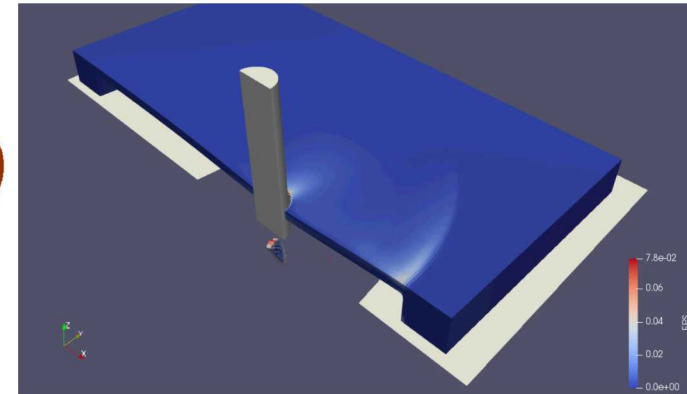


Exceptional service in the national interest



NOMAD



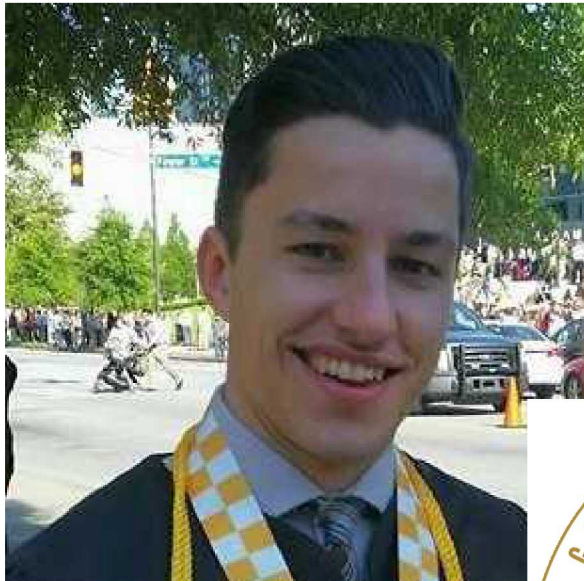
NOMAD Institute 2018 Project 5: Material Failure Model and Properties for Puncture Simulations

Nathan Bieberdorf
Zachary Towner

Research Team

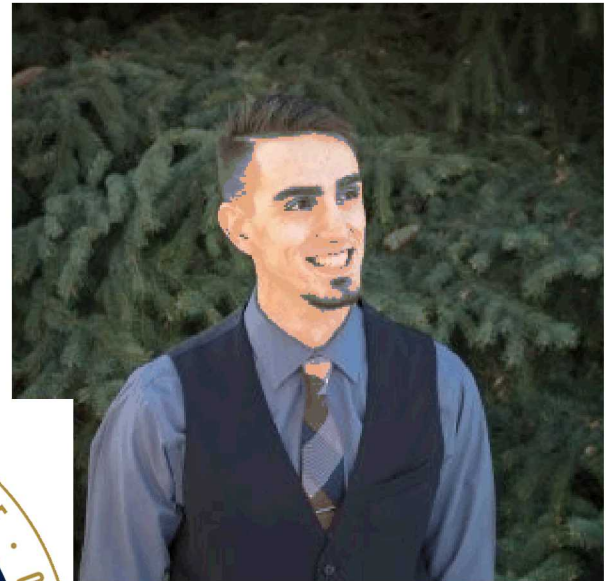
Nathan Bieberdorf

Georgia Institute of Technology



Zachary Towner

Georgia Institute of Technology



Mentor Team

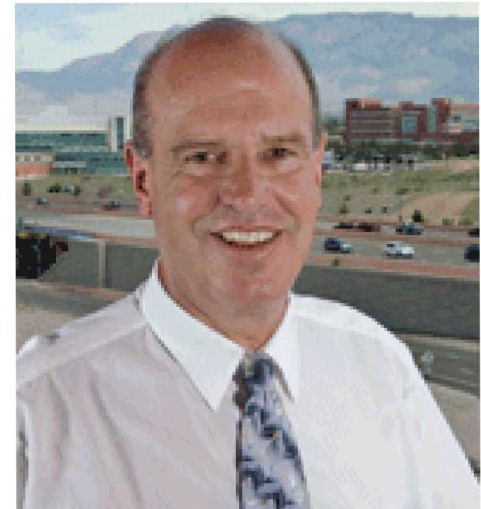
Neal Hubbard

Sandia National Laboratories



Walter Gerstle

University of New Mexico



Problem Motivation and Background

Damascus, AR accident (1980)

- Maintenance worker in missile silo dropped a tool approx. 80' struck the fuel tank
- Fuel exploded launching 740-ton door and warhead into surrounding area
- Warhead did not detonate
- 1 dead, 21 injured, facility destroyed



Arkansas Times, "Coming: Behind-the-scenes account of the 1980 Titan missile accident in Damascus, Ark.," 26 May 2013. [Online].

Org. 9432 Weapon Analysis Mission:
"Provide customers with performance, risk, and safety analyses...to assure the safety of nuclear weapons during [various] operations"

