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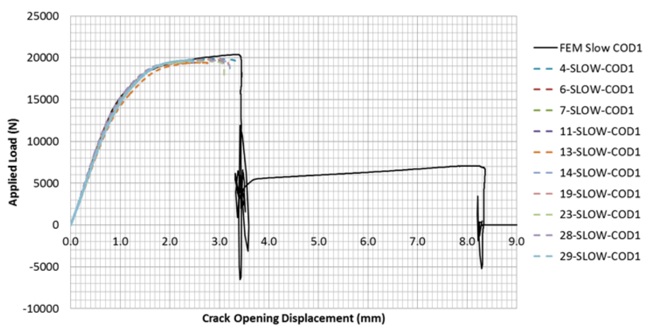

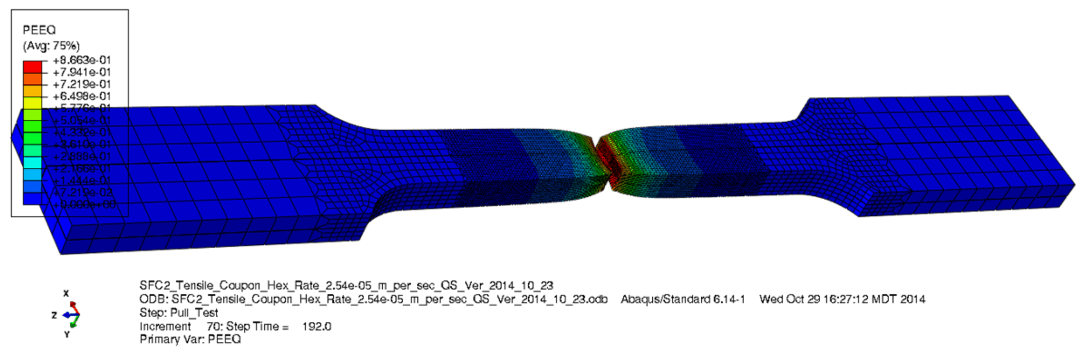

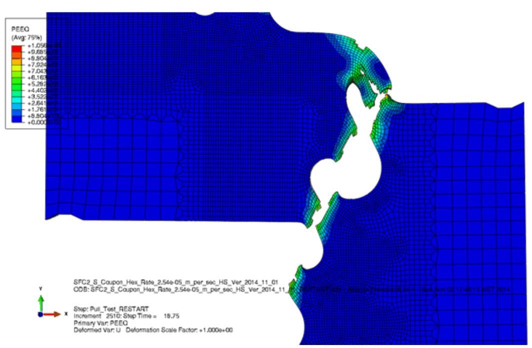

Sandia Fracture Challenge 2

SNL 6233 (Team I)

John Bignell, Scott Sanborn, Chris Jones

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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Team I – Who Are We?

- Sandia National Laboratories
  - Scott Sanborn – Civil/Structural Engineer
  - John Bignell – Civil/Structural Engineer
  - Chris Jones – Civil/Structural/Materials Engineer

- What We Do:
  - Hazardous Materials Transportation Packaging
    - Design, Analysis, Test, and Certification
  - Radioisotope Power System (RPS) Launch Safety
    - Blast and Impact Modeling
  - Nuclear Power Industry
    - System and Component Modeling.

- Motivation:
  - We care about accurately modeling complex mechanical system behavior (response and failure) subject to a wide range of environments.

General Approach

- Standard Finite Element Method
  - Implicit Solver w/ Numerical Stabilization
  - Reduced Integration 8-Node Hexahedral Elements
- Commercially Available Code
  - Abaqus Standard (Implicit) Versions 6.13 and 6.14
- Well Established Material Model
  - Hill Plasticity w/ Rate Dependence
- Material Degradation and Failure
  - Strain to Failure vs. Stress Triaxility and Strain Rate
  - Material Stress Reduced to Zero Following Exceedance of Failure Criterion.
    - Removal of Degraded Elements (Optional).

Material Failure Model

- Based on critical plastic failure strain.

$$\bar{\varepsilon}_D{}^{pl}\left(\eta, \dot{\bar{\varepsilon}}_D{}^{pl}\right), \text{ where } \eta = -\frac{p}{q}$$

- Material degradation/failure initiates when:

$$\omega_D = \int \frac{\mathrm{d}\bar{\varepsilon}_D{}^{pl}}{\bar{\varepsilon}_D{}^{pl}\left(\eta, \dot{\bar{\varepsilon}}_D{}^{pl}\right)} = 1$$

- Once initiation criterion is met, material stress degraded as follows:

$$\boldsymbol{\sigma} = (1 - D)\bar{\boldsymbol{\sigma}}$$

- Evolution of the damage variable with increasing plastic strain is based on the material fracture energy (G_f):

$$\dot{D} = \frac{L\dot{\bar{\varepsilon}}^{pl}}{\bar{u}_f{}^{pl}} = \frac{\dot{\bar{u}}^{pl}}{\bar{u}_f{}^{pl}}, \text{ where } \bar{u}_f{}^{pl} = \frac{2G_f}{\sigma_{y0}}$$

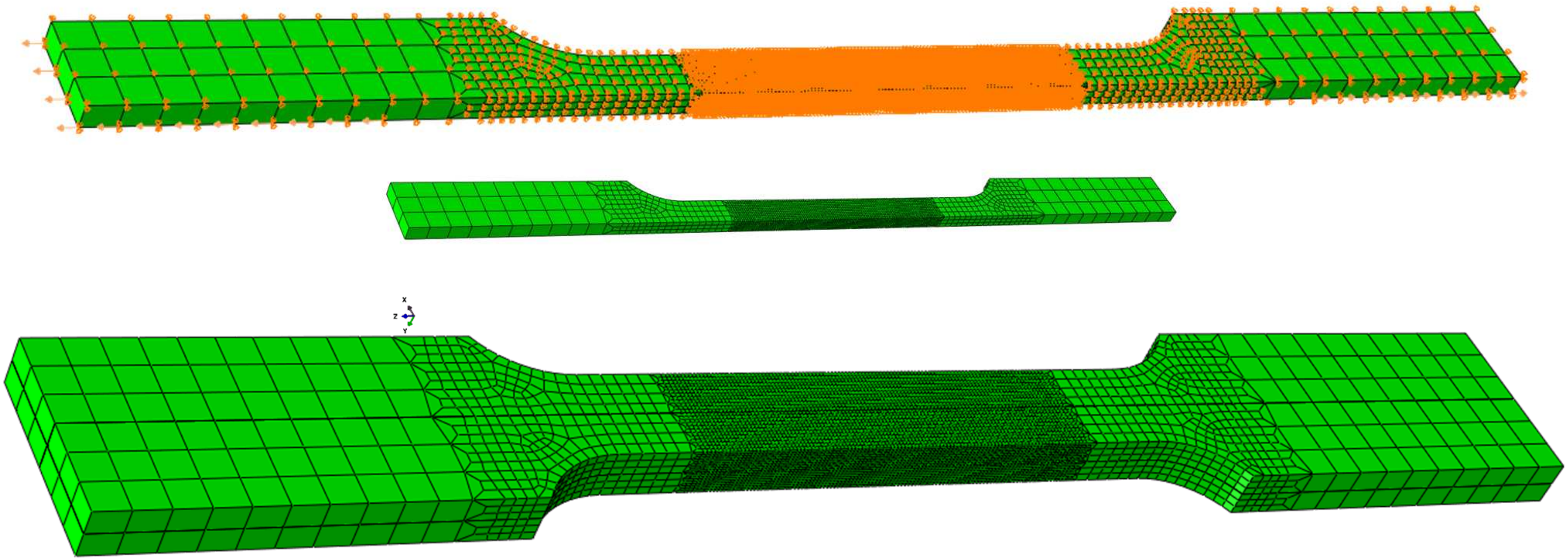
- L is the characteristic element length and σ_{y0} is the value of the yield stress at the time of failure initiation.
  - This method attempts to ensure that the energy dissipated during the damage evolution process equals the fracture energy for the material.

