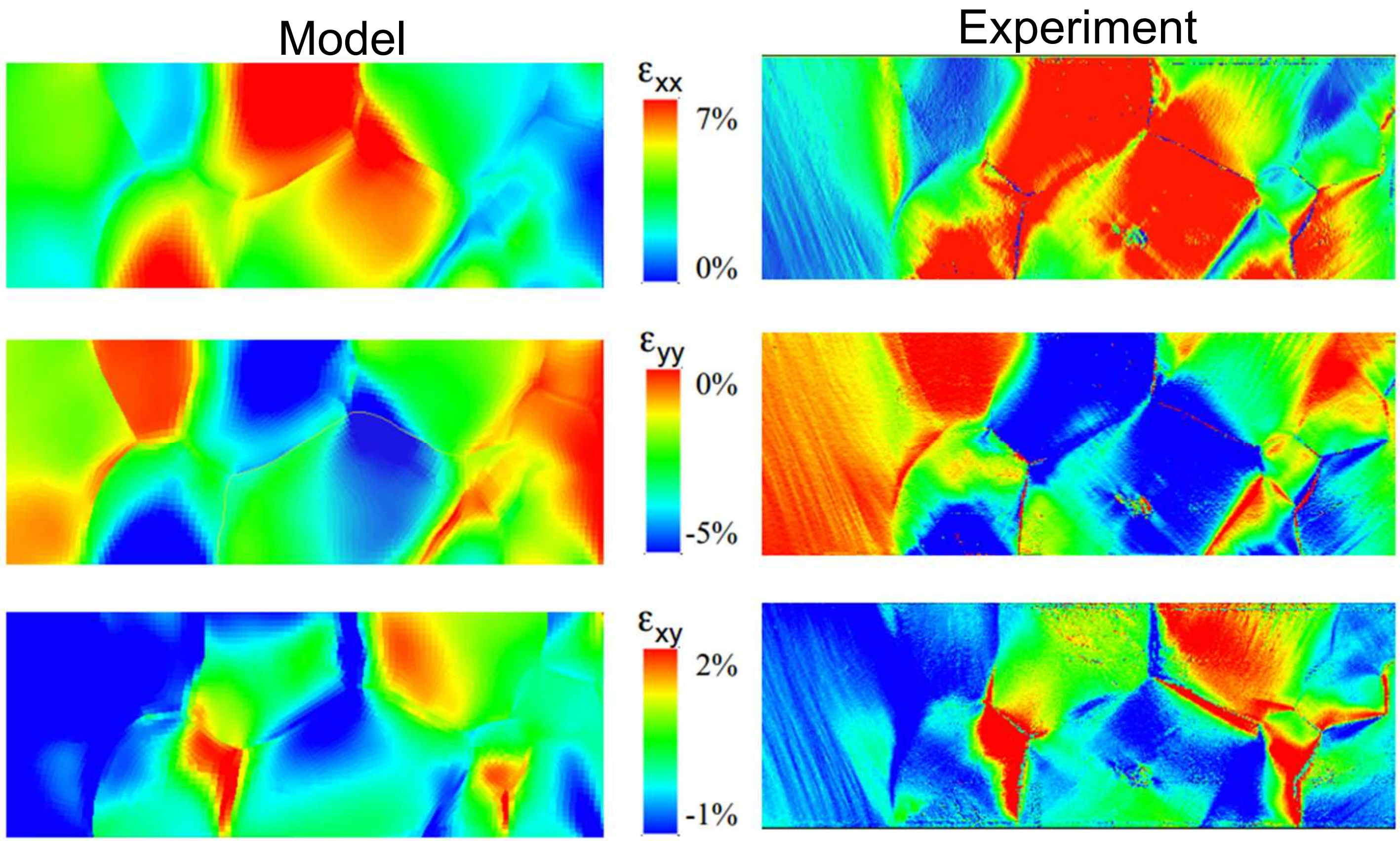
Opportunities for Lower Length Scale Modeling…





- Contact, friction & surface roughness effects
- Yield surface evolution predictions, complex load paths
- Thermal coupling effects
- Triaxiality-dependent damage initiation criterion (?)
- Complex tensile-to-shear crack propagation profiles (?)

