SAND2017-13363PE

Interfacial Fracture

Fracture Mechanics Seminar Series

Lecture 8: December 14, 2017

Dave Reedy

edreedy@sandia.gov
Component Science and Mechanics (1556)
Sandia National Laboratories
Albuquerque, NM

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. SAND NO. 2017-XXXXP

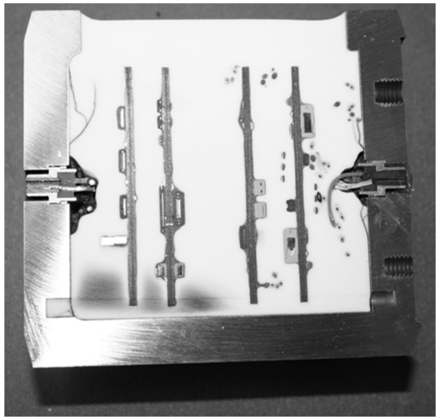
Seminar series outline

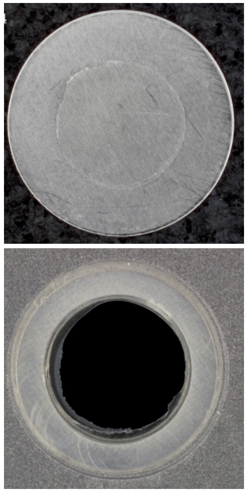
https://snl-wiki.sandia.gov/display/FMSS/Fracture+Mechanics+Seminar+Series+Home

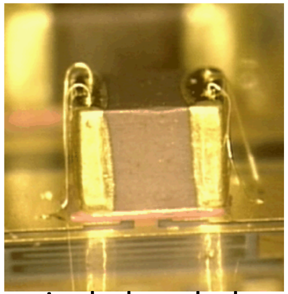
Lecture 1: **Basic Theory Part I**, Scott Grutzik (1851)	
Lecture 2: **Experimental Fracture Mechanics**, Jay Carroll (1851)	
Lecture 3: **Basic Theory Part II**, Scott Grutzik (1851)	
Lecture 4: **Fracture Resistant Design**, Jay Carroll (1851)	
Lecture 5: **Computational Methods for Brittle Fracture**, John Emery (1556)	
Lecture 6: **Computational Approaches for Resolving the Driving Force and the Resistance**, Jay Foulk (8343)	
Lecture 7: **The Materials Science of Fracture**, Brad Boyce (1881)	Nov 9, 2017
Lecture 8: **Interfacial Fracture**, Dave Reedy (1556)	Dec 14
Lecture 9: **Ductile Fracture Experiments**, Brad Boyce (1881)	Jan 11, 2018
Lecture 10: **Ductile Fracture Analysis**, Jay Foulk (8343)	Feb 8
Lecture 11: **Dynamic Fracture**, Bo Song (1528)	Mar 8
Lecture 12: **Shock/spall**, Tracy Vogler (8343)	Apr 12
Lecture 13: **Phase field fracture modeling**, Mike Tupek (1542)	May 10

Interfacial fracture

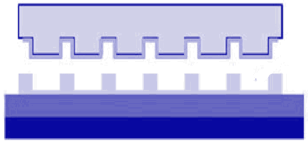
The performance and the reliability of many structures and components depend on the integrity of interfaces between dissimilar materials.

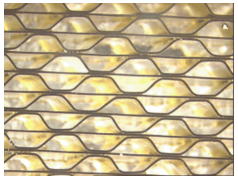

encapsulated printed circuit boards

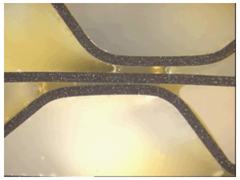

Adhesively bonded rupture disk


adhesively bonded electrical components


encapsulated components


NIL imprint and release


aluminum honeycomb



Outline

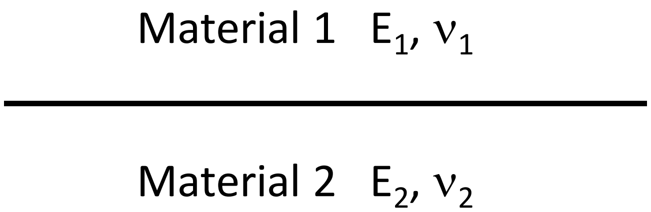
- Unique aspects of interfacial fracture
- Interfacial toughness
- Using cohesive zone models to analyze interfacial fracture

Dave Reedy edreedy@sandia.gov

Unique aspects of interfacial fracture

Dundurs' bimaterial mismatch parameters (JAM, 1969)

- The solution of a wide class of bimaterial plane elasticity problems depends only on 2 nondimensional combinations of the 4 elastic moduli (instead of the 3 that one might expect).
  - requires traction BCs and constraints on loads applied to holes in the body.



E_i, and ν_i are Young's modulus and Poison's ratio of linear elastic, isotropic material *i*.

for plane strain

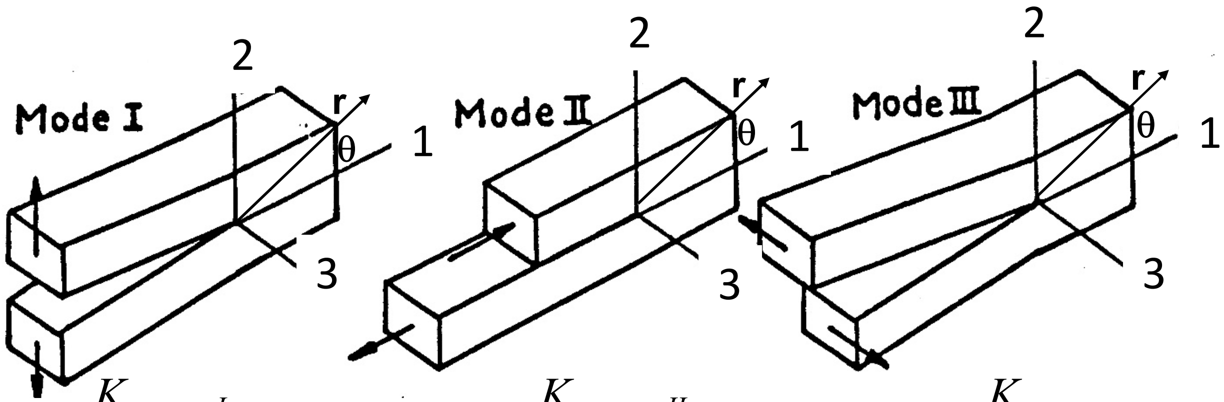
$$\alpha = \frac{\left(\bar{E}_1 - \bar{E}_2\right)}{\left(\bar{E}_1 + \bar{E}_2\right)}$$

$$\beta = \frac{1}{2}\frac{\mu_1\left(1-2\nu_2\right) - \mu_2\left(1-2\nu_1\right)}{\mu_1\left(1-\nu_2\right) + \mu_2\left(1-\nu_1\right)}$$

$$\text{where} \quad \bar{E}_i = \frac{E_i}{1-\nu_i^{\,2}} \quad \text{and} \quad \mu_{\mathrm{i}} = \frac{E_i}{2(1+\nu_i)}$$

