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Experiments and Modeling of Viscoelastic Delamination Through a Transition in Validity of Small-Scale Yielding

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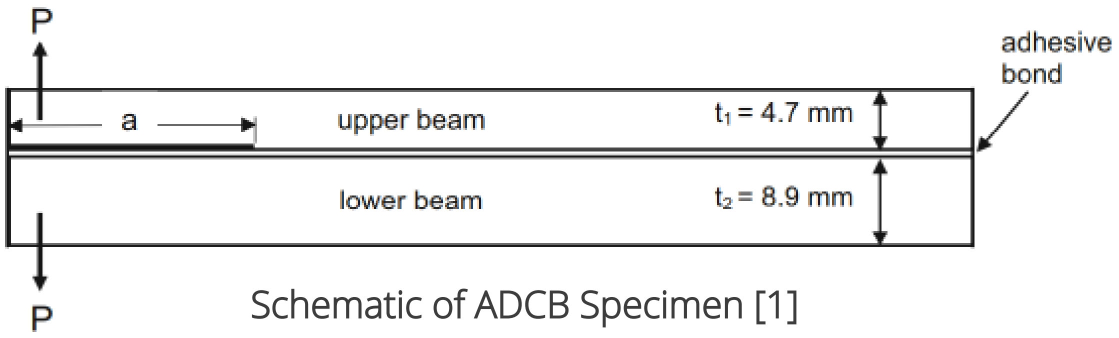
Motivation

- Accurate modeling of interfacial fracture is a critical aspect of modeling component behavior, reliability, and lifetime [1]
  - Interfacial fracture introduces additional complexity compared to traditional LEFM (e.g., strong dependence of toughness on crack-tip mode mixity) [2]
- However, most analyses assume the bonded materials remain linearly elastic
  - What if this assumption fails and one or more of the materials exhibit inelastic behavior (e.g., viscoelastic behavior)?
    - For example, EPON 828/DEA has a T_g of $\sim 70°C$, will exhibit time- and temperature-dependent responses above and below the T_g [1]
  - How can the energy loss in the system be partitioned into bulk dissipation and interface separation?
- **Goal:** Evaluate whether the combination of **bulk viscoelasticity** and **cohesive zone models** can accurately predict experimentally observed trends in interfacial fracture tests

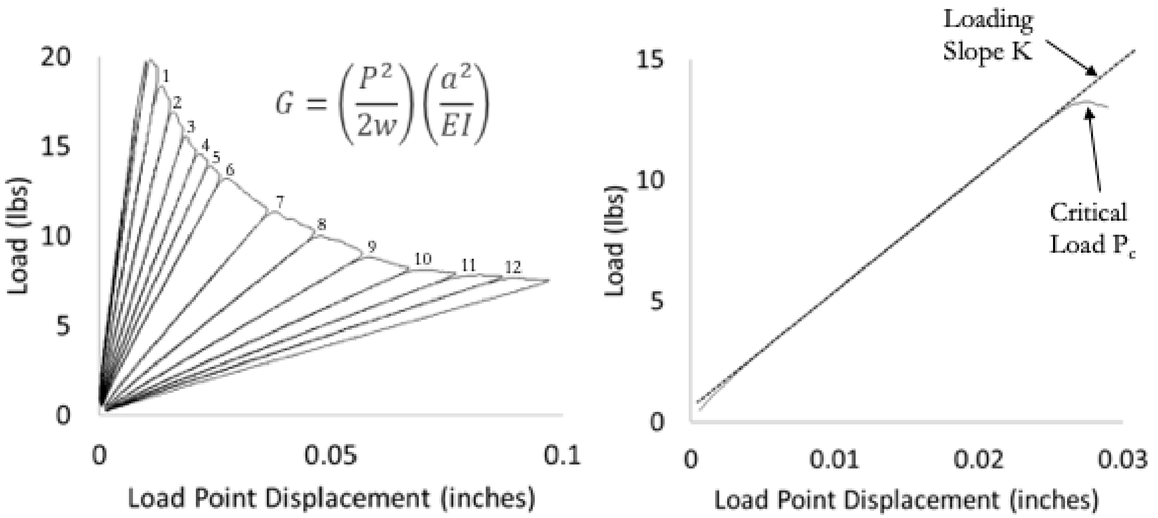
[1] Reedy & Stavig. (2020). *Int. J. Fracture*, *222*(1).
[2] Hutchinson & Suo. (1991). *Adv. Appl. Mech.*, *29*.

Experimental Method: ADCB Test

- Asymmetric double cantilever beam (ADCB) test used to measure the toughness of an epoxy-aluminum interface
- Asymmetry introduces slight mode-mix ($\approx -12°$) that constrains the crack along the top interface [1]
  - Sufficiently small to approximate Mode I toughness [3]
- ADCB subjected to end loads via displacement control, calculate specimen compliance and critical load [3]
- Determine the interface toughness using crack length inferred from the compliance [3]
- Multiple measurements obtained from each specimen by repeatedly loading/unloading [3]



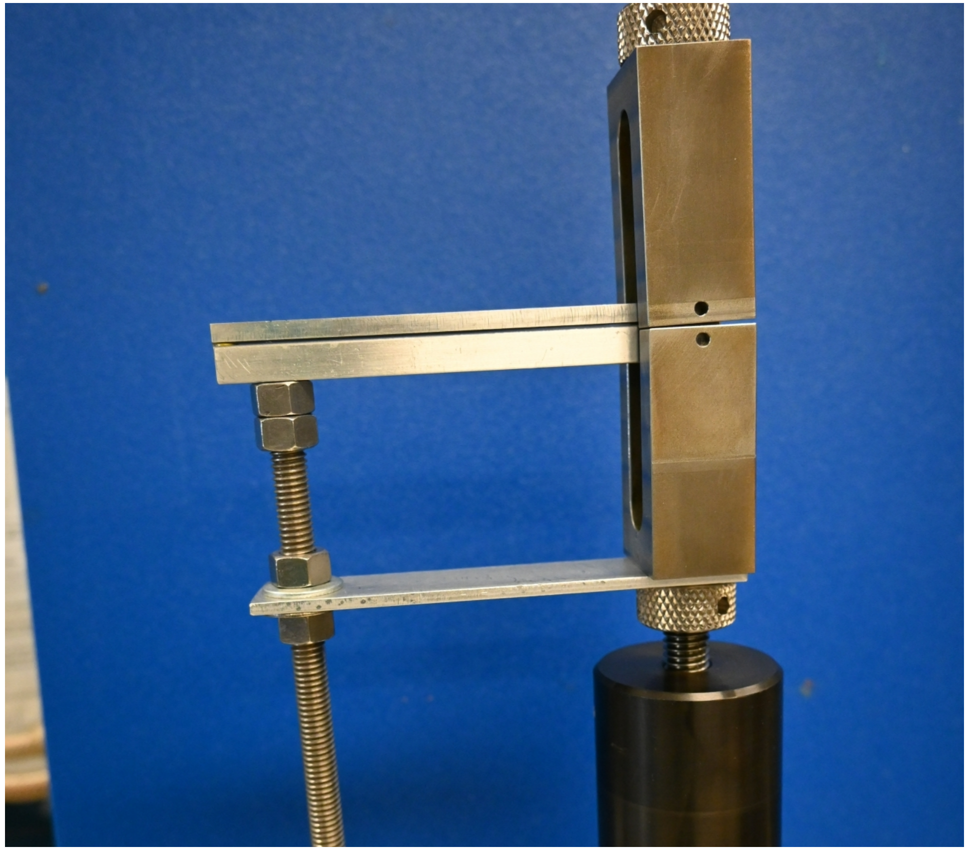
Schematic of ADCB Specimen [1]

