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Towards Eliminating Element Size Dependence in Ductile Tearing

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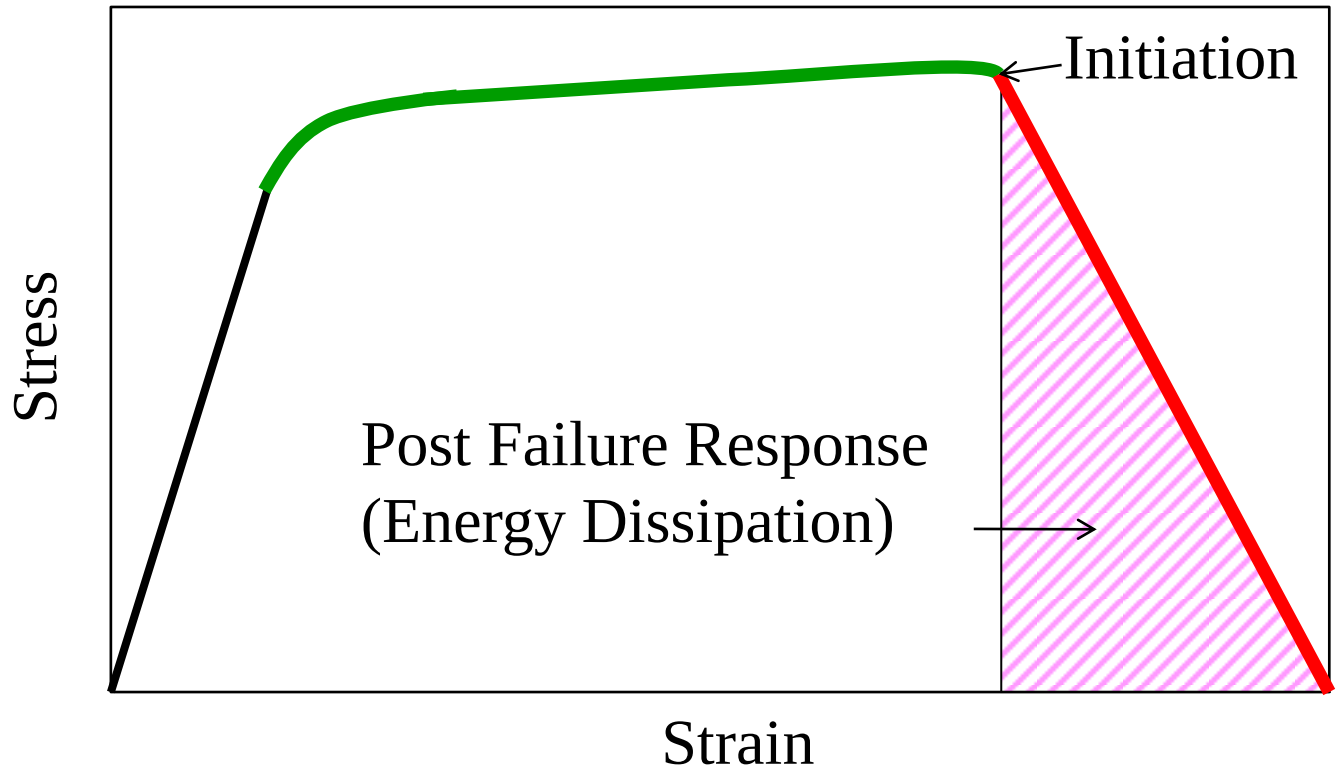
Outline

- Multi-Linear Elastic-Plastic Failure (MLEPF) Material Model Basics
- Tearing Parameter an Initiation Criteria
- Critical Crack Opening Strain (CCOS)
- Motivating Analysis Results
- Setting CCOS to Eliminate Mesh Dependence
- Application to the Motivating Analysis
- 3 Hole Test Results
- Questions for Future Work
- Conclusions

MLEPF Material Model Basics

Piece-wise Linear Elastic-Plastic Constitutive Model



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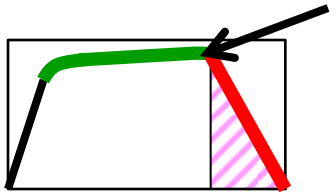
Tearing Parameter an Initiation Criteria

$$TP = \int_0^{\varepsilon_f} \left\langle \frac{2\sigma_T}{3(\sigma_T - \sigma_m)} \right\rangle^N d\varepsilon_p$$



σ_T = maximum principal stress

σ_m = mean or hydrostatic stress

ε_p = equivalent plastic strain

ε_f = plastic strain at failure

N = power fit

$\langle\ \rangle$ Macaulay Brackets, accumulates if quantity is positive

- Failure Criterion is Local Integral of Stress State over Plastic Strain[1]
- The critical value of the tearing parameter can be determined from a tensile test.

[1] Brozzo, P., Deluca, B. And Rendina, R., *A New Method for the Prediction of the Formability Limits of Metal Sheets, Proceedings of the 7th Biennial Congress of International Deep Drawing Research Group, 1972.*

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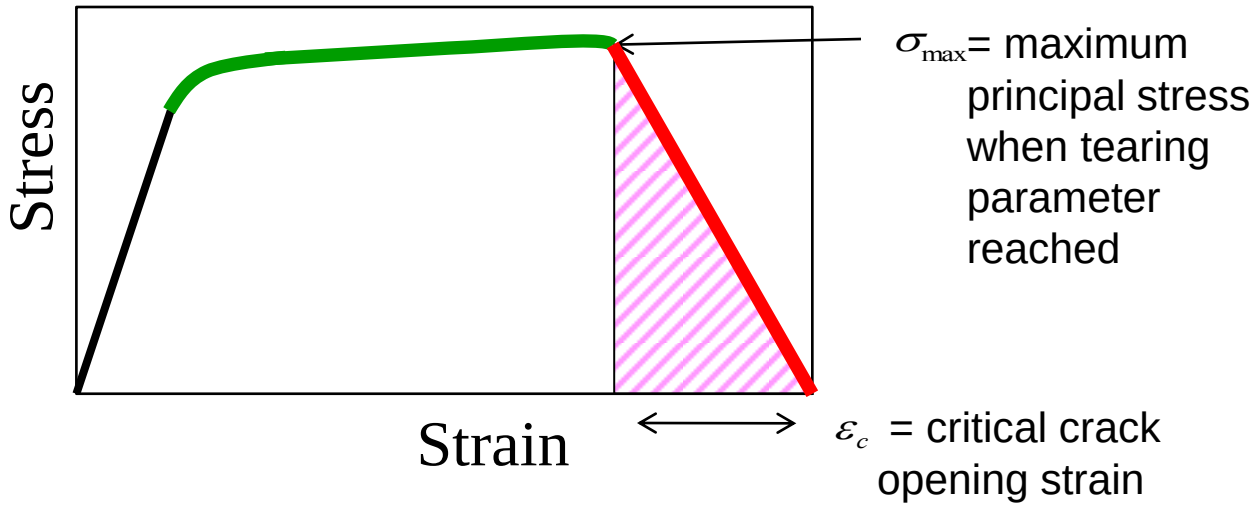
Critical Crack Opening Strain (CCOS)