- Flip materials, change sign of α and β.
  - $|\,\alpha\,| \le 1$, $|\,\beta\,| \le 0.5$, with α = 0 when the material 1 and 2 are the same.
  - When the bottom material is rigid
    - α = -1 and β= -1/2(1-2ν_1)/(1-ν_1) and if ν_1 = 1/3, β=-1/4

Review: Linear Elastic Fracture Mechanics



$$\sigma_{\alpha\beta} = \frac{K_I}{\sqrt{2\pi r}}\tilde{\sigma}^{I}_{\alpha\beta}(\theta) \qquad \sigma_{\alpha\beta} = \frac{K_{II}}{\sqrt{2\pi r}}\tilde{\sigma}^{II}_{\alpha\beta}(\theta) \qquad \sigma_{z\alpha} = \frac{K_{III}}{\sqrt{2\pi r}}\tau_{\alpha}(\theta) \qquad \alpha, \beta = 1 \text{ or } 2$$

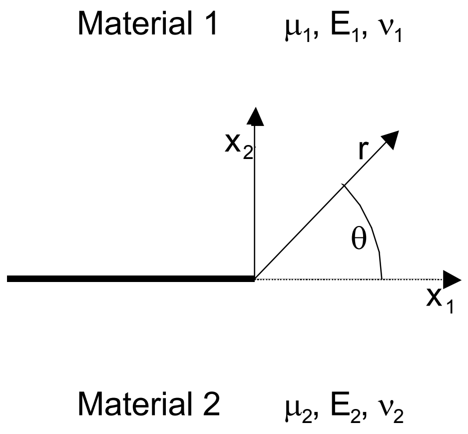
- Three independent modes of deformation, with magnitude defined by their respective *K*
- Can define crack-tip mode mixity as the ratio of shear-to-normal stress (θ=0). In the region dominated by the K-field

$$\psi = \tan^{-1}\left[\left(\frac{\sigma_{12}}{\sigma_{22}}\right)_{\theta=0}\right] = \tan^{-1}\left[K_{II} / K_{I}\right]$$

  - does not vary with distance from the crack tip.

- Typically only concerned with the Mode I toughness, K_{IC} since a crack tends to propagate along a path defined by pure mode I opening.

1st difference: crack-tip stress fields

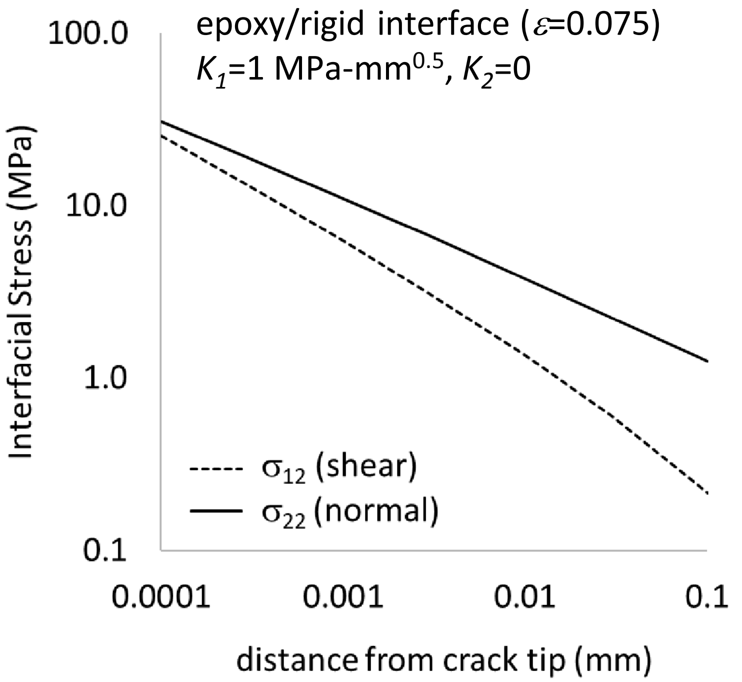


$$\left(\sigma_{22}+i\sigma_{12}\right)_{\theta=0}=\frac{Kr^{i\varepsilon}}{\sqrt{2\pi r}}$$

where $K=K_1+iK_2$ and $i\equiv\sqrt{-1}$

with $\varepsilon=\frac{1}{2\pi}\ln\left(\frac{1-\beta}{1+\beta}\right)$

when $\alpha=-1,\quad \varepsilon=\frac{\ln(3-4\nu)}{2\pi}$



$$\left(\sigma_{22}\right)_{\theta=0}=\frac{K_1\cos(\varepsilon\ln r)-K_2\sin(\varepsilon\ln r)}{\sqrt{2\pi r}}$$

$$\left(\sigma_{12}\right)_{\theta=0}=\frac{K_1\sin(\varepsilon\ln r)+K_2\cos(\varepsilon\ln r)}{\sqrt{2\pi r}}$$

Crack-tip stress fields for an interfacial crack have several unusual features:

- cannot separate into Mode 1 and Mode 2.
- the ratio of shear to normal stress varies with distance from the crack tip.

Definition of energy release rate *G* and mode-mixity ψ

- The energy release rate for crack advance in the interface *G* is an easier to understand quantity:

$$G = \frac{(1-\beta^2)(K_1^2 + K_2^2)}{E^*} \quad \text{where} \quad \frac{1}{\mathrm{E}^*} = \frac{1}{2}\left(\frac{1}{\overline{E}_1} + \frac{1}{\overline{E}_2}\right)$$

- To fully define crack-tip stress fields, need another quantity. The common choice is the crack-tip mode mixity ψ

$$\hat{\psi}_{r=\hat{l}} = \tan^{-1}\left[\left(\frac{\sigma_{12}}{\sigma_{22}}\right)_{\theta=0,r=\hat{l}}\right] = \tan^{-1}\left[\frac{\mathrm{Im}\left(K\hat{l}^{\,i\varepsilon}\right)}{\mathrm{Re}\left(K\hat{l}^{\,i\varepsilon}\right)}\right]$$

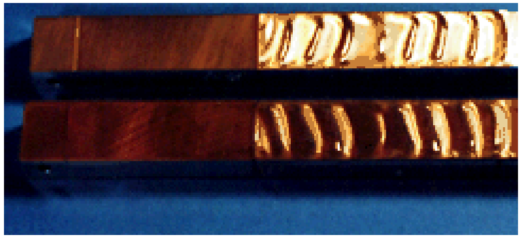
when $\hat{l}$ is chosen so that it is within the region dominated by the *K*-field

- $\hat{l}$ often chosen to be on the order of fracture process zone or plastic zone size.
- Note: $$\hat{\psi}_{r=\hat{l}_2} = \hat{\psi}_{r=\hat{l}_1} + \varepsilon \ln\left(\hat{l}_2 / \hat{l}_1\right)$$
- For an epoxy/rigid interface ε=0.075, and there is ~10º shift in $\hat{\psi}_{r=\hat{l}}$ when $\hat{l}$ is increased by a factor of 10.

