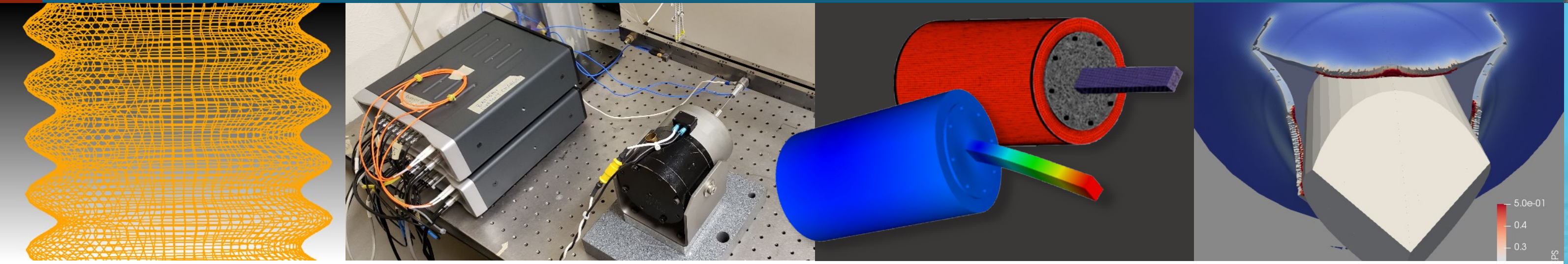
Project 4: Modeling Rate Dependent Interface Separation with Cohesive Zone Models and Bulk Viscoelasticity



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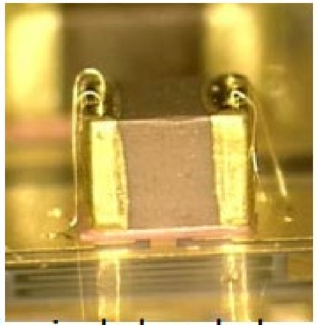
SAND2021-8886 PE

Motivation

- Components tend to fail at interfaces
- Accurate modeling of interface mechanics and failure is a critical aspect of modeling component behavior, reliability, and lifetime.
- While interfacial delamination overlaps with traditional LEFM, there are a number of differences
  - A crack can become constrained to stay on a weak interface and forced to propagate under a mix of tensile and shear loading, interfacial toughness is strongly dependent on mode mixity
- Such cracks are often modeled using cohesive zone methods. Various experimental methods may be used to calibrate such models.
  - Asymmetric Double Cantilever Beam (ADCB)
  - To interpret ADCB data assume all materials are linear elastic.
- **Project Goal:** explore the extent to which current Sandia capabilities (existing cohesive zone models and bulk viscoelasticity) can predict delamination at various rates and temperatures by comparing against measured data



adhesively bonded electrical components

Adhesively bonded rupture disk

encapsulated components

Images courtesy of Dave Reedy

Background: Cohesive Zone Models

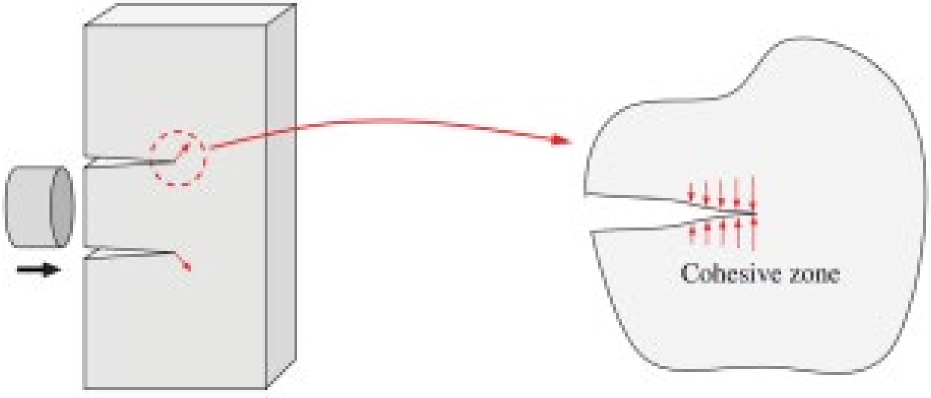
Versatile fracture mechanics model

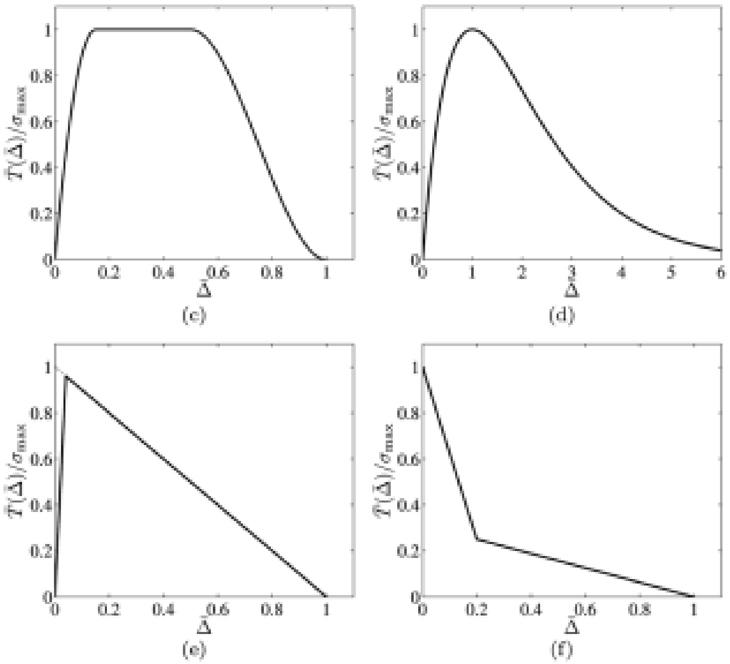
- Fracture resisted by “cohesive tractions”
- Must specify a traction-displacement relationship
- Crack confined to propagate along cohesive layer

Tvergaard-Hutchinson Model

$$T_n = \frac{T(\bar{\Delta})}{\bar{\Delta}} \frac{\Delta_n}{\delta_n}$$

$$T_t = \frac{T(\bar{\Delta})}{\bar{\Delta}} \frac{\Delta_t}{\delta_t} \alpha_e$$



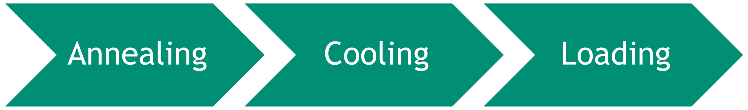


(Park and Paulino)

SINGLE ELEMENT MODEL

Viscoelastic Behavior of the Epoxy

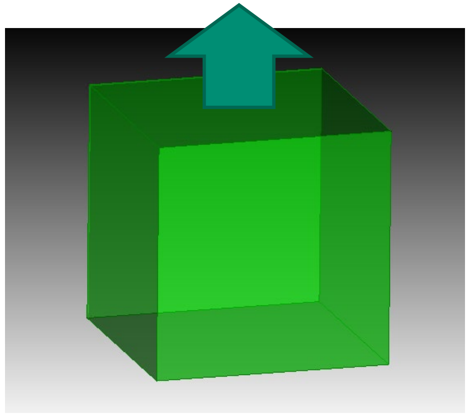
- Often there is adhesive material used to bond two beams together
  - An epoxy bonded interface may be used near or above its glass transition temperature
  - Results in inelastic effects
- Single element of epoxy, bottom is fixed, 1/8th symmetry, put into tension
- Universal Polymer model (SPEC) based on 828/DEA cured fit

