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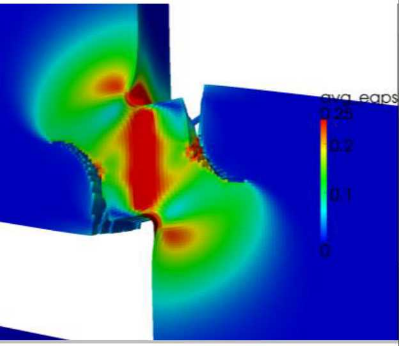

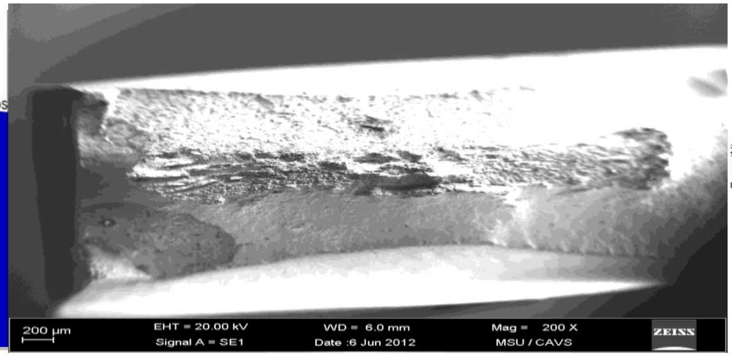

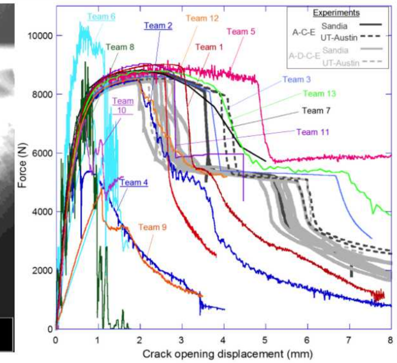

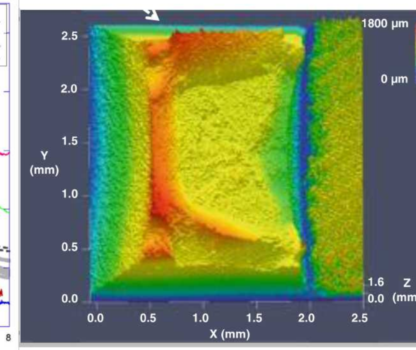

Sandia Fracture Challenge and the Structural Reliability Partnership:

Moving from Cooperative Assessment to Collaborative Research

Jim Redmond
Sandia National Laboratories

August 7, 2017

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Purpose

- Motivate failure understanding and prediction of failure process for specific applications
- Overview Sandia Fracture challenge as a successful model for collaborative Government, Industry, and University capability assessment
- Propose Structural Reliability Partnership to focus pre-competitive capability advancements

Why model failure?

- Most design problems focus on preventing failure in normal service conditions
- A specialized subset must accommodate failure **as part of the** the performance envelop

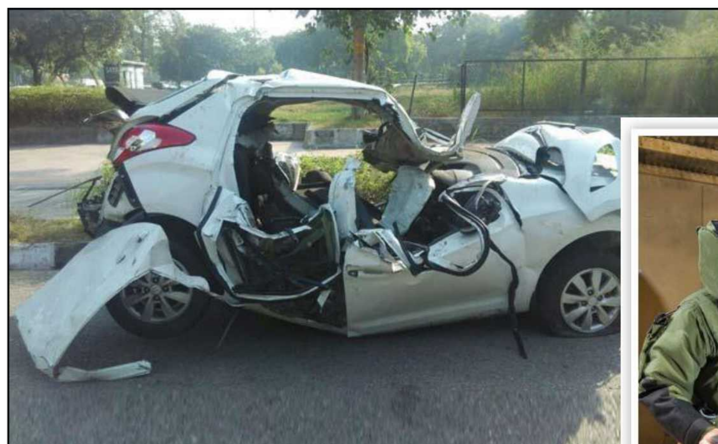

Photo Courtesy of Sandia National Laboratories (Photo by Randy Montoya)

Sandia's stewardship mission drives predictive failure capabilities

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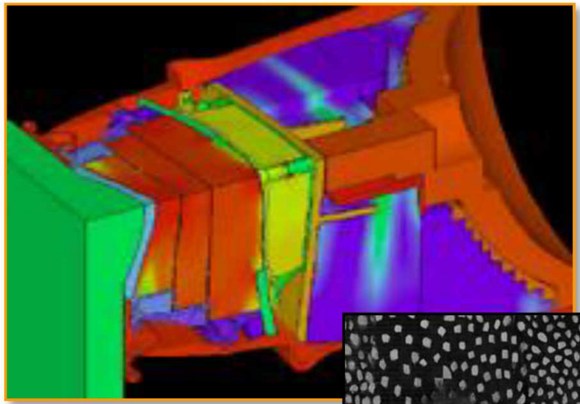
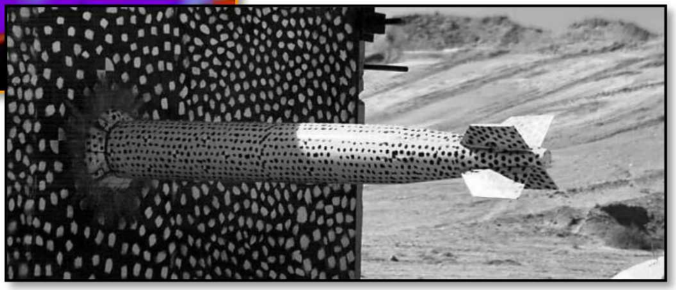
- Predicting performance in normal environments