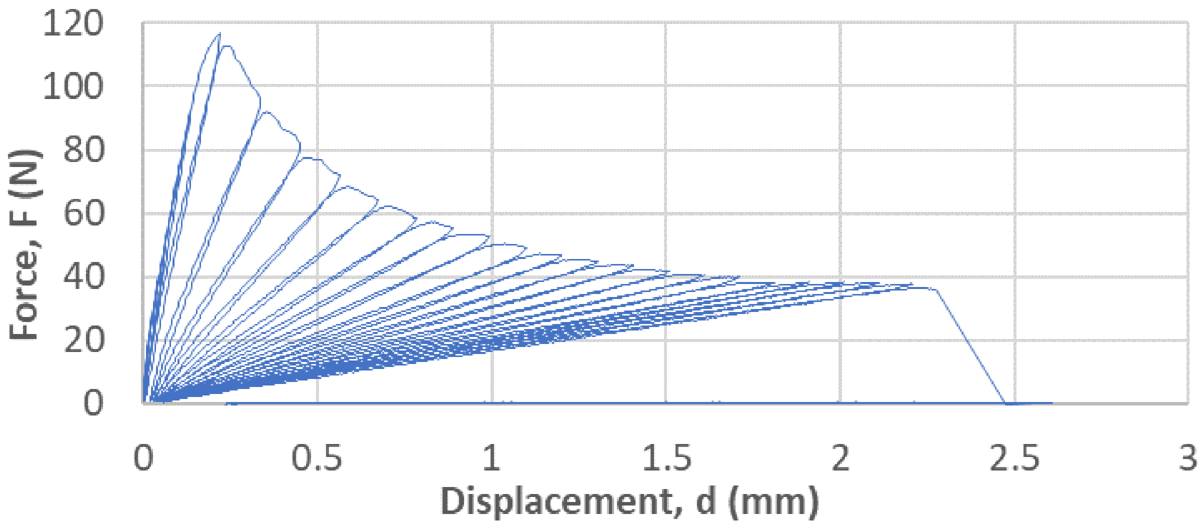


Example of Measured Load-Displacement Curves from ADCB Test [3]

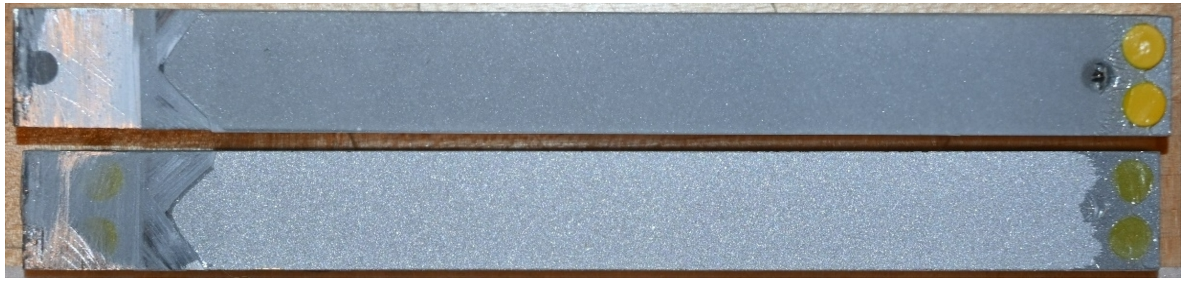
[1] Reedy & Stavig. (2020). *Int. J. Fracture*, *222*(1).
[3] Stavig, Jaramillo, Larkin, Dugger, & Reedy. (2019). *SAND-2019-14935.*

Experimental Method: ADCB Test


ADCB Set-up and Specimen

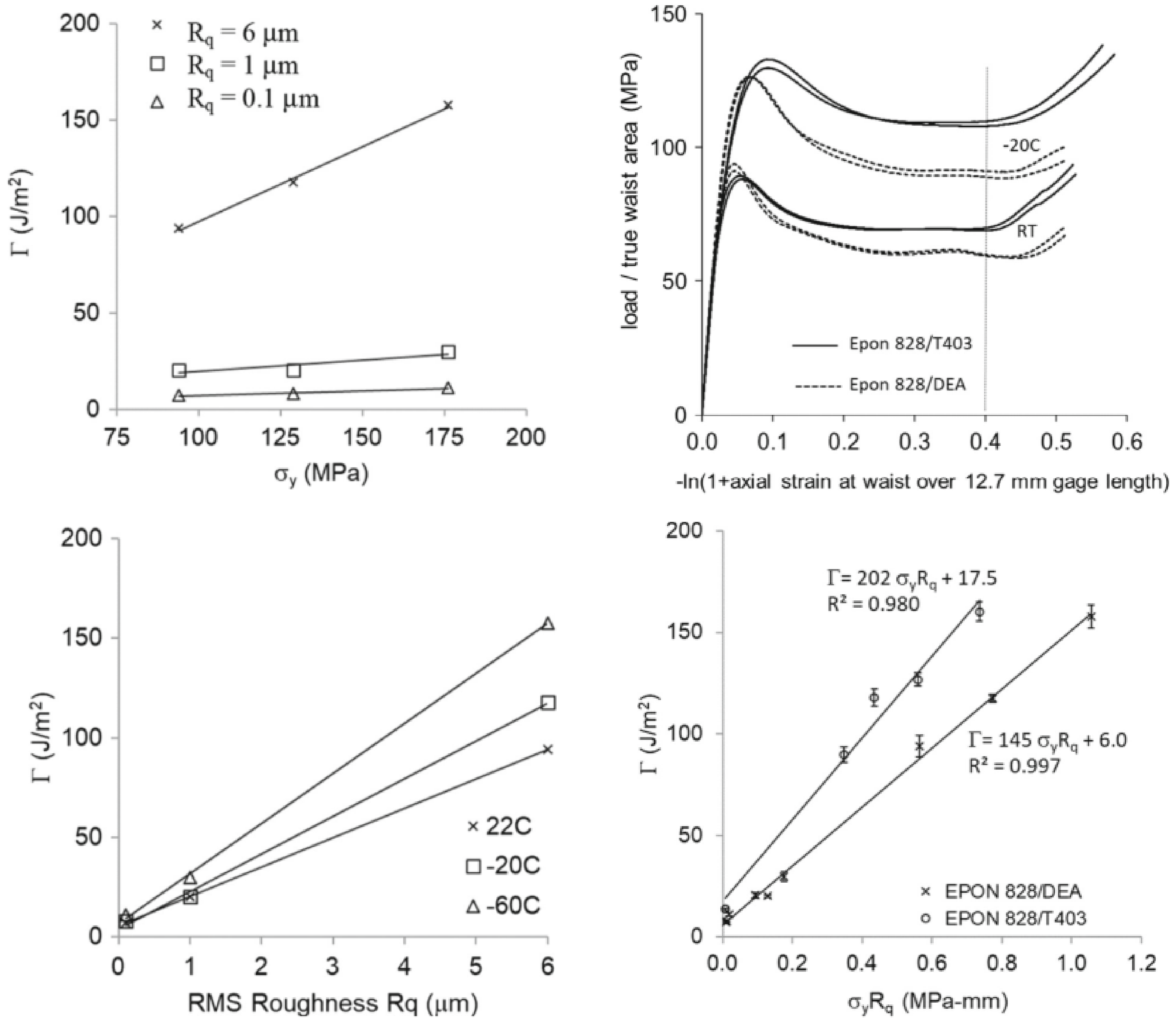


Example of Measured Load-Displacement Curves from ADCB Test


Fractured ADCB Specimen

Previous Work [1]