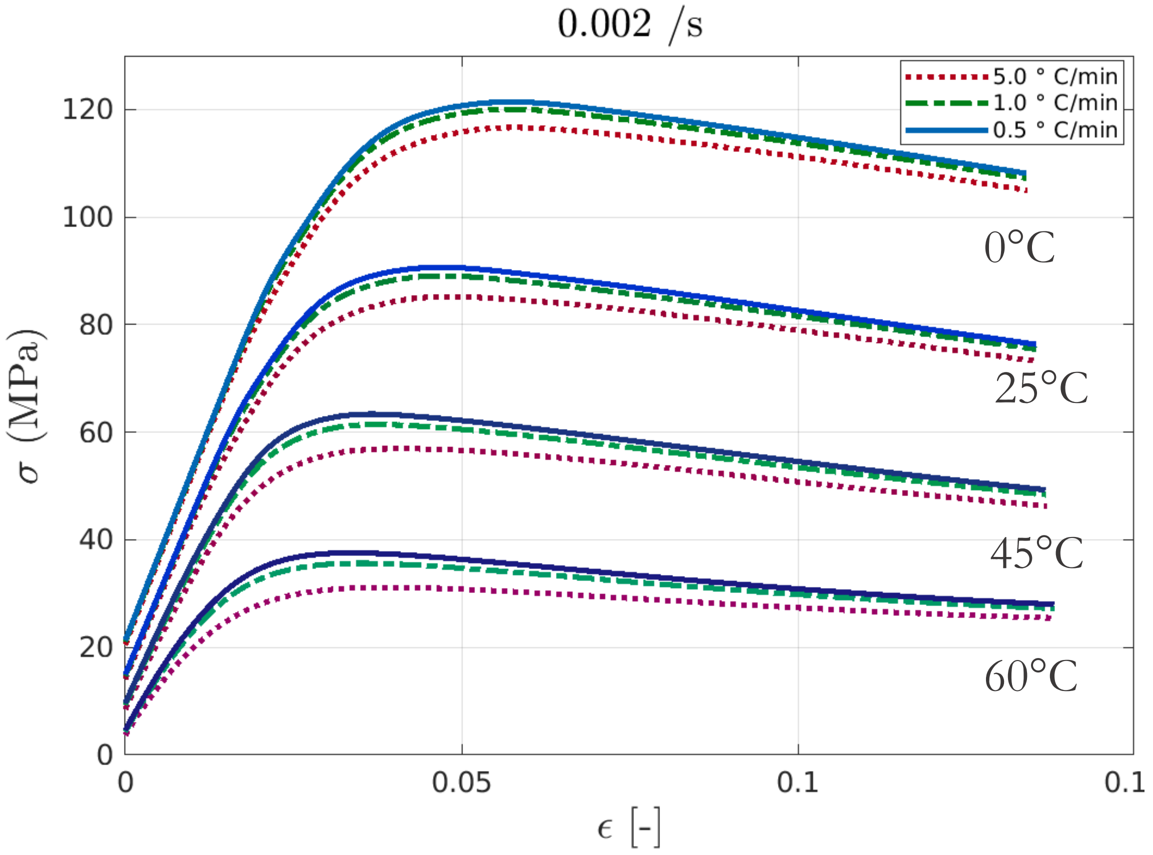


Annealing

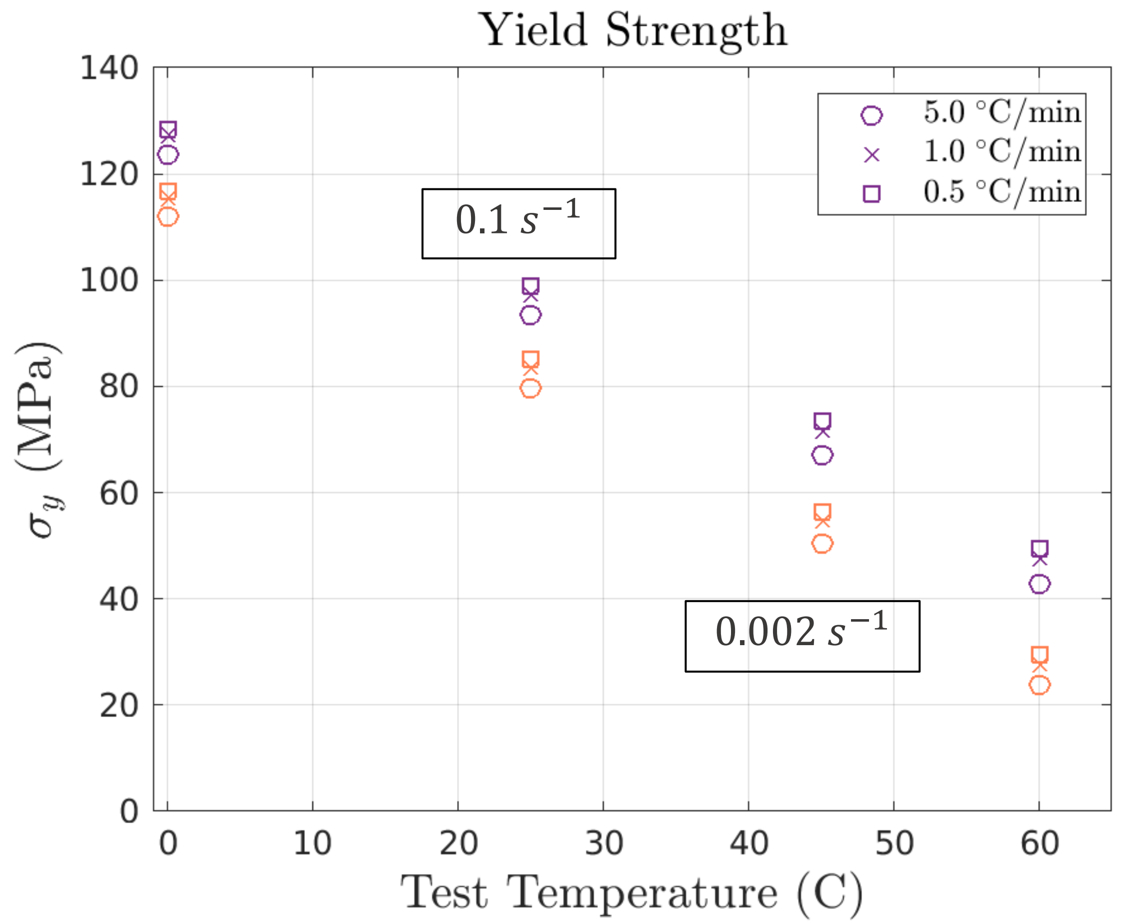
Cooling

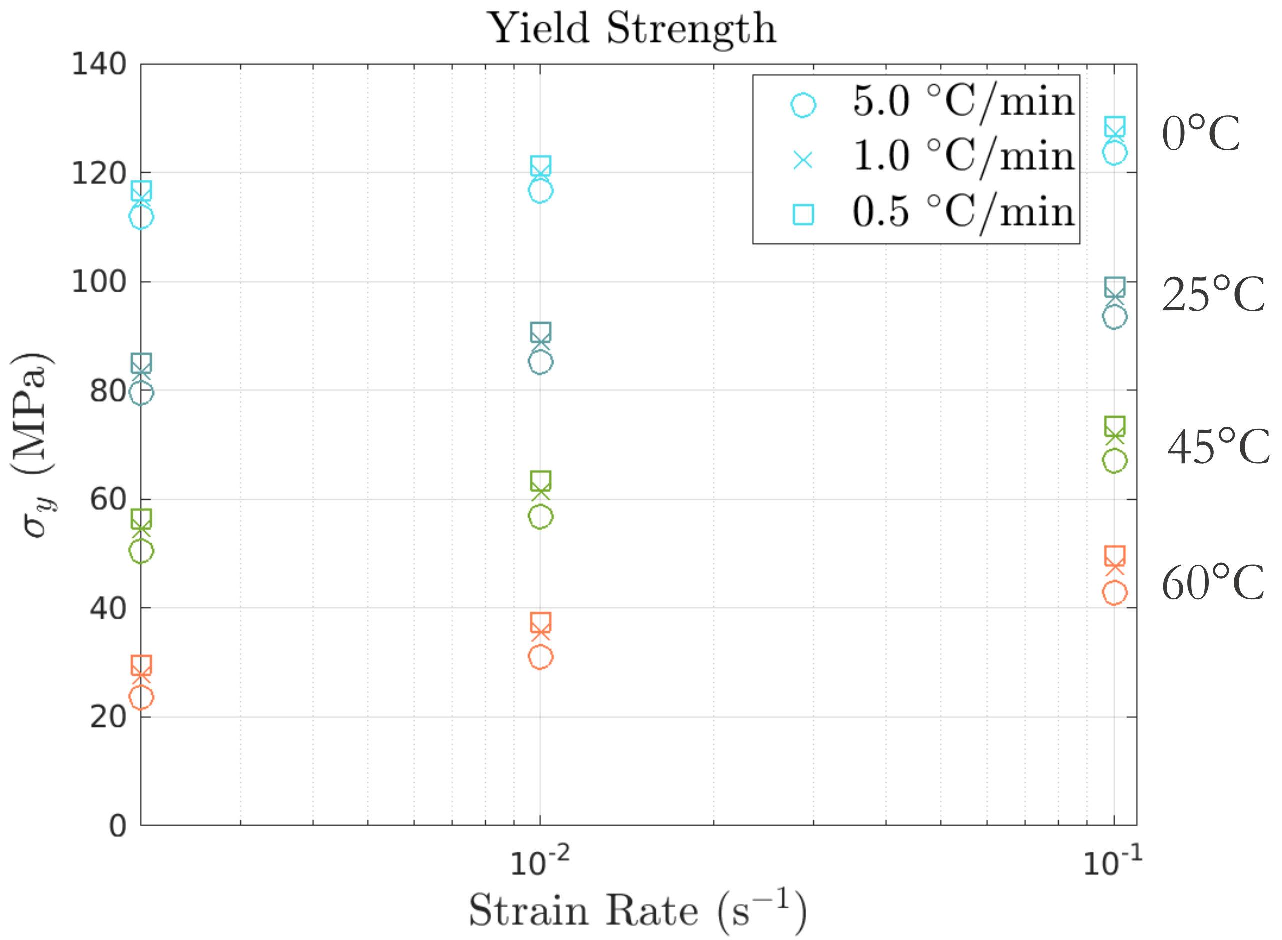
Loading





Yield vs Temperature and Strain Rate