Calibration Procedure Overview

- Use uniaxial tension test data to determine material hardening parameters:
  - Curves → Yield Stress vs. Equivalent Plastic Strain vs. Strain Rate.
- Use shear test data to define hill plasticity factors.
  - Shear Stress Ratios.
- Use uniaxial tension test data to determine failure initiation parameters in tension regime ($\eta \geq 0.33$).
  - Curves → Critical Failure Strain vs. Stress Triaxiality vs. Strain Rate
- Use shear test data to determine failure initiation parameters in pure shear regime ($\eta = 0.0$).
  - Curves → Critical Failure Strain vs. Stress Triaxiality vs. Strain Rate
- Use uniaxial tension and shear test data to verify all inputs.
- Make double-notch test predictions.

Tension Test Coupon Model

- Element Type: Reduced Integration Hexahedral (C3D8R)
- Number of Elements: Quarter Symmetry Model → 12,756
- Element Size: ~0.25 mm
- Boundary Conditions
  - Symmetry
  - Applied Nodal Velocity (Grip Ends)



Material Hardening Parameters

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- Strain Rate Relationship – Log-Linear (Assumed).

$$\sigma_y(\dot{\bar{\varepsilon}}^{pl}) = \left(1 + C(\bar{\varepsilon}^{pl}) ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\bar{\varepsilon}}^{pl}{}_{ref}}\right)\right)\sigma_{y0.001}$$

- Hardening Relationship – Power Law (Assumed).

$$\sigma_{y0.001}(\bar{\varepsilon}^{pl}) = A_{0.001} + B_{0.001}\bar{\varepsilon}^{pl^{n_{0.001}}}$$
$$\sigma_{y1.0}(\bar{\varepsilon}^{pl}) = A_{1.0} + B_{1.0}\bar{\varepsilon}^{pl^{n_{1.0}}}$$

- Rate multiplier parameter $C(\bar{\varepsilon}^{pl})$ determined as follows.

$$C(\bar{\varepsilon}^{pl}) = \frac{\left(\left(\sigma_{y1.0}(\bar{\varepsilon}^{pl})/\sigma_{y0.001}(\bar{\varepsilon}^{pl})\right) - 1\right)}{ln(1.0/0.001)}$$

- $A_{0.001}, B_{0.001}, n_{0.001}, A_{1.0}, B_{1.0}, n_{1.0}$ determined by fitting model response to available tension test data.

Material Hardening Parameters

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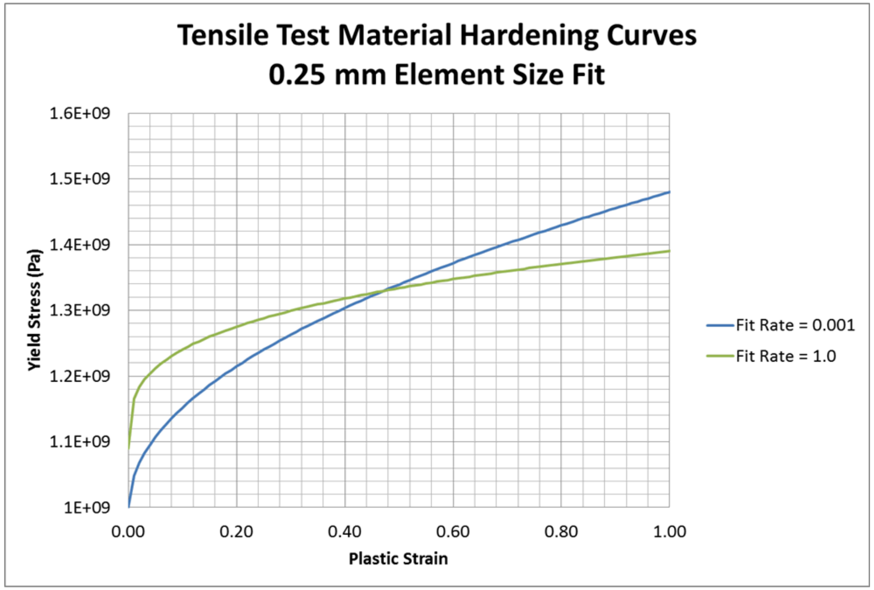
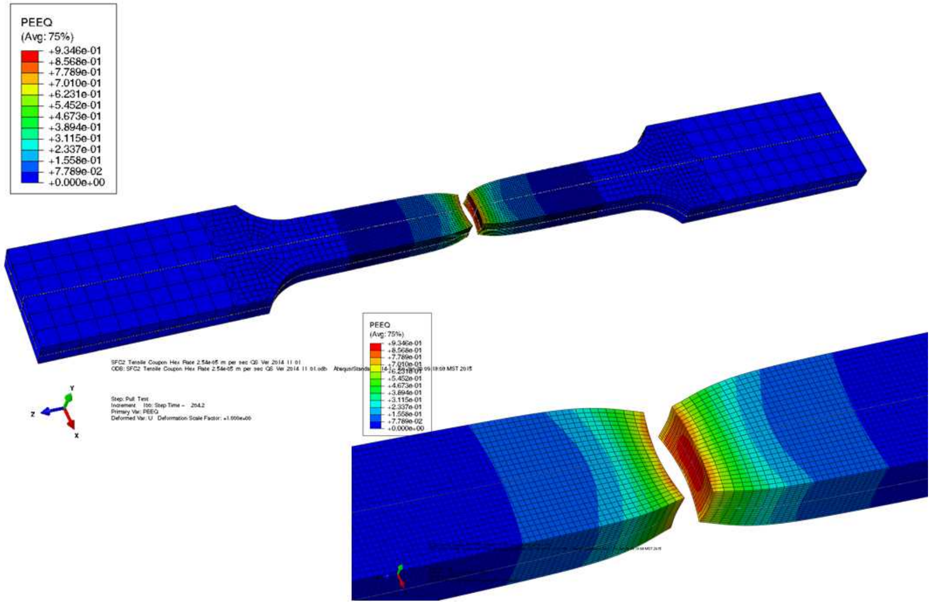
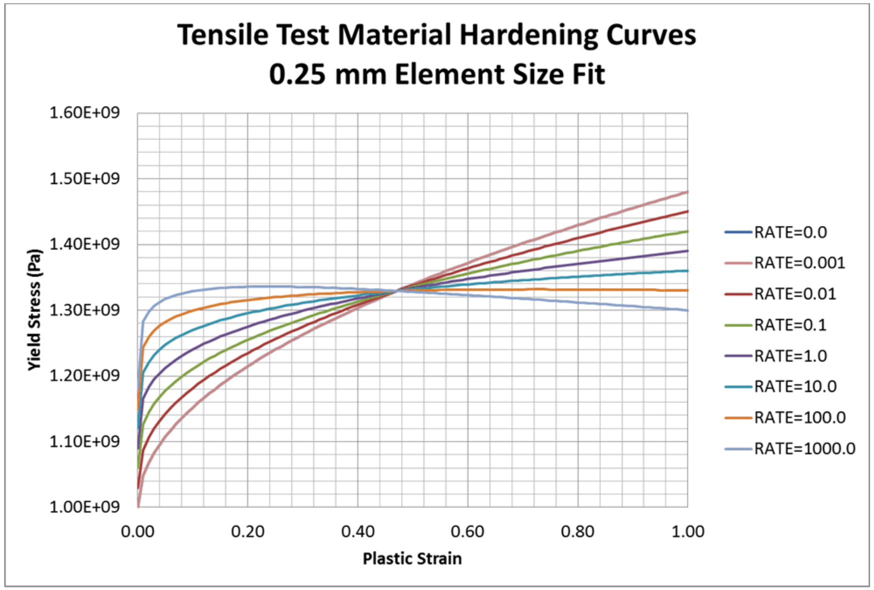
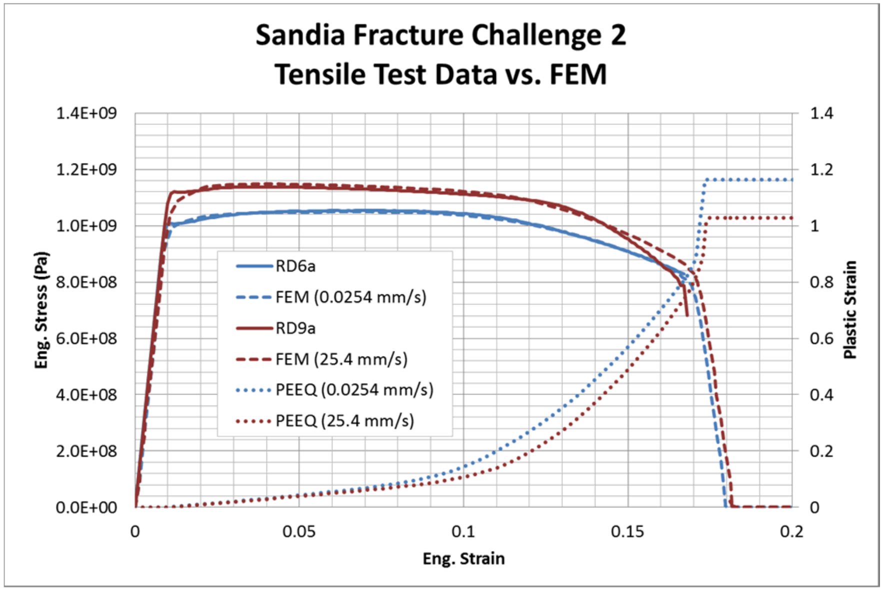