- Experiments conducted using ADCB method
- Toughness of epoxy/aluminum interface increases as temperature decreases
- Linear relationship observed between toughness and product of yield stress and surface roughness
- Proposed mechanism: Toughness related to energy required to yield material in a surface pit to the hardening strain

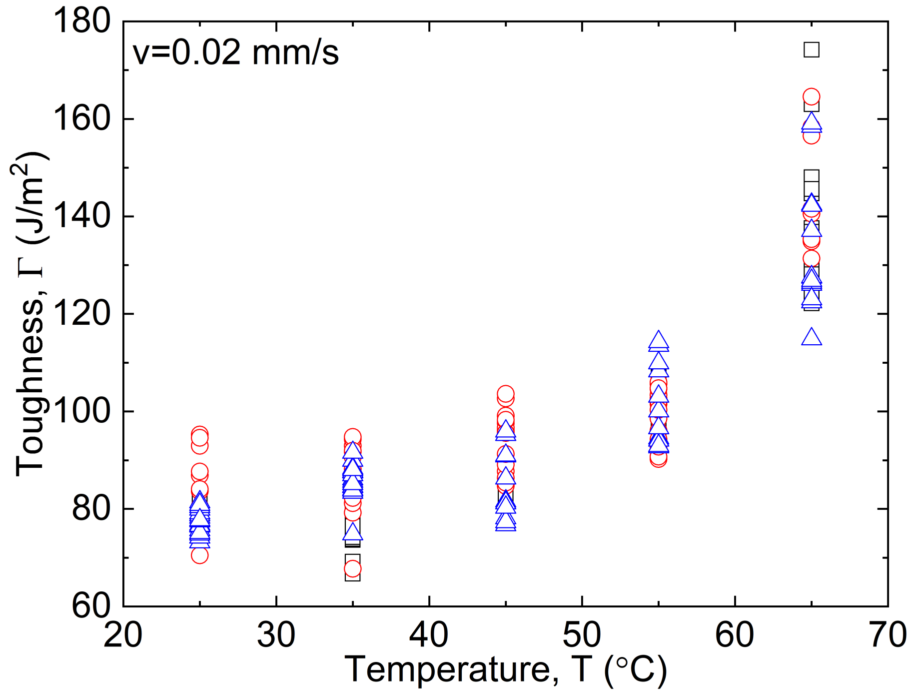


Results from ADCB Tests of Epoxy/Aluminum Interfaces, Compression Tests of Epoxy Adhesives [1]

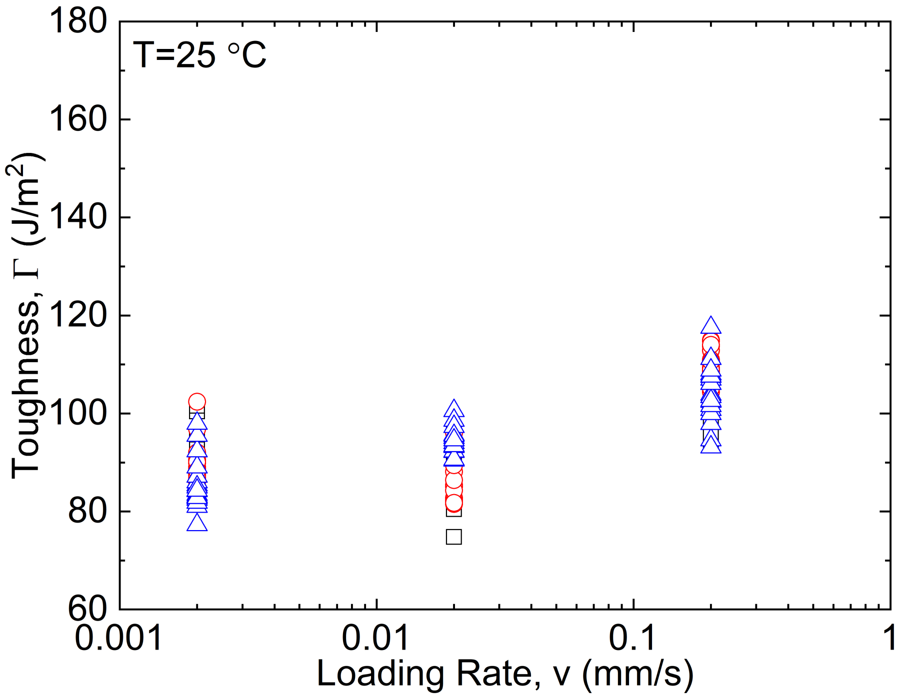
[1] Reedy & Stavig. (2020). *Int. J. Fracture*, *222*(1).

Measured Toughness Results

- ADCB tests conducted on epoxy/aluminum interfaces at 3 loading rates and 5 test temperatures
- Toughness minimized at room temperature, increases with loading rate
- Results indicate a transition from surface-dominated to bulk-dominated regimes



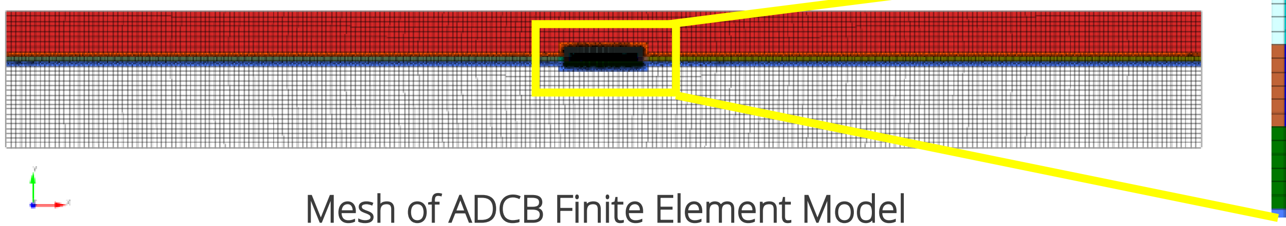
Toughness as a Function of Temperature (Fixed Loading Rate)



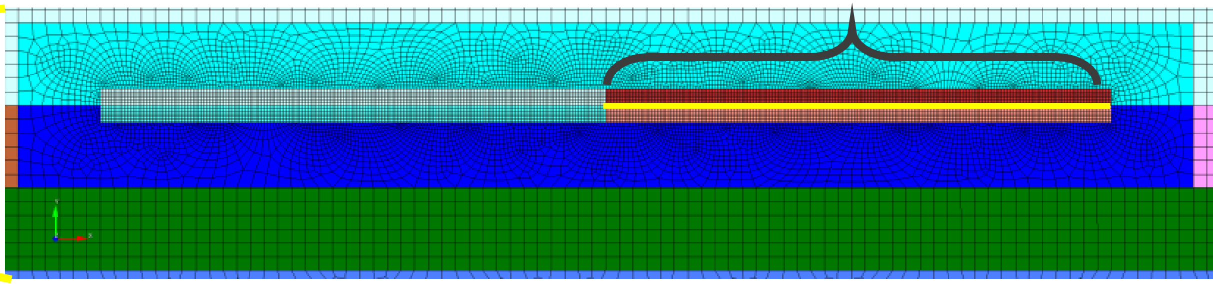
Toughness as a Function of Loading Rate (Fixed Temperature)

Modeling Approach

- Meshing performed using Cubit, FE solution calculated using Sierra/Solid Mechanics
- Mesh highly refined around the crack tip to resolve the cohesive zone, transitions to a coarser mesh in the bulk aluminum and epoxy
- Elastic model assumed for aluminum, nonlinear viscoelastic model assumed for epoxy [4-6], mode-dependent G_c cohesive zone model [7] assumed for epoxy/aluminum interface
- **Procedure**: Generate mesh for single crack length, anneal and cool epoxy, heat to test temperature, and apply end displacement at constant velocity until failure of the first (crack-tip) cohesive surface element