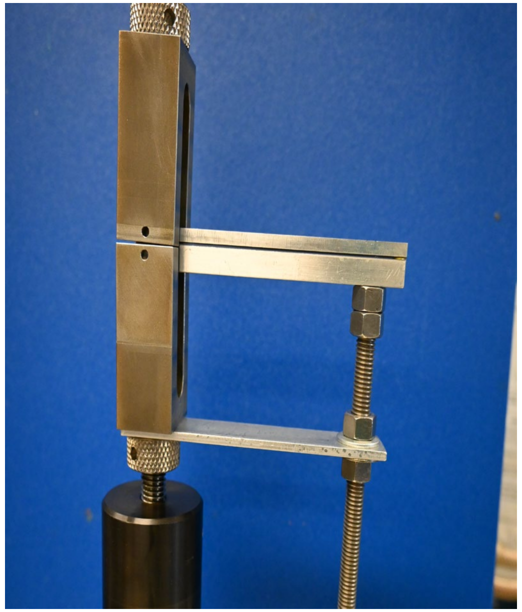


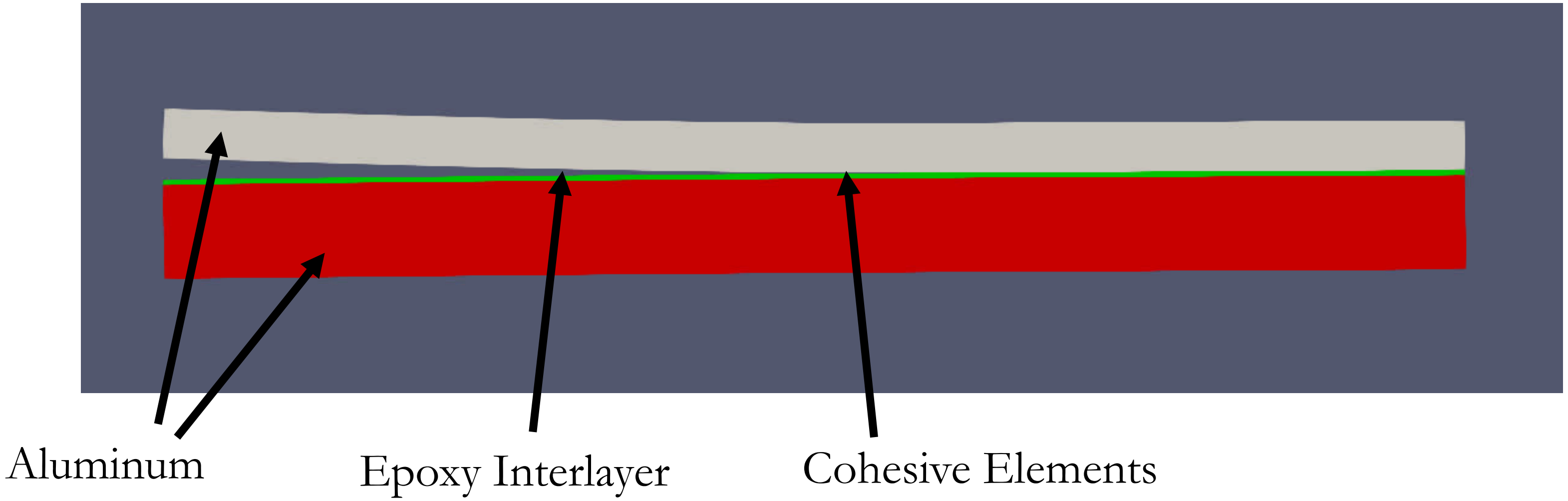


- T_g = 70° C
- Yield increases with strain rate
- Decreases with temperature and cooling rate