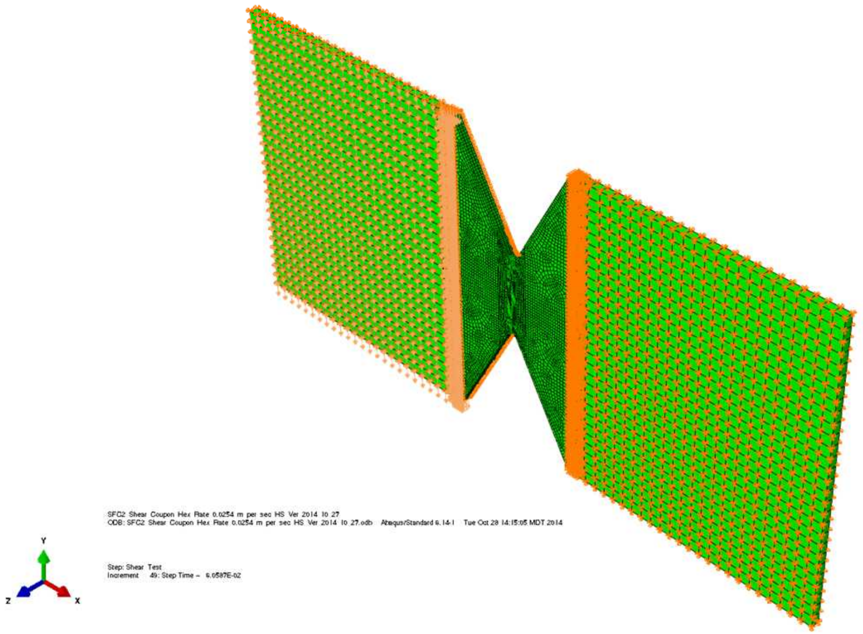


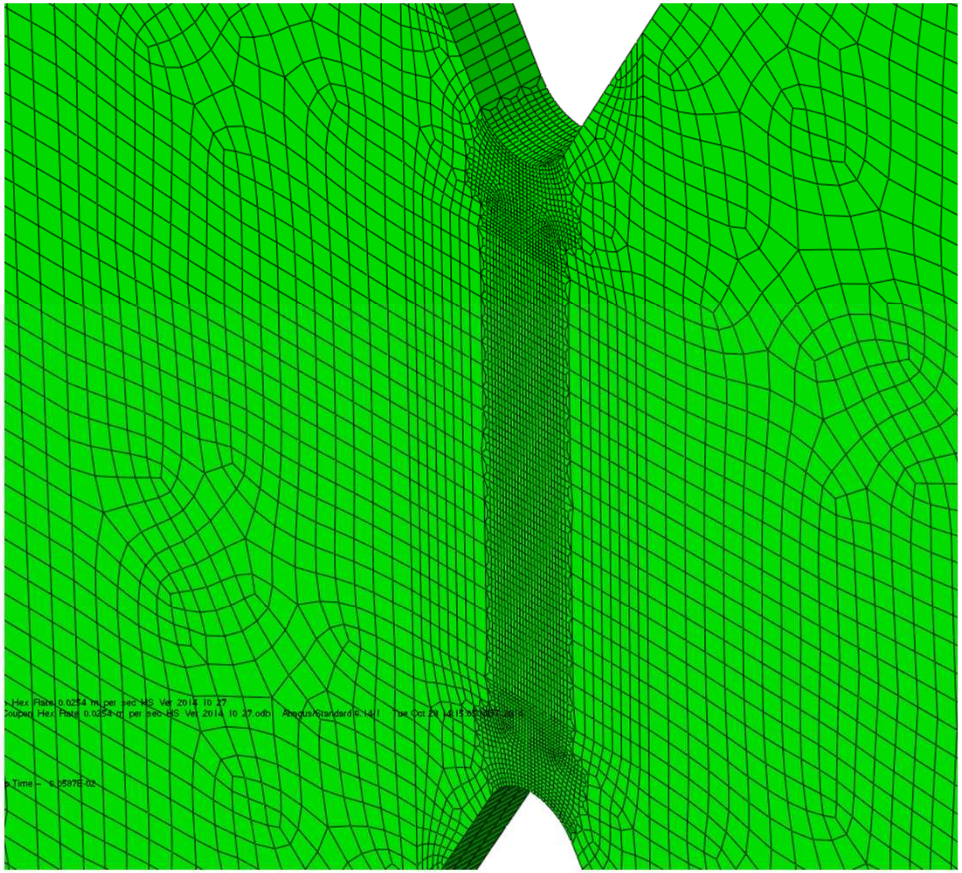




Shear Test Coupon Model

- Element Type: Reduced Integration Hexahedral (C3D8R)
- Number of Elements: Half Symmetry Model → 40,236
- Element Size: ~0.25 mm
- Boundary Conditions
  - Symmetry
  - Fixed (X, Y, Z) One End
  - Applied Velocity (Y) Opposite End
  - Fixed (X, Z) Opposite End