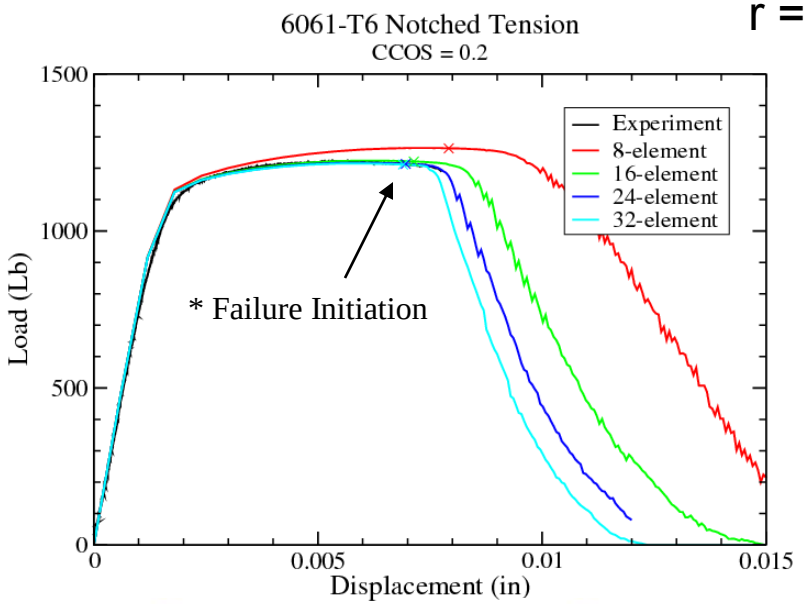


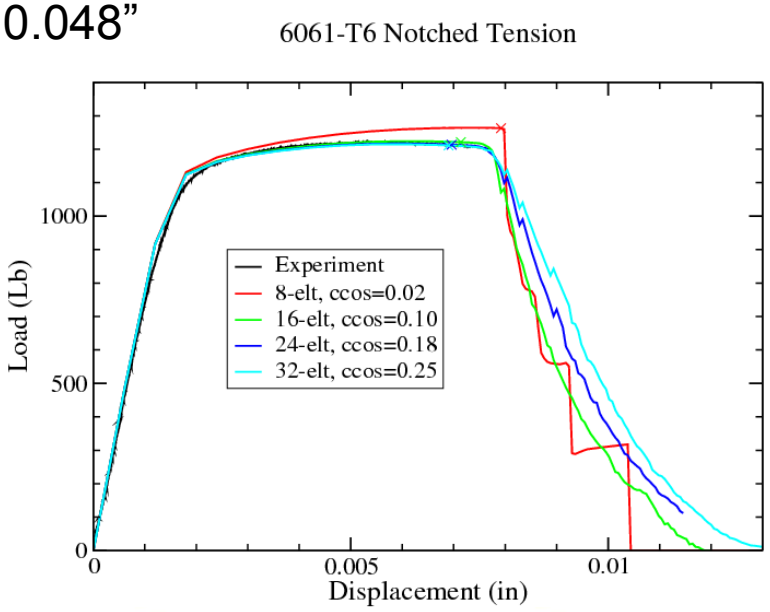
- Critical crack opening strain set with material properties.
- Failure direction set with corresponding eigenvector to maximum principal stress at onset of failure.
- Decay behaves like cohesive surface model.
- Only decayed when strained in failure direction.
- Unloads along elastic modulus.

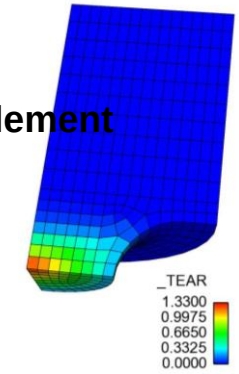
Motivating Analysis Results

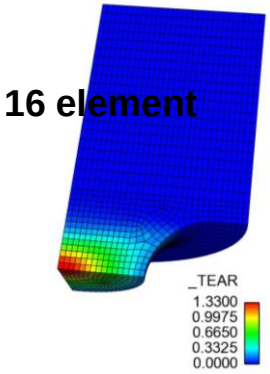
Mesh dependence and Critical Crack Opening Strain (CCOS)

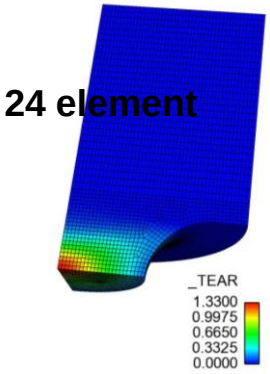
r = 0.048”

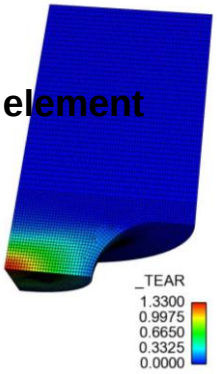












Analysis original performed by Nicole L. Breivik.

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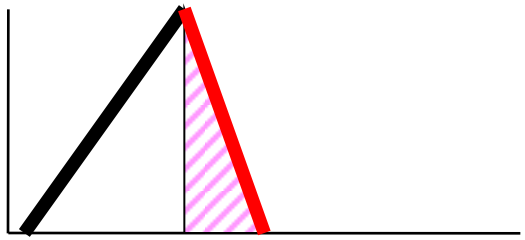
Constant Decay Energy for Eliminating Mesh Size Dependence ?