FULL ADCB MODEL – SET-UP

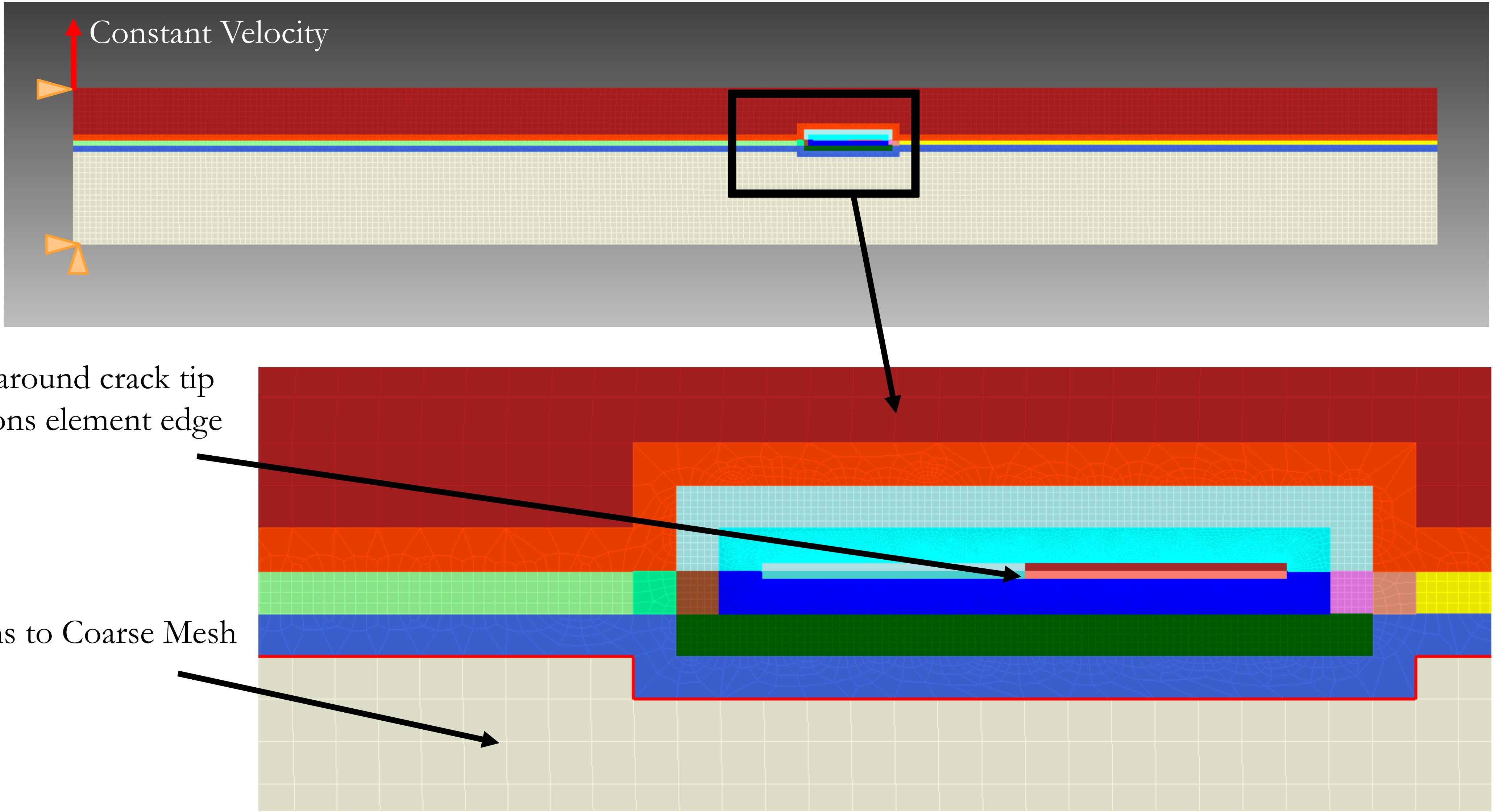
Model Layout





Simplify true geometry to single-thickness plane-stress model

Mesh And Boundary Conditions



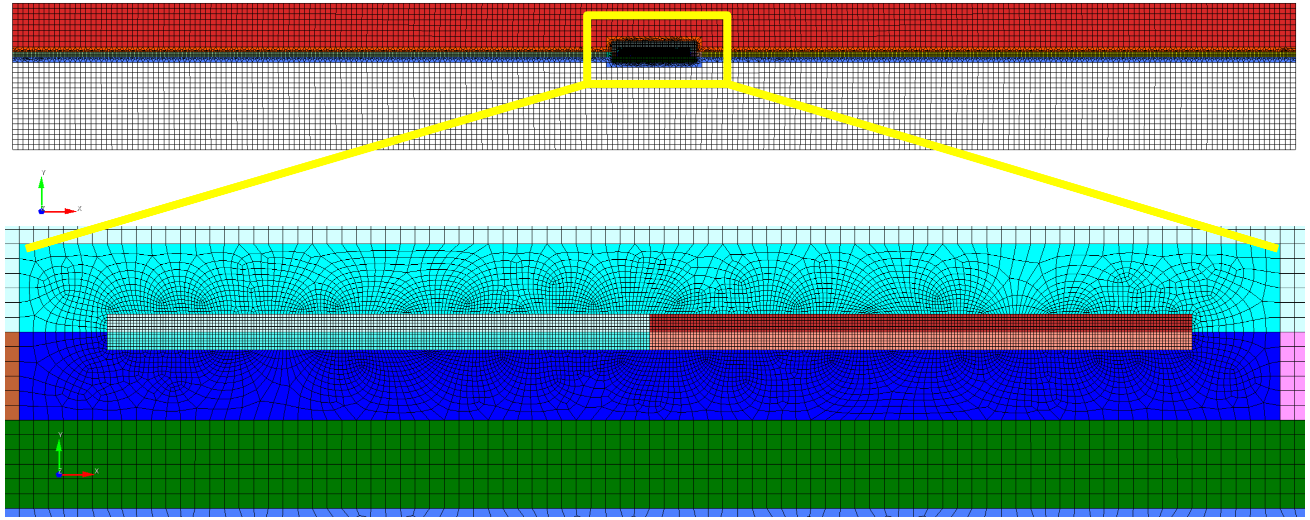
Fine Mesh around crack tip (~ 20 microns element edge length)

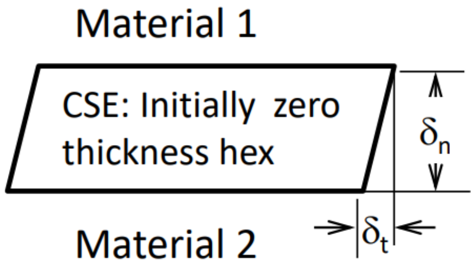
Transitions to Coarse Mesh

COHESIVE ZONE MODEL (CZM) CONVERGENCE

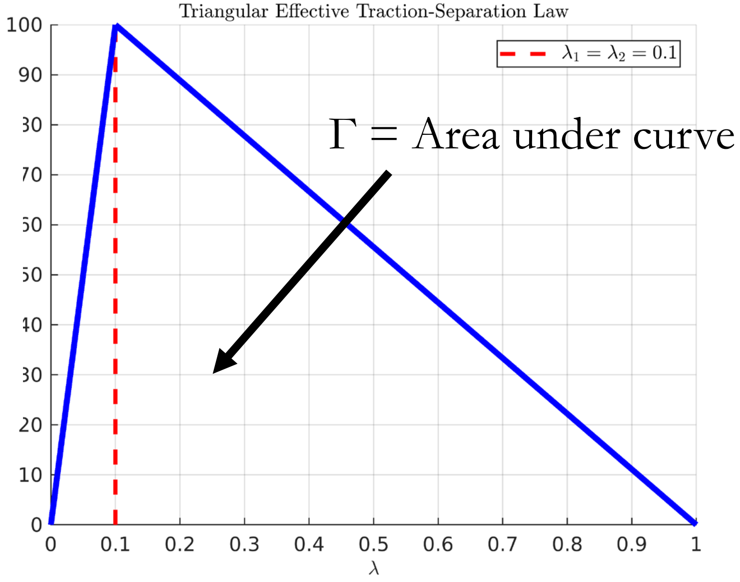
CZM Convergence Evaluation without Viscoelasticity

- **Aim:** Determine largest mesh size that resolves the cohesive zone
- Elastic epoxy model – isolate energy dissipation to cohesive surface element (CSE) failure
- Cohesive zone model: Tvergaard-Hutchinson
    - Triangular traction-separation law: $\lambda_1 = \lambda_2 = 0.1$
    - Normal toughness: $\Gamma = 100\ \mathrm{J\ m^{-2}}$
    - Simulated with three peak tractions: $\hat{\sigma} = 50, 75, 100$ MPa
- Mesh: Simulate with four different element sizes in cohesive region: 5, 8.33, 16.7, 33.3 μm
    - Crack length: 60 mm
- Toughness calculations performed using applied load and specimen compliance at first CSE failure
    - Based on LEFM for a beam on an elastic foundation



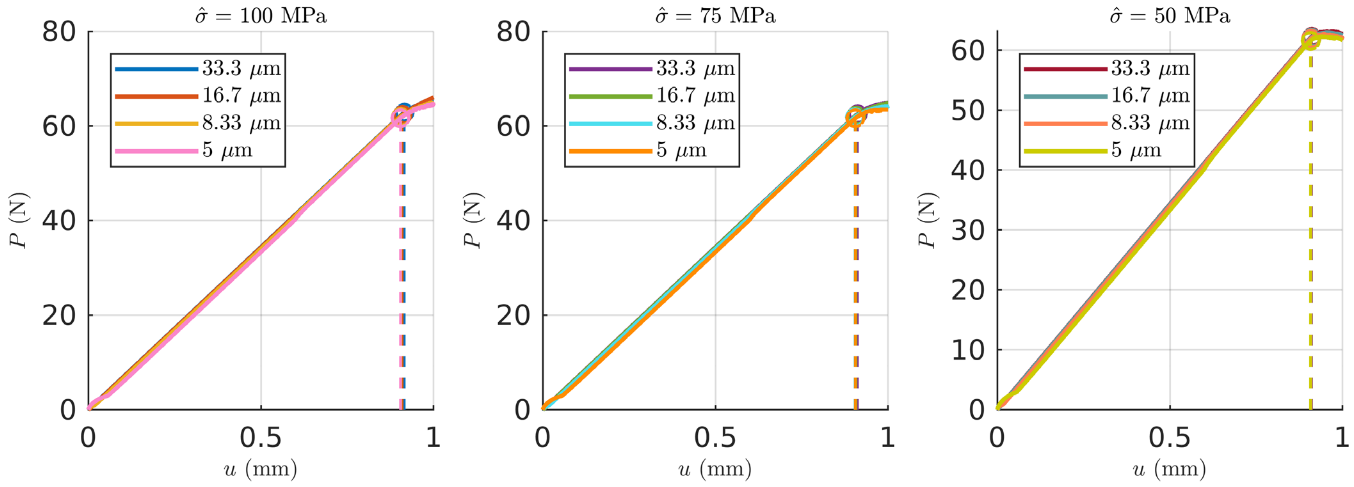


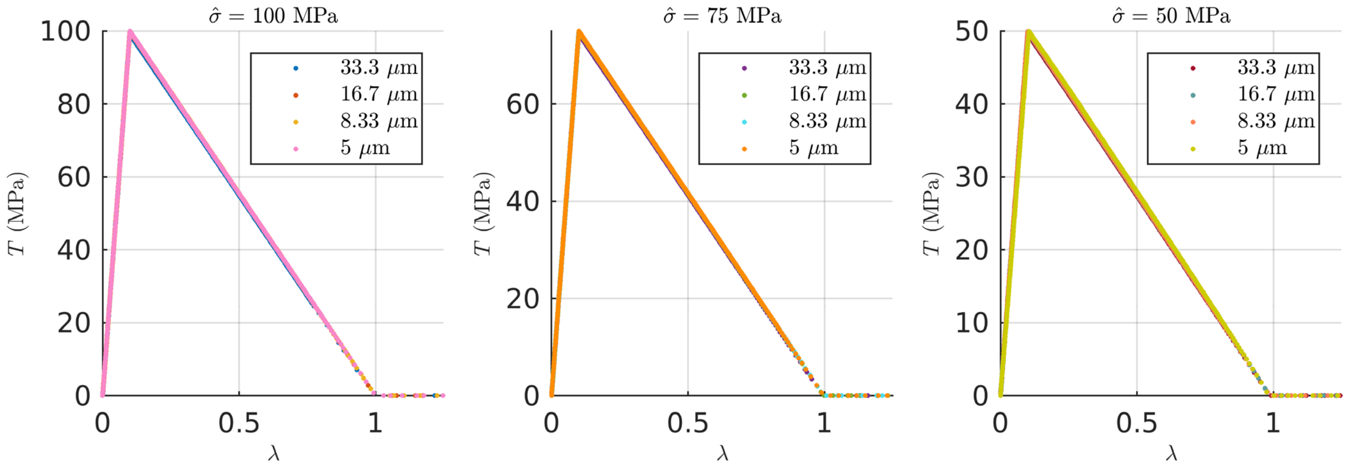
Courtesy of Dave Reedy (SNL-Retired)