Project Overview

Analyze puncture failure of 7075-T651 plate from steel probes

- Simulate and predict tooling damage

Compare different descriptions of material response

- Constitutive laws
- Failure criteria

Sandia Fracture Challenge

- Minimal experimental data, characterization provided

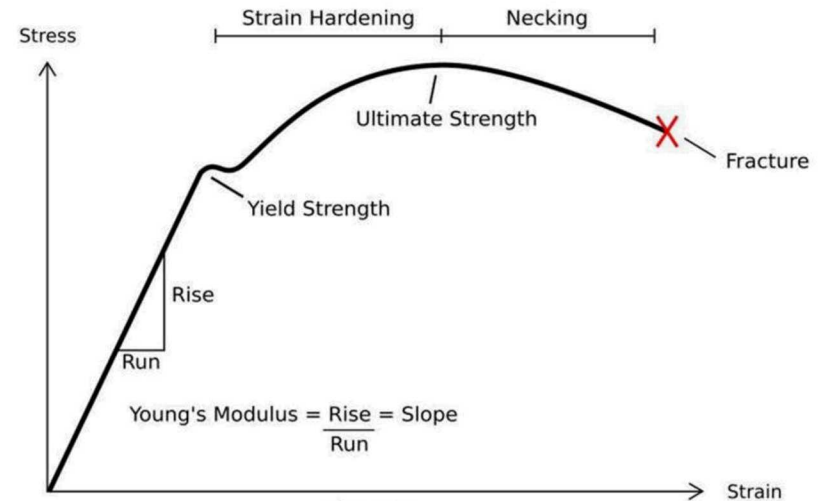


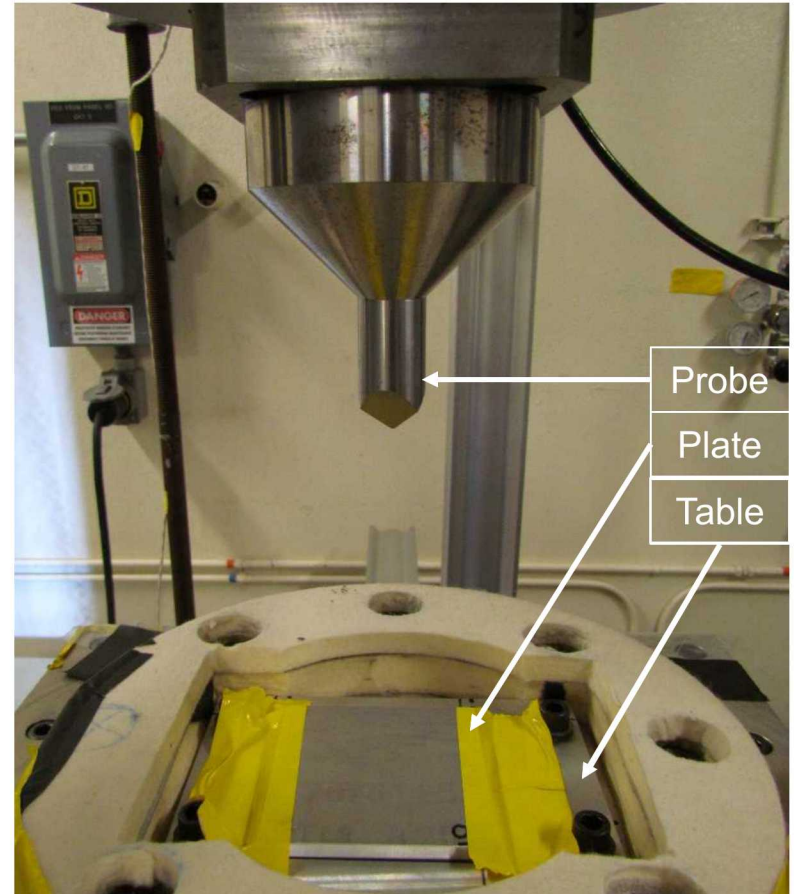
Figure 1

Experiment Description

Steel probes dropped from various heights onto aluminum coupon

Aluminum coupon primarily constrained to movement normal to impact

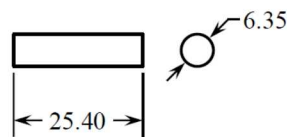
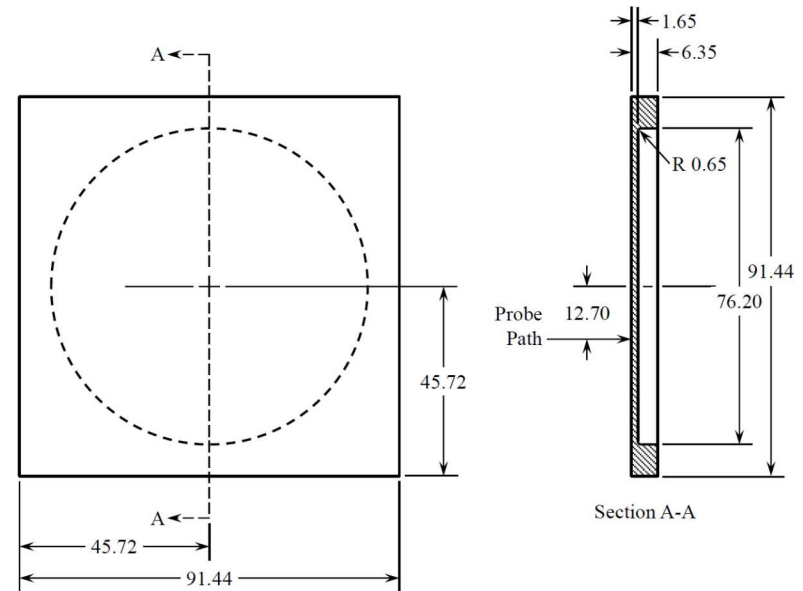
Energy absorption of the plate determined by ΔKE of the probe



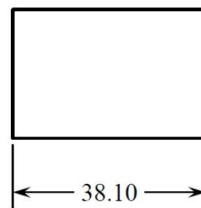
Experiment Description

Several different phenomena

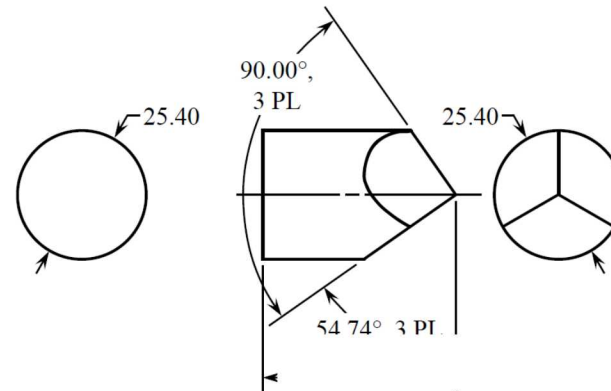
- Complex loading state (biaxial tension, bending)
- Wide range of strain rates
- Fracture, spallation
- Contact mechanics



F0250



F1000



C1000

Constitutive Laws vs. Failure Criteria

Constitutive models define material behavior (hardening, viscoplasticity, damage, etc.)

- Multilinear Elastic-Plastic (MLEP)
- Johnson-Cook (JC)

Failure criteria define the limits from when the stress is reduced to zero (failed)

- Failure Strain
- Failure Stress
- Strain Energy Density
- Wellman Tearing Parameter
- Johnson-Cook Damage Criterion

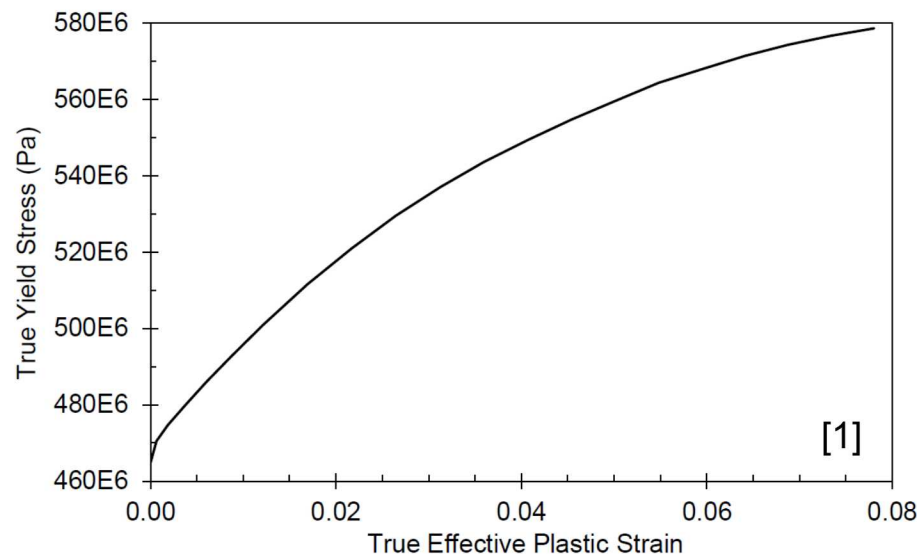
Review: MLEP Model

Rate-independent, temperature-dependent plasticity model

Piecewise linear hardening curve created from uniaxial stress vs. plastic strain curve from experimental data

Yield surface defined according to Von Mises

Does not inherently incorporate damage or failure



Review: JC Model [2,3]

Rate- and temperature-dependent constitutive law most commonly used and accepted in practice for large strains and strain rates

$$\sigma_e = \left[A + B(\varepsilon_e^p)^n \right] \left[1 + C \ln \frac{\dot{\varepsilon}_e^p}{\dot{\varepsilon}_{eo}^p} \right] [1 - \hat{T}^m]$$

Damage model based on accumulation of plastic strain

$$\bar{D} = \int \frac{d\hat{\varepsilon}_e^p}{\varepsilon_{ef}^p \left(\eta, \varepsilon_e^p / \varepsilon_{eo}^p, \hat{T} \right)}$$
$$\varepsilon_{ef}^p = [d_1 + d_2 e^{d_3 \eta}] \left[1 + d_4 \ln \frac{\dot{\varepsilon}_e^p}{\dot{\varepsilon}_{eo}^p} \right] [1 + d_5 \hat{T}]$$

Failure occurs when $\bar{D} = 1$

[2] G. R. Johnson and W. H. Cook, *A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures*. Proc. 7th Int. Symp. on BuNistics, pp. 541-547. The Hague, The Netherlands (April 1983).