Mesh of ADCB Finite Element Model

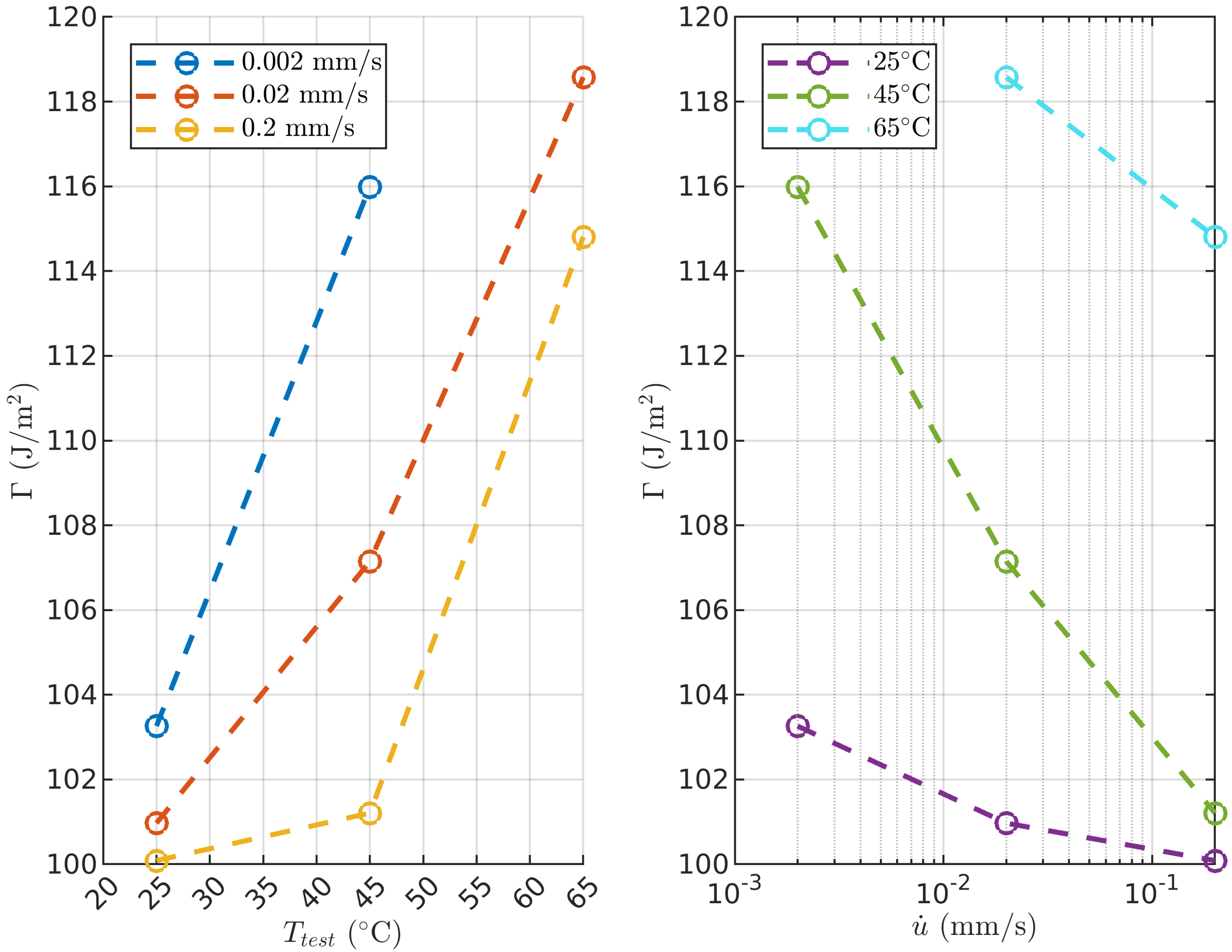


Local Mesh Refinement around Crack-Tip

[4] Adolf, Chambers, & Caruthers. (2004). *Polymer, 45*(13).
[5] Adolf, Chambers, & Neidigk (2009). *Polymer, 50*(17).
[6] Cundiff, Long, Kropka, Carroll, & Groves. (2021). *SAND-2021-11193.*
[7] Reedy & Emery. (2014). *Int. J. Solids Struct.*, *51*(21-22).

Initial Model Predictions

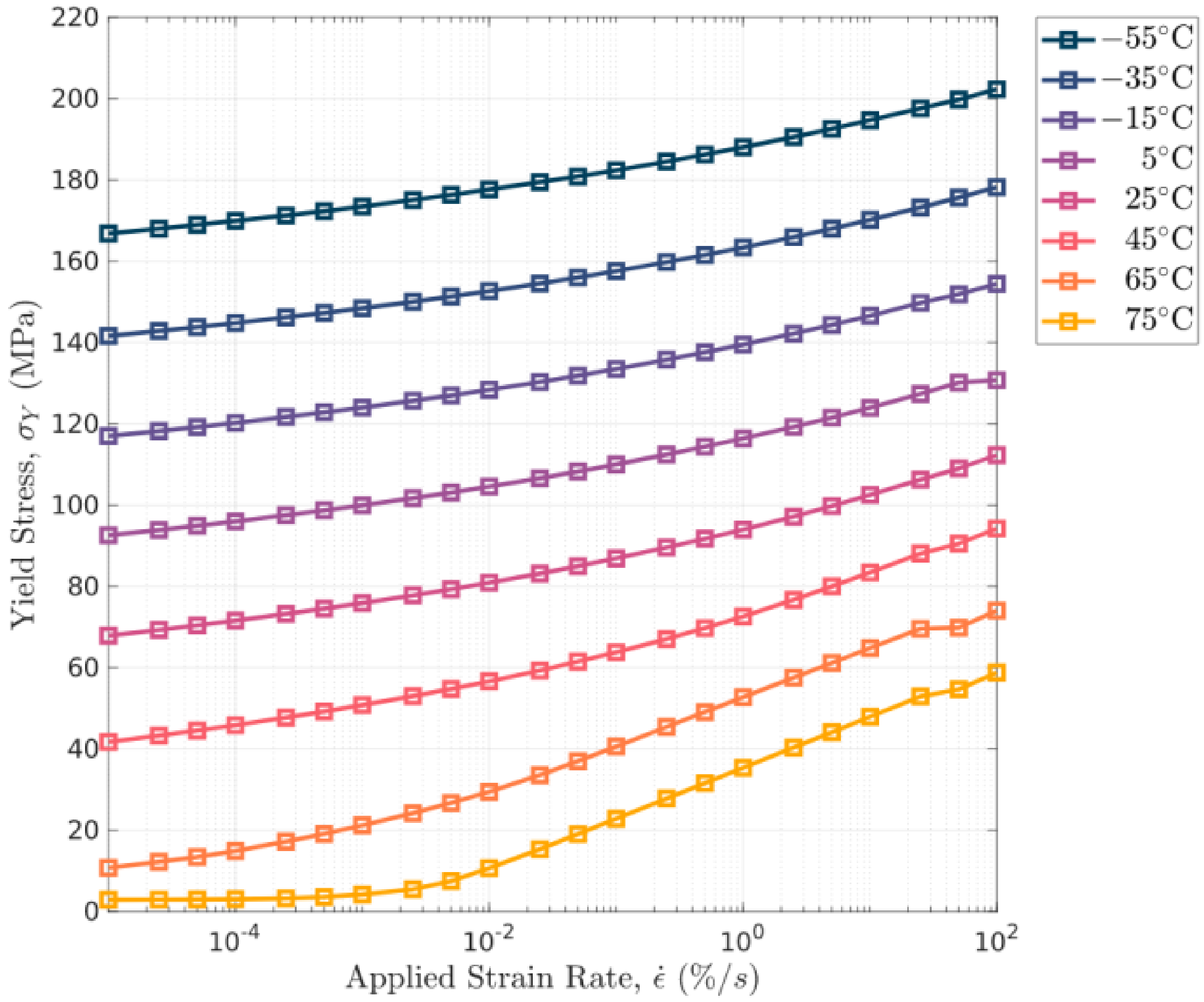
- For initial tests of the model, assumed a nominal toughness and strength of 100 J/m² and 100 MPa, respectively, for the interface
- Toughness predicted to **increase** with temperature, **decrease** with loading rate
- Cohesive zone parameters are independent of rate and temperature at this stage