Γ = Area under curve

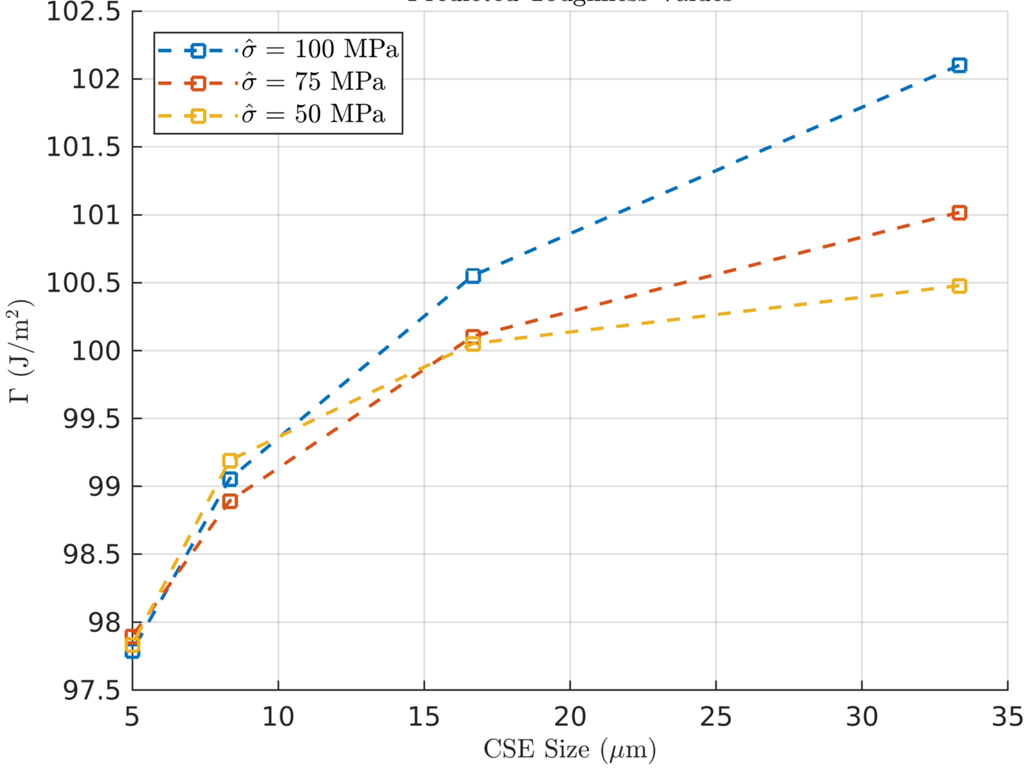
CZM Convergence Evaluation without Viscoelasticity


Load-Displacement Curves


Effective Traction-Separation Curve for 1^{st} CSE - Integration Point 4

- Selected mesh size for CSE region: 16.7 µm
  - Excellent convergence – 0.5% relative error in Γ
  - Faster run times than smaller meshes

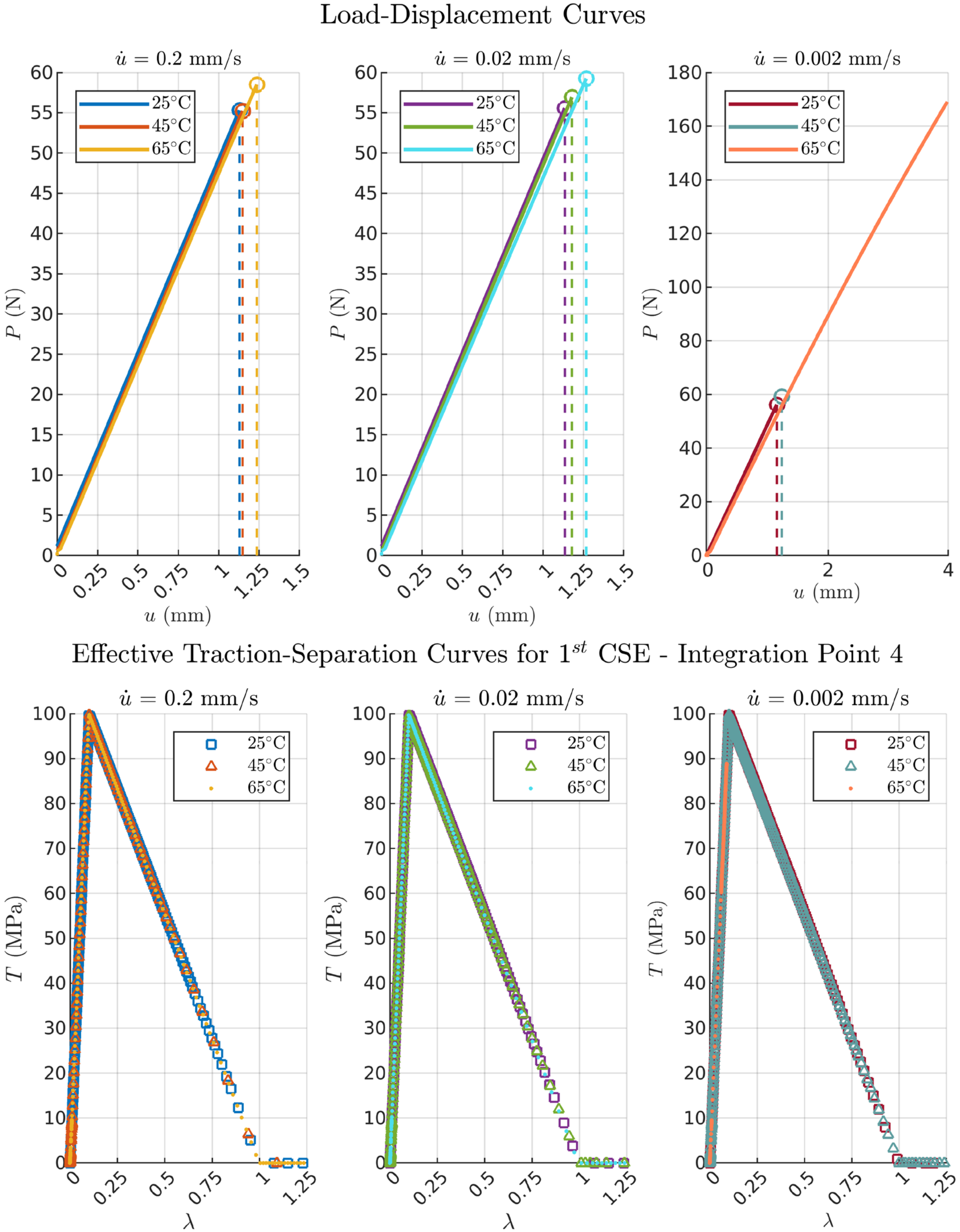
Appendix: Tabulated numerical results for toughness values


Predicted Toughness Values

FULL SIMULATION

Full Simulation Results

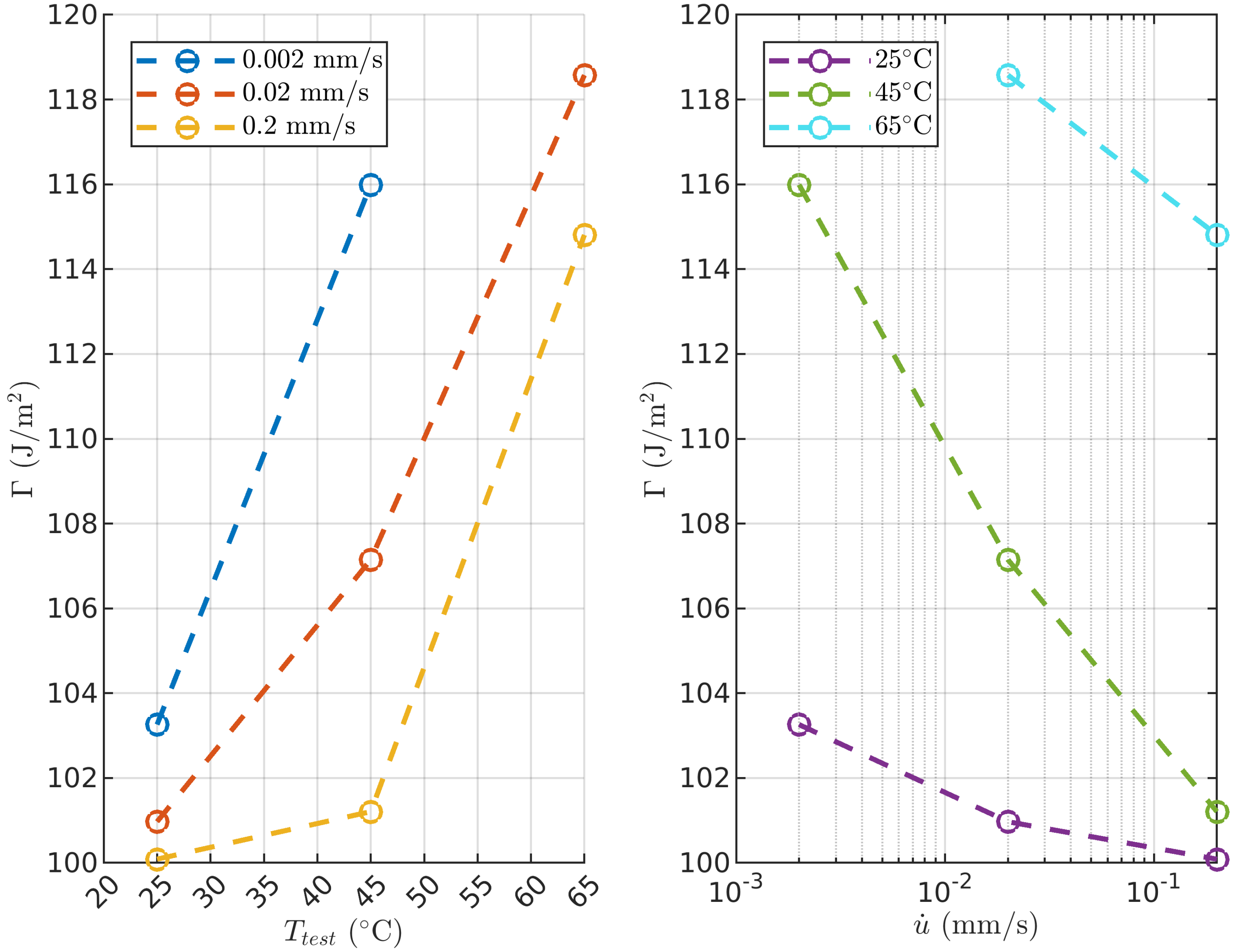
- Includes viscoelastic epoxy model and CSEs along interface
- Three applied displacement rates: 0.2 mm/s, 0.02 mm/s, 0.002 mm/s
- Three test temperatures: 25°C, 45°C, 65°C
- Temperature history:
  - Anneal at 70°C, cool to 25°C at rate of 0.8°C/min
  - Rest at 25°C for 24 hours
  - For 25°C test: Begin loading after rest
  - For 45°C and 65°C tests: Heat to test temperature at rate of 0.8°C/min
- Results capture rate and temperature dependence of crack growth initiation