Hill Plasticity Parameters

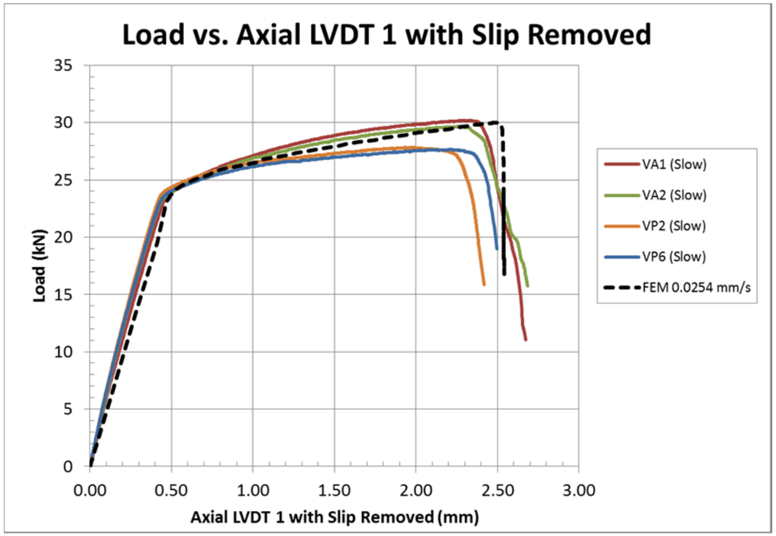
- Hill plasticity shear yield strength scaling factors determined using shear test data:
  - $R_{11} = R_{22} = R_{33} = 1.0$
  - $R_{12} = R_{23} = R_{13} = 0.88$

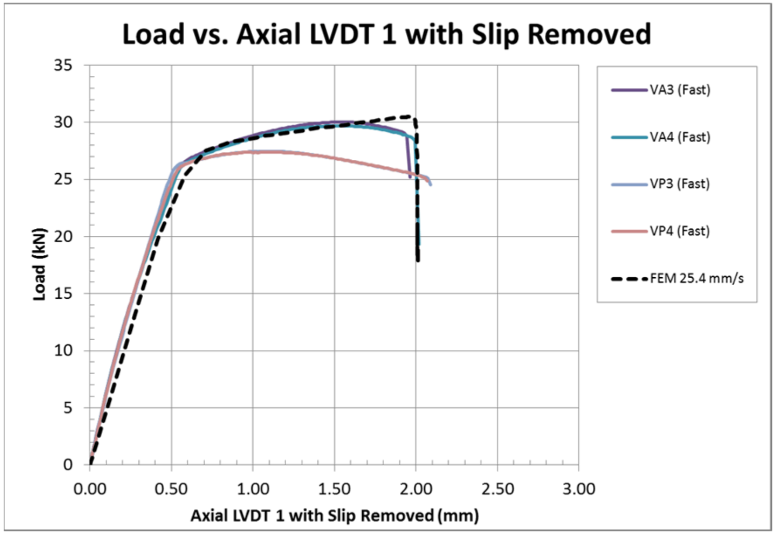
$$f(\boldsymbol{\sigma}) = \sqrt{H(\sigma_x - \sigma_y)^2 + F(\sigma_y - \sigma_z)^2 + G(\sigma_z - \sigma_x)^2 + 2N\tau_{xy}{}^2 + 2L\tau_{yz}{}^2 + 2M\tau_{zx}{}^2}$$

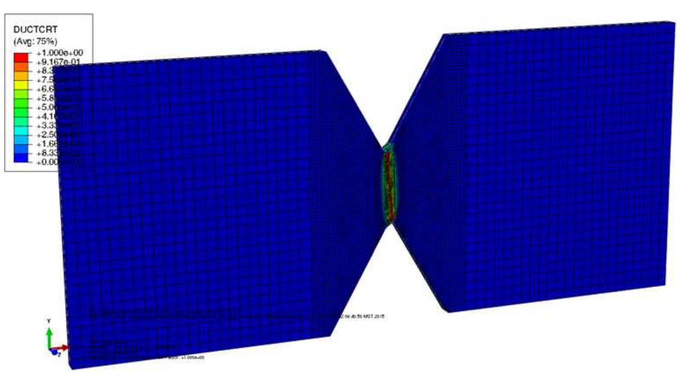
$$H = \frac{\sigma_0{}^2}{2}\left(\frac{1}{\bar{\sigma}_{11}{}^2} + \frac{1}{\bar{\sigma}_{22}{}^2} + \frac{1}{\bar{\sigma}_{33}{}^2}\right) = \frac{1}{2}\left(\frac{1}{R_{11}{}^2} + \frac{1}{R_{22}{}^2} + \frac{1}{R_{33}{}^2}\right) \qquad N = \frac{3}{2}\left(\frac{\tau_0}{\bar{\tau}_{12}}\right)^2 = \frac{3}{2R_{12}{}^2}$$

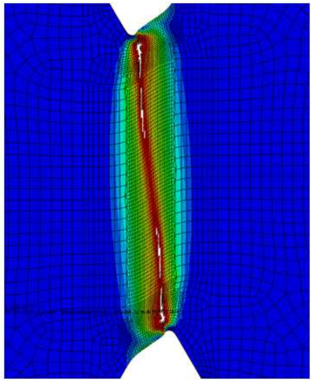
$$F = \frac{\sigma_0{}^2}{2}\left(\frac{1}{\bar{\sigma}_{22}{}^2} + \frac{1}{\bar{\sigma}_{33}{}^2} + \frac{1}{\bar{\sigma}_{11}{}^2}\right) = \frac{1}{2}\left(\frac{1}{R_{22}{}^2} + \frac{1}{R_{33}{}^2} + \frac{1}{R_{11}{}^2}\right) \qquad L = \frac{3}{2}\left(\frac{\tau_0}{\bar{\tau}_{23}}\right)^2 = \frac{3}{2R_{23}{}^2}$$

$$G = \frac{\sigma_0{}^2}{2}\left(\frac{1}{\bar{\sigma}_{33}{}^2} + \frac{1}{\bar{\sigma}_{11}{}^2} + \frac{1}{\bar{\sigma}_{22}{}^2}\right) = \frac{1}{2}\left(\frac{1}{R_{33}{}^2} + \frac{1}{R_{11}{}^2} + \frac{1}{R_{22}{}^2}\right) \qquad M = \frac{3}{2}\left(\frac{\tau_0}{\bar{\tau}_{13}}\right)^2 = \frac{3}{2R_{13}{}^2}$$









Failure Criterion Parameters

- Initial reference critical failure strain vs. stress triaxiality ($\bar{\varepsilon}_{D-ref}{}^{pl}(\eta)$) based on M. Giglio et al.

- Rate Dependence Relationship – Log-Linear (Assumed).

$$\bar{\varepsilon}_D{}^{pl}\left(\eta, \dot{\bar{\varepsilon}}_D{}^{pl}\right) = \left(1 + E(\eta) ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\bar{\varepsilon}}^{pl}{}_{ref}}\right)\right)\bar{\varepsilon}_{D-ref}{}^{pl}(\eta) Q(\eta)$$

- Performed fit between model and shear/tensile test data by determining scaling factor ($Q(\eta)$) and rate multiplier constant ($E(\eta)$).