- Mesh size dependence shown to be eliminated in smeared crack approach where decay set with constant energy per unit surface.[2]

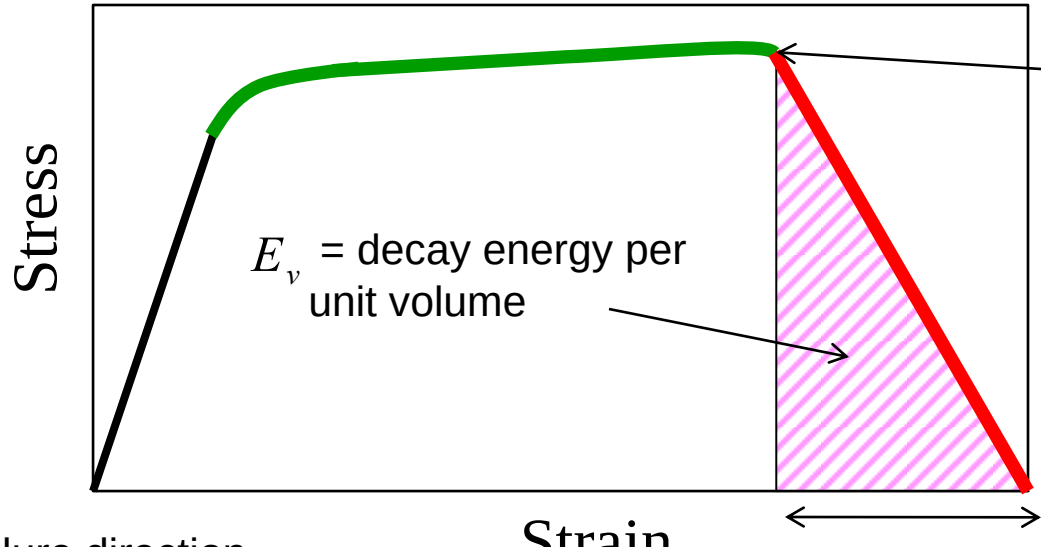
- Caveats: No plasticity. Decay energy is the only unrecoverable energy.



- Will this work in the presence of plasticity and with the tearing parameter criterion?

[2] Bazant, Zednek P. and Oh, B. H., *Crack Band Theory for Fracture of Concrete, Materials and Structures 16, 1983.*

Setting Critical Crack Opening Strain (CCOS) for Constant Decay Energy

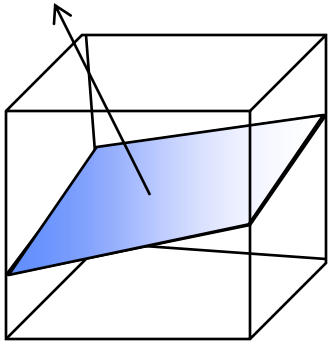


σ_{max} = maximum principal stress when tearing parameter reached

E_v = decay energy per unit volume

ε_c = critical crack opening strain

f_{dir} = failure direction



Element

A = crack surface area

V = element volume

$$E_v = \frac{1}{2}\sigma_{max}\varepsilon_c$$

E_A = energy per unit area

$$\varepsilon_c = \frac{2E_A A}{V\sigma_{max}}$$

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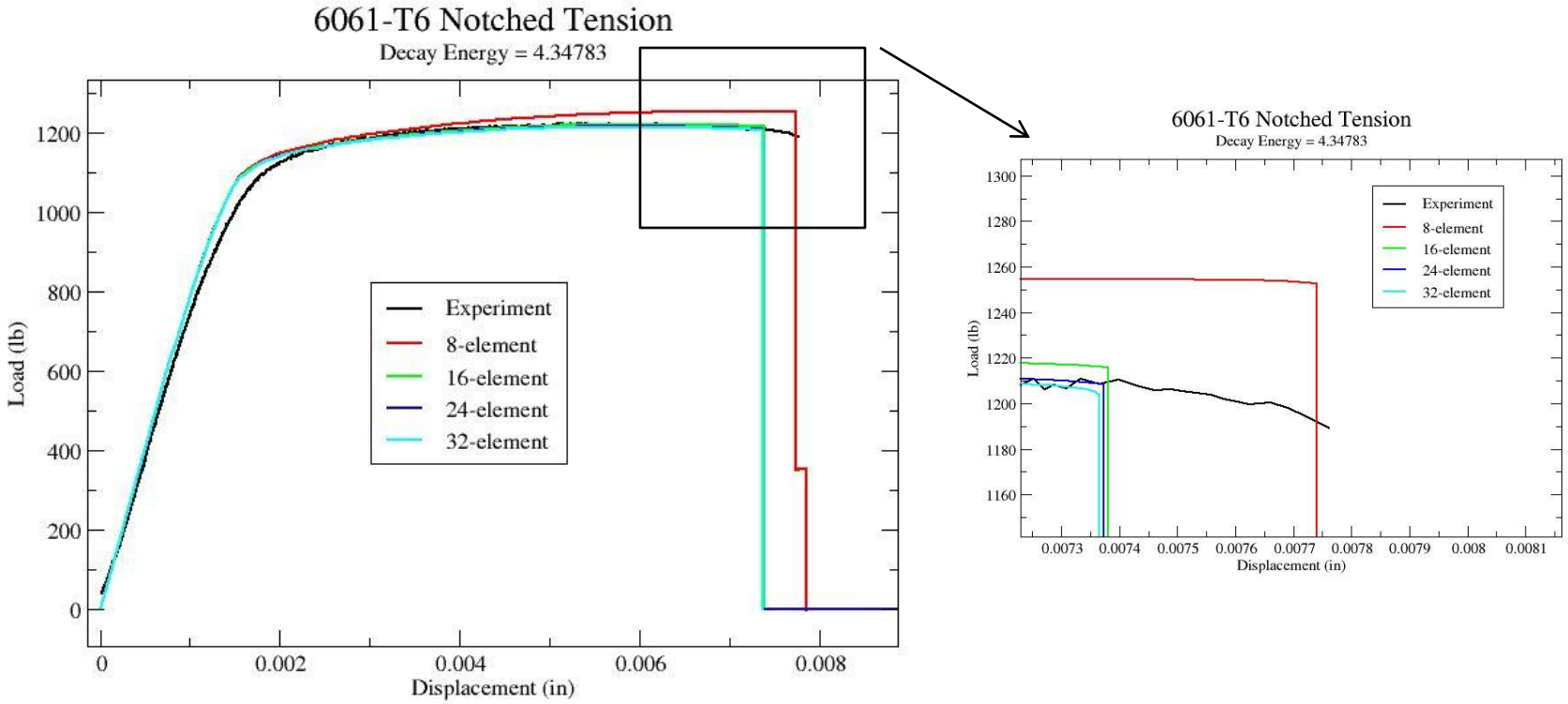
Constant Decay Energy Applied to Motivating Analysis



Decay portion not a major factor in this test.