Initial Model Predictions of Toughness Trends

Model Corrections

- Next, introduce temperature/rate dependence of the toughness and yield strength as follows:
  1. Calculate the epoxy yield stress as a function of temperature and strain rate using 1-element viscoelastic simulations
  2. Set peak stress as a function of calculated yield stress
  3. Calculate the interface toughness as a function of yield stress using Reedy-Stavig relation for EPON 828/DEA [1]
     - Assumed $R_q = 0.01$ mm
  4. Prescribe calculated peak stress and interface toughness *a priori* for each test temperature of interest
- Effect of loading rate on yield strength and toughness not yet incorporated

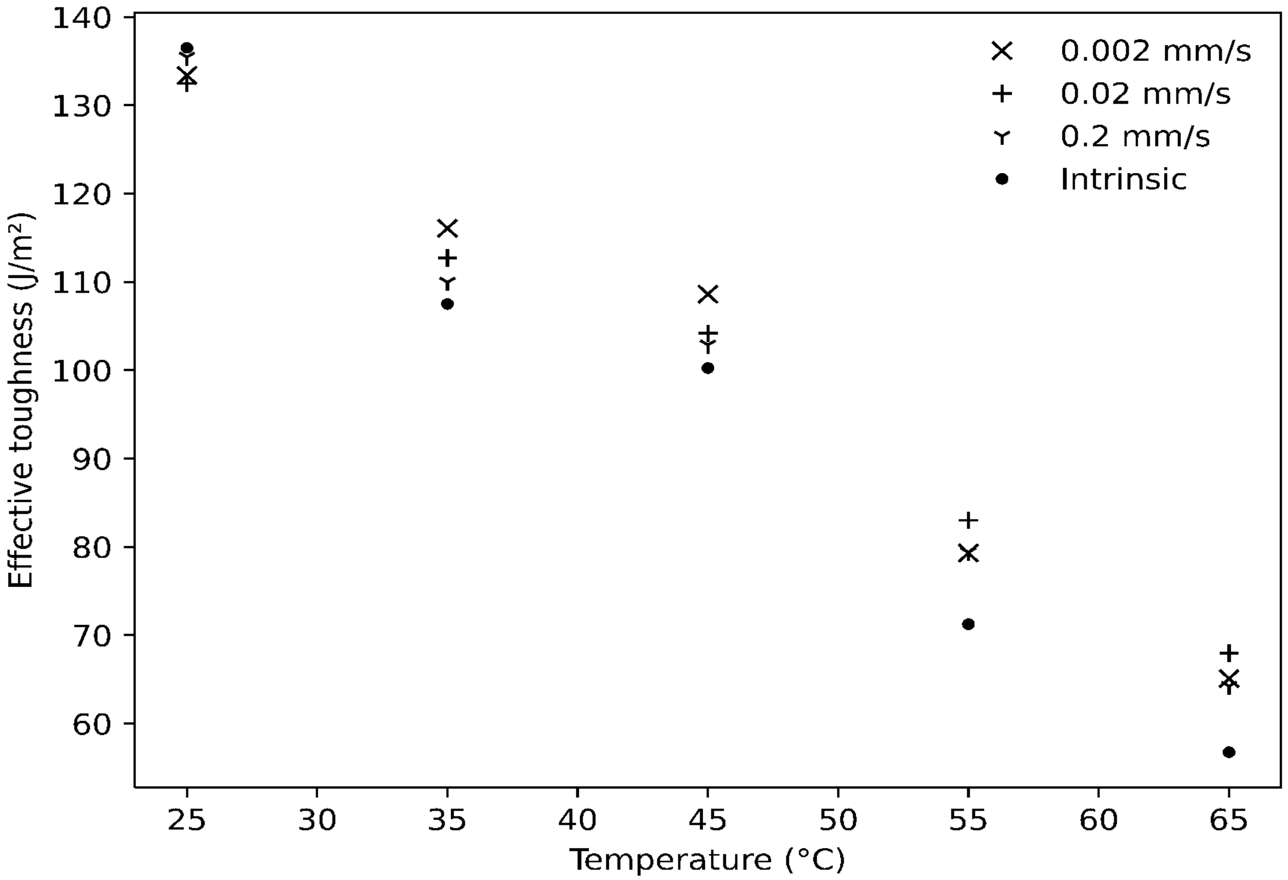


Yield Strength of Epoxy Element Subject to Uniaxial Tension

[1] Reedy & Stavig. (2020). *Int. J. Fracture*, *222*(1).

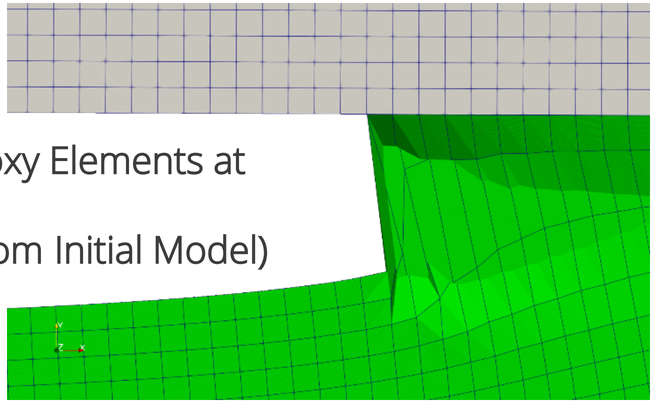
Updated Model Predictions

- Interface-dominated regime successfully captured, but the bulk-dominated regime is not fully resolved
- Some increase in effective toughness observed at higher temperatures
- Selection of peak stress results in different model behavior
  - Setting peak stress << yield stress results in interface failure with minimal dissipation
  - Setting peak stress >> yield stress results in epoxy softening and flow without failure of the interface
- Epoxy constitutive model does not include post-yield hardening, loses ellipticity after yielding



Initial Model Predictions of Toughness Trends
(Peak Stress Set to Twice the Epoxy Yield Stress)

Severe Distortion of Epoxy Elements at Crack-Tip
(65 C and 0.002 mm/s, from Initial Model)