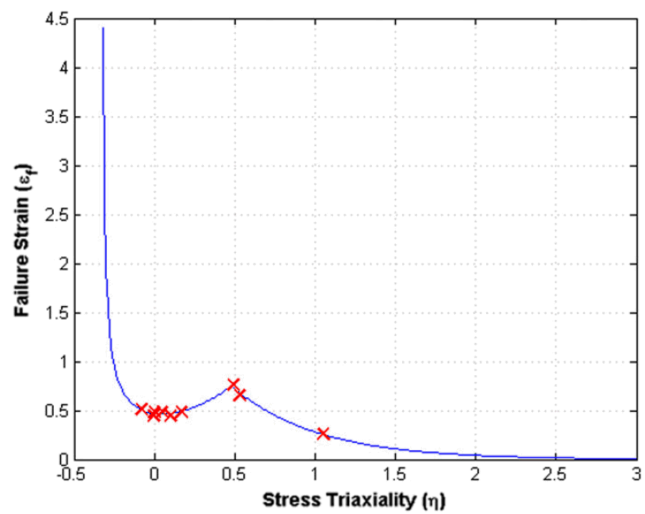
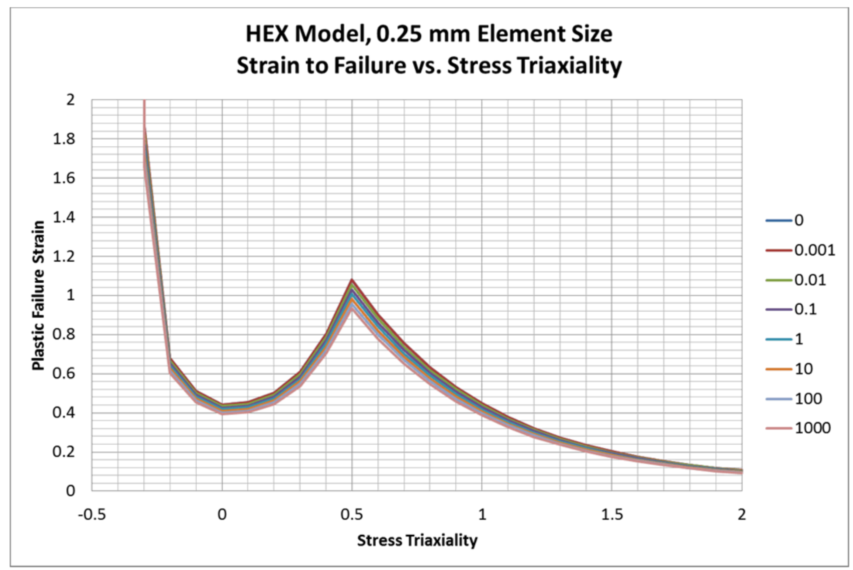


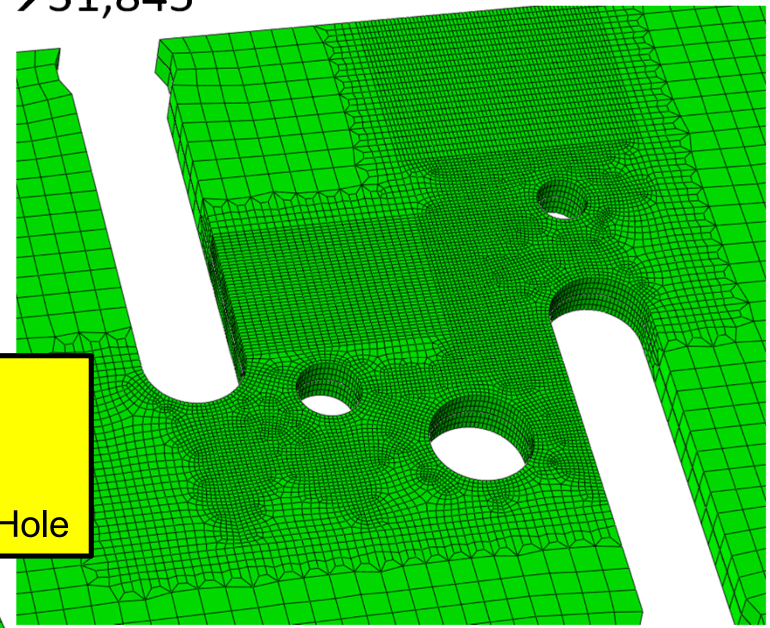
Fig. 12. Fracture locus of the Ti–6Al–4V according to the Bao–Wierzbicki [1] model.

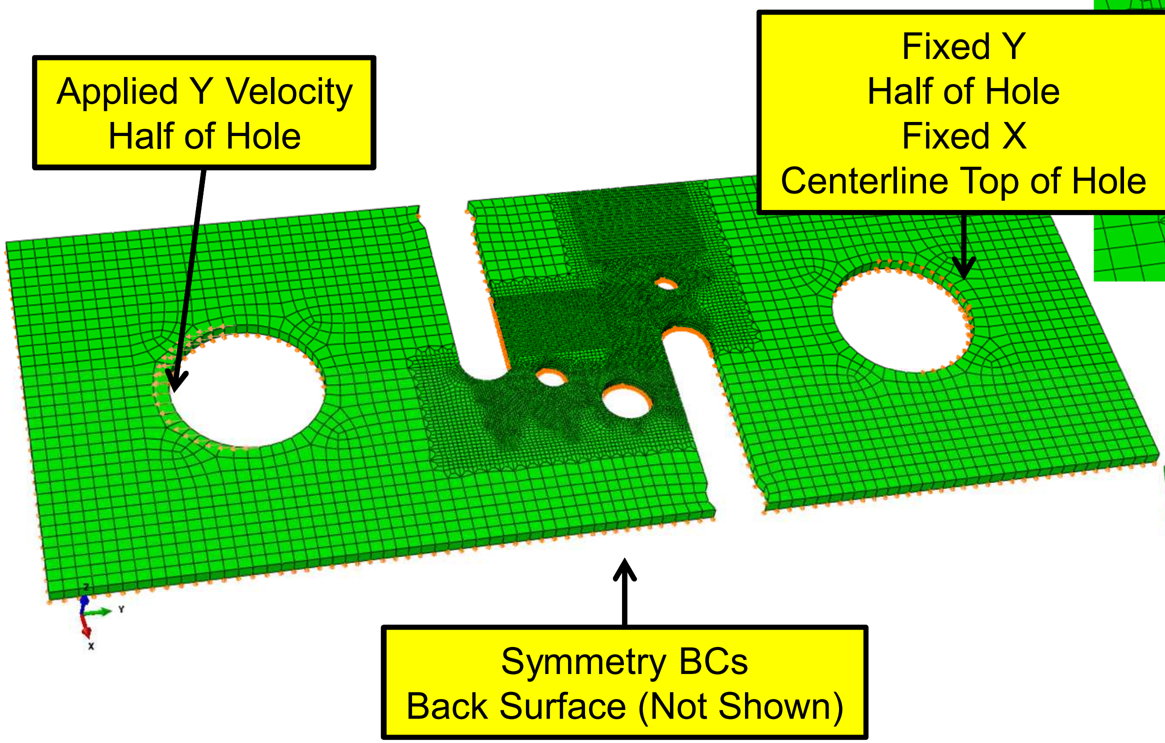


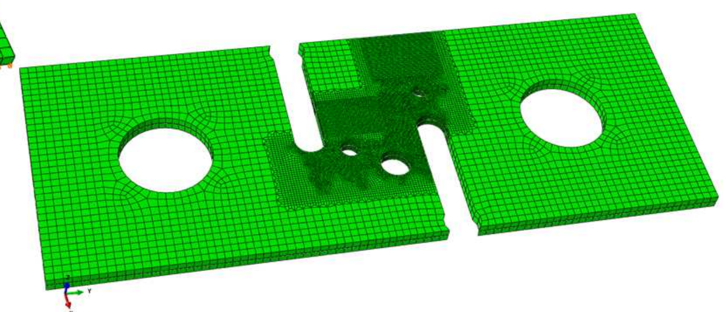
M. Giglio et al. / International Journal of Mechanical Sciences 54 (2012) 121–135