Tearing Parameter and no decay may have been sufficient.

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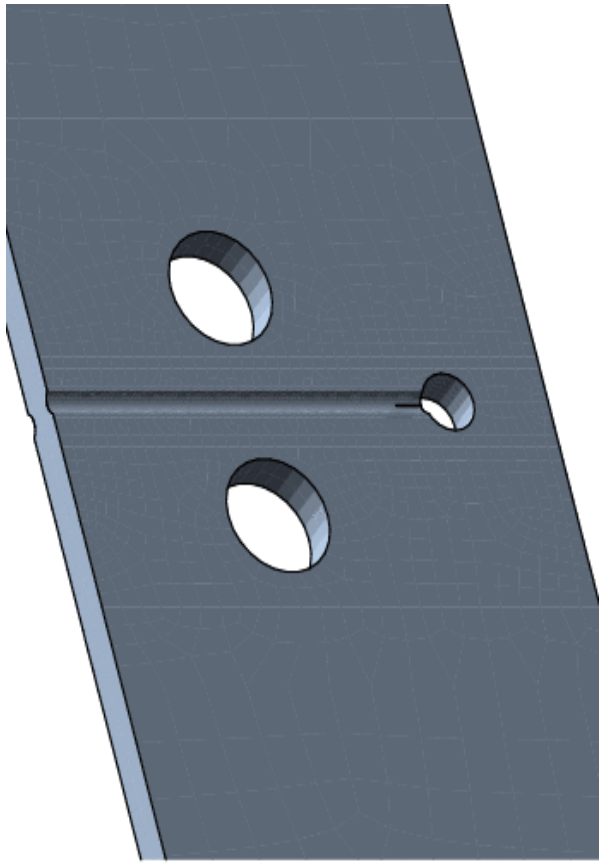
Newman's[5] 3-Hole Tension Specimen

- Tension dominated – starter hole/notch precludes cracking to near free surface, minimizing bending.
- Two large holes provide a "shadow" for the tensile stress providing for extensive stable crack growth.
- Shallow side grooves provide for direction control of crack and reduce required load.

[5]Newman and Loss, 1985



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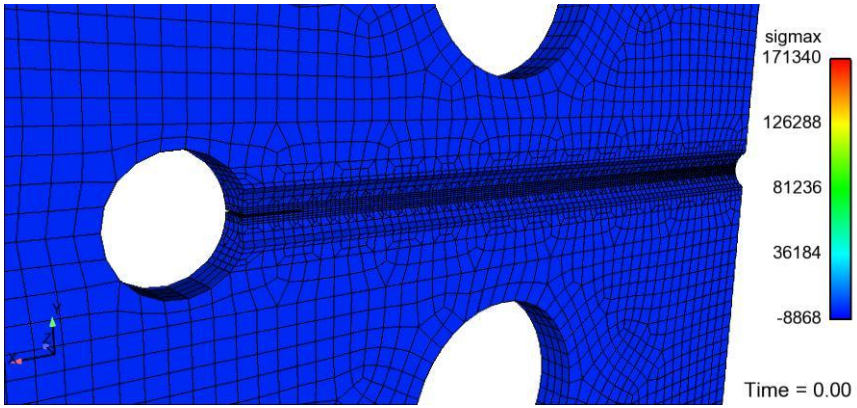
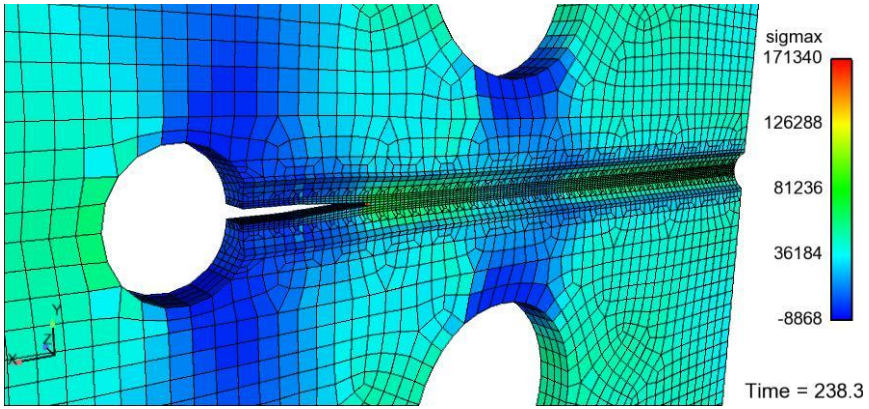
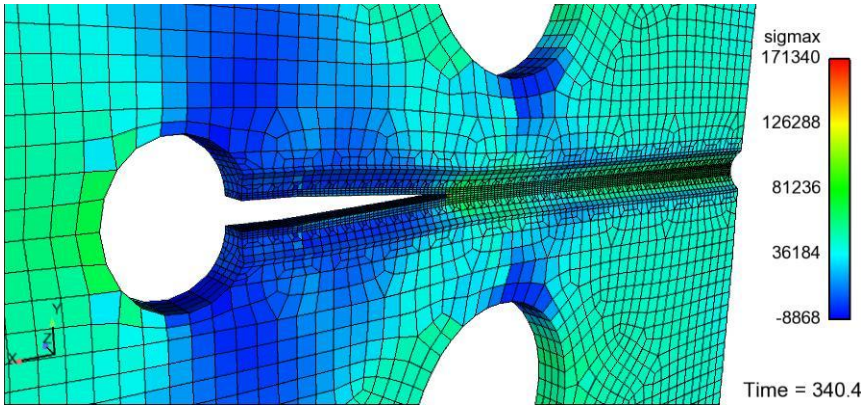
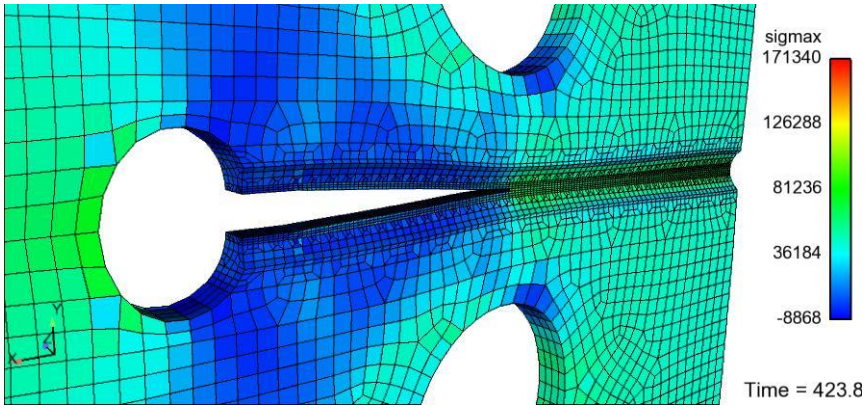
Stable Crack Growth