2nd difference: toughness and fracture path are strongly dependent on Ψ

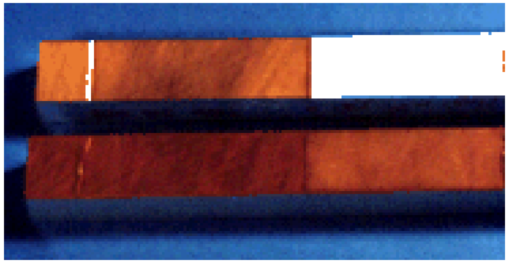
- Mode mixity $\Psi_{r=l}$ is a measure of shear-to-opening deformation at in the region of the crack tip

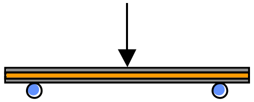
- Interfacial cracks are subjected to a mixed mode loading because of material and geometric asymmetries.



DCB
ADHERENDS SAME THICKNESS

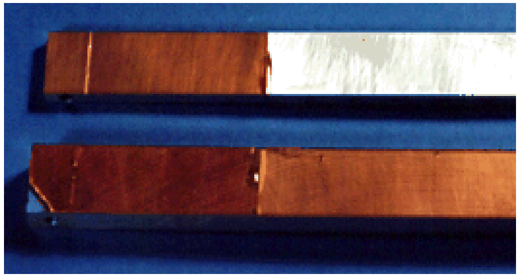
$\Gamma = 140\ \mathrm{J/m^2}$
$\psi_{l=10\mu m} = 8^o$





ENF
ADHERENDS SAME THICKNESS

$\Gamma = 2000\ \mathrm{J/m^2}$
$\psi_{l=10\mu m} = -83^o$



ADCB
TOP ADHEREND HALF AS THICK

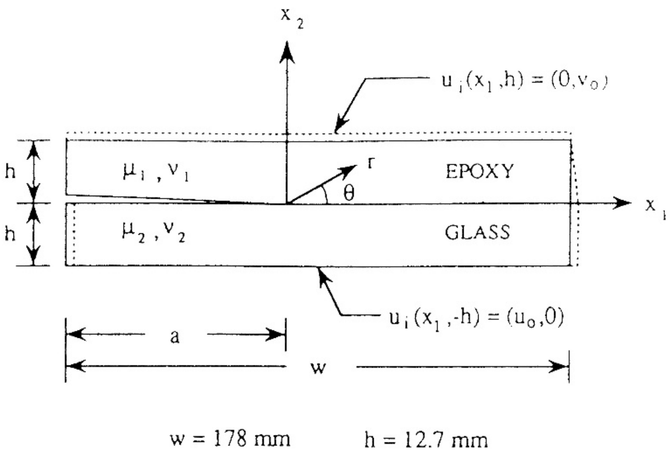
$\Gamma = 60\ \mathrm{J/m^2}$
$\psi_{l=10\mu m} = -8^o$

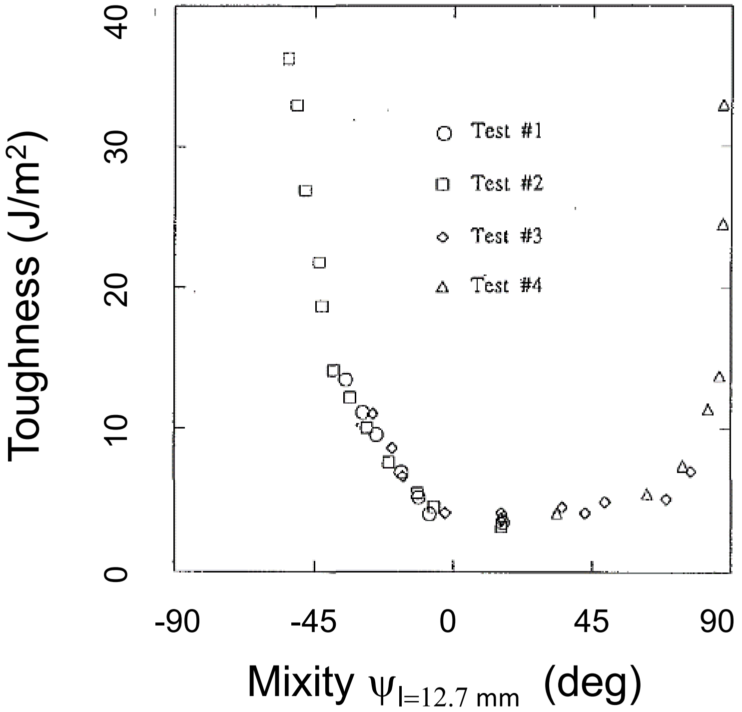
All specimens cut from the same bonded plate. Teflon film on portion of upper interface to initiate crack.

8.7 mm thick 6061-T6 plates and 1 mm thick 828 Z adhesive bond.

Reedy/Guess 1997

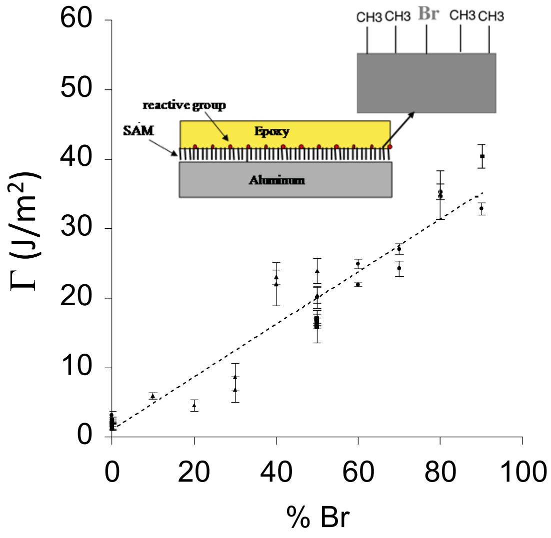
Liechti and Chai: mode-mixity dependent toughness





- Epoxy/glass edge-cracked bimaterial beam (low toughness interface).
- Apparent interfacial toughness is a strong function of crack-tip mode-mixity.
- Toughness increases by about a factor of 10.
- Liechti, K.M. and Chai, Y.S., Journal of Applied Mechanics, 1992. 59: p. 295-304.