[3] Johnson, G. R., & Cook, W. H. (1985). *Fracture characteristic of three metals subjected to various strains, strain rates, temperatures and pressures*. *Engineering Fracture Mechanics*, 21(1), 31-48.

Review: Wellman Tearing Parameter [4]

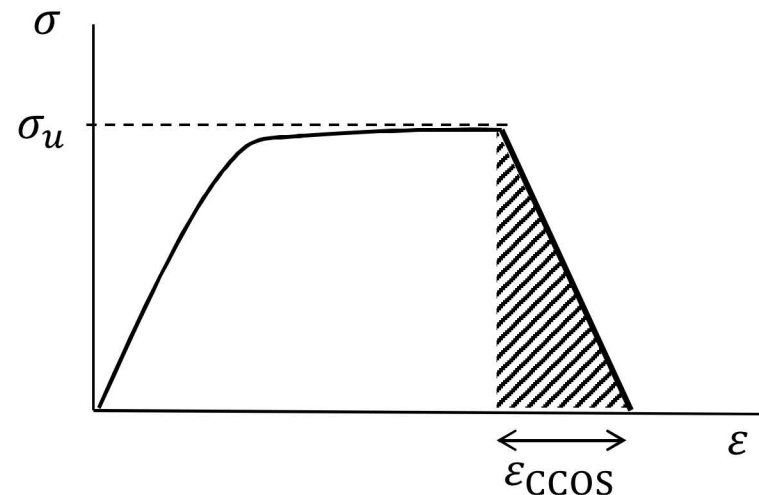
Proposed by Wellman (Sandian!) in 2013

- Goal to make energy dissipation scale with element size, eliminate mesh dependency of crack growth

Phenomenological failure term to homogenize void nucleation and growth

$$t_p = \int_0^\varepsilon \left\langle \frac{2\sigma_1}{3(\sigma_1 - \sigma_m)} \right\rangle^m d\varepsilon_p$$

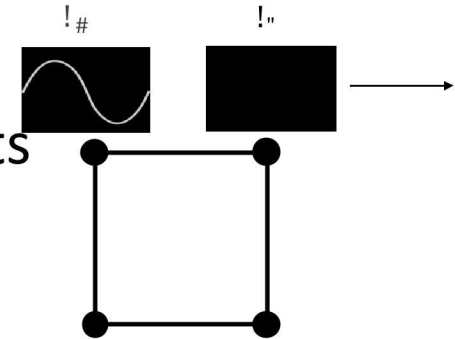
Once $t_p = t_{crit}$, stress reduces to zero linearly until $\varepsilon = \varepsilon_{CCOS}$



Capturing Elastic Waves: Time Step

Elastic wave response must be captured by elements

- Co-dependent temporal and spatial sampling



Time-step: Every node observes every wave

Waves cannot move further than characteristic element length

$$l_e \geq C_w \Delta t$$

$$(\Delta t)_{max} = \frac{(l_e)_{min}}{C_w}$$

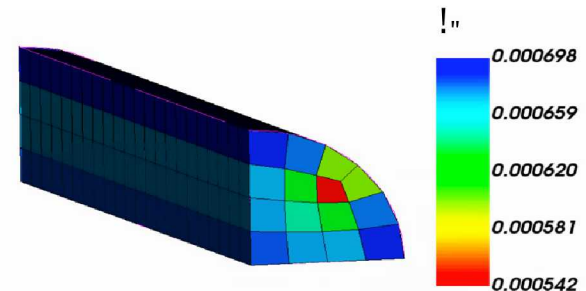
l_e : characteristic element length
 C_w : sound wave speed
 Δt : time step

$$(C_w)_P = \sqrt{\frac{K + \frac{3}{4}G}{\rho}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$

Sierra will automatically maintain a max allowable time step

- Based on element length, stiffness, and mass density

$$(\Delta t)_{max} = (l_e)_{min} \sqrt{\frac{\rho(1+\nu)(1-2\nu)}{E(1-\nu)}}$$



Capturing Elastic Waves: Element Size

Element Size: At least one element per wave

- Often $n_e = 6 - 20$ [5]

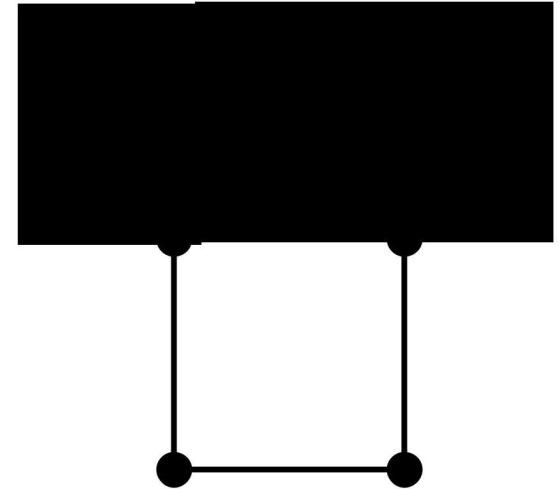
$$l_e \leq \lambda = \frac{c_w}{n_e f}$$

Modal analysis reveals: $f_0 = 2.5$ kHz

$$(l_e)_{max} = \frac{(c_w)_P}{n_e f} = \frac{6129 \frac{\text{m}}{\text{s}}}{20 \cdot 2.5 \text{ kHz}} = 0.12 \text{ m}$$

Maximum element size vs. plate geometry

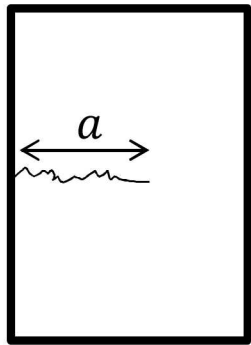
- Plate thickness is 1.65 mm
- Mesh size controlled by material response (convergence study)



Objectivity in Fracture

When material fails/cracks, two new surfaces are created

- Free surface creation requires some energy, E_s



$$E_s = 2\gamma_s a^2$$

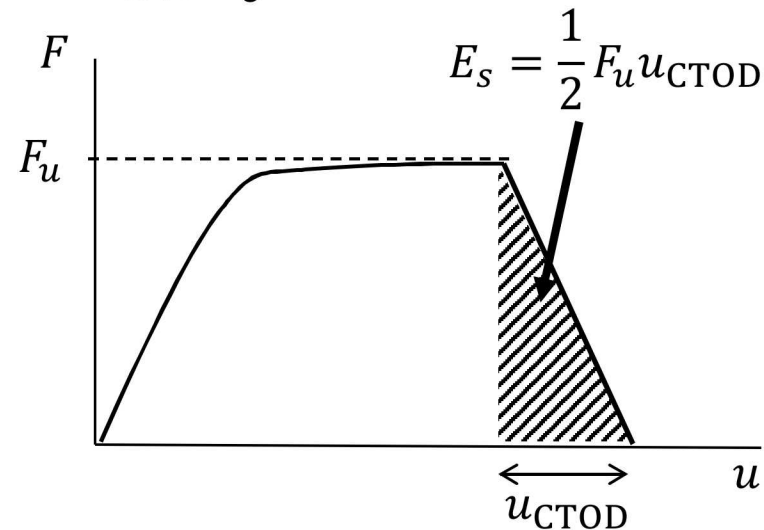
E_s : Fracture energy

γ_s : Free surface energy density

a : Crack length and width

F_u : Ultimate force

u_{CTOD} : Crack tip opening disp.



This failure is modeled by some metric (stress, strain, etc.)