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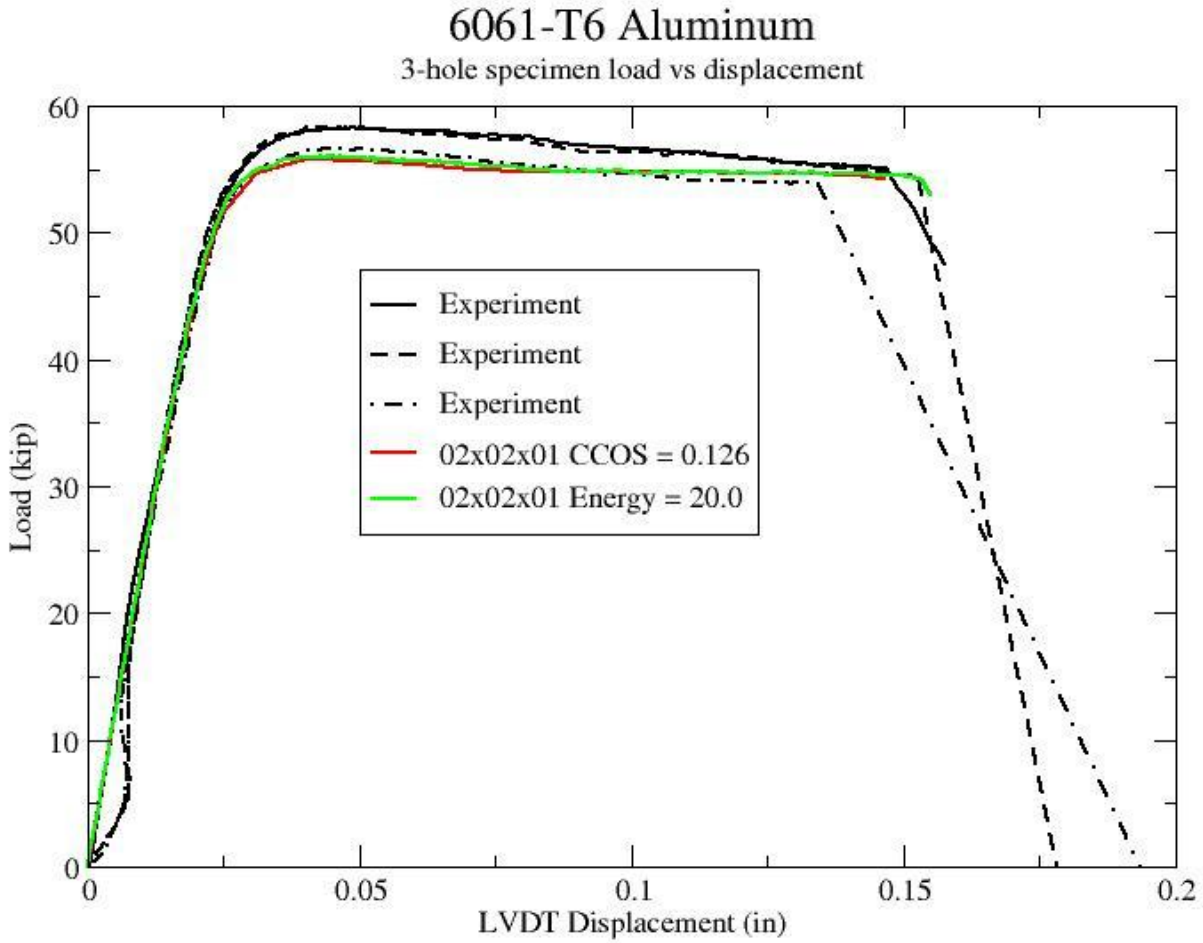
3-Hole Tension Specimen
Load vs. Displacement