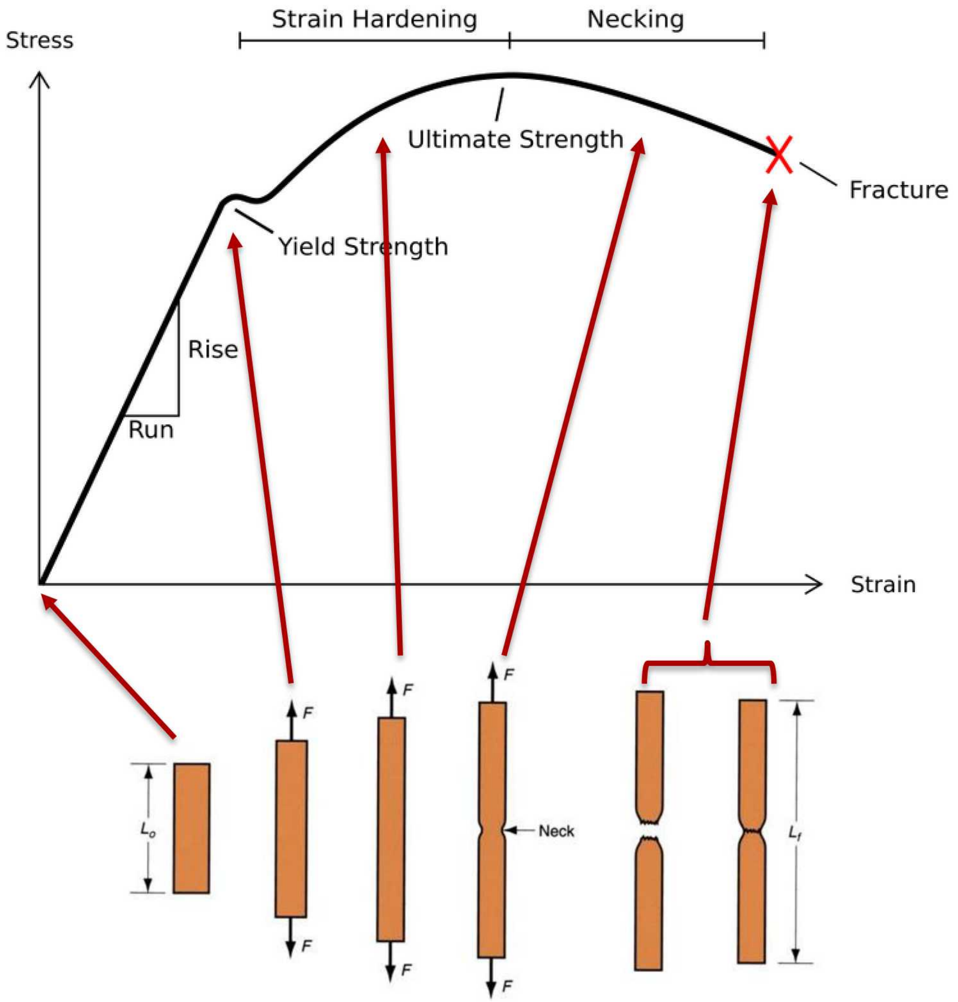




- Assessing safety in accident or adversarial scenarios

Predicting ductile failure requires many elements

- Includes full load history
  - Elasticity
  - Yielding (isotropic or orthotropic)
  - Plasticity
  - Hardening
  - Localization / stress concentration
  - Crack initiation
  - Propagation
  - Strain rate & temperature effects
- Simulation requires
  - Verified simulation code
  - Calibrated material model
  - Appropriate failure criteria (uniaxial vs multiaxial loading)
  - Cracking - arbitrary crack initiation & propagation, crack branching, free surface, convergent result, …



Sandia Fracture Challenge – cooperative assessment of existing capabilities

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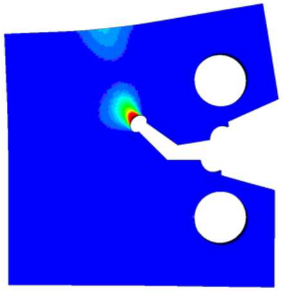
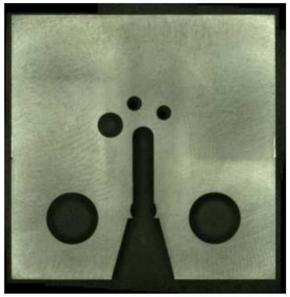
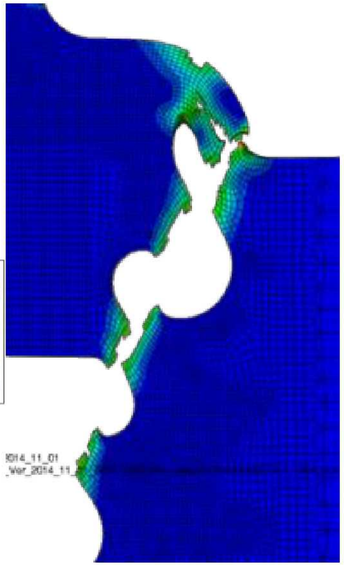
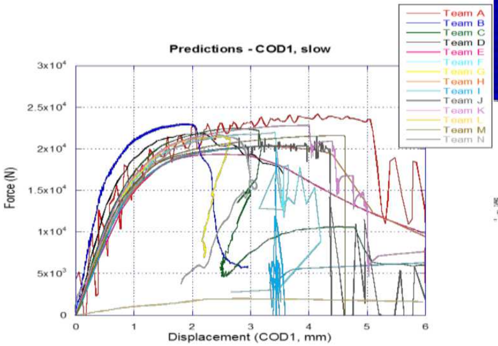
- Leverages the international research community to advance failure modeling for ductile metals
- Three Challenges have fostered a model of ‘coopetition’ with voluntary participation and full autonomy in approach
- A double blind approach with parallel independent experimental assessments
- Information provided:
  - Extensive materials characterization
  - Structure geometry and tolerances
  - Loading conditions
  - Metrics
- Teams predict response through failure and submit for assessment against a set of pre-determined metrics









SFC features a diversity of participants and approaches

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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