- An element reaches some critical value, and “erodes”
- Larger surfaces should require more energy to create
- Larger elements should require more energy to erode

Objectivity in Fracture

Solving for displacements, strains required for erosion

$$\varepsilon_{\text{CCOS}} = \frac{u_{\text{CTOD}}}{a} = \frac{4\gamma_s a}{F_u} = \frac{4\gamma_s}{\sigma_u a}$$

Inputting death steps into Sierra

- Calculate erosion time from average strain rates ($10^1 - 10^2$)
- Solve for death steps using time-step size

$$\begin{aligned} t_{\text{erosion}} &= \frac{\varepsilon_{\text{CCOS}}}{\dot{\varepsilon}} = \frac{4\gamma_s}{\dot{\varepsilon} \sigma_u a} \\ &= \Delta t \cdot s_d \propto l_e \cdot s_d \end{aligned}$$

$$s_d \propto \frac{4\gamma_s}{\dot{\varepsilon} \sigma_u a^2}$$

t_{erosion} : erosion duration
 s_d : number of death steps

Smaller elements increase erosion time, and decrease time steps

- Death steps increase exponentially as element size is reduced

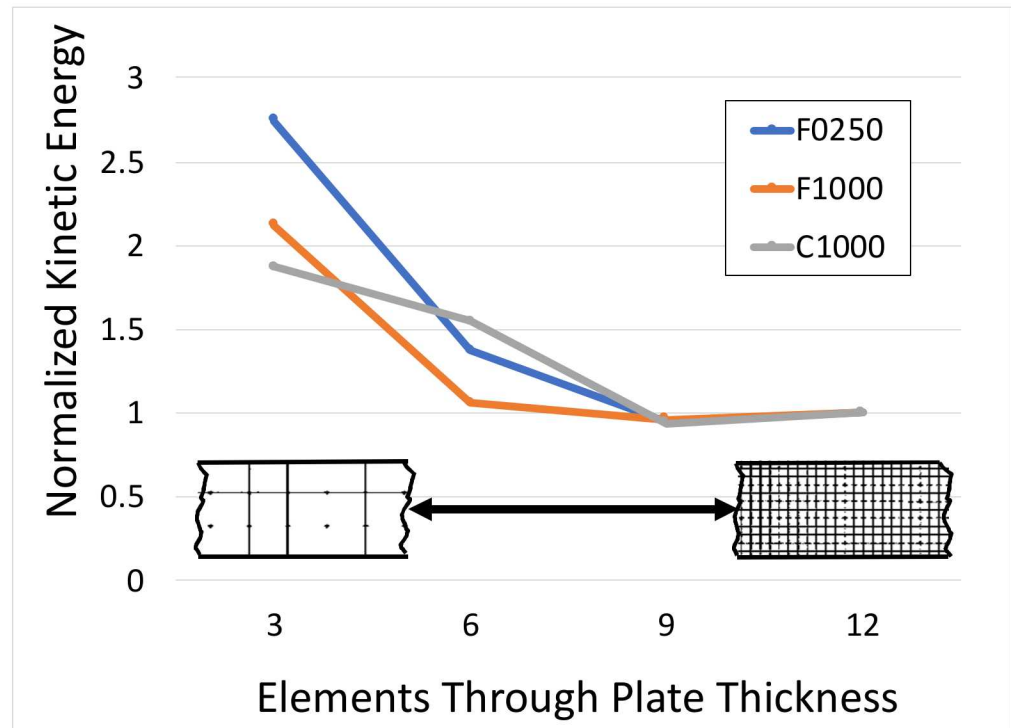
Mesh Refinement

Meshes are typically refined spatially

- However, our erosion criterion assumes consistent element sizing

Mesh convergence

- 9 elements through the thickness captures material response



Model Description

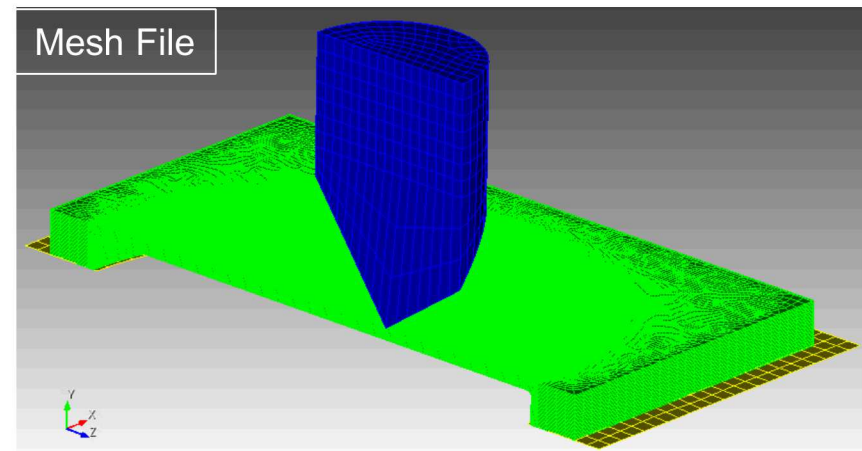
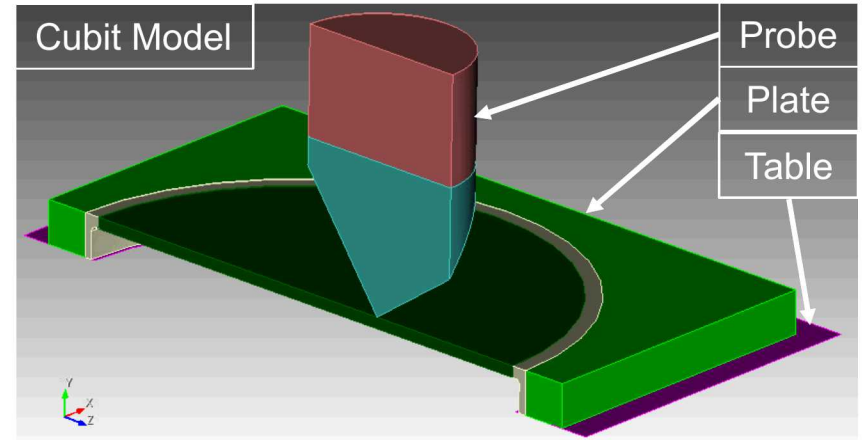
Sierra/Solid Mechanics Presto
(Explicit) Analysis