3rd difference: interfacial toughness depends on additional physical quantities



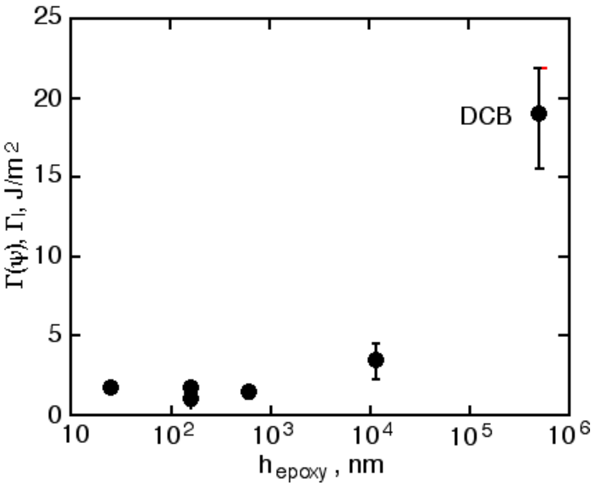
Surface Chemistry

Reedy, Kent, and Moody,26th Annual Meeting of The Adhesion Society, Myrtle Beach, SC (2003) .

Surface Roughness (microns)	Γ (J/m²)	Standard Deviation (J/m²)
0.2	22	3
1.0	31	7
5.0	126	11
7.0	168	5

Surface Roughness

Emerson, Guess, Adkins, Curro, Reedy, Lopez, and Lemke, SAND2000-1042



Layer Thickness

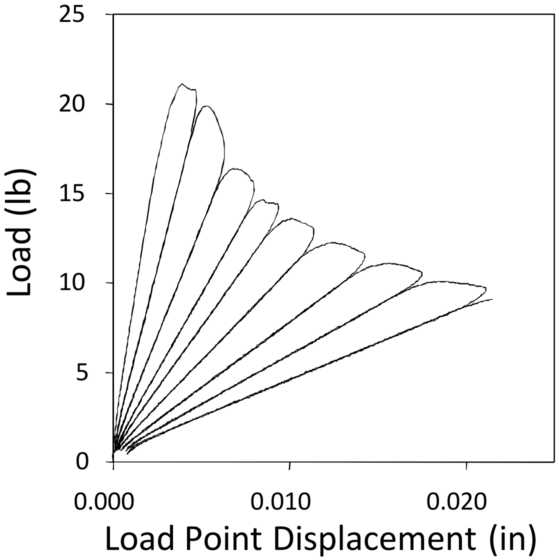
Moody, Reedy, and Kent, SAND2002-8567.

All data for an aluminum/epoxy interface

- Can also depend on temperature, loading rate, environmental aging, radiation, etc.
- Good source for additional information on the theory of interfacial fracture: Hutchinson, J. W. and Suo, Z. (1992). Mixed mode cracking in layered materials. Advances in Applied Mechanics. J. W. Hutchinson and T. Y. Wu, Academic Press. 29: 63-191. (can be found on the web).

Interfacial toughness

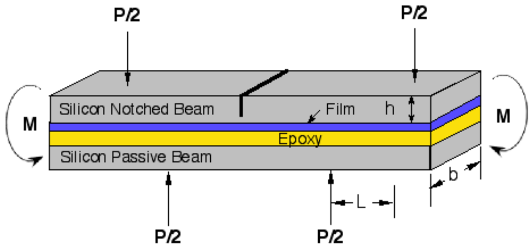
Asymmetric Double Cantilevered Beam Sandwich specimen

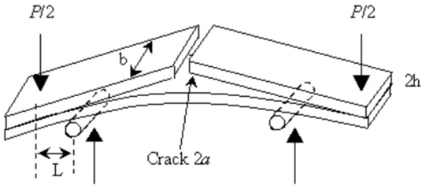


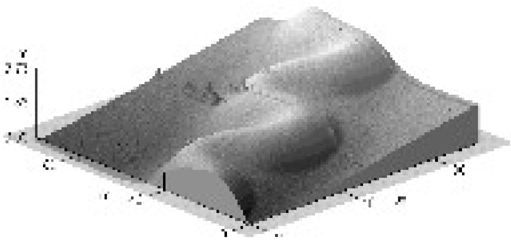
- Our workhorse specimen for measuring interfacial toughness.
- Can make multiple Γ measurements per specimen (crack propagates stably).
- Use unloading compliance to determine crack length.
- Produces a predominantly Mode I crack-tip loading with a slight tendency to push the crack towards the interface $(\Psi_{l=10\mu m} = -8^o)$.
- Γ depends on surface chemistry, roughness, adjacent bulk materials, temperature, loading rate, environmental aging, etc.

Example of other methods to measure interfacial toughness

- Four-Point Bend Test
  - -Infer toughness from load to propagate crack.
  - - Imposes nominally balanced mode mixity.
  - -Requires a relatively large sample size.
  - -Issues include: precracking, cracking on desired interface, epoxy yielding.
  - -Can impose direction of crack propagation.
- Stressed Overlayer Test
  - -Compressively stressed overlayers generate buckles.
  - -Infer toughness from buckle shapes.
  - -Imposes nominally mode II shear loading.
  - -Requires a relatively small sample.
  - -Issues include: 'tune in' the overlayer thickness to match interfacial toughness and cracking on desired interface.
  - -buckles will tend to grow in direction of lowest toughness.