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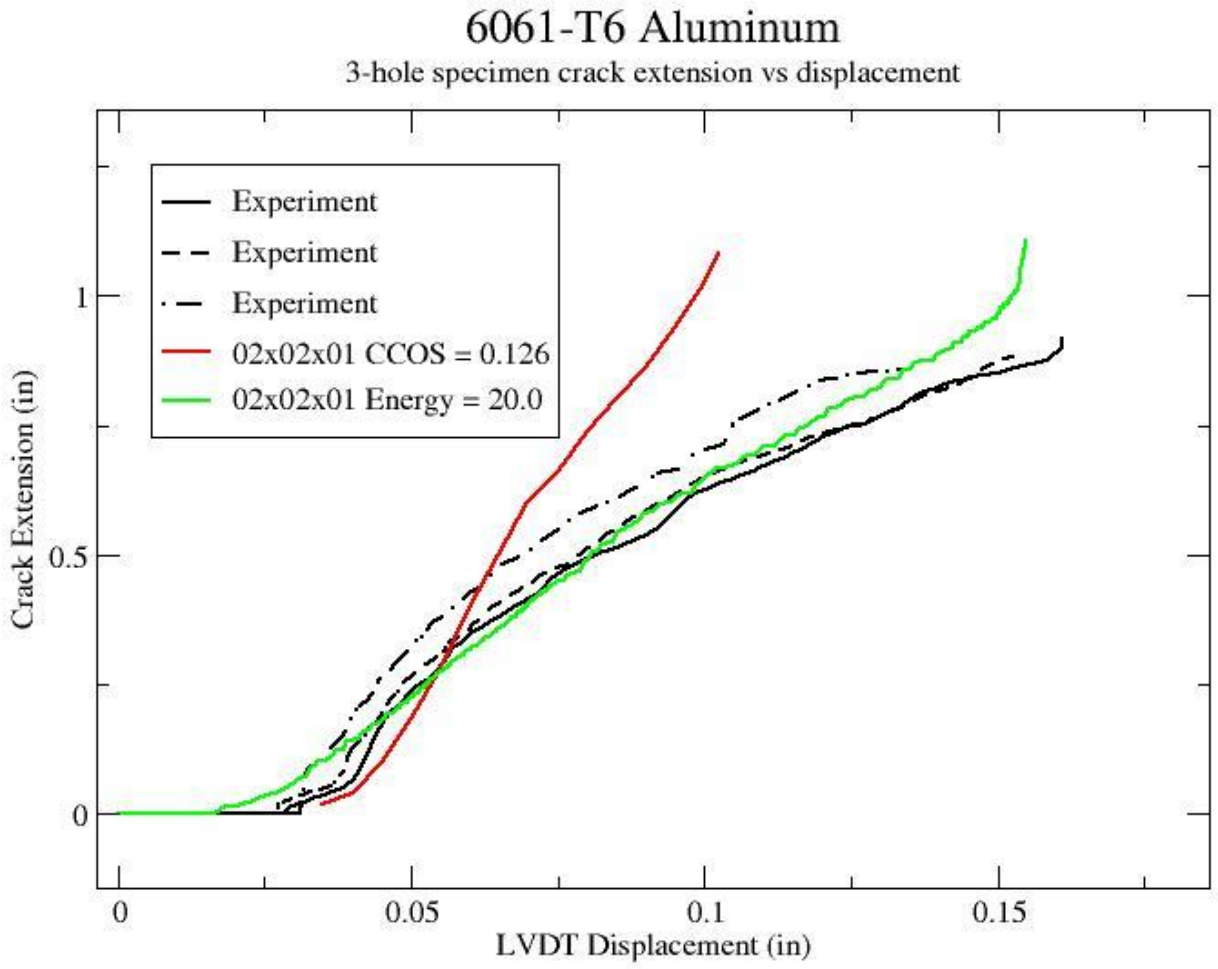
3-Hole Tension Specimen
Crack Extension vs. Displacement



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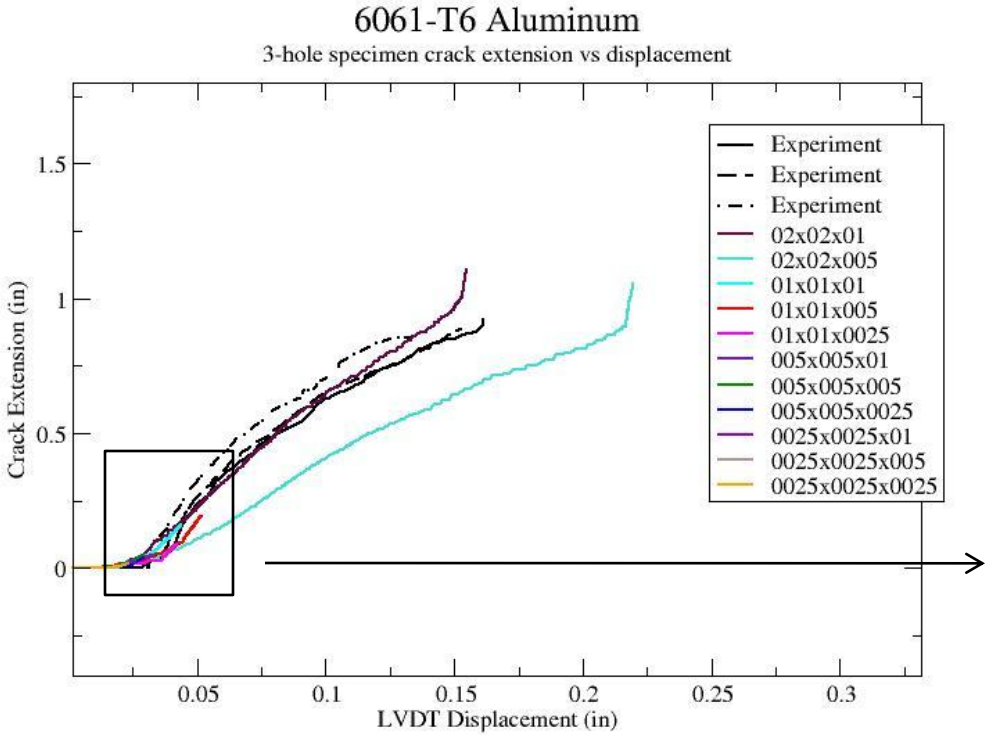
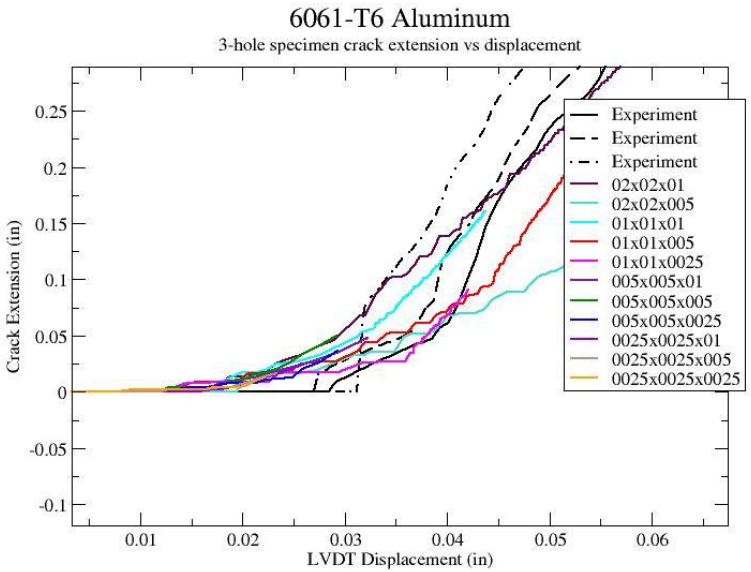
3-Hole Tension Specimen
Crack Extension vs. Displacement
Multiple Mesh Sizes