Notes about Geometry

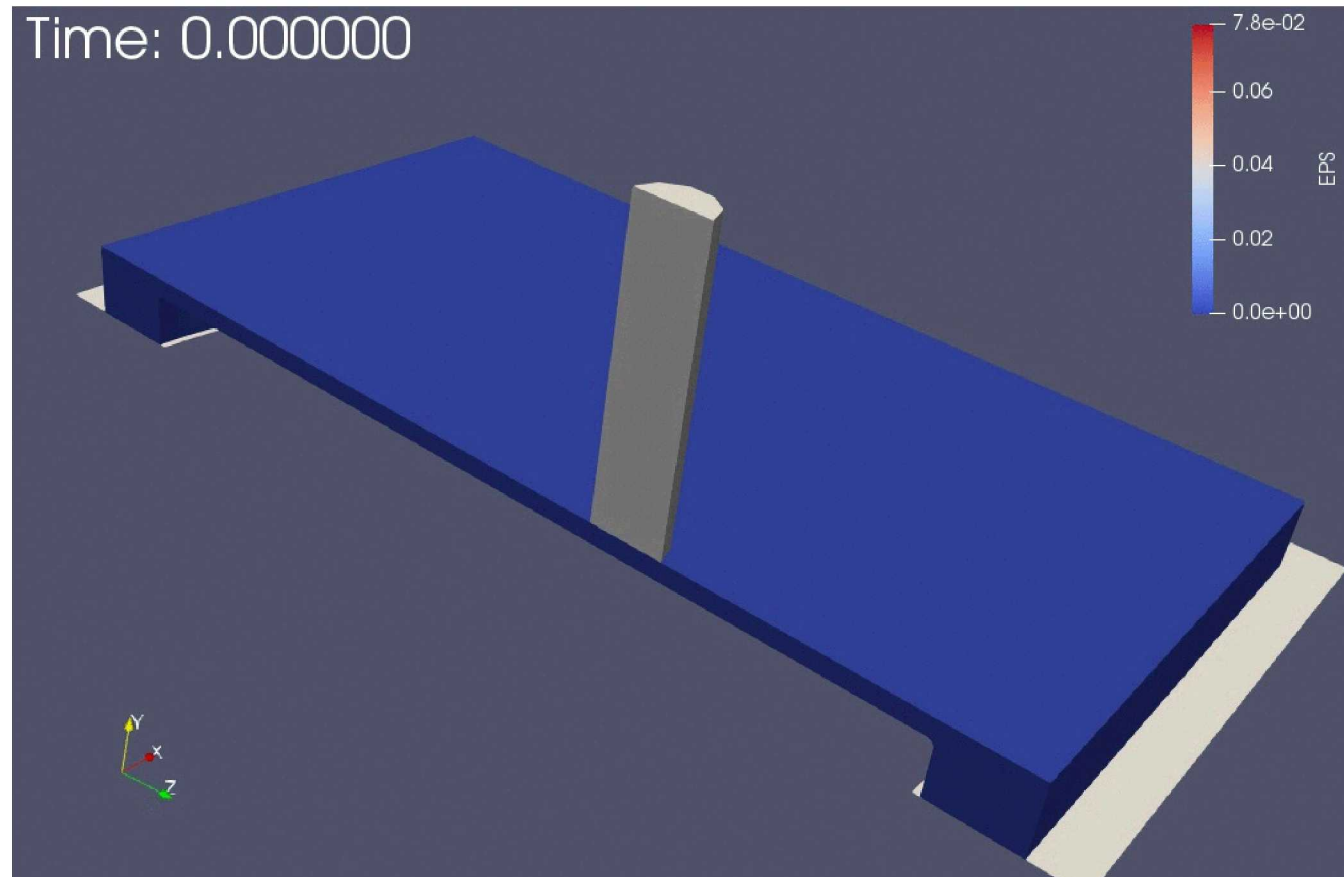
- 9 elements through thickness
- ≈ 1.1 million elements

Initial and boundary conditions

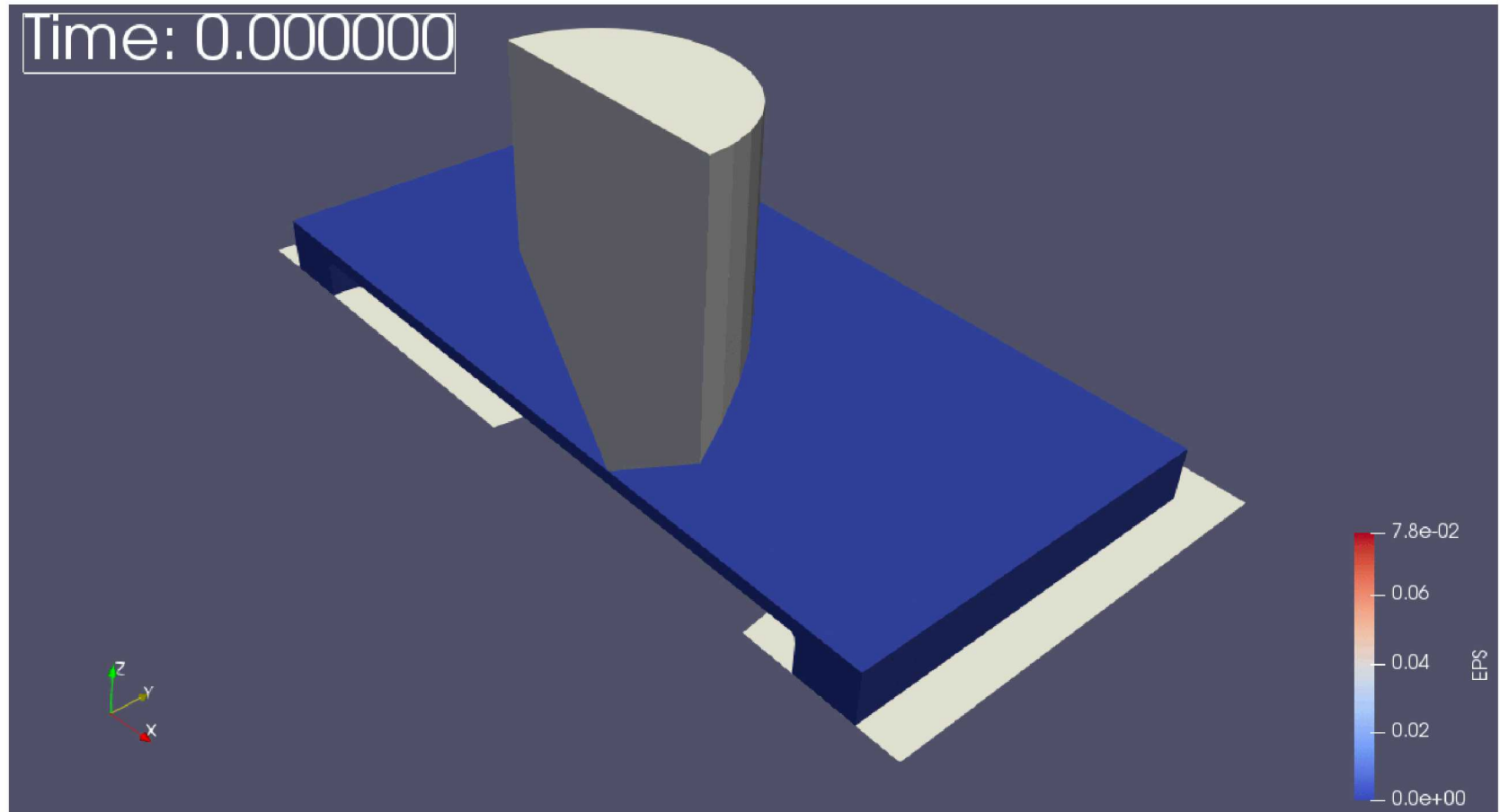
- Initial probe velocity varies 0.54-0.99 m/s
- Plate restrained by contact force and friction with Table
- Table fully fixed