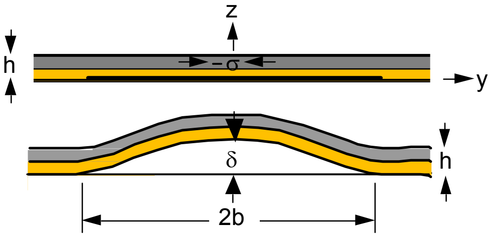






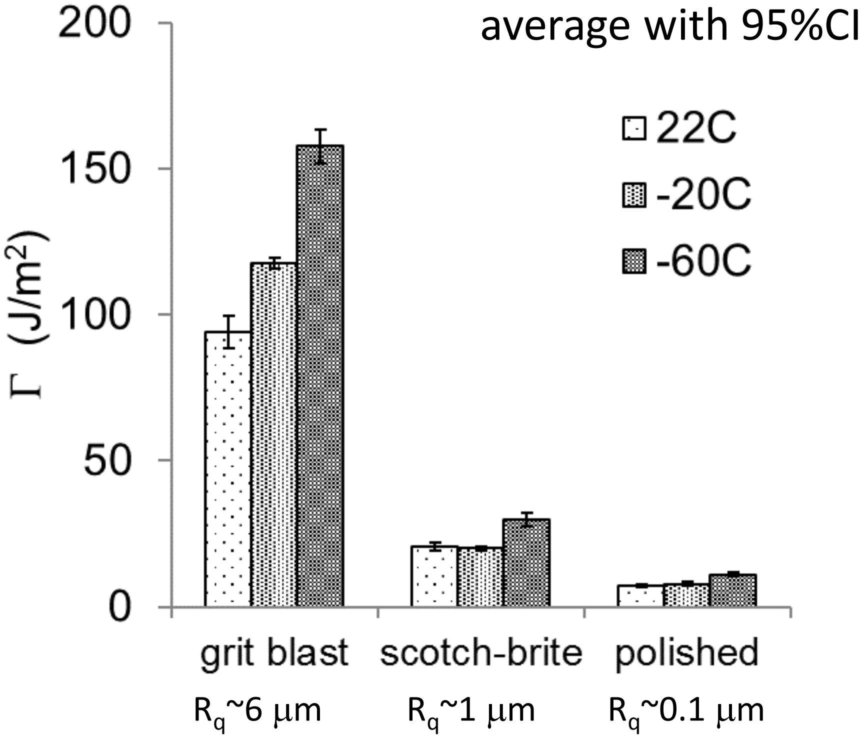
Often generate telephone cord blisters.

Compressive stress in W is easily controlled during DC magnetron sputtering deposition.



Dependence on surface roughness and test temperature

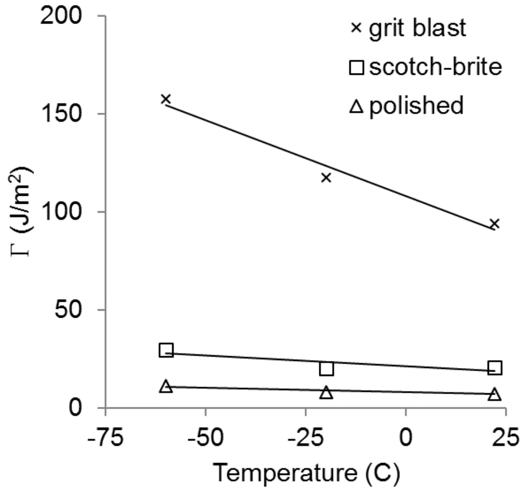
- Tested an epoxy/aluminum interface
    - Epon828/DEA epoxy (100:12 mix ratio 71C cure)
    - 6061-T6 aluminum cleaned prior to bonding
- Both temperature and surface roughness have a strong impact on interfacial toughness
- Used ADCBS to measure Γ

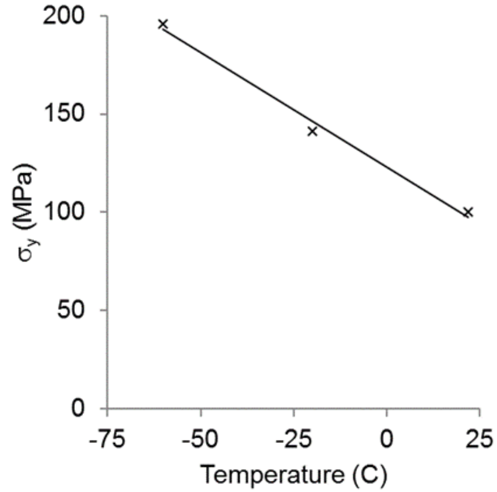


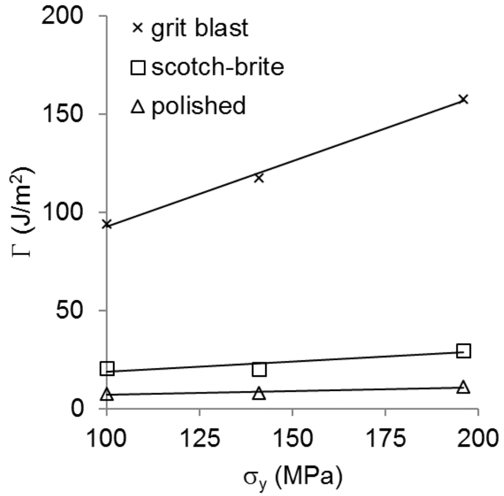
At RT average Γ=

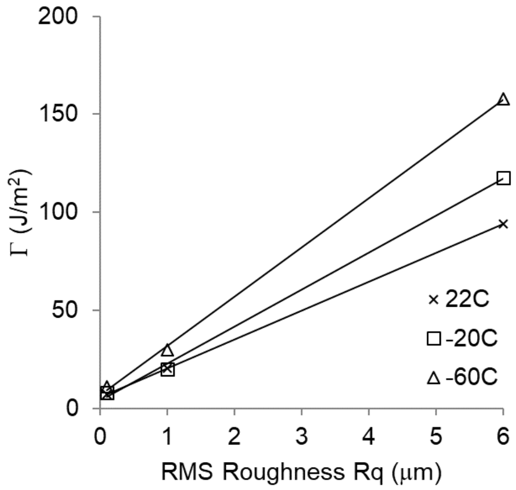
- 7 J/m^2 for polished surface
- 20 J/m^2 for scotch-brite roughened surface
- 94 J/m^2 for grit-blasted surface