Opportunity: Failure model at the Grain Scale?



Empirical Continuum Scale Model???

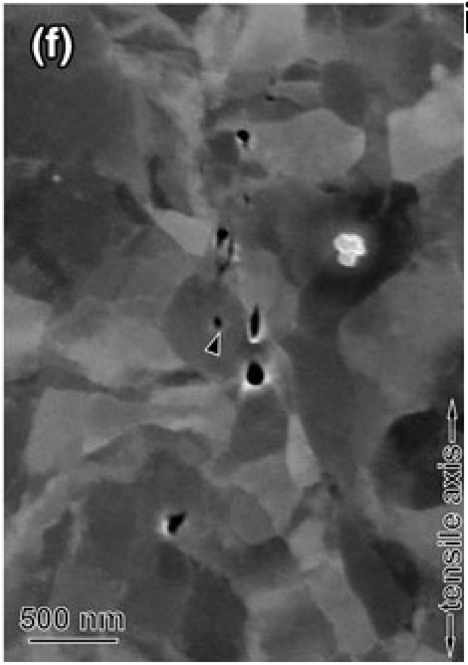
$$\dot{\phi} = \underbrace{\sqrt{\frac{2}{3}}\dot{\epsilon}_p \frac{1-(1-\phi)^{m+1}}{(1-\phi)^m} \cdot \sinh\left[\frac{2\,(2m-1)}{2m+1}\,\frac{\langle p\rangle}{\sigma_e}\right]}_{\text{Void growth}} + \underbrace{(1-\phi)^2\,\dot{\eta} v_{vo}}_{\text{Void nucleation}}.$$

Lim, Carroll, Battaile, Buchheit, Boyce, Weinberger. Grain-scale experimental validation of crystal plasticity finite element simulations of tantalum oligocrystals. *International Journal of Plasticity*, vol. 60 (2014).

Opportunity: Failure model at the Grain Scale?

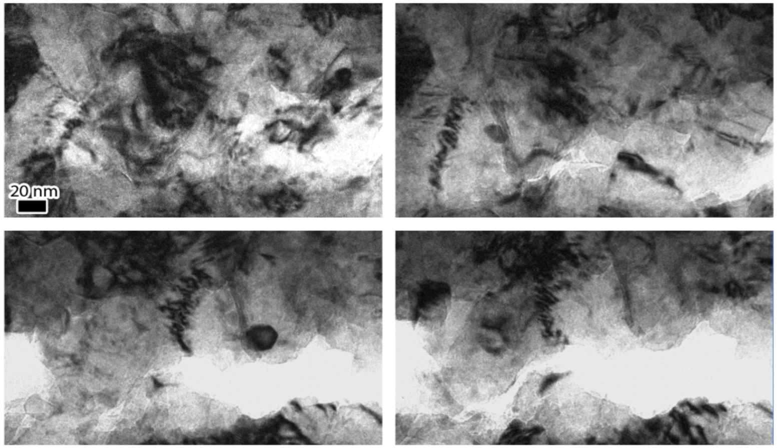
Sandia National Laboratories

In-situ TEM deformation experiments may not fail by the same processes as bulk samples due to the lack of hydrostatic stress to drive