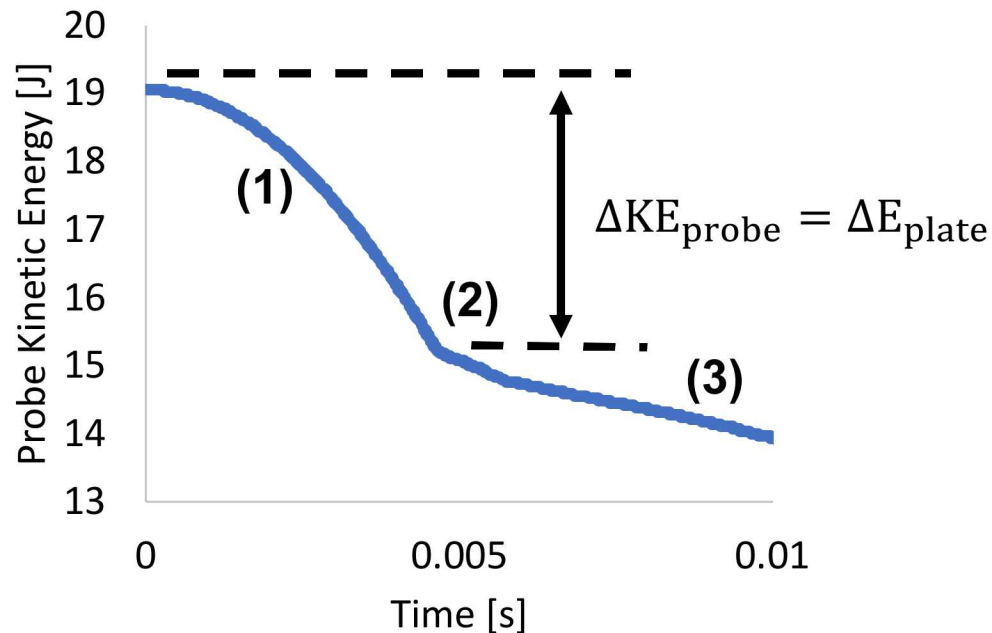
Flat Probe Simulations



Corner Probe Simulation



Kinetic Energy of Probe



(1): Probe begins deforming plate

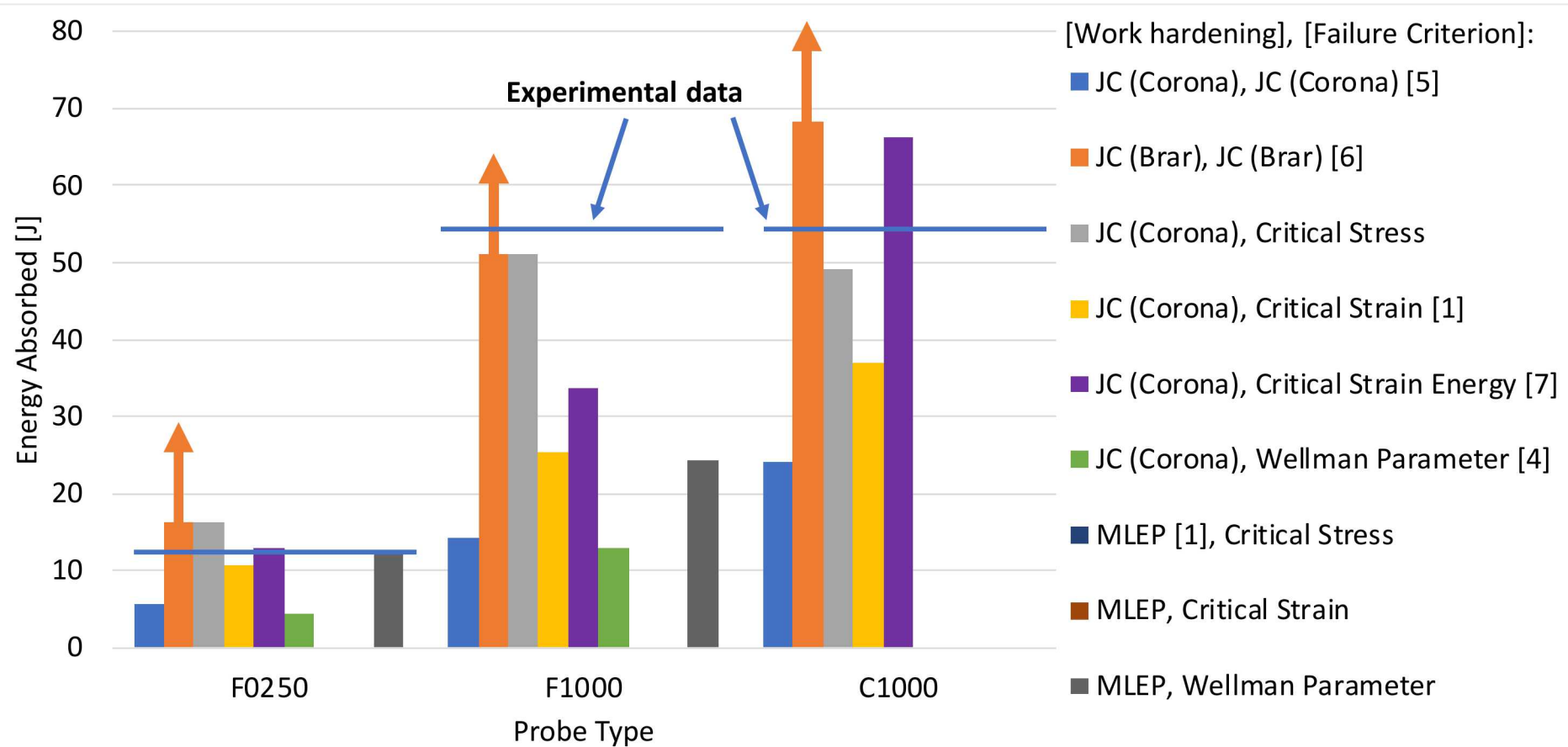
(2): Probe fully penetrates plate

(3): Probe continues to slow down from scraping along tear-out

Assume that energy from probe is 100% absorbed by plate

- Matches experimental assumptions

Energy Absorption Results



[6] Corona, E., and Orient, G. E., SAND2014-1550, "An Evaluation of the Johnson-Cook Model to Simulate Puncture of 7075 Aluminum Plates," Sandia National Laboratories, February 2014.

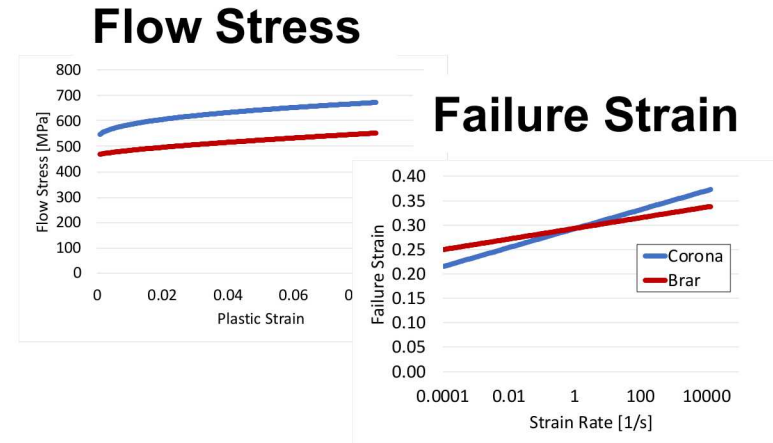
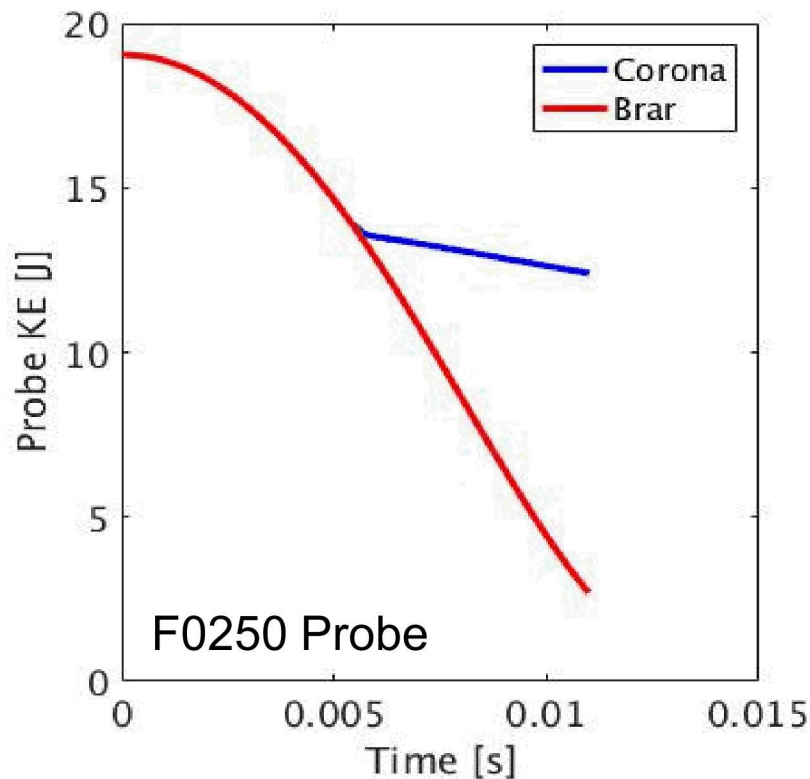
[7] Brar, N. S., Joshi, V. S., & Harris, B. W. (2009). *Constitutive model constants for Al7075-T651 and Al7075-T6*. In AIP Conference Proceedings (Vol. 1195, pp. 945–948). <https://doi.org/10.1063/1.3295300>

[8] Børvik, T., Hopperstad, O. S., Pedersen, K. O., "Quasi-brittle Fracture During Structural Impact of AA7075-T651 Aluminum Plates," International Journal of Impact Engineering, Vol. 37, pp. 537–551, 2010.