Dependence on surface roughness and test temperature



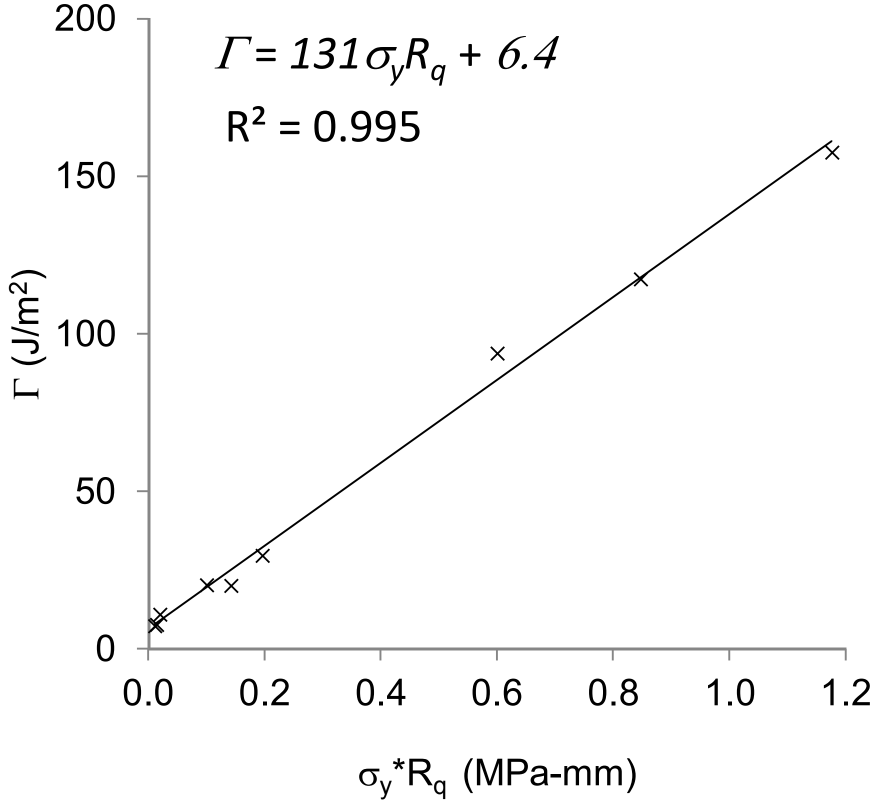






- ~50 % increase in Γ when test temperature is decreased from RT to -60C (~independent of roughness level).
- > factor of 15 increase in Γ when R_q is increased from 0.1 µm to 6 µm (~independent of test temperature)
- $\Gamma = C{*}\sigma_y{*}R_q + \Gamma_o$??

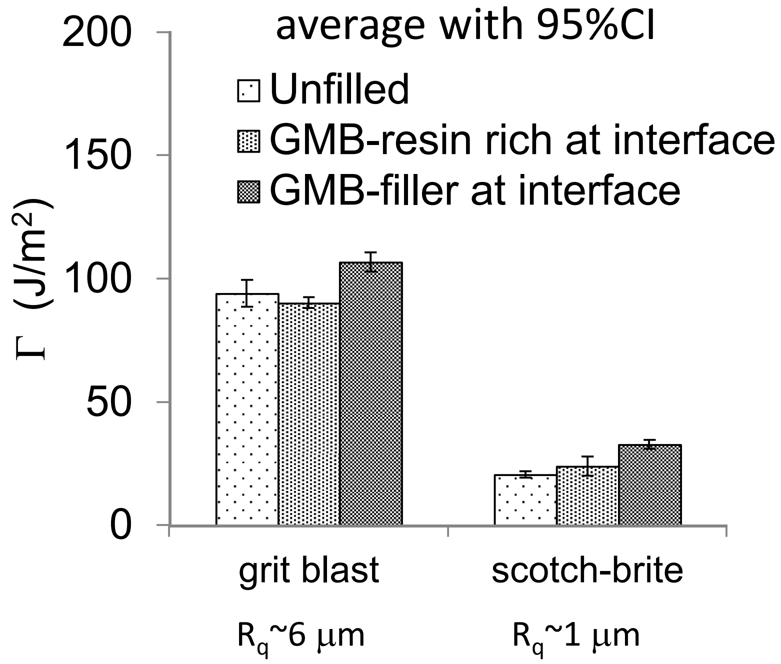
Dependence on surface roughness and test temperature



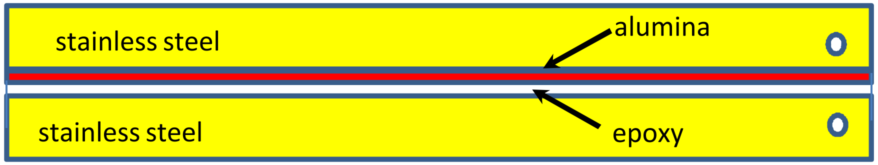
- Form of relationship is consistent with a simple model based on work to pull epoxy from a pit of depth R_q when the epoxy strain softens and then hardens (with crack-tip plastic zone size commensurate with R_q).

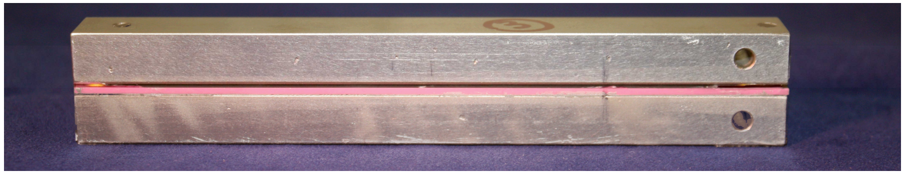
Effect of filler on interfacial toughness

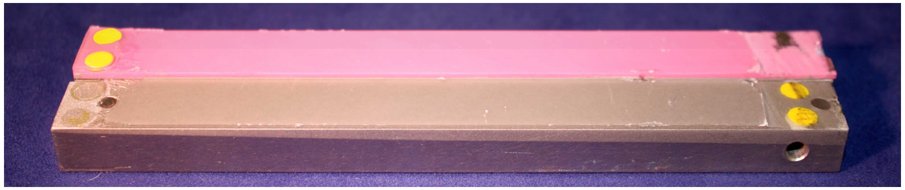
- Measured the toughness Γ of an GMB-filled epoxy/aluminum interface at RT
- Aluminum interface either grit blasted or roughened with scotch-brite.
- Epoxy either unfilled or with ~30% by weight glass microballoons (GMB).
  - during cure sample oriented so that GMB either floats to the interface or away from the interface (resin rich).
- Roughness has a large effect on Γ.
- GMB filler has a modest effect on Γ when the GMB floats to the interface.