Full Simulation Results

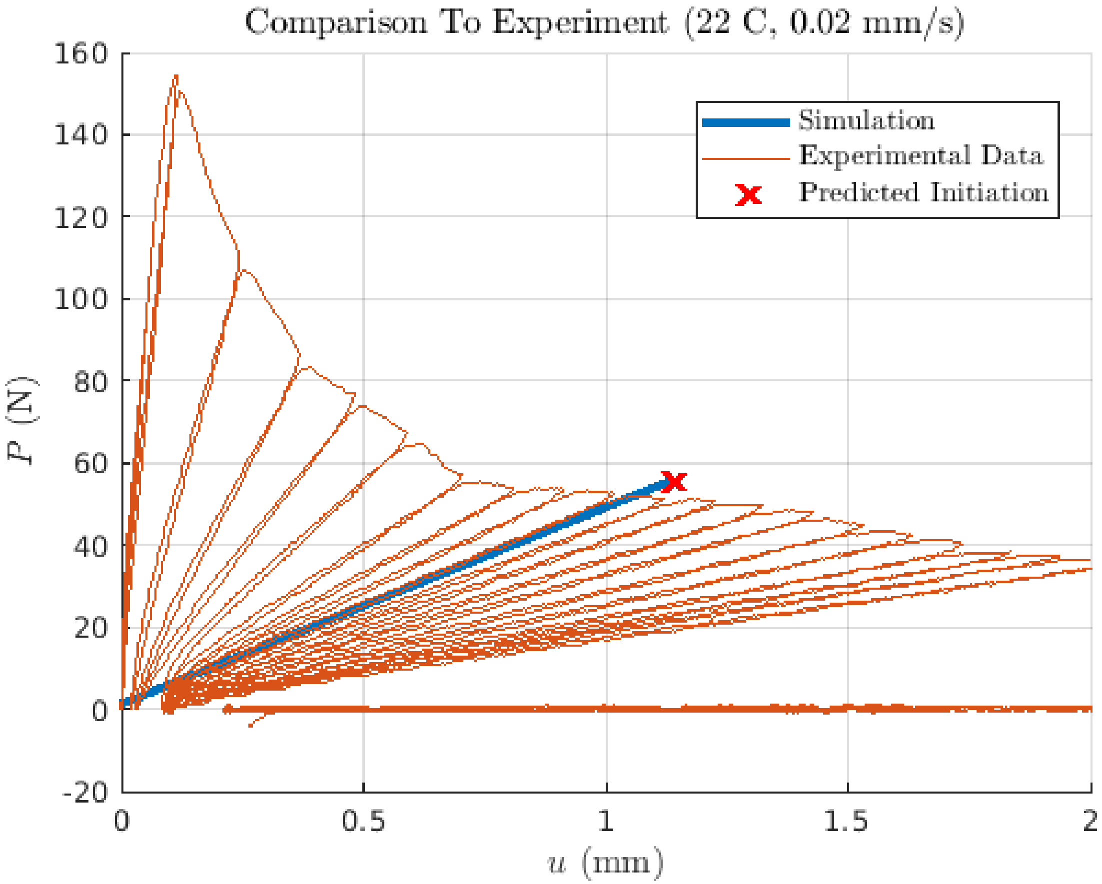
- Predicted toughness values dependent on displacement rate and temperature
- In general, toughness increases with increasing test temperature, decreasing displacement rate
    - For higher temperatures, lower rates: viscoelastic effects more pronounced in epoxy
    - Greater degree of energy dissipation in bulk epoxy
- For 65°C test at 0.002 mm/s
    - Epoxy yields excessively, crack growth does not occur

Effect of Displacement Rate and Test Temperature on Predicted Toughness



Appendix: [Tabulated numerical results for toughness values]

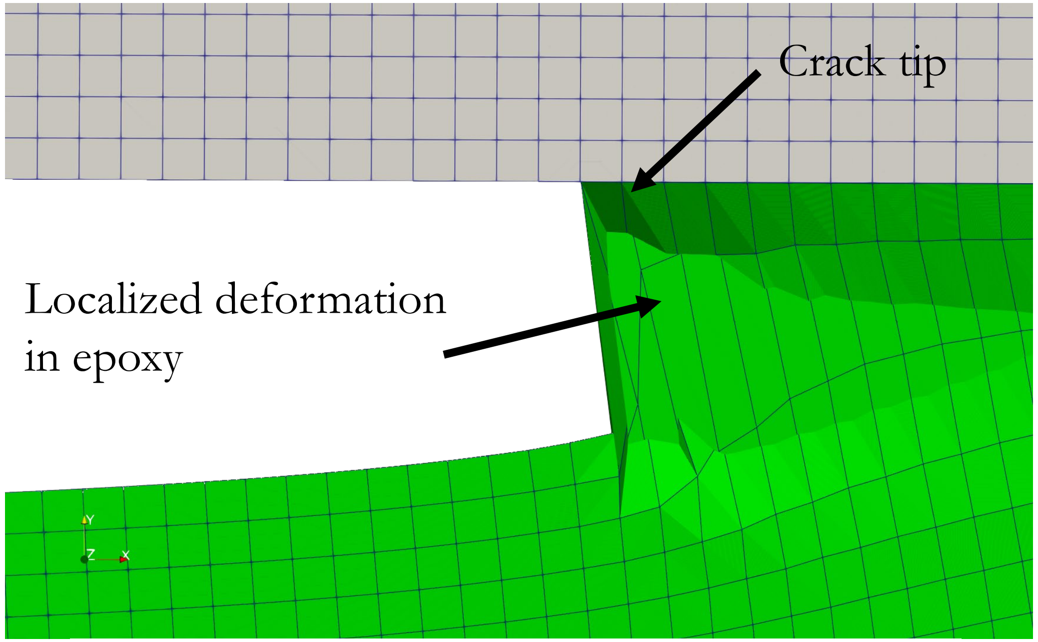
Comparison To Experimental Data

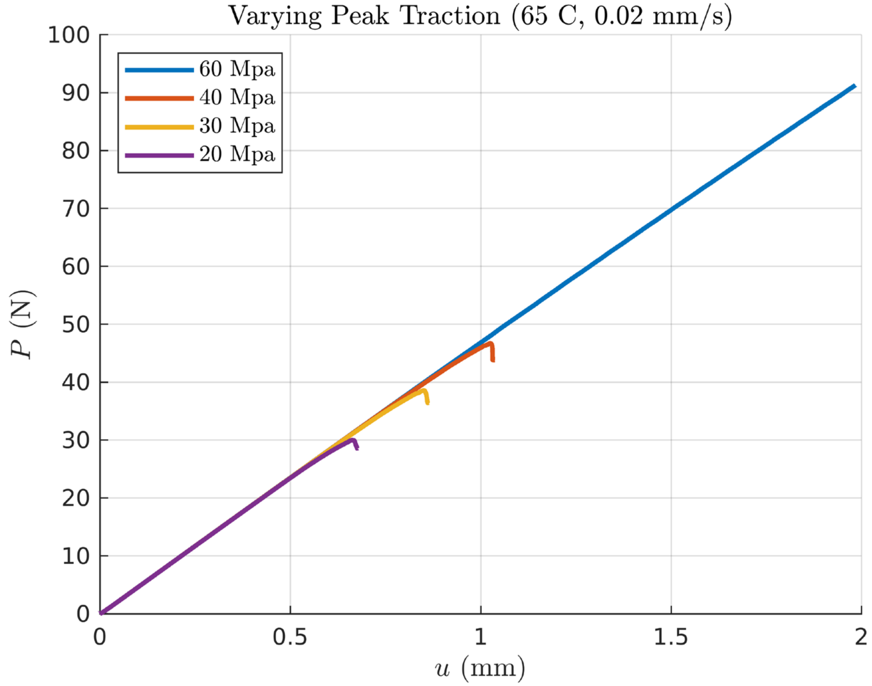


- Good agreement with experimental compliance and analytical calculations
  - Beam theory predicts crack length of 70.8 mm, crack length used in sim is 70 mm
- Over predicts displacement at initiation