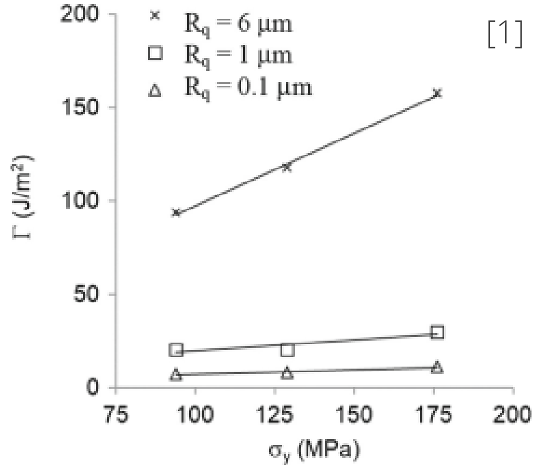
Conclusions and Future Work

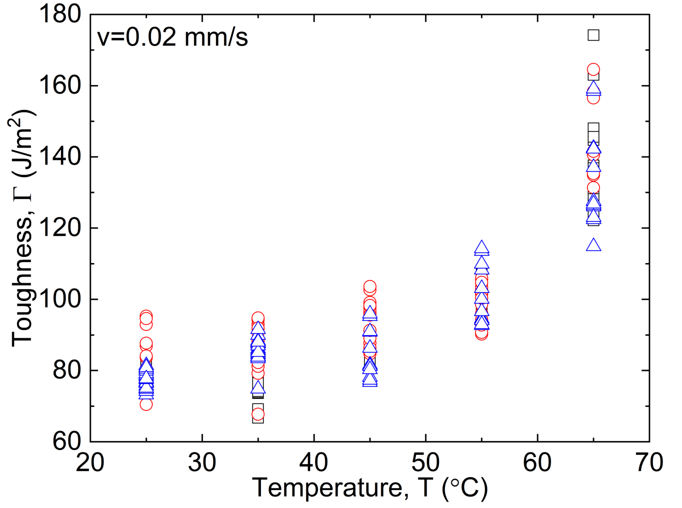
Conclusions

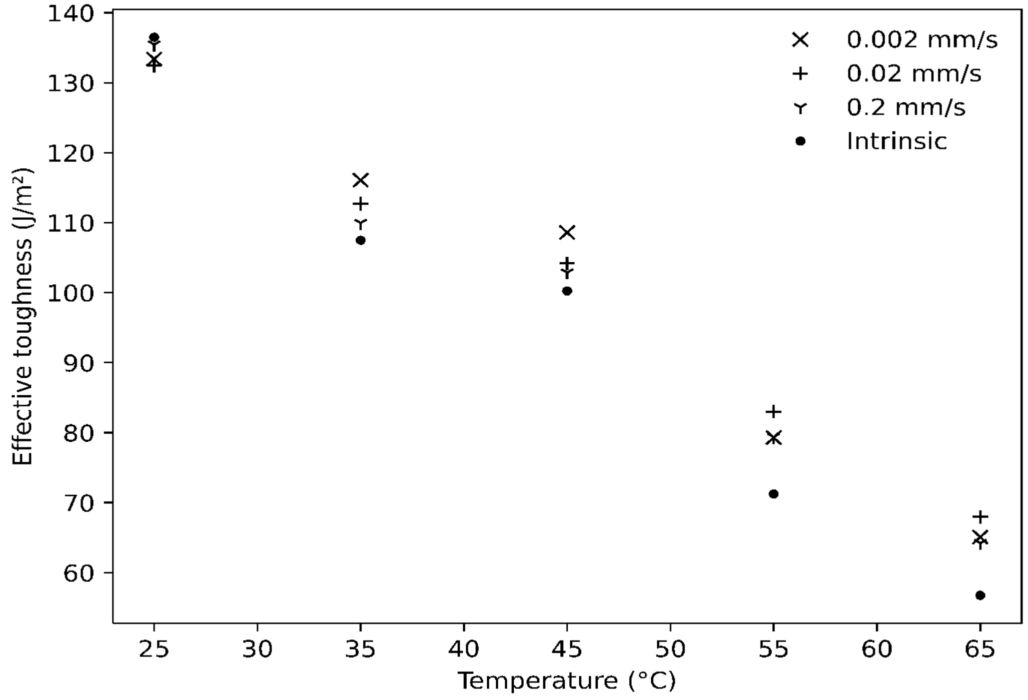
- Observed toughness of epoxy/aluminum interface is minimized at room temperature, increases with loading rate
- Model captured interface-dominated trends observed in experiments (i.e., toughening at low temperatures), but did not capture bulk-dominated trends (i.e., toughening at high temperatures)

Future Work

- Incorporate post-yield hardening or regularize softening in epoxy
- Include sub-critical crack growth and R-curve behavior
- Directly tie cohesive element parameters to epoxy state in the model







[1] Reedy & Stavig. (2020). *Int. J. Fracture*, *222*(1).

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- Experimental PI: Frank DelRio
- Experimental Technician: Todd Huber
- Robert C. Flicek

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Questions?