الجامعة الأمريكية بالقاهرة

The American University in Cairo

UIC University of Illinois at Chicago

Natural Resources Canada / Ressources naturelles Canada

CanmetÉNERGIE

Leadership en écoInnovation

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

清华大学

Tsinghua University 1911

浙江大学

Zhejiang University 1897

University of Cincinnati

Missouri

Dalian University of Technology 1949

大连理工大学

Naval Surface Warfare Center NSWC

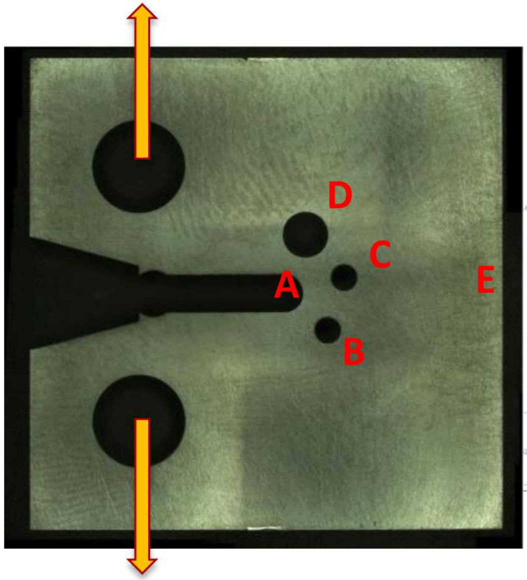
A Tradition of Excellence

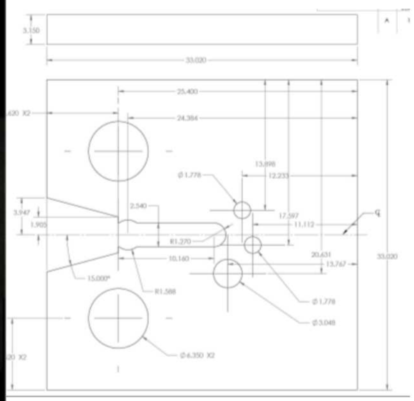
The University of Arizona

Ruhr Universität Bochum

RUB

First external challenge - SFC1 2012

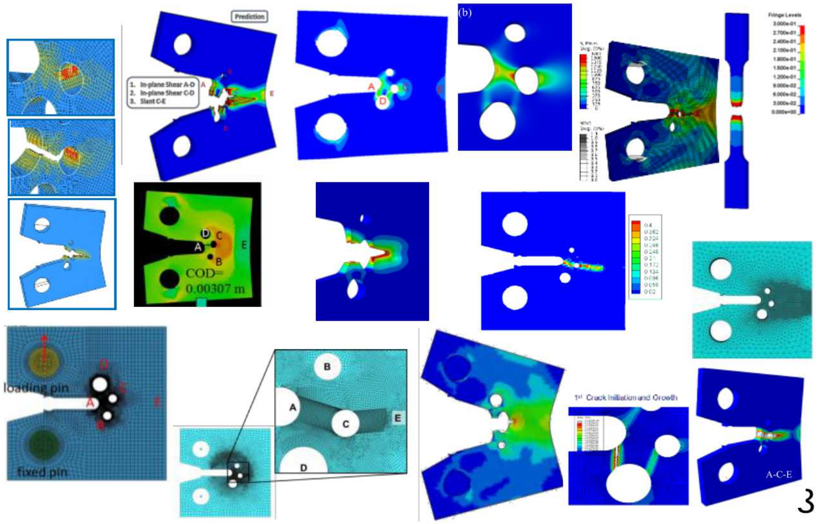




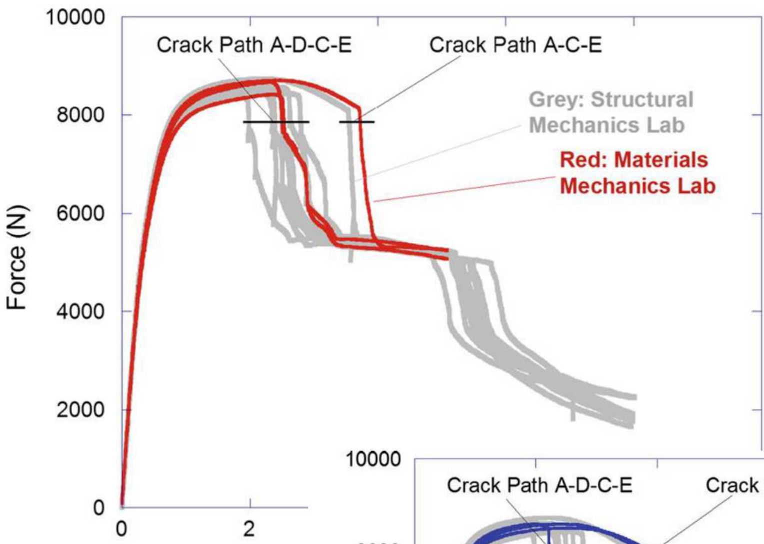
Alloy: 15-5PH H1100

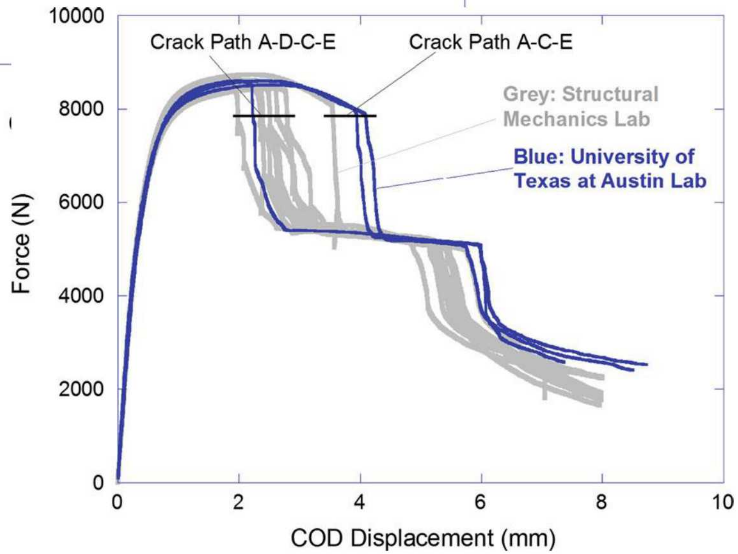
- Given tensile data in rolling and transverse plate directions, fracture toughness-like experimental data, microstructural data… for the 15-5 PH stainless steel plate
- Given Challenge geometry and boundary conditions (0.0005 in/s loading rate)
- Predict crack path and critical load and crack-opening-displacement (COD) of the first two crack initiations

Over 50 researchers from 14 institutions participated in the SFC1 with a variety of prediction approaches spanning from simple of complex, both for the failure models and the computational approaches.

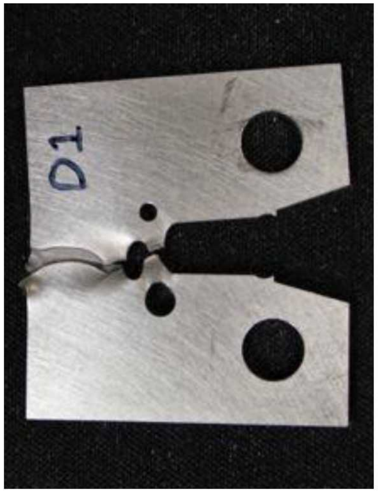


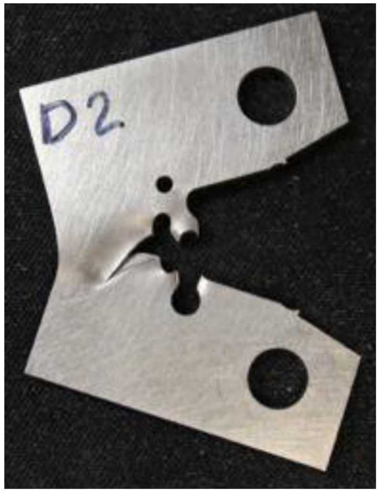
Experimental variability identified interesting complexity





Crack Paths A-C-E (left) and A-D-C-E (right)





Two different crack paths observed by three independent labs from minor geometric/loading variations!