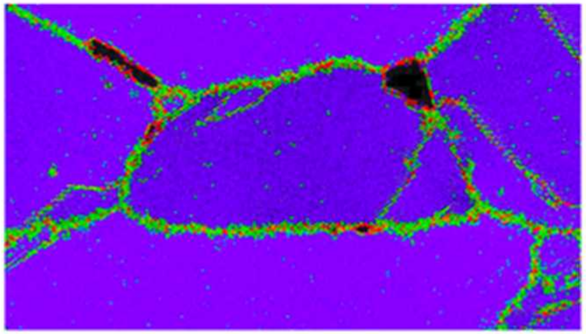


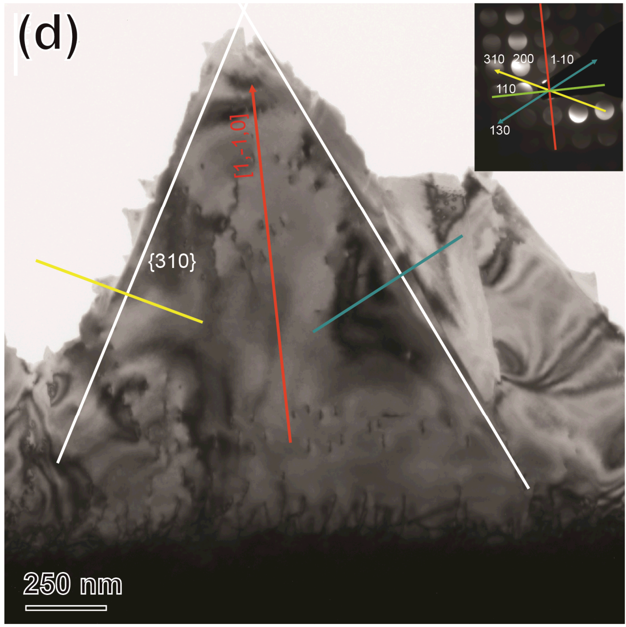
Nanoscale voids found by post-mortem xsection

ion



In-situ crack progression in nc Fe (Hattar)





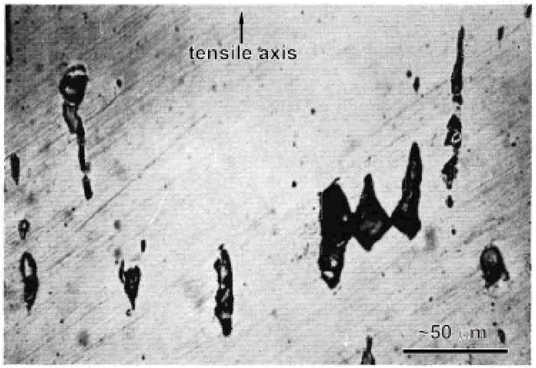
Serrated crystallographic fracture during in-situ deformation of Ta

Can MD replicate failure mechanisms?

For additional details, see *Boyce et al., Metall. Mater. Trans. A, 2013.*
also see work by K. Hattar; L. Smith, J. Zimmerman, D. Farkas

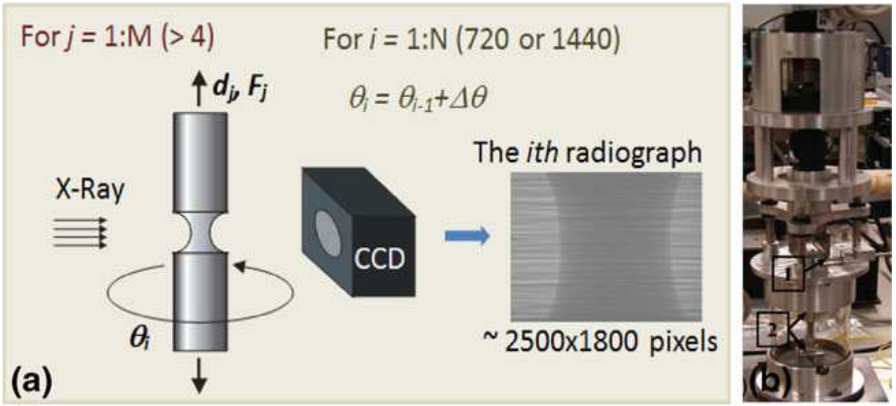
Solution: Apply in-situ micromechanical techniques (CT, HR-EBSD, HEDM) to quantify the micromechanical states associated with damage evolution