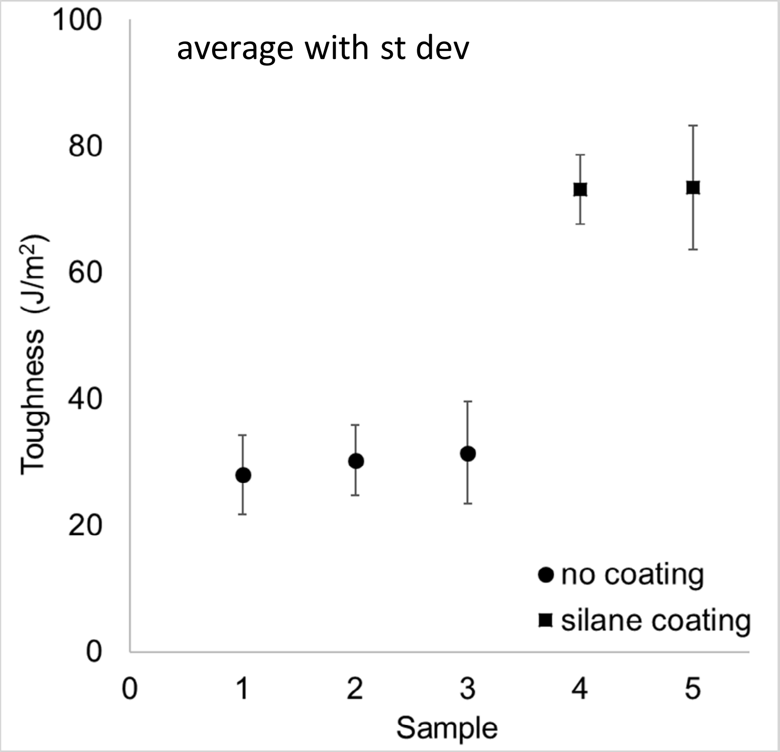


Toughness of an alumina/epoxy interface





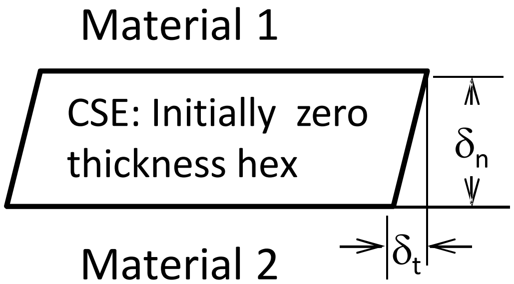


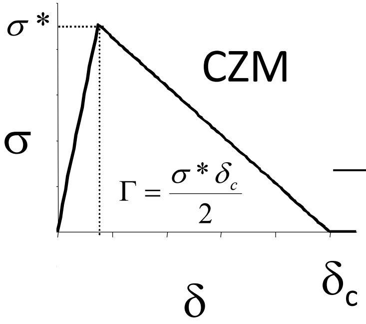


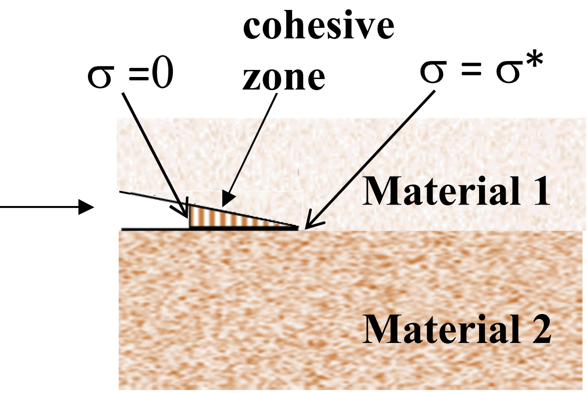
Dave Reedy edreedy@sandia.gov

Using cohesive zone models to analyze interfacial fracture

Cohesive surface element (CSE) and cohesive zone model (CZM)







- CSE: collapsed hex (tet) with zero initial thickness.
  - formulated in terms of normal and tangential displacement jumps across the interface.
  - CZM determines how interfacial tractions resist these displacement jumps.
- Crack growth is a natural outcome of the solution; bond failure is a gradual process with tractions resisting separation.
- Well-suited for modeling interfacial crack growth when crack path is known.
- Material separation specified in terms of a traction-separation (σ–δ) relationship.
- Key parameters are the interfacial strength σ^* and the work of separation/unit area of interface Γ.
- Mesh-independent results.
- CZMs can generalize response to include interfacial shear, $\Gamma = \Gamma(\Psi)$, etc.

Cohesive Zone (CZ) Model: Some background

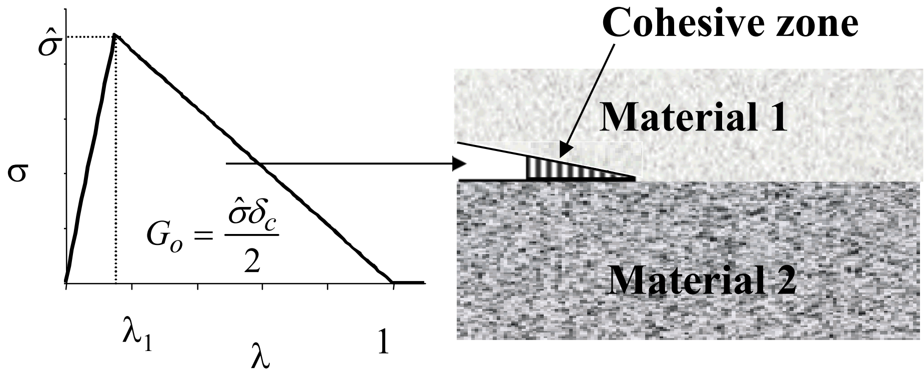
- Extensive literature : > 400 journal papers with CZ in title/abstract in 2017.
- Notable work includes:
  - Dugdale (JMPS, 1960) and Barenblatt (Adv. Appl Mech, 1962) are often credited as originating the concept of a cohesive zone (with tractions at crack tip to remove the singularity).
  - Initial attempts to model interfacial debonding: Needleman (JAM, 1987), Xu and Needleman (JMPS, 1994).
  - Application to elastic-plastic materials to investigate how bulk yielding affects apparent toughness: Tvergaard and Hutchinson (JMPS, 1992 and 1993).
  - Experimental data showing that the apparent interfacial toughness increases with crack-tip shear (i.e., mode mixity): Liechti and Chai (JAM, 1992).
  - Mixed mode formulation for beam-like joints. Yang and Thouless (IJF 2001).
  - Using MD to determine CZ model Gall, et. al. (JMPS, 2000), Zhou (MOM, 2008, Acta Materialia, 2009).

Dave Reedy edreedy@sandia.gov

Cohesive Zone Model can be used in several ways

- Phenomenological model that can be used in many ways. Still many issues.
- Interface between two linear elastic materials
  - essentially LEFM provided that CZ is small relative to model dimensions.
  - crack propagates at G_c (need a CZM that directly includes Ψ effects).
  - can pick $\hat{\sigma}$ so CZ is sufficiently small and resolved for element size used.
- Interface between materials that can yield
  - can possibly model LSY and generate a mode mixity effect.
  - not always clear how to apportion dissipation between CZ and bulk.
  - $\hat{\sigma}$ controls amount of crack-tip yielding --- may need constitutive model that is accurate to very large strains, etc.
- CZ replaces a finite thickness adhesive bond
  - Can choose CZ parameters to model bond stiffness and yield strength as well as bond toughness.

Tvergaard and Hutchinson (J.Mech. Phys. Solids, 1993).