Variability in computational predictions dwarfed experimental uncertainty

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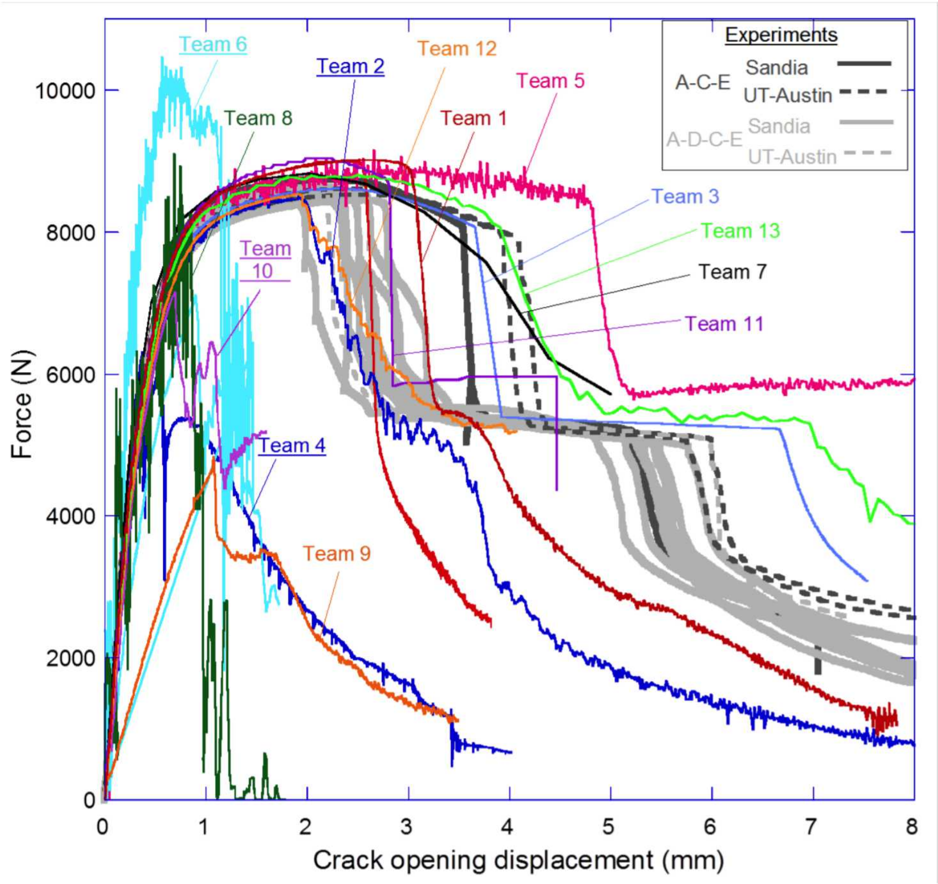
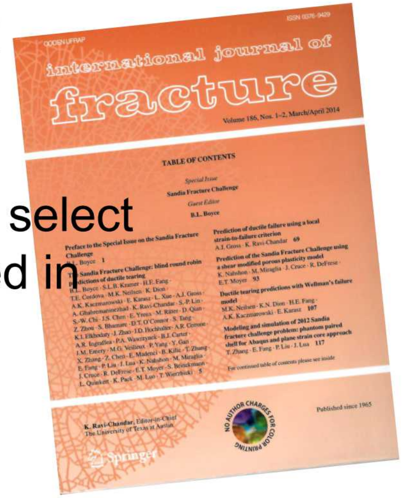


Methods Exercised

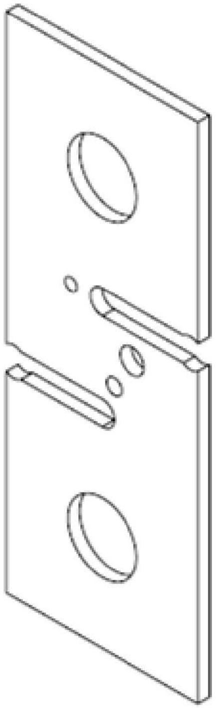
- Explicit vs Implicit Solver
- Boundary Conditions
- Element Type
- Discretization Level
- Material Model
- Thermomechanical Coupling
- Failure Criterion (strain parameter, damage law, triaxiality dependence)
- Fracture Method (deletion, cohesive surface, etc)
- Calibration Data Used
- …

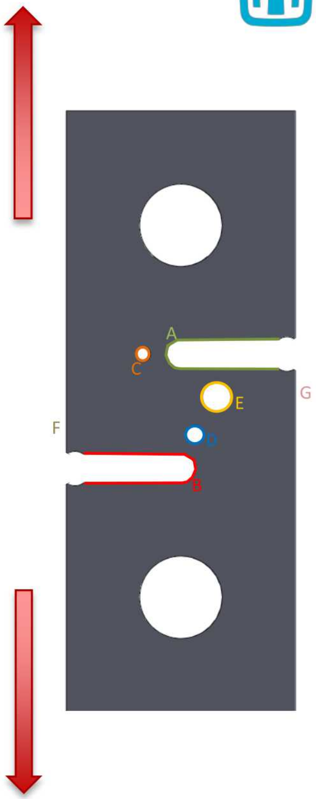
Overview article and select approaches published in special edition of *IJ of Fracture*

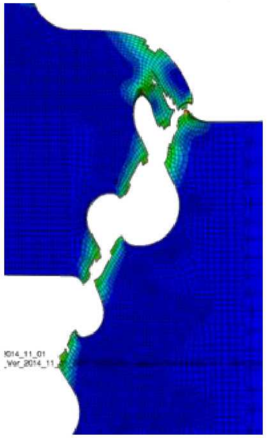


SFC2 2014 – Exploring rate effects

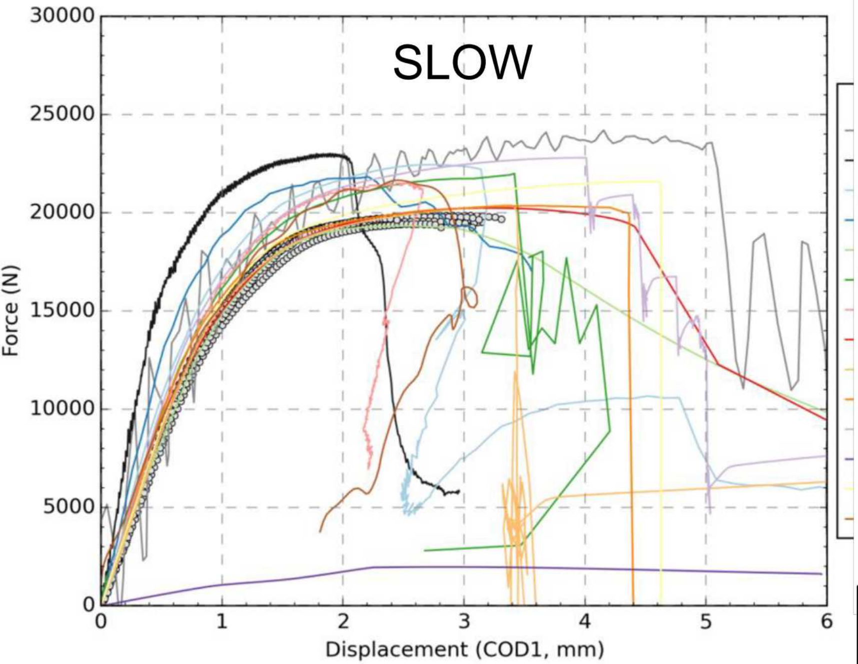
- 14 international teams participated
- Predict the forces and gap opening
  - Material: Ti-6Al-4V, 3.15 mm-thick sheet
  - Two different loading rates: 0.0254 mm/sec, 25.4 mm/sec.
- All teams provided extensive materials characterization and asked to predict component response
  - Tensile and shear failure data in both axes at 2 rates
  - Images of all broken samples
  - Exact measured geometry of each test coupon