Sandia National Laboratories



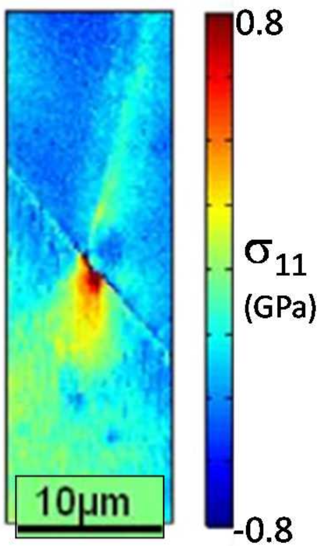
Existing failure models are based on limited, archaic qualitative observations such as this classic example of microvoid growth in copper (Puttick, Phil. Mag., 1959)

1) In-situ computed tomography



From Jin et al., *Exp. Mech.*, 2013

2) High-Resolution Electron Backscatter Diffraction



From Guo et al., *Acta Mater.*, 2014

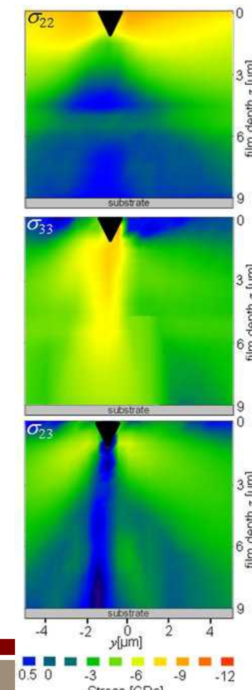
*in-house at Sandia with existing experimental tools

*~50 nm resolution

*quantify "geometrically necessary" dislocation content and stress gradients.

*only works on exposed surface – thus requires dissection for sub-surface voids (e.g. via Sandia's new Plasma FIB)

3) Synchrotron High-energy Diffraction Microscopy



*technique available at several synchrotron sources

*quantify local stress tensor with micron resolution.

*semi-quantitative estimate of dislocaiton content via peak broadening.

* high-energy x-ray sources (e.g. APS) allow some degree of subsurface measurement.

From Zeilinger et al., *Sci. Reports*, 2016

IMPACT…. Who cares; how is this helping?

1. Provides a documentation of **'state-of-the-art'**.
   - Evidence to support use of codes in engineering problems
   - Educates analysts who use but do not develop these methods

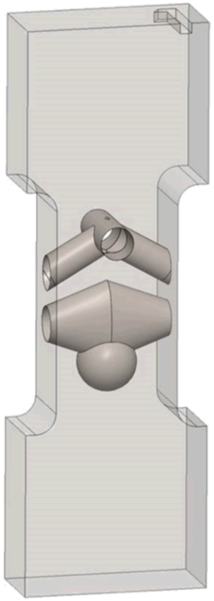
2. Illustrates **key deficiencies** in structural mechanics predictions
   - Fracture is not a readily 'solved' problem in some cases
   - Motivates mechanicians and code developers to fix deficiencies
   - **Opportunities for lower length scales** to address gaps?

3. Raises International **awareness on the need for improved simulation capabilities**
   - Revitalize & guide funding in this 'mature' area (e.g. NSF)
   - Revitalize the prestige in working on failure of structural metals
   - Establishes well-documented 'toy problems' for future assessment & benchmarking

Minnesota I-35W Bridge Collapse.

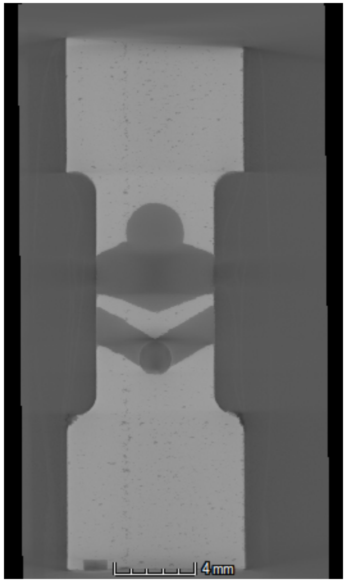
Underway… The 3rd Sandia Fracture Challenge

An additively manufactured structure with internal chambers that cannot be manufactured by conventional methods