Differences in Material Description

Parameters are subjective

- Corona and Brar found uniaxial material response to vary by ~25%



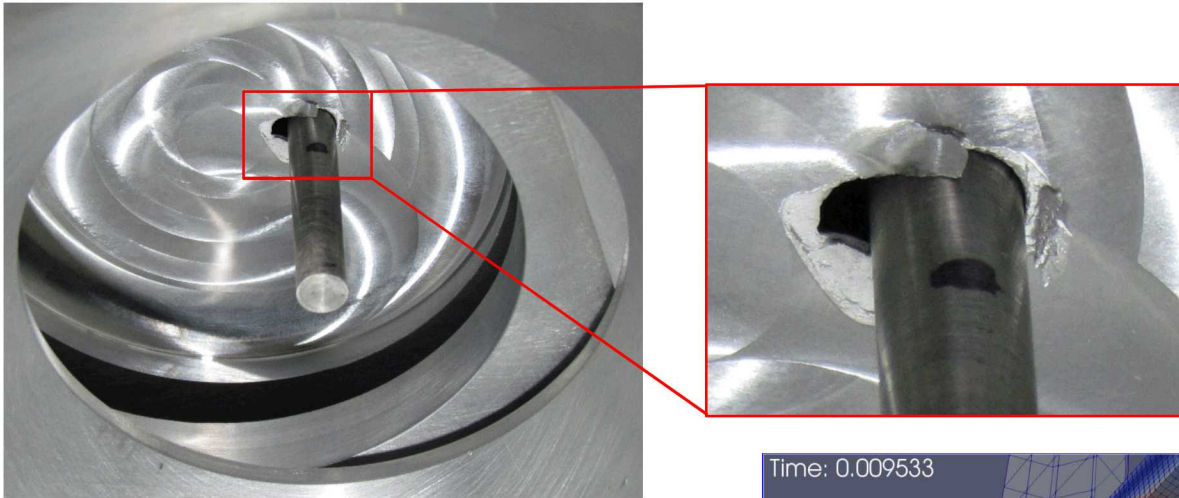
Plastic responses are identical

- Before the first element erodes in Corona simulation

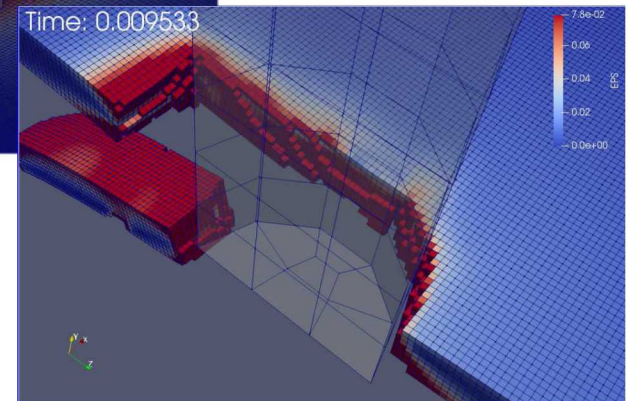
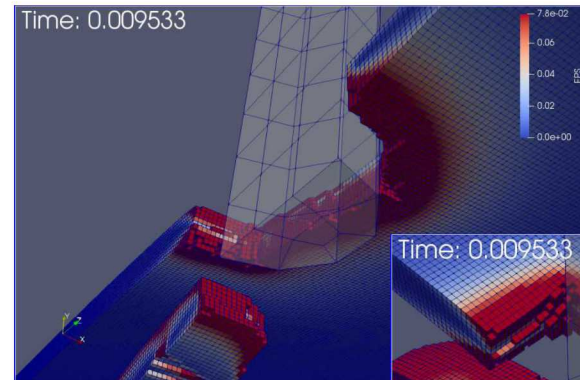
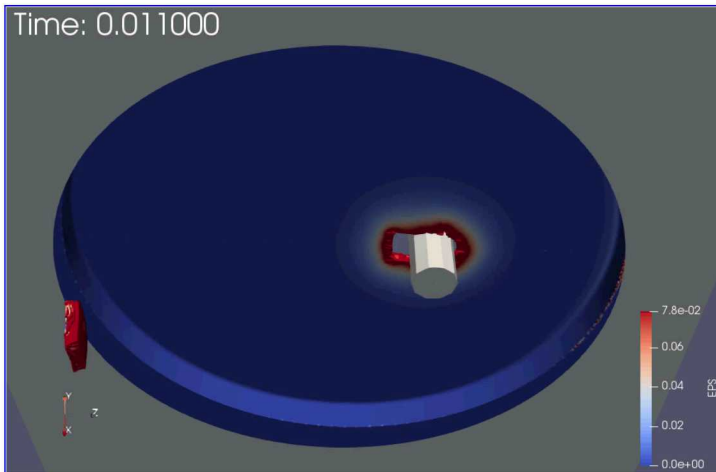
Failure leads to deviation

- Over 100% difference in energy absorption

Failure Geometry – 0.25in, Flat

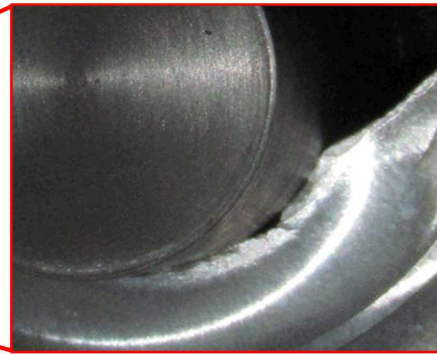
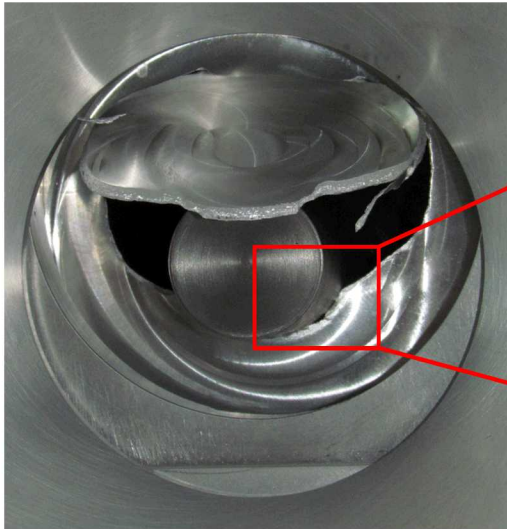