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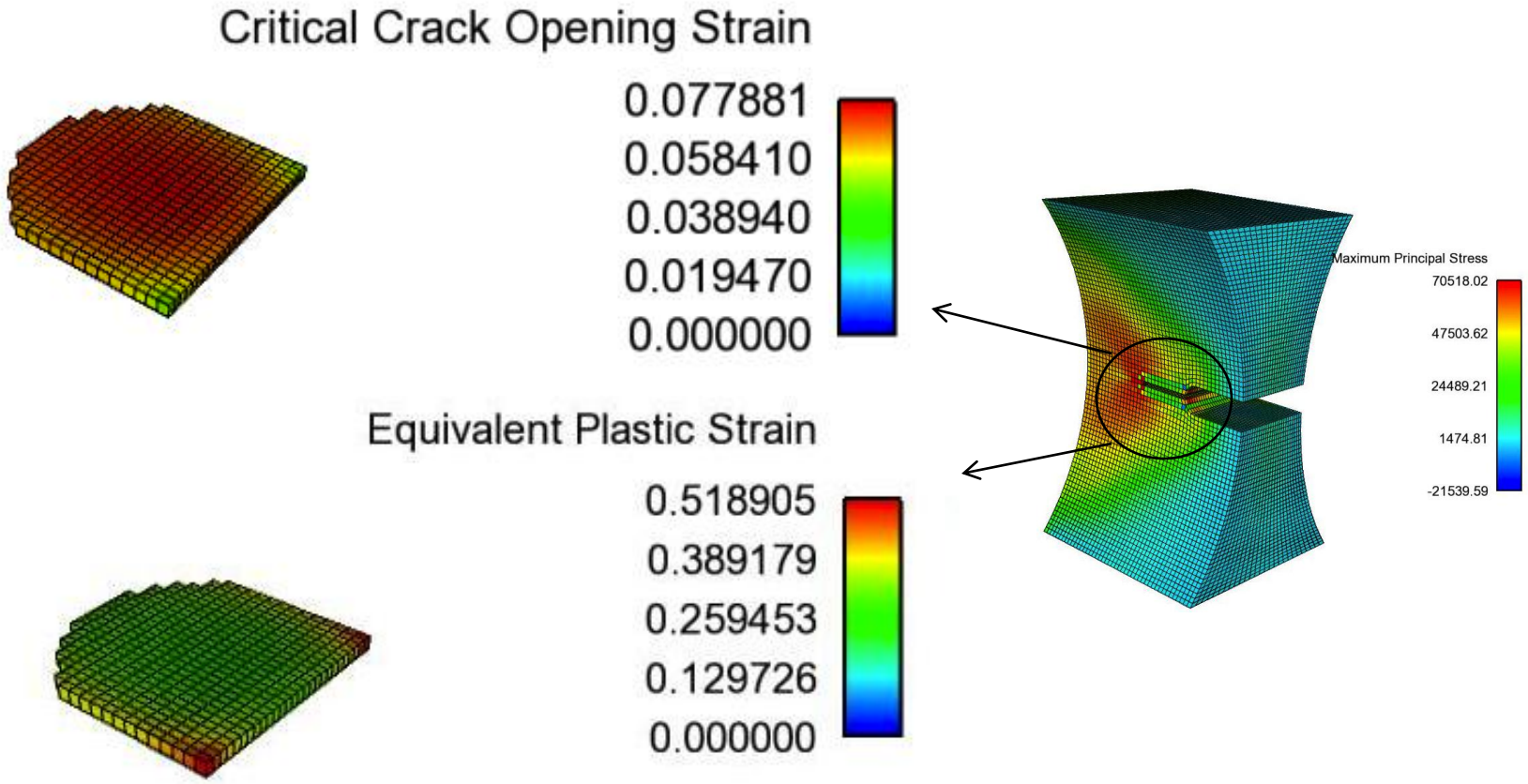
Competing Energies: Possible Reason Mesh Dependence Still Exist in Stable Crack Growth