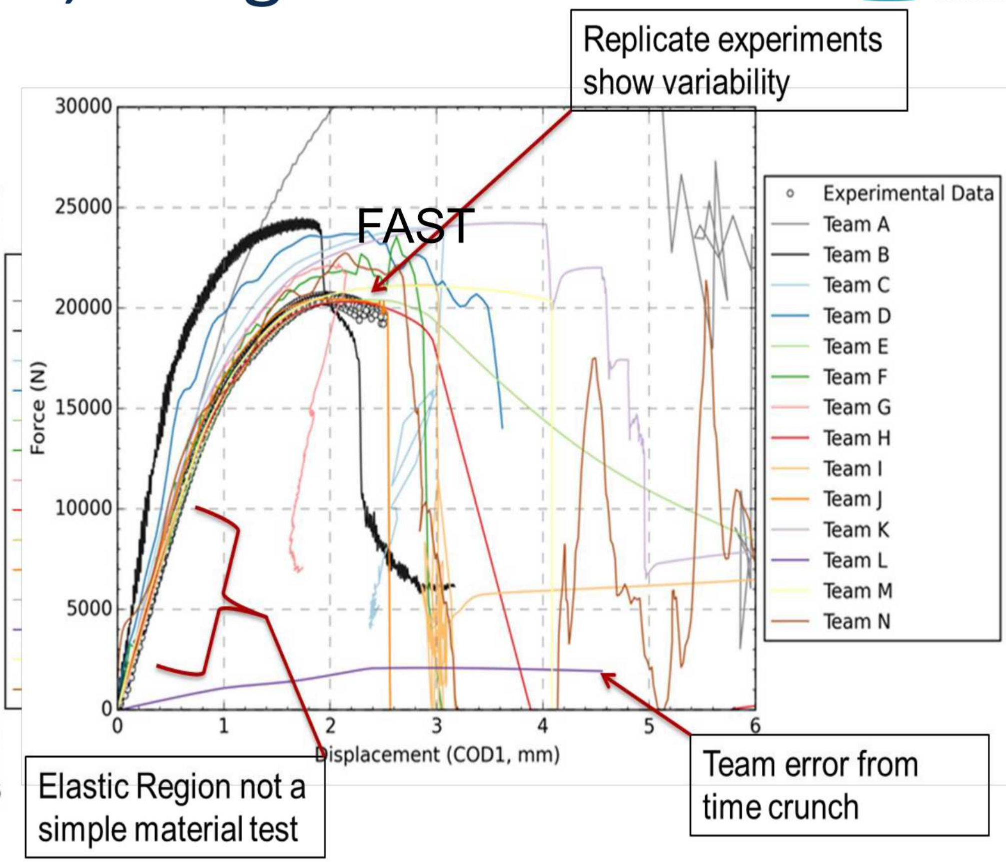






A complex comparison, but general improvement…





<u>Lessons Learned from SFC2</u>:

- Boundary condition model played an unexpectedly important role in simulations
- Thermal work contribution is significant, even for modest strain-rates
- Models must account for anisotropy in plasticity
- Shear calibrations tests help, but are not standardized
- Little consideration for uncertainty and absence of microstructure

SFC3 – AM Challenge 2017

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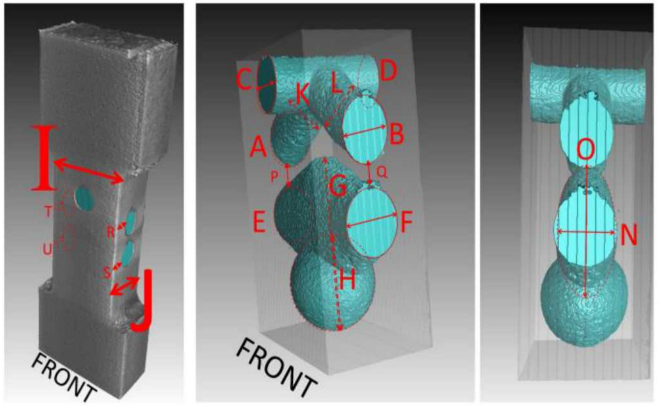
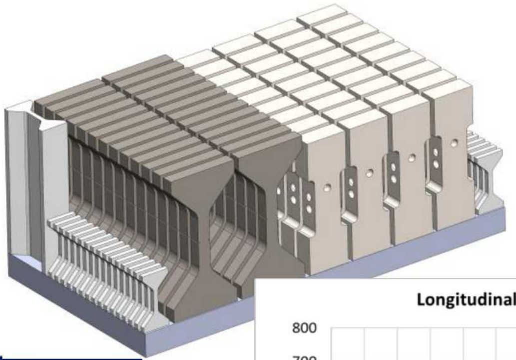
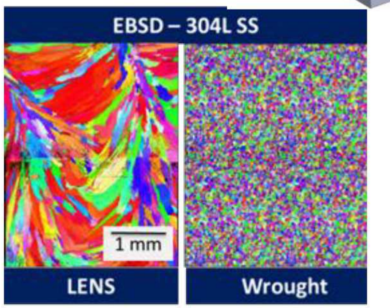
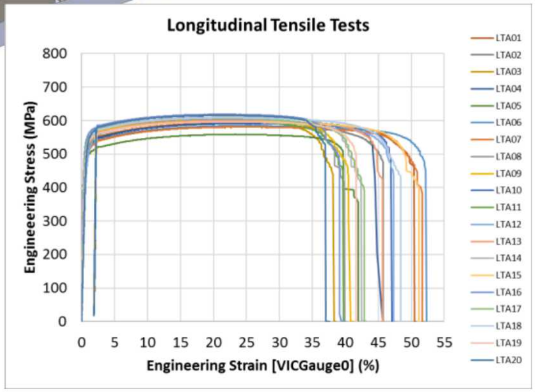
- AM chosen in hopes of driving grain scale effects and uncertainty
- Results submitted July 2017 and currently under assessment
- High throughput testing used for material characterization
- Porosity may be dominant effect