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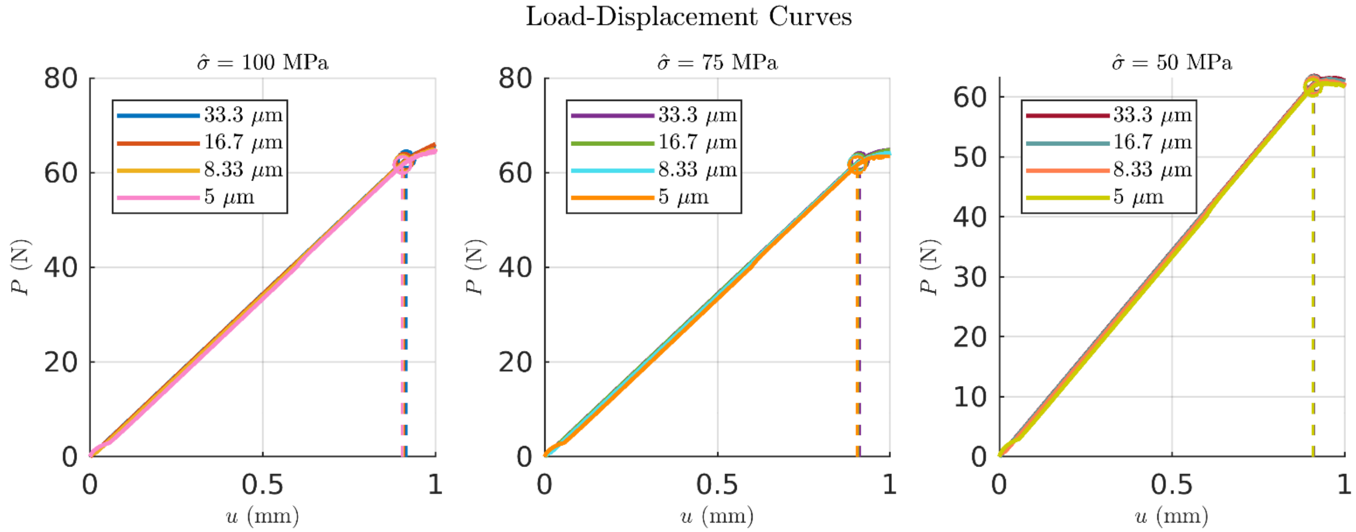
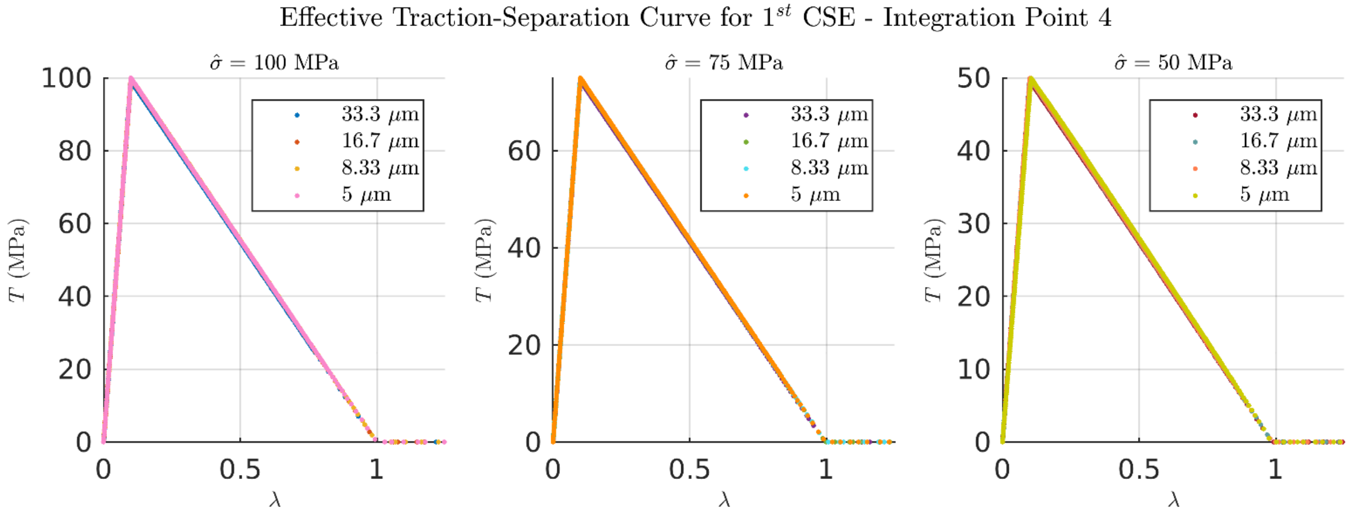
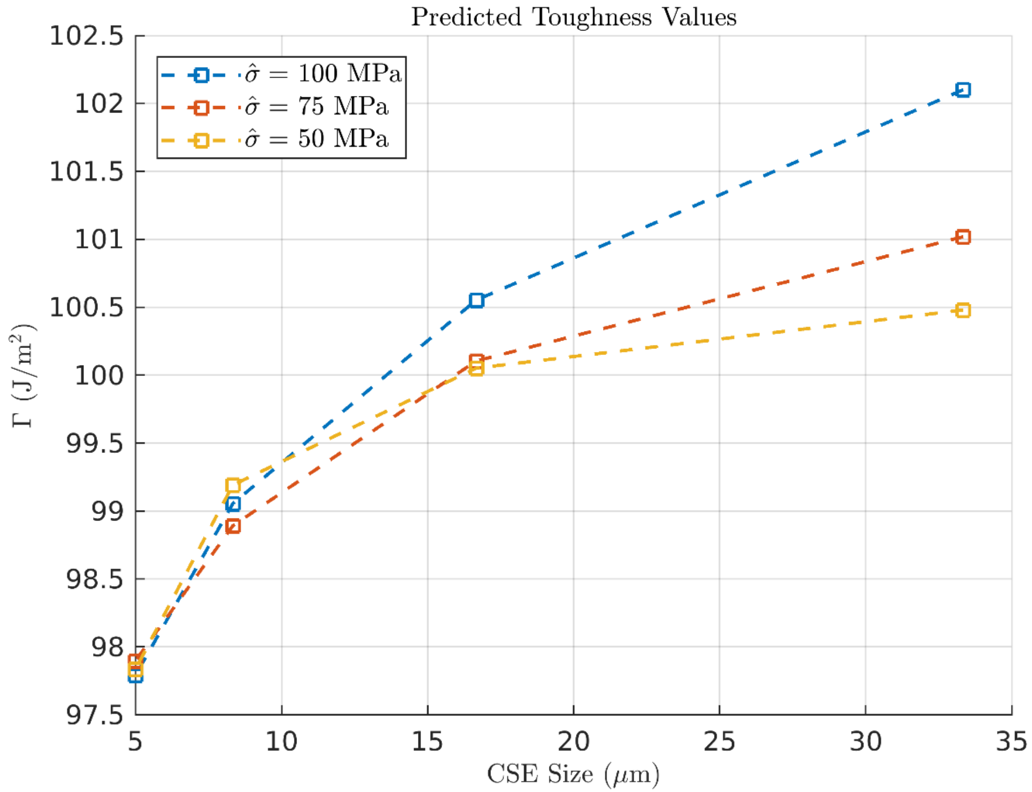
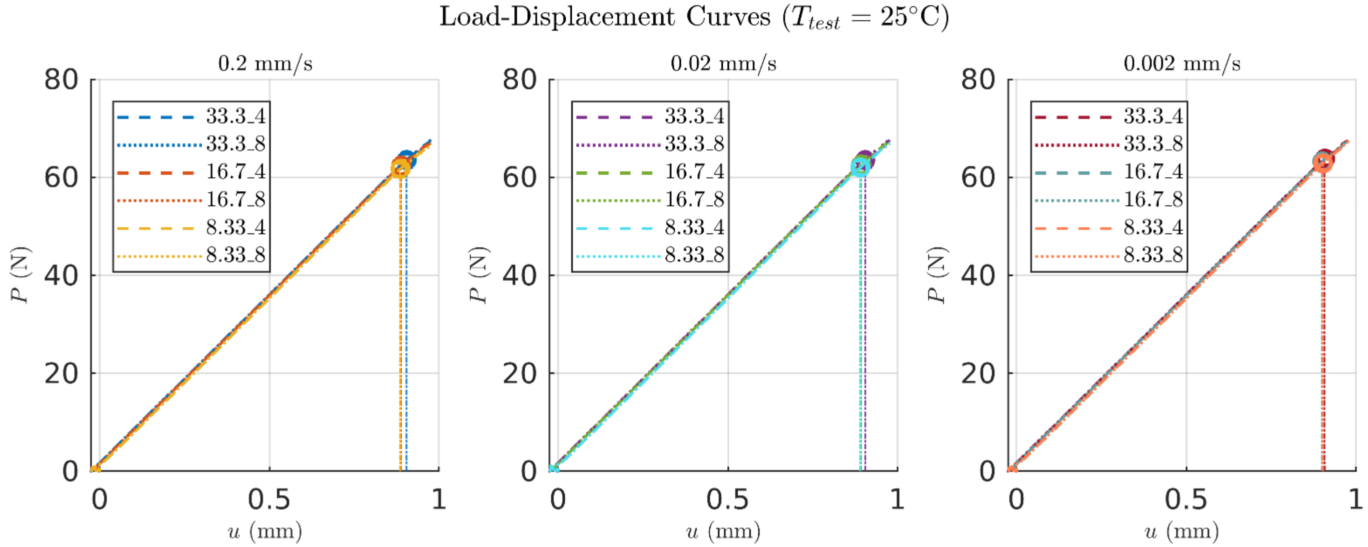
Supplementary: Mesh Convergence without Viscoelasticity