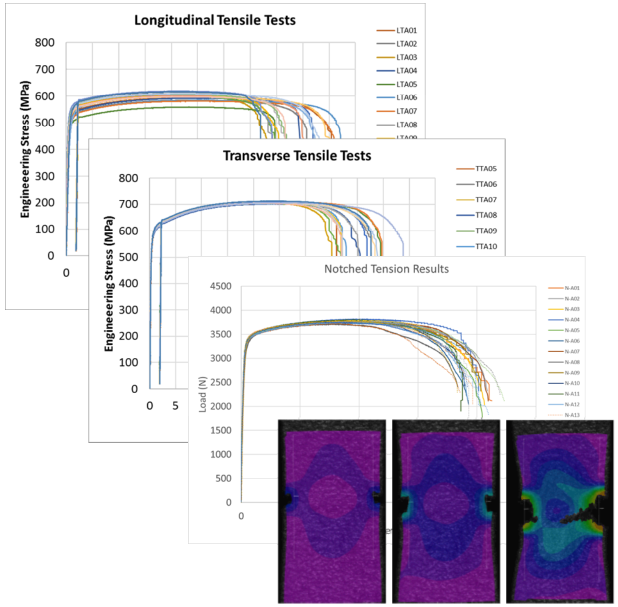


CAD

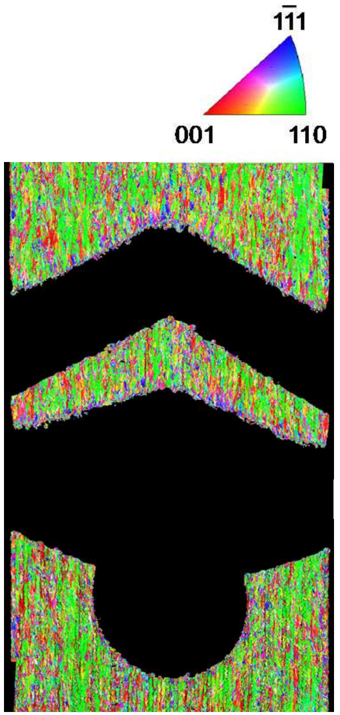
Optical Image



CT Scan showing internal porosity



Notch & smooth bar calibration data (with DIC) from the same build



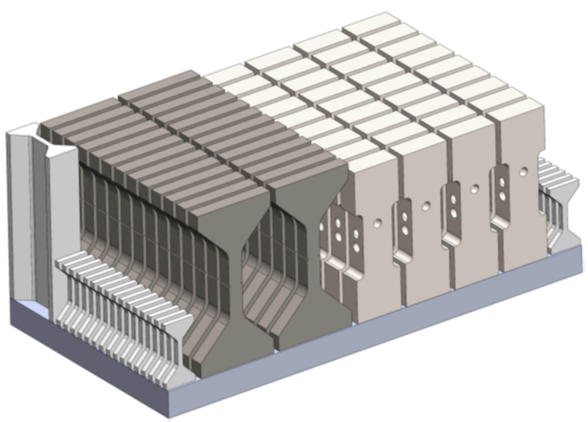
Microstructure & Texture data

Provided the following engineering data…

- x-ray CT scans
- tensile & notch tensile tests
- EBSD Microstructure, surface roughness, etc.

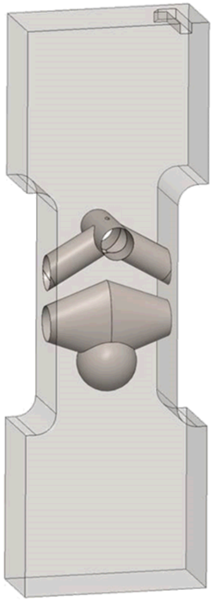
Predict the variability in failure response…

- location of crack initiation
- forces associated with crack initiation
- local surface strains during deformation



Underway… The 3rd Sandia Fracture Challenge

An additively manufactured structure with internal chambers that cannot be manufactured by conventional methods