Double Notch Coupon Model

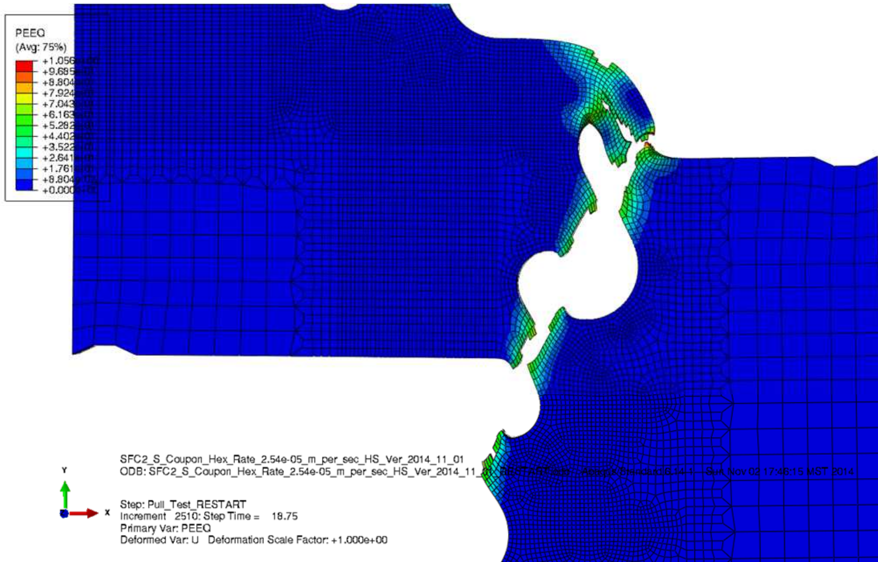
- Element Type: Reduced Integration Hexahedral (C3D8R)
- Number of Elements: Half Symmetry Model →31,845
- Element Size: ~0.25 mm
- Boundary Conditions:
  - Symmetry
  - Applied Nodal Velocity (One End)
  - Fixed (Opposite End).

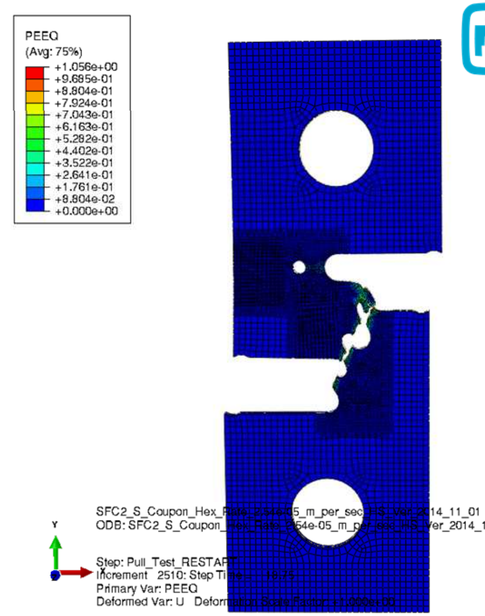


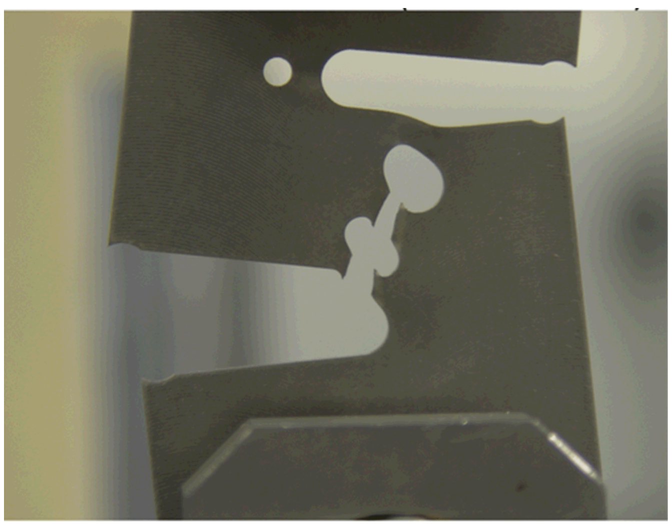


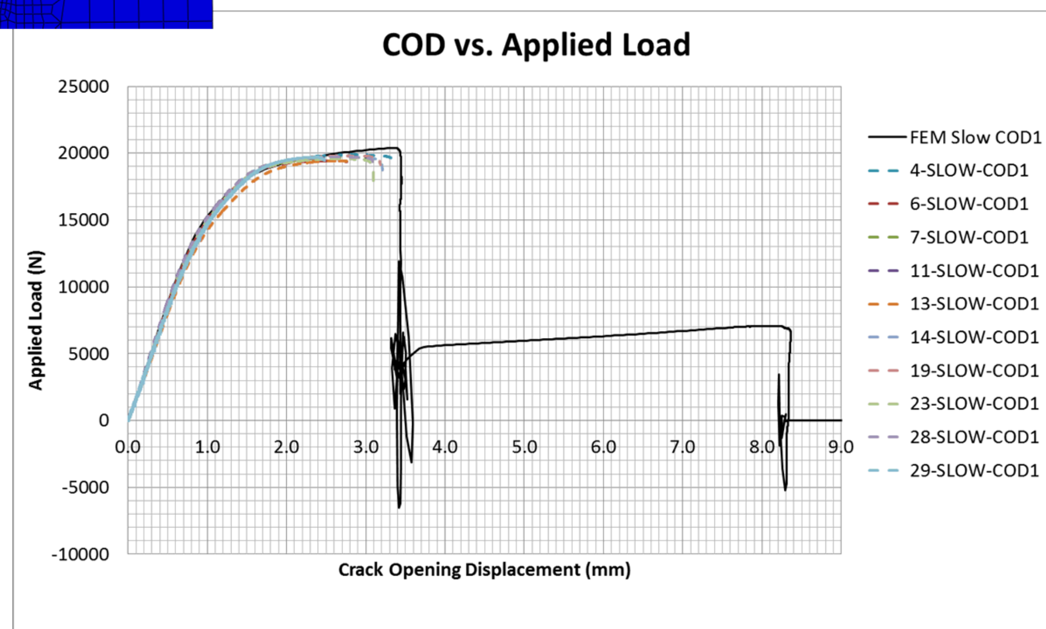


Results Comparison (Slow)