SFC3 Challenge Commitments

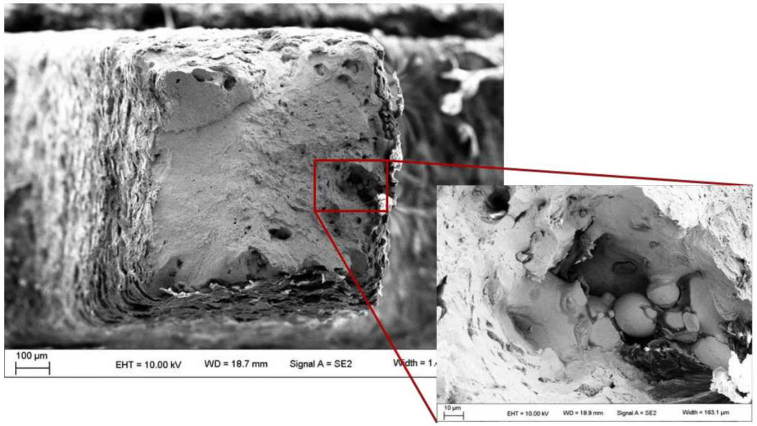








Rough Fracture Surface with Porosity

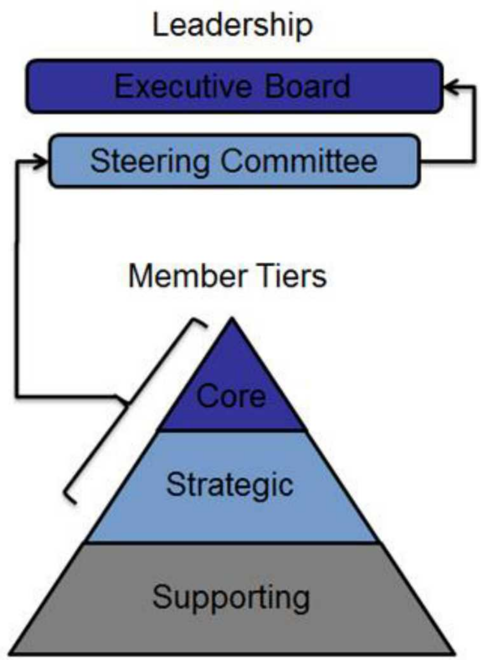


Moving from collective assessment to collaborative capability advancement

Charter Institutions

Initial SRP meeting August 29-30 in Albuquerque.

A partnering model of tiered in-kind support to organize challenges and focus research efforts



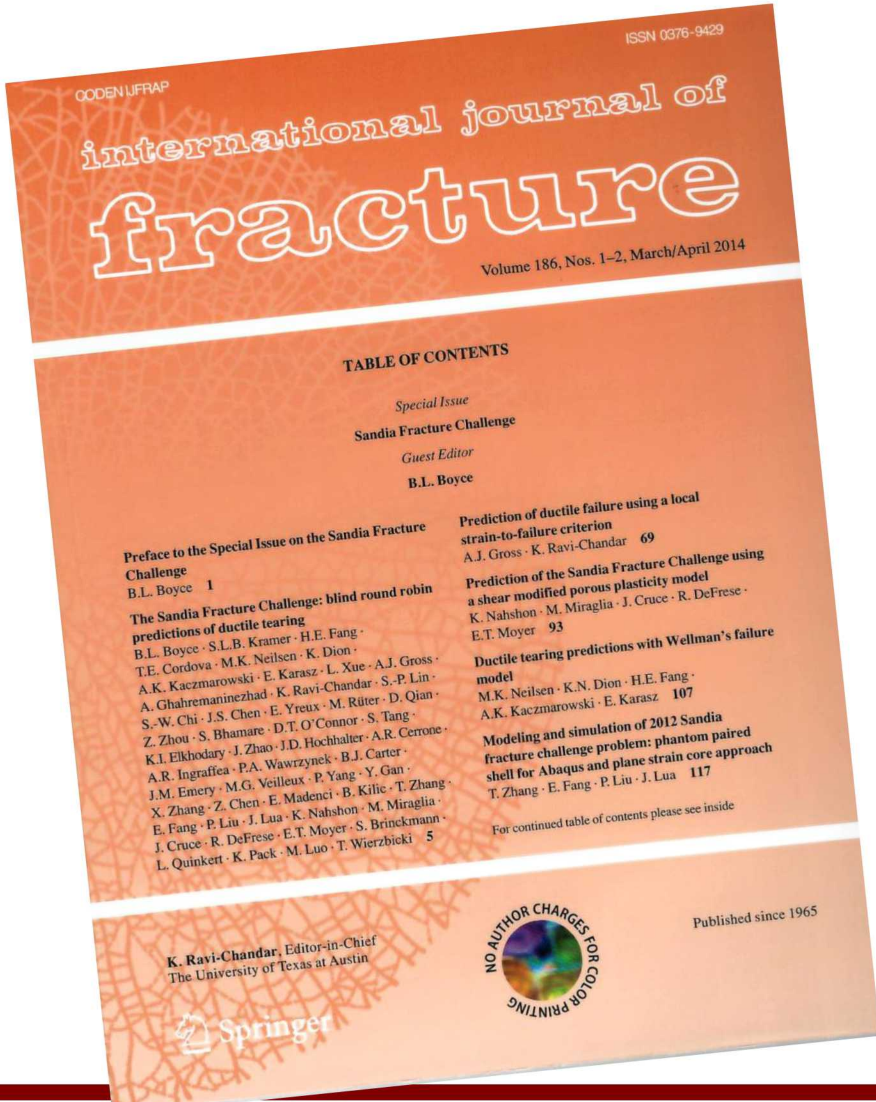
Summary Remarks

- Sandia's National Security mission motivates deeper understanding of the complete failure process
- Sandia Fracture Challenge brings together Government, Industry, and academic partners from around the world for collective assessment
- Structural Reliability Partnership moves to collective capability advancement through leveraged pre-competitive in-kind support.

- Acknowledgement
  - Eliot Fang, Brad Boyce, Jonathan Zimmerman, Alyssa Kolski at Sandia
  - SFC partner institutions
  - Exxon Mobil and UT Austin partners in SRP
- For more information about Structural Reliability Partnership, please contact:
  - Jim Redmond
  - jmredmo@sandia.gov