- Highly localized deformation
- Plug formation
- Spallation

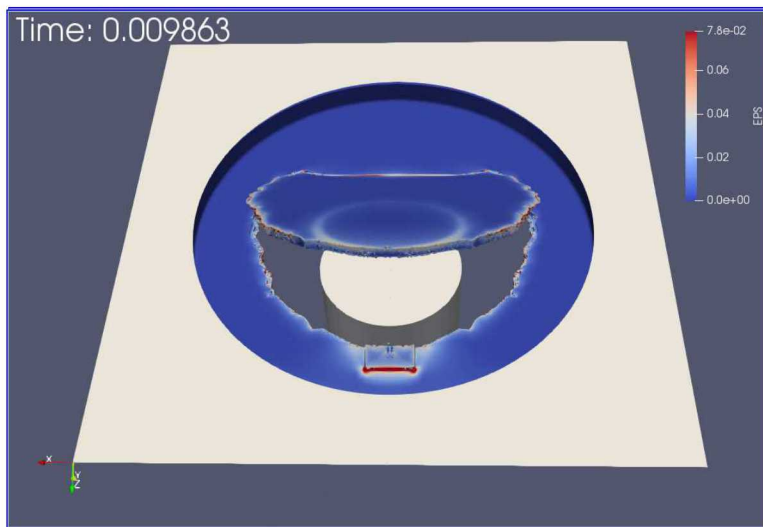


*JC, SED
Simulation

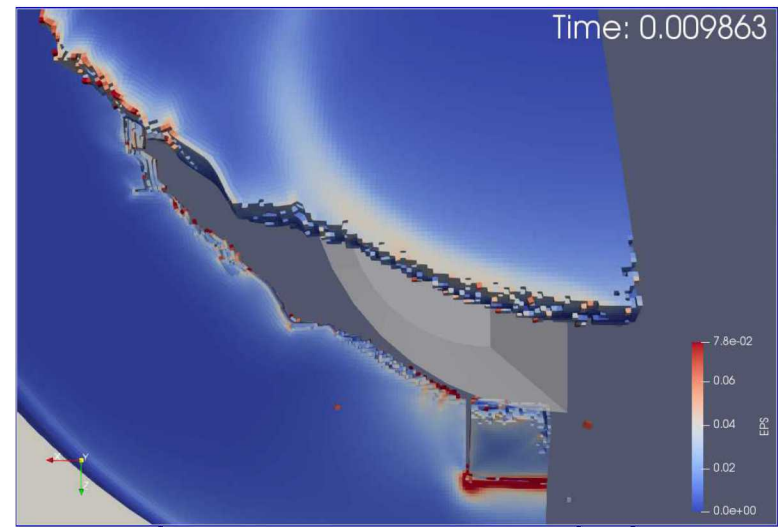
Failure Geometry – 1.00in, Flat



- Shear failure on leading edge
- Crack deviation from probe
- "Can-opening"

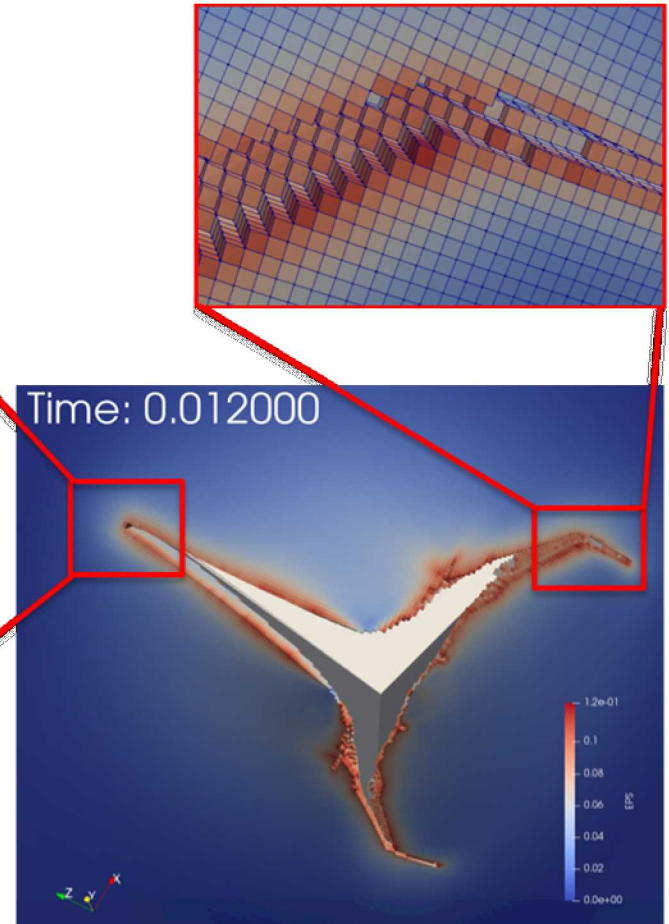
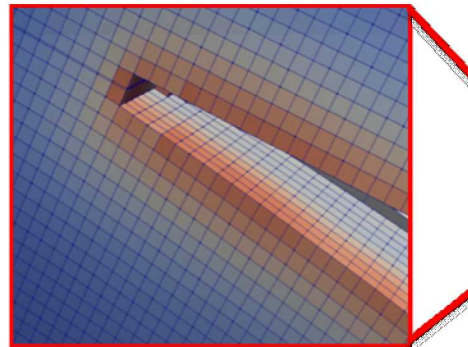
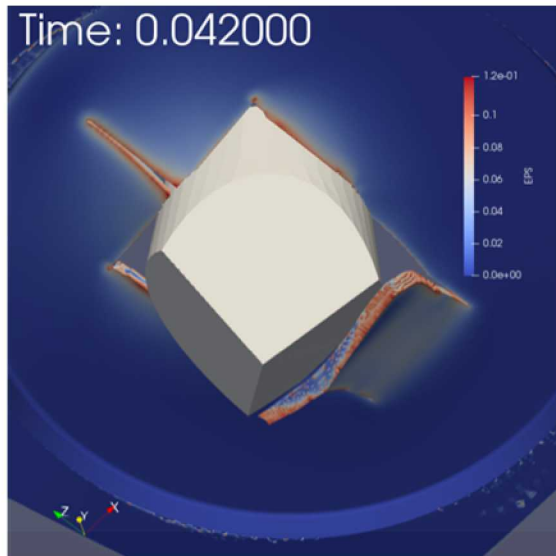
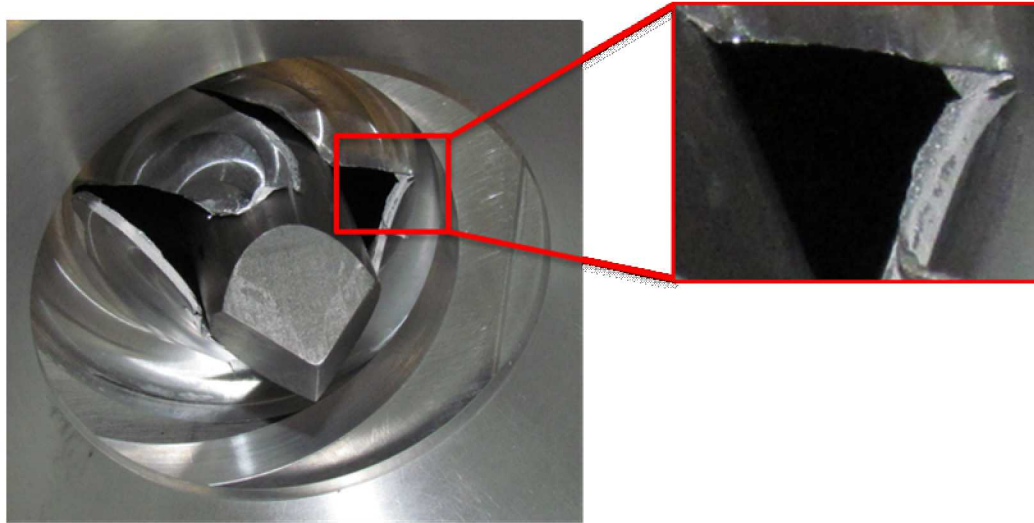


*JC, SED
Simulation



Energy may agree, but
geometry may not...

Failure Geometry – 1.00in, Corner



Conclusions and Next Steps

Failure criterion determines energy absorption

- Differences in elastic/plastic response are negligible

Parameterization of failure is subjective

- Based on mesh density
- Johnson-Cook damage terms stand to be reconsidered

Fracture is mesh dependent

- Once crack begins, difficult to change direction
- Perhaps consider different discretization techniques

Acknowledgments

- This research was conducted at the 2018 Nonlinear Mechanics and Dynamics Research Institute hosted by Sandia National Laboratories and the University of New Mexico.
- 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.