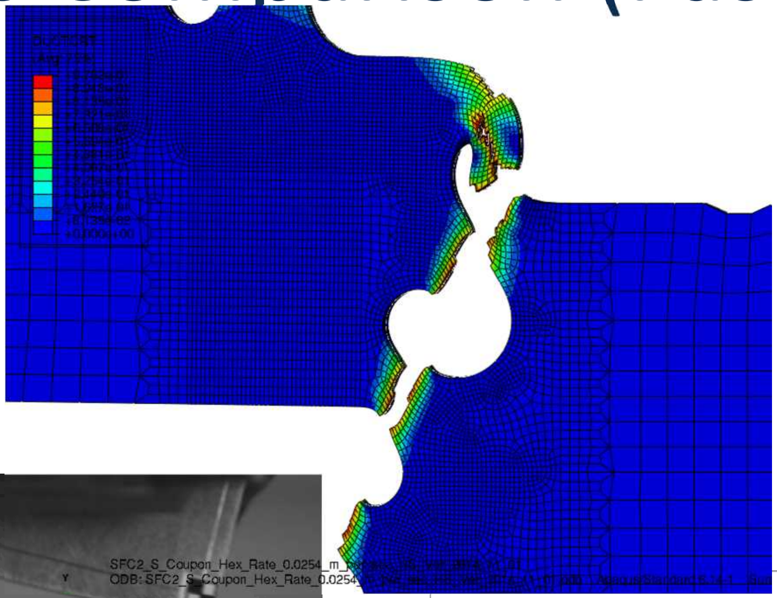


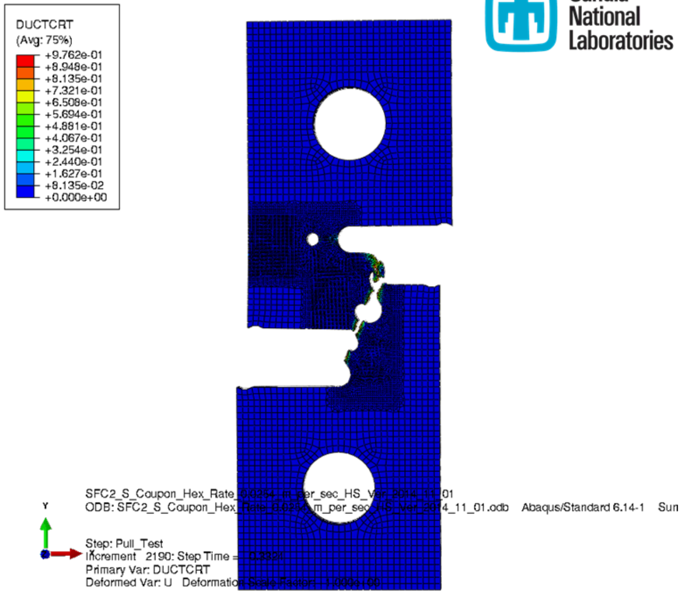


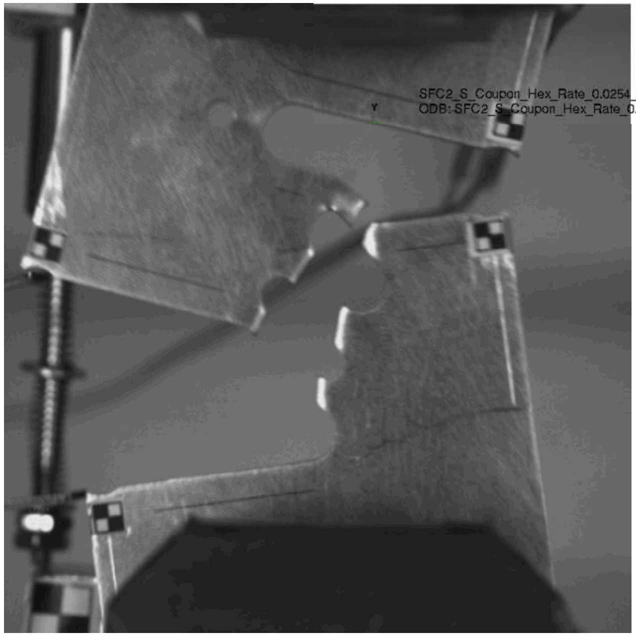


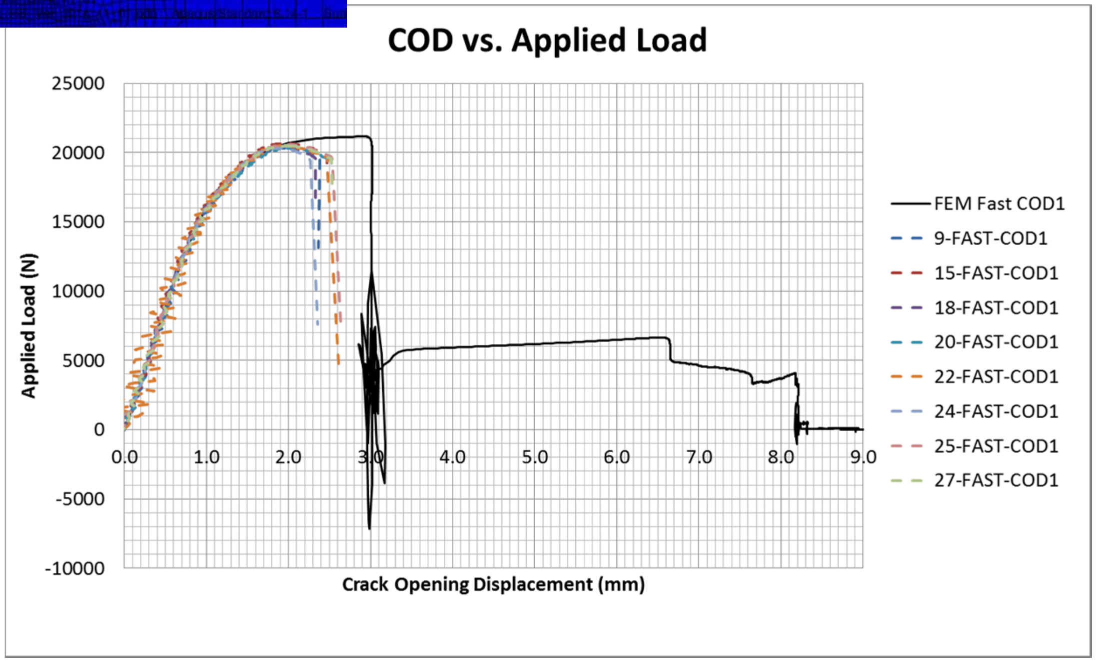


Results Comparison (Fast)









Model Limitations

- Thermal effects not incorporated (material model does not include temperature dependence or plasticity induced heating).
- Boundary conditions on double notch specimen not entirely representative of the test setup.
- Assumptions made on the form of the yield stress vs. plastic strain vs. strain rate relationship unverified.
- Limited time to develop and assess model.
  - Mesh and element type sensitivity.
  - Assumptions and sensitivity to assumptions.
  - Anisotropic behavior of material.
  - Temperature effects and couple thermal-mechanical analyses.