Challenges and Next Steps

- Initially experienced stability issues in CSEs when using trapezoidal and rectangular traction-separation relationships
- Extreme localized deformation in epoxy at the crack tip observed during test at 65℃ with 0.002 m/s displacement rate
- Determine appropriate cohesive zone model parameters for different temperatures and displacement rates to match future experimental data
- Expand quasi-plane stress model to full-width model





Acknowledgements

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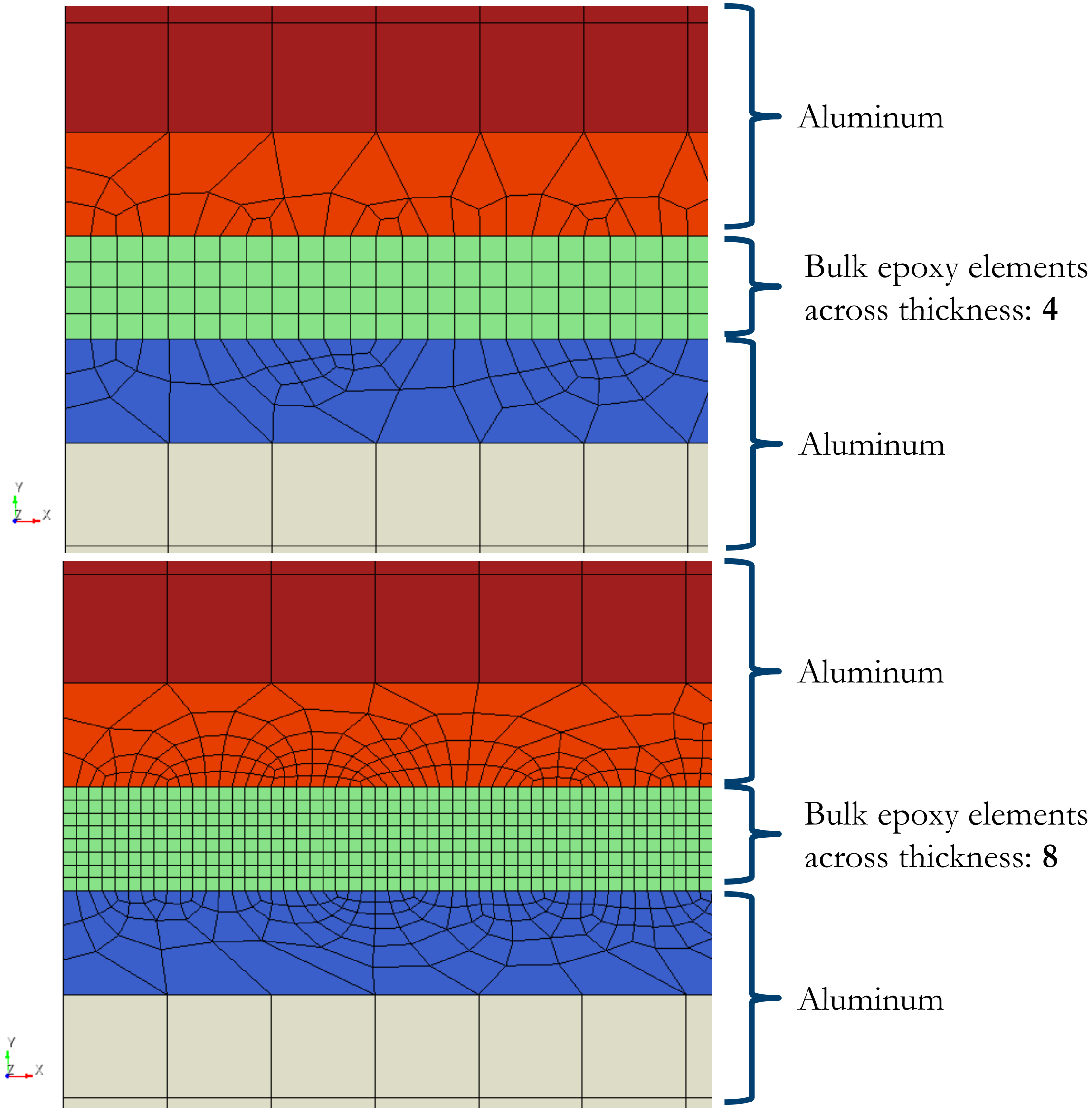
References

[1] K. Park and G. Paulino, "Cohesive Zone Models: A Critical Review of Traction-Separation Relationships Across Fracture Surfaces," *Applied Mechanics Reviews*, vol. 64, no. 6, November, 2011.