Un-deformed Cracked Elements

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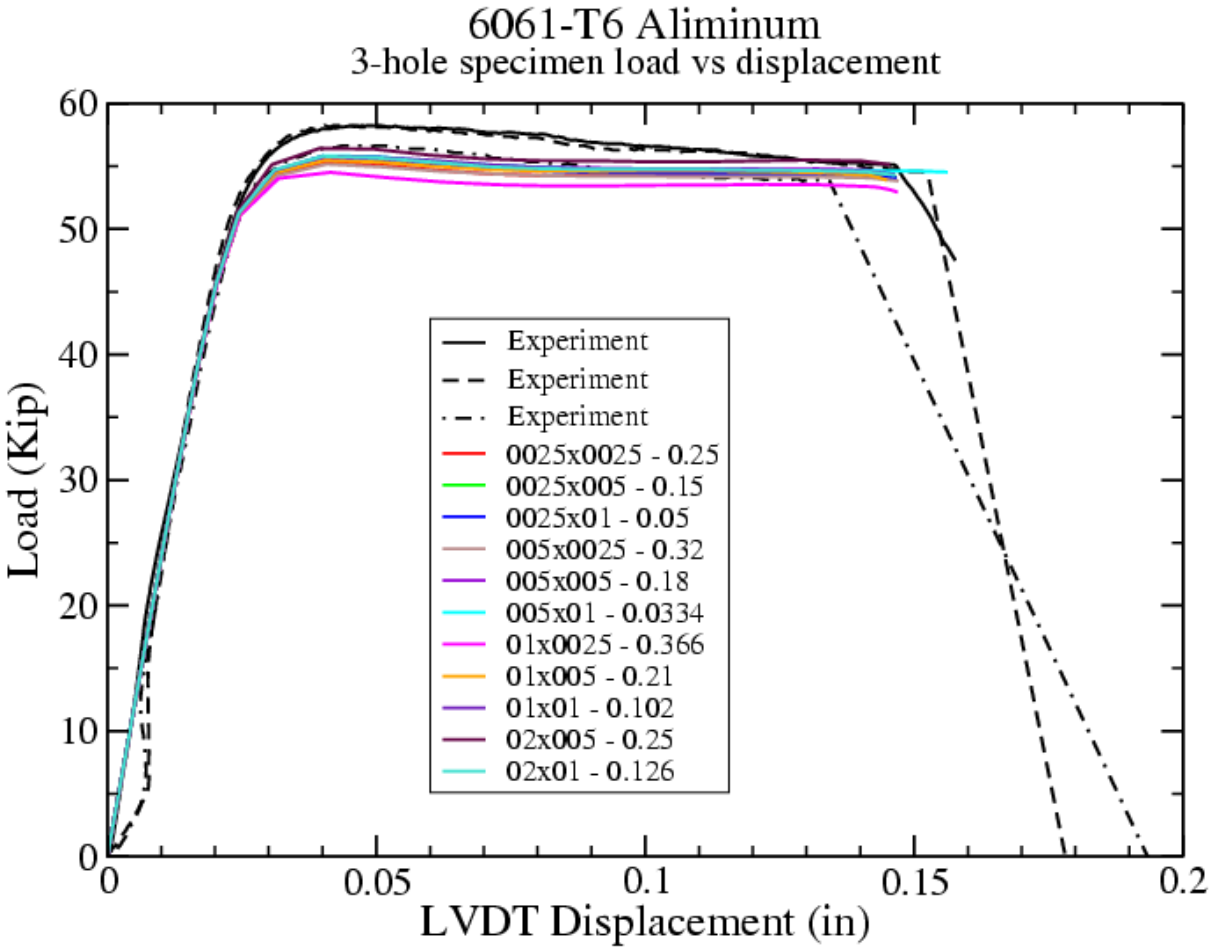
Questions for Future Exploration

- **Should a crack band width be included in determining the critical crack opening strain (CCOS)?**
- **Should we consider the amount of plastic energy dissipated when setting the CCOS with the decay energy?**
- **Is this convergent in a problem that has stable crack growth?**
- **How do we determine the decay energy?**

Conclusions

- We have a simple approach to crack initiation and propagation that shows promise
- We are making progress towards mesh independence
- A framework is in place for exploration in setting the CCOS with knowledge of the element dimensions
- We have existing experimental data to validate the model against

Backup 1



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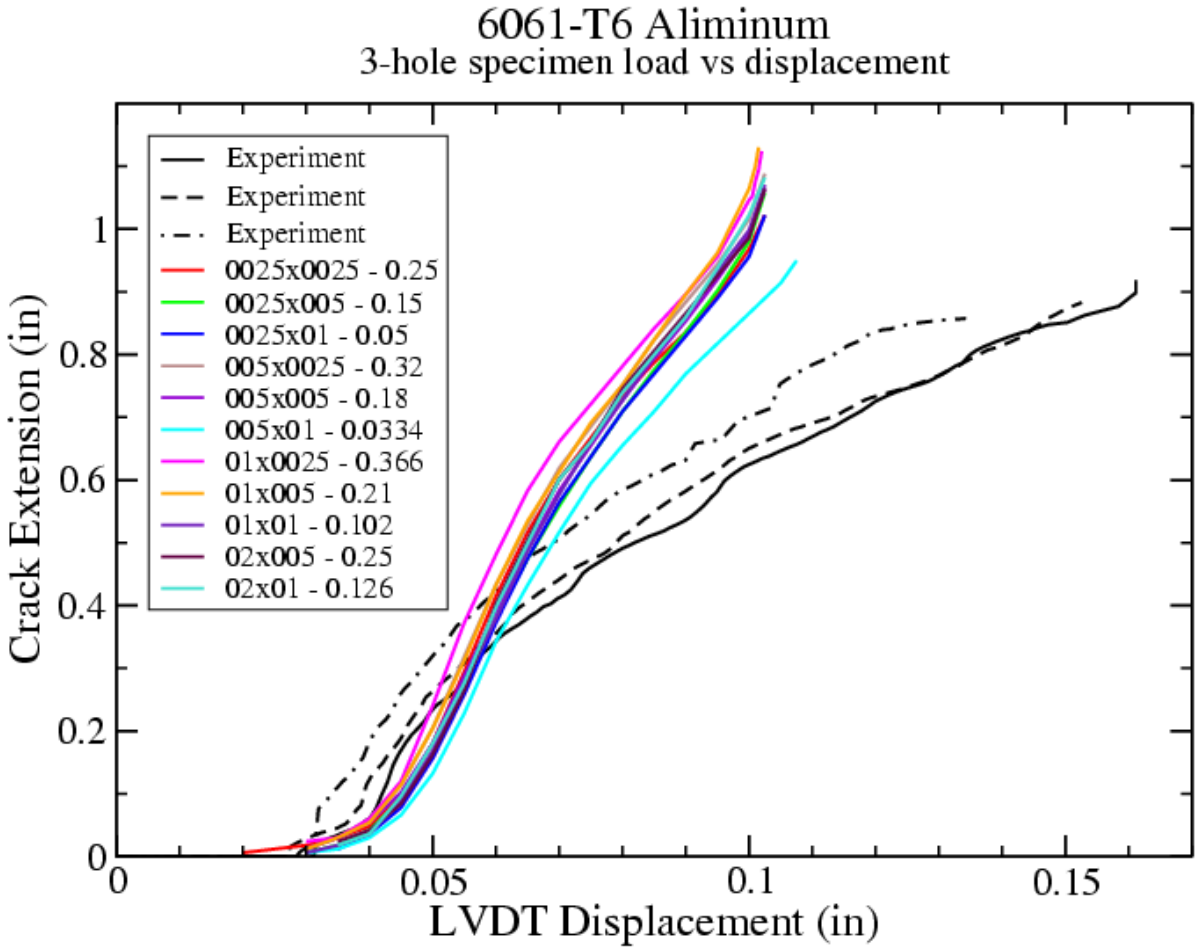
Backup 2



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