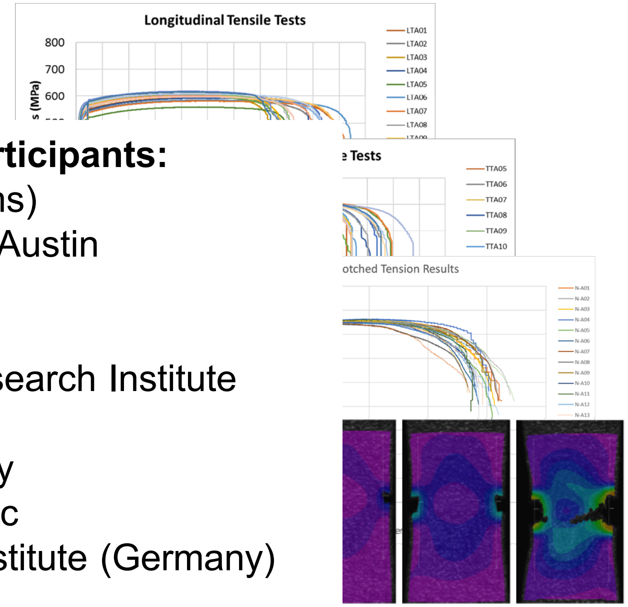


CAD

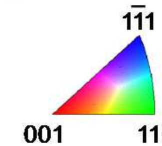
Optical Image

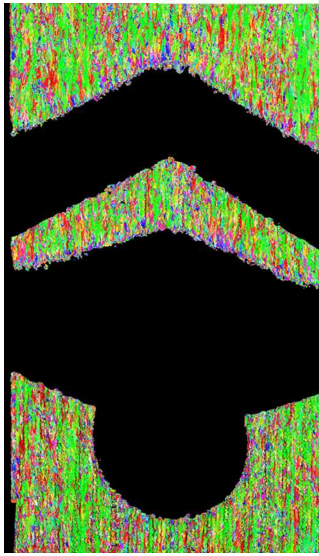
Pre-registered Participants:

1. Sandia (3 teams)
2. Univ. of Texas-Austin
3. MIT
4. Purdue
5. Southwest Research Institute
6. Exponent
7. Pratt & Whitney
8. General Electric
9. Max-Planck Institute (Germany)
10. Univ. of Utah
11. OCAS NE (France)
12. RWTH Aachen (Germany)
13. Thinkviewer
14. Regensburg Univ. (Germany)
15. Kazimierz Wielki Univ. (Poland)
16. Tecnalia Research (Spain)
17. US Army Corps of Engineers
18. US Army ARDEC



ar calibration
n the same build

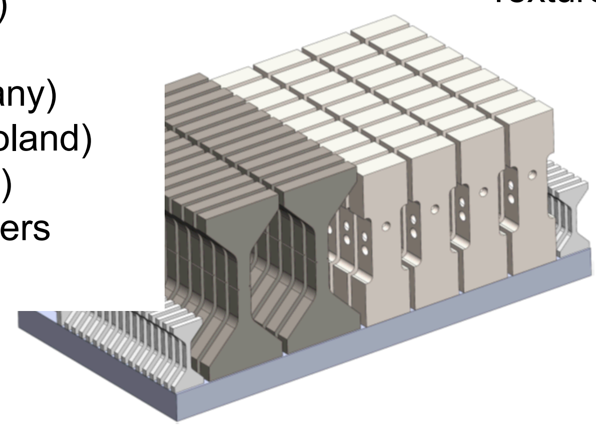




Microstructure & Texture data

Provided the following en
- x-ray CT scans
- tensile & notch tensile
- EBSD Microstructure,

Predict the variability in f
- location of crack initiat
- forces associated with crack initiation
- local surface strains during deformation



The purpose of the Structural Reliability Partnership is to leverage expertise and investments from multiple institutions on areas of mutual interest in the domain of structural reliability.

Preliminary pilot partners:

Sandia National Laboratories

ExxonMobil

Massachusetts Institute of Technology

TEXAS
The University of Texas at Austin