Lessons Learned & Observations

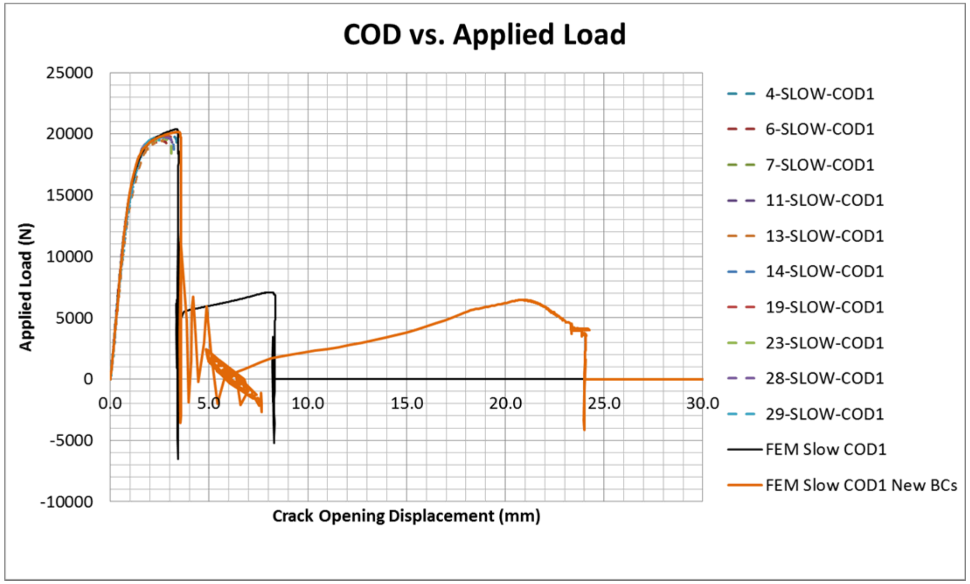
- It is critical to include the following material response characteristics.
  - Strain Rate Dependence.
  - Temperature Dependence.
  - Stress Triaxiality Informed Failure.
  - Plasticity Induced Heating (Coupled Thermal-Mechanical Analysis).
  - Anisotropy (to a Lesser Extent?).

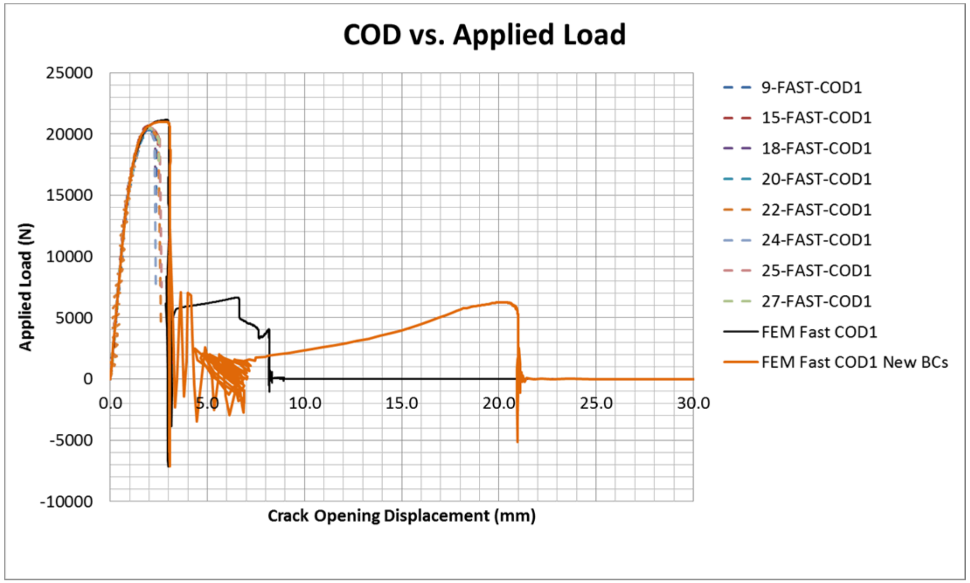
- If ***properly implemented***, continuum models are capable of reasonable accuracy in predicting the response of the coupon.

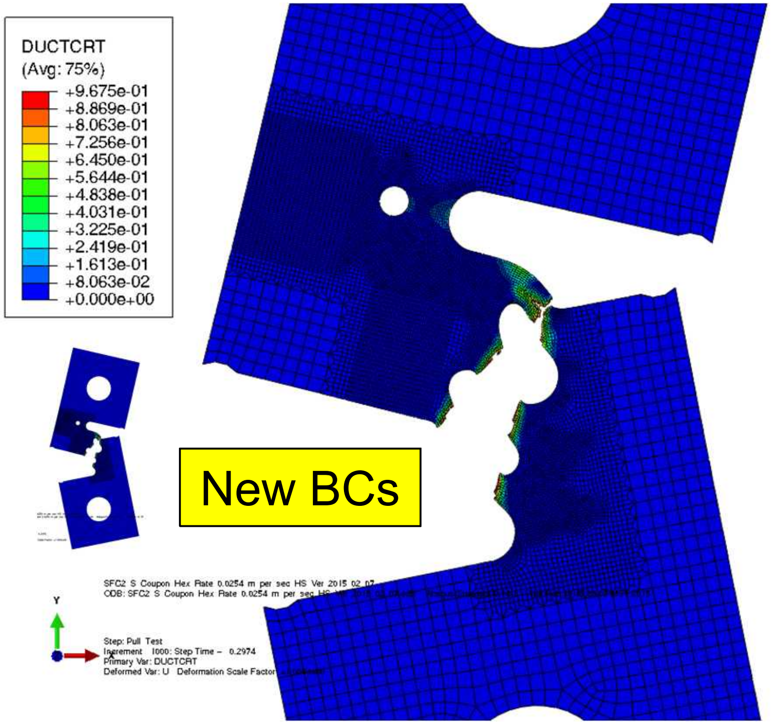
- Mesh sizes required to accurately resolve failure processes generally not scalable to system level analyses.

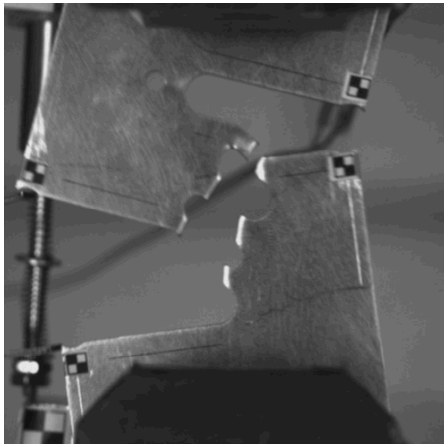
- Having sufficient test data to determine material model inputs over the applicable range of loading environments is necessary.

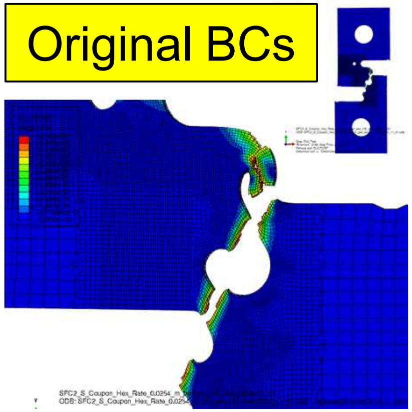
Double Notch – B.C. Comparison











Moving Forward

- Implement Abaqus Capability into Sierra SM
  - Hydra Plasticity Model Complete
    - General Plasticity
    - Rate Dependence
    - Triaxiality Based Failure
    - Temperature Dependent Material Response
    - Adiabatic Heating
- Evaluate Past SFCs with Sierra SM and Hydra Plasticity
  - Evaluate and Demonstrate Model
- Develop Plane Stress Model for Shell Elements
  - Useful for Engineering Problems
  - Computational Efficiency