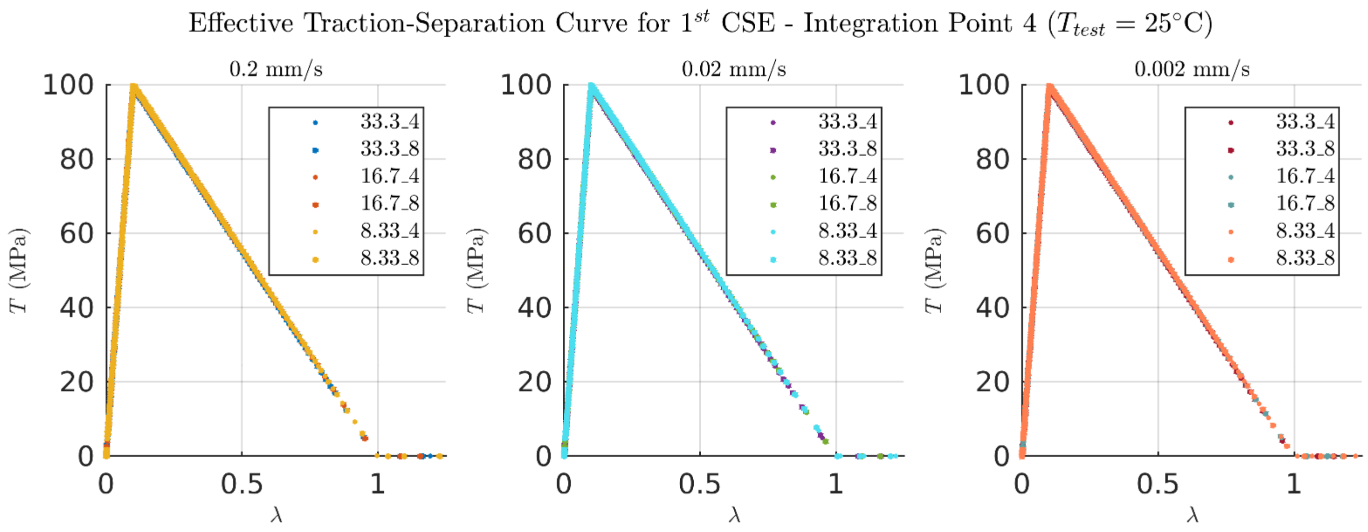


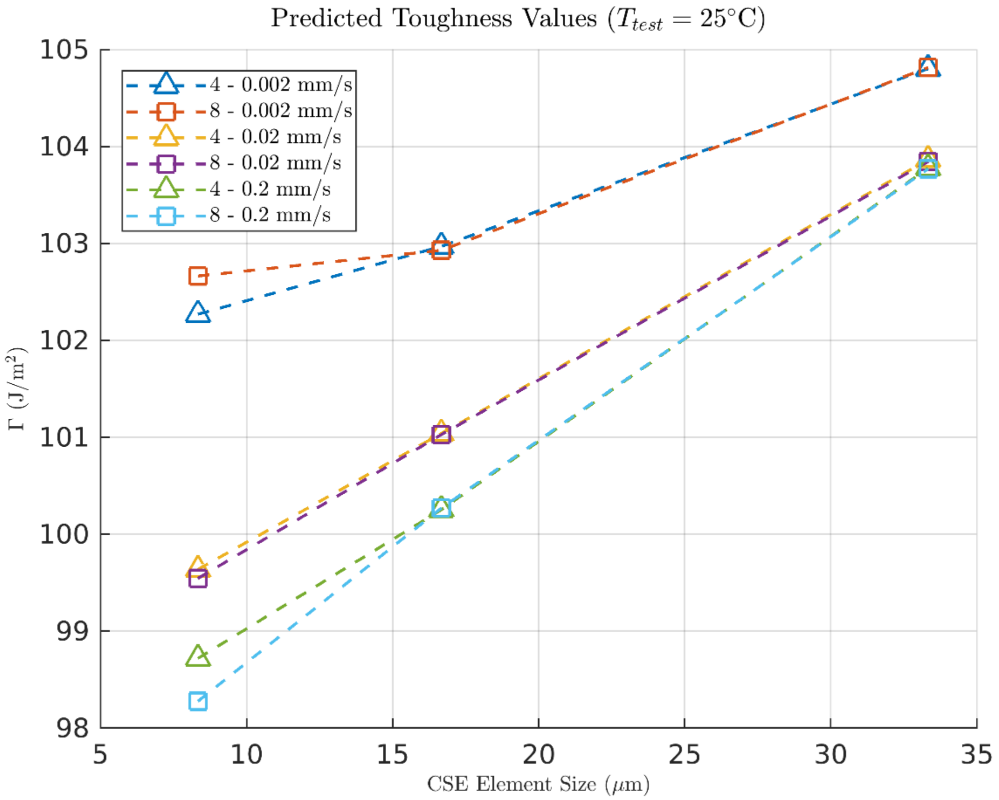




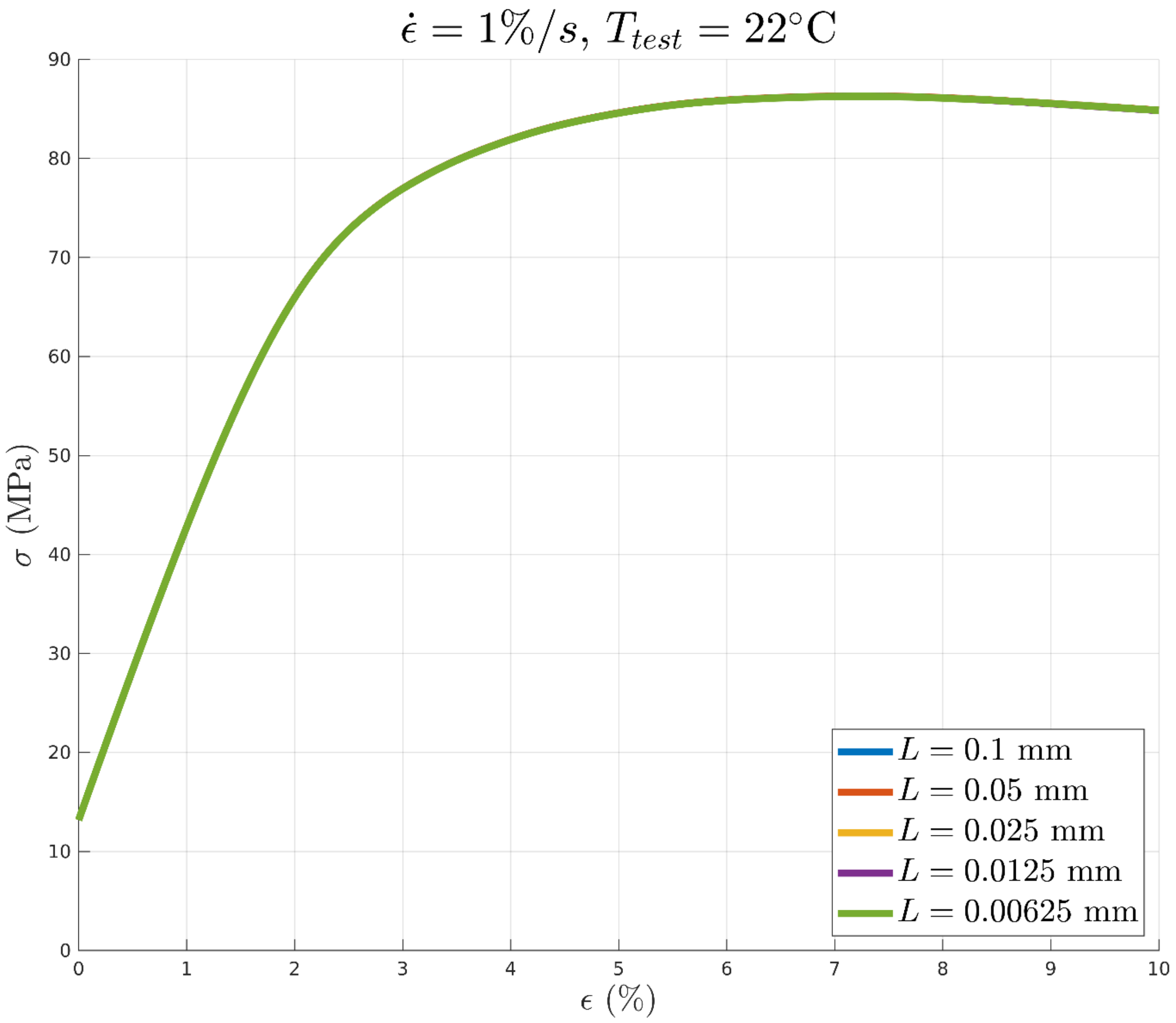
Supplementary: Mesh Convergence with Viscoelasticity







Supplementary: 1-Element Epoxy Study Convergence



Element Size L (mm)	Yield Stress σ_Y (MPa)
0.1	86.29
0.05	86.29
0.025	86.28
0.0125	86.27
0.00625	86.27