Back-Up

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

B.L. Boyce

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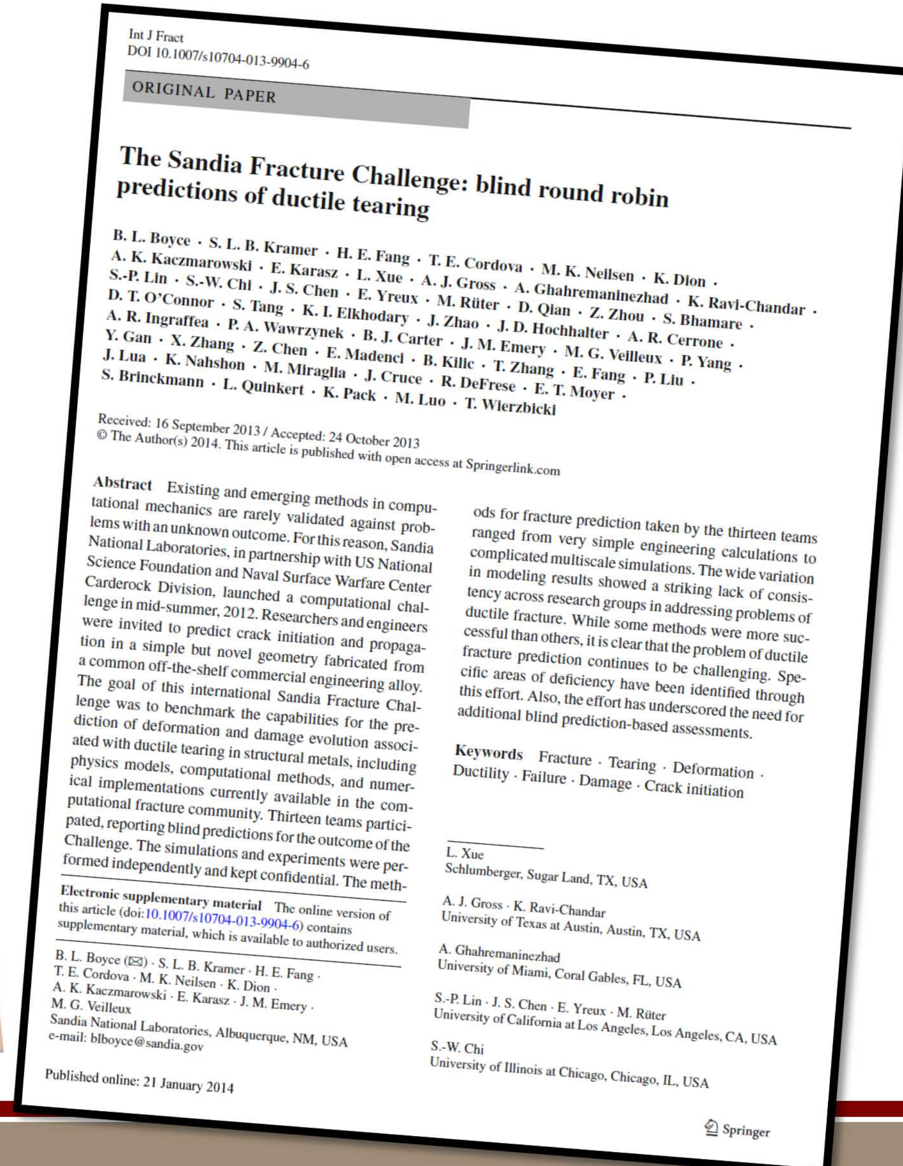

Int J Fract
DOI 10.1007/s10704-013-9904-6

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 · P. Liu · J. Lua · K. Nahshon · M. Miraglia · J. Cruce · R. DeFrese · E. T. Moyer · S. Brinckmann · L. Quinkert · K. Pack · M. Luo · T. Wierzbicki

Received: 16 September 2013 / Accepted: 24 October 2013

Abstract Existing and emerging methods in computational mechanics are rarely validated against problems with an unknown outcome. For this reason, Sandia National Laboratories, in partnership with US National Science Foundation and Naval Surface Warfare Center Carderock Division, launched a computational challenge in mid-summer, 2012. Researchers and engineers were invited to predict crack initiation and propagation in a simple but novel geometry fabricated from a common off-the-shelf commercial engineering alloy. The goal of this international Sandia Fracture Challenge was to benchmark the capabilities for the prediction of deformation and damage evolution associated with ductile tearing in structural metals, including physics models, computational methods, and numerical implementations currently available in the computational fracture community. Thirteen teams participated, reporting blind predictions for the outcome of the Challenge. The simulations and experiments were performed independently and kept confidential. The methods for fracture prediction taken by the thirteen teams ranged from very simple engineering calculations to complicated multiscale simulations. The wide variation in modeling results showed a striking lack of consistency across research groups in addressing problems of ductile fracture. While some methods were more successful than others, it is clear that the problem of ductile fracture prediction continues to be challenging. Specific areas of deficiency have been identified through this effort. Also, the effort has underscored the need for additional blind prediction-based assessments.

Keywords Fracture · Tearing · Deformation · Ductility · Failure · Damage · Crack initiation

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.

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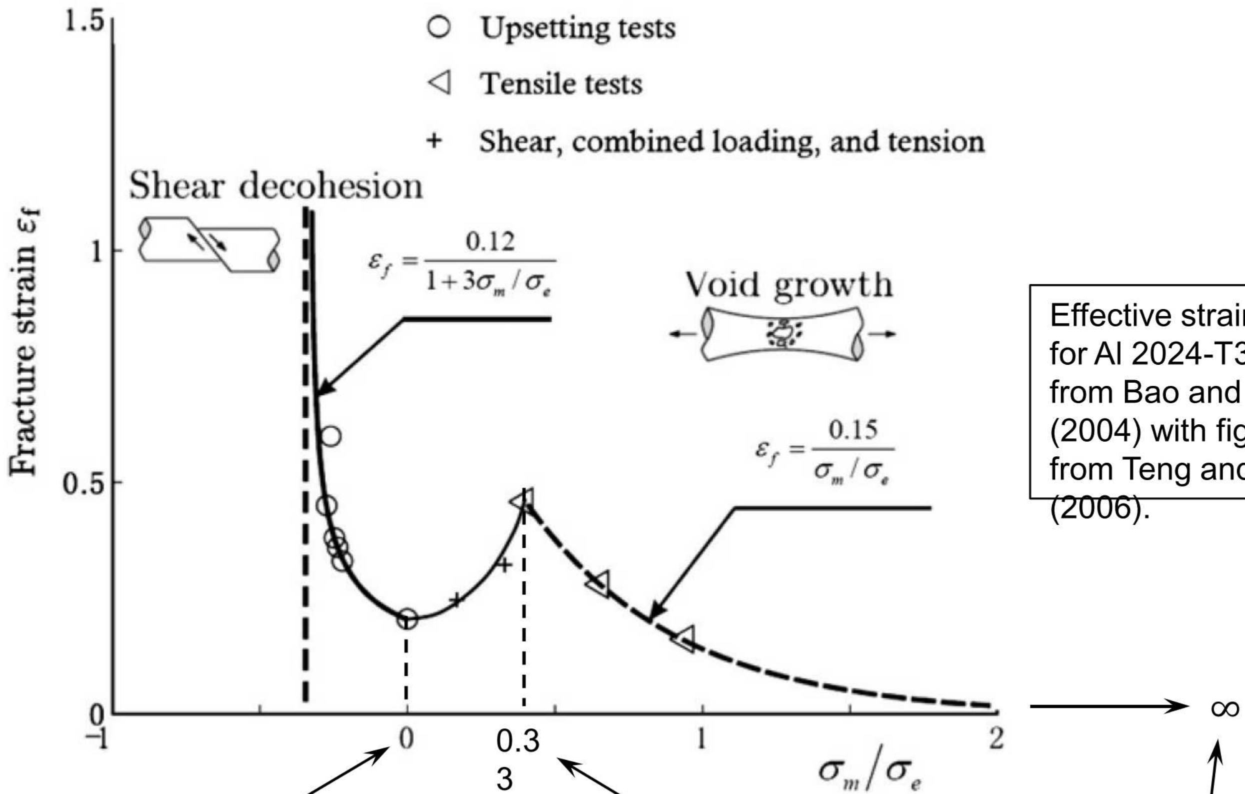
Springer