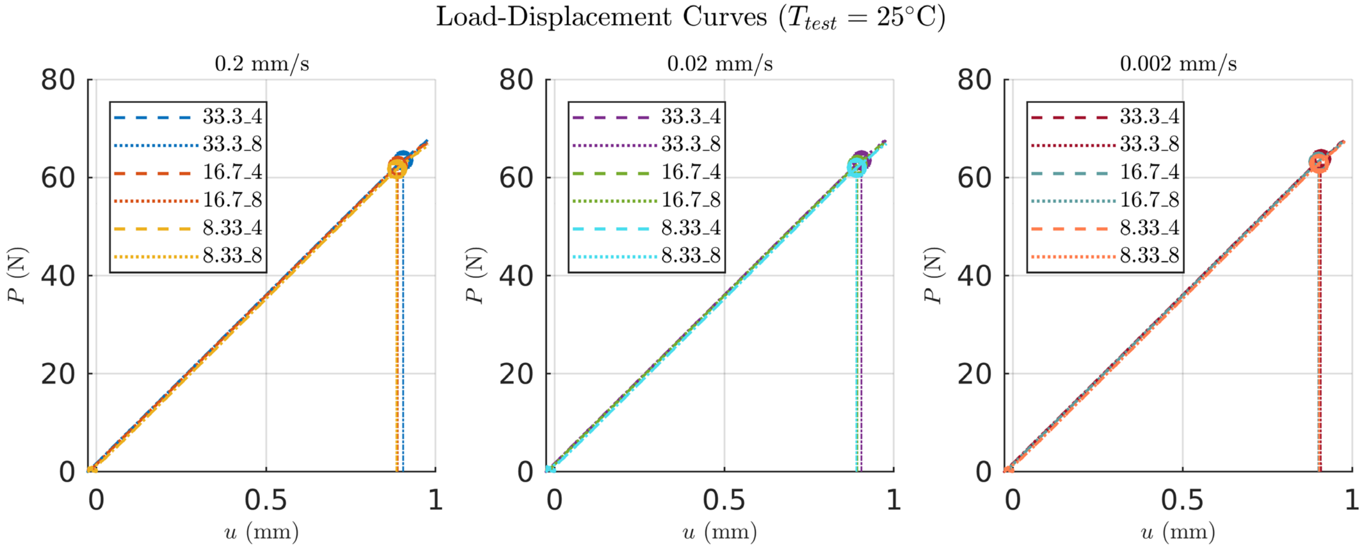
APPENDIX

CZM Convergence Evaluation with Viscoelasticity

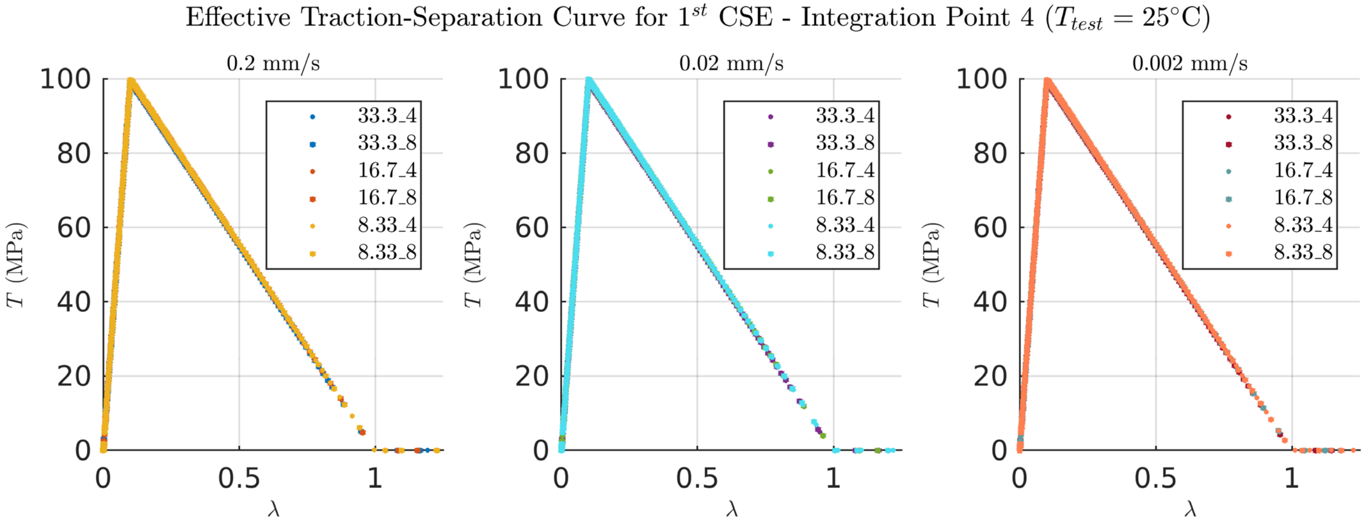
- **Aim**: Evaluate effect of viscoelasticity on mesh sensitivity
- Viscoelastic epoxy model
- Same CZM
- Simulate with same mesh sizes for CSE region and bulk aluminum, test with two bulk epoxy sizes
- Temperature history:
  - Anneal at 70°C
  - Cool to 25°C at rate of 0.8°C/min
  - Rest at 25°C for 24 hours
  - Test at 25°C
- Simulate each mesh with three displacement rates: 0.2 mm/s, 0.02 mm/s, and 0.002 mm/s



CZM Convergence Evaluation with Viscoelasticity



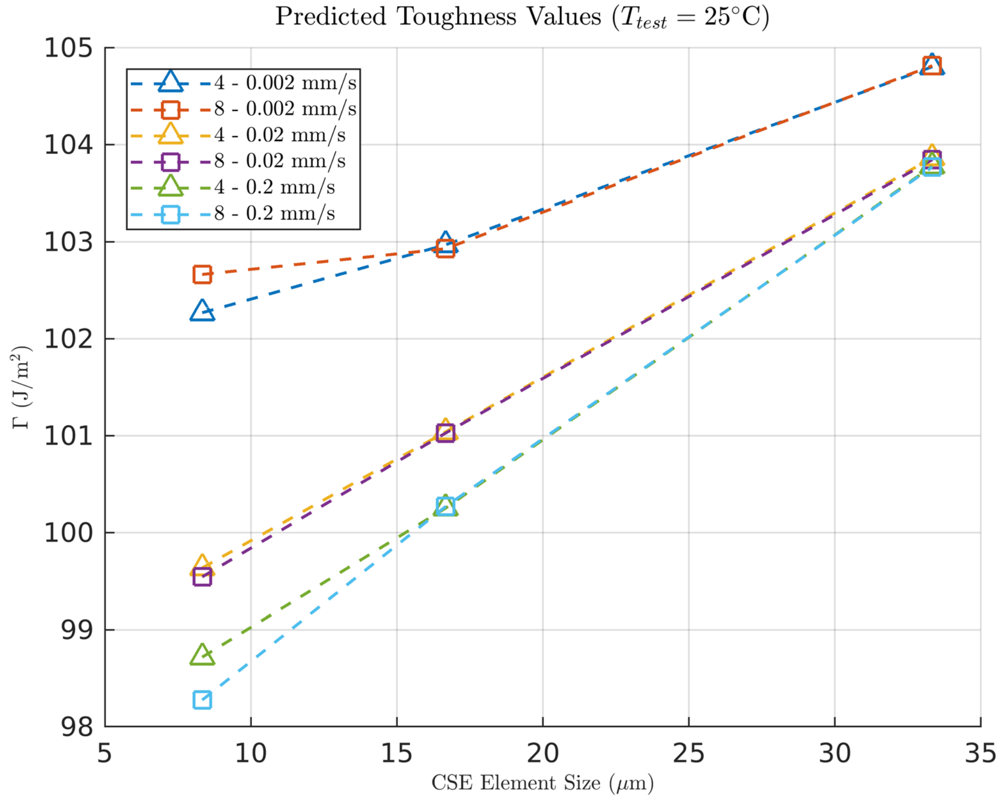
Load-Displacement Curves ($T_{test} = 25°C$)



Effective Traction-Separation Curve for 1^{st} CSE - Integration Point 4 ($T_{test} = 25°C$)

- Increased mesh sensitivity of predicted toughness values with viscoelastic epoxy behavior
- Effect likely to be more pronounced at higher test temperatures

Appendix: [Tabulated numerical results for toughness values]



Predicted Toughness Values ($T_{test} = 25°C$)

CZM Convergence without Viscoelasticity: Failure Conditions

Simulation (CSE Size, $\hat{\sigma}$)	Applied Disp, u (mm)	Applied Load, P (N)	Toughness, Γ (J m^{-2})
33.3 μm, 100 MPa	0.915	62.854	102.101
16.7 μm, 100 MPa	0.909	62.338	100.553
8.33 μm, 100 MPa	0.905	61.952	99.055
5 μm, 100 MPa	0.904	61.925	97.790
33.3 μm, 75 MPa	0.911	62.473	101.019
16.7 μm, 75 MPa	0.907	62.184	100.105
8.33 μm, 75 MPa	0.904	61.886	98.892
5 μm, 75 MPa	0.905	61.941	97.897
33.3 μm, 50 MPa	0.910	62.261	100.479
16.7 μm, 50 MPa	0.0909	62.122	100.052
8.33 μm, 50 MPa	0.908	61.886	98.892
5 μm, 50 MPa	0.907	61.895	97.837

CZM Convergence with Viscoelasticity: Failure Conditions

Simulation (CSE Size, $\dot{u}$, n)	u (mm)	P (N)	Γ (J m^{-2})
33.3 µm, 0.2 mm/s, 4	0.903	63.521	103.776
16.7 µm, 0.2 mm/s, 4	0.888	62.386	100.251
8.33 µm, 0.2 mm/s, 4	0.885	61.705	98.717
33.3 µm, 0.02 mm/s, 4	0.903	63.547	103.862
16.7 µm, 0.02 mm/s, 4	0.892	62.623	101.038
8.33 µm, 0.02 mm/s, 4	0.889	61.990	99.635
33.3 µm, 0.002 mm/s, 4	0.907	63.829	104.801
16.7 µm, 0.002 mm/s, 4	0.900	63.214	102.968
8.33 µm, 0.002 mm/s, 4	0.901	62.803	102.267

Simulation (CSE Size, $\dot{u}$, n)	u (mm)	P (N)	Γ (J m^{-2})
33.3 µm, 0.2 mm/s, 8	0.903	63.520	103.767
16.7 µm, 0.2 mm/s, 8	0.887	62.392	100.268
8.33 µm, 0.2 mm/s, 8	0.883	61.566	98.275
33.3 µm, 0.02 mm/s, 8	0.903	63.542	103.843
16.7 µm, 0.02 mm/s, 8	0.891	62.625	101.026
8.33 µm, 0.02 mm/s, 8	0.888	61.962	99.542
33.3 µm, 0.002 mm/s, 8	0.907	63.834	104.812
16.7 µm, 0.002 mm/s, 8	0.899	63.208	102.928
8.33 µm, 0.002 mm/s, 8	0.903	62.923	102.662

u: Applied displacement
$\dot{u}$: Applied displacement rate
n: Number of elements spanning epoxy thickness
P: Applied load
Γ: Predicted toughness

Full Simulation: Failure Conditions

Simulation (T, $\dot{u}$)	Applied Disp, u (mm)	Applied Load, P (N)	Toughness, Γ (J m^{-2})
25°C, 0.002 mm/s	1.148	56.169	103.260
25°C, 0.02 mm/s	1.136	55.547	100.970
25°C, 0.2 mm/s	1.130	55.307	100.086
45°C, 0.002 mm/s	1.230	59.209	115.992
45°C, 0.02 mm/s	1.180	56.924	107.147
45°C, 0.2 mm/s	1.149	55.207	101.207
65°C, 0.002 mm/s	-	-	-
65°C, 0.02 mm/s	1.268	59.248	118.575
65°C, 0.2 mm/s	1.236	58.506	114.807

T: Test temperature

$\dot{u}$: Applied displacement rate