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

$$\text{Triaxiality} = \frac{\sigma_{mean}}{\sigma_{effective}} = \frac{\sigma_{hydrostatic}}{\sigma_{von\ Mises}} = \frac{\frac{1}{3}(\sigma_1+\sigma_2+\sigma_3)}{\frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}}$$



Effective strain at fracture for Al 2024-T351. Data from Bao and Wierzbicki (2004) with figure adapted from Teng and Wierzbicki (2006).

Pure Shear Loading

$$\boldsymbol{\sigma} = \begin{bmatrix} 0 & \tau & 0 \\ \tau & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \text{ or } \begin{bmatrix} \sigma & 0 & 0 \\ 0 & -\sigma & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

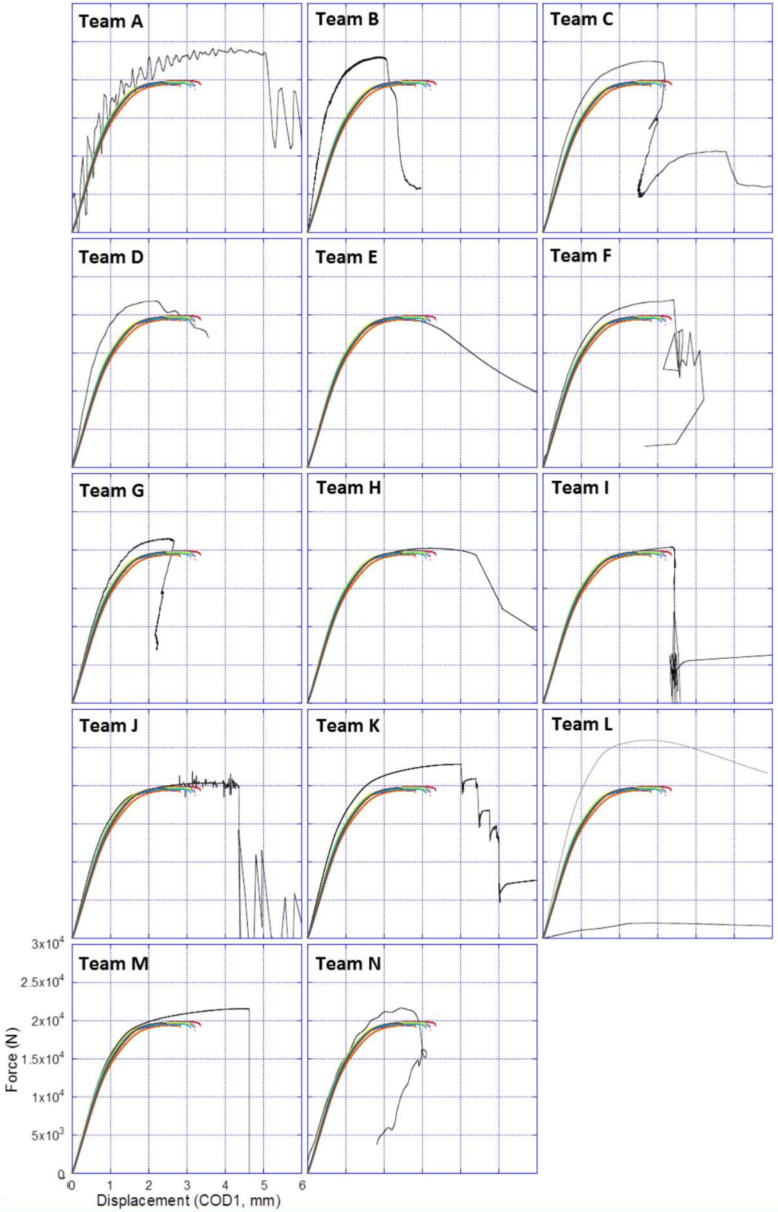
Uniaxial Loading

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Hydrostatic Loading

$$\boldsymbol{\sigma} = \begin{bmatrix} \sigma & 0 & 0 \\ 0 & \sigma & 0 \\ 0 & 0 & \sigma \end{bmatrix}$$

Parsing the Individual Team Issues



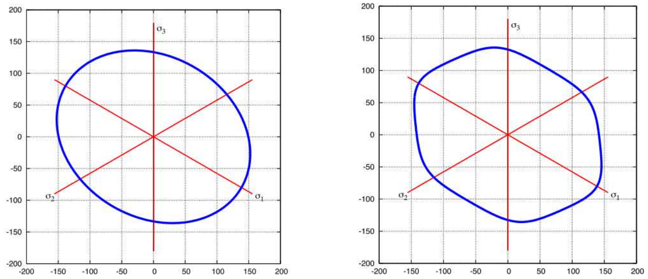
- Explicit vs Implicit Solver
- Thermomechanical Coupling
- Boundary Conditions
- Element Type
- Discretization Level
- Fracture Method (deletion, cohesive surface, etc)
- Uncertainty Method
- Anisotropic Plasticity Model (J2, Hill)
- Hardening Law (Power-law, Swift, Piecewise Linear)
- Failure Criterion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

<u>Lessons Learned from SFC2</u>:

- Results were overly sensitive to boundary condition models
- Thermal work contribution is significant, even for modest strain-rates
- Models with anisotropy and lode-angle effects are necessary
- Shear calibrations tests help, but are not standardized
- Insufficient capture of uncertainty
- No consideration to microstructure in predicting failure

UT hosted workshop identified collective deficiencies and opportunities

- Boundary conditions, thermal effects, rate dependence, and anisotropy were all important
- Extensive testing was still insufficient! – need more sophisticated approaches to material parameter calibration particularly for hear
- Limited use uncertainty bounds, and material multiscale was absent
- Internal Sandia research portfolio influenced by SFC
  - Improved void nucleation and growth models to account for shear dependence
  - New anisotropic plasticity and failure models
  - Improved viscoplasticity models
  - New methods to eliminate mesh dependence (non-local, gradient, X-FEM)
  - Multi-scale methods to couple meso and continuum material mechanics



Improved yield surface models