- $\sigma(\lambda)$ is the effective traction-separation relationship, where the effective separation λ is

$$\lambda = \sqrt{\left(\frac{\delta_n}{\delta_n^c}\right)^2 + \left(\frac{\delta_t}{\delta_t^c}\right)^2}$$

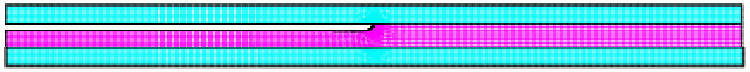
and δ_n and δ_t are the normal and tangential displacement jump across the interface while δ_n^c and δ_t^c are the respective critical values.

- Normal and tangential interfacial tractions are defined via a potential (no intrinsic mode-mixity effect).

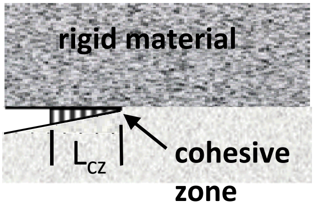
$$\phi(\delta_n, \delta_t) = \delta_n^c \int_0^\lambda \sigma(\lambda')d\lambda'$$

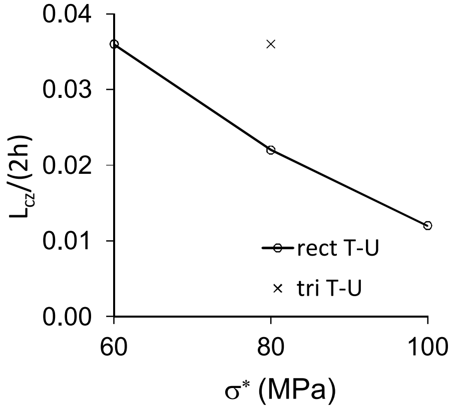
$$T_n = \frac{\partial\phi}{\partial\delta_n} = \frac{\sigma(\lambda)}{\lambda}\frac{\delta_n}{\delta_n^c} \quad \text{and} \quad T_t = \frac{\partial\phi}{\partial\delta_t} = \frac{\sigma(\lambda)}{\lambda}\frac{\delta_n^c}{\delta_t^c}\frac{\delta_t}{\delta_t^c}$$

Does the shape of the T-U relationship matter? Propagation of a long interfacial crack

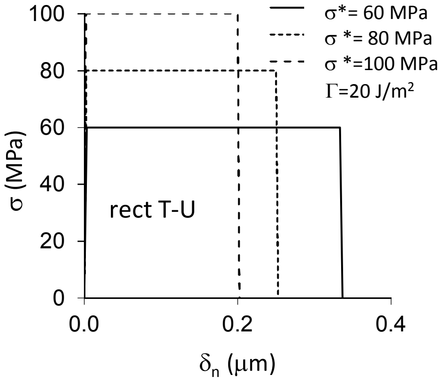


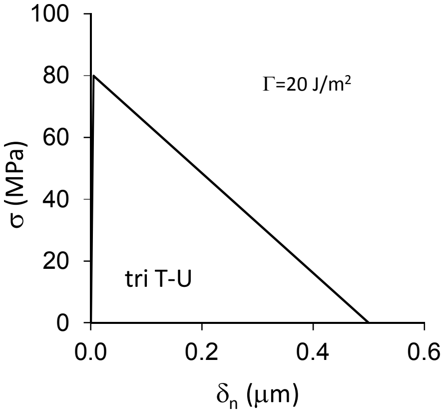
- Long interfacial crack in a edge-loaded bi-beam (deformation magnified by 100x)
- linear elastic layer sandwiched between rigid adherends with
- top adherend displaced upward and bottom adherend fixed
- *E*=3.5 GPa, *ν*=0.35, 2*h*=0.5 mm thick
- TH CZM (no intrinsic mode-mixity effect)

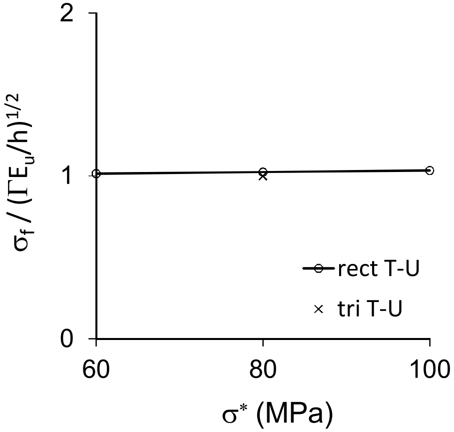




T-U when pure Mode I loading





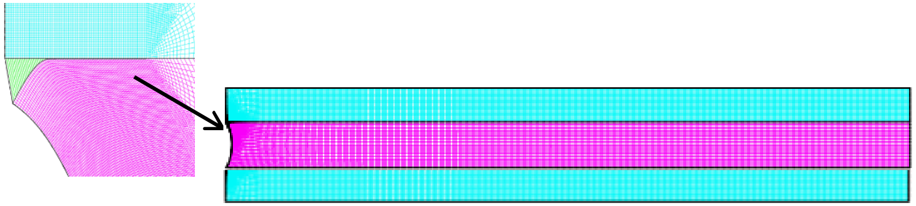


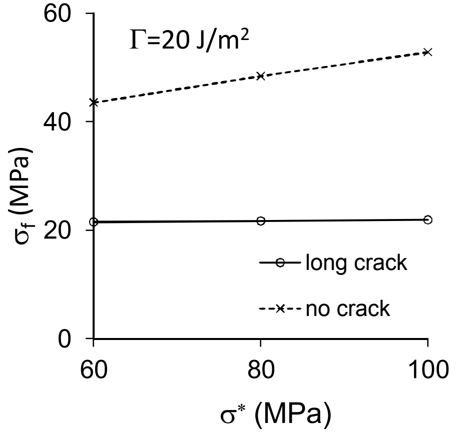
LEFM

$$\sigma_f = \left(\frac{E_u \Gamma}{h}\right)^{1/2}$$

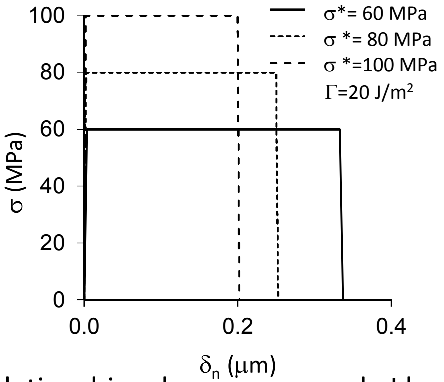
Γ is the interfacial toughness, $2h$ = bond thickness, uniaxial strain modulus E_u *= (1-v) E /((1+v)(1-2n))*, and σ_f is the stress in ligament (far from crack) when crack propagates.

Can CZM be used for analyzing nucleation and propagation?
Sharp-edged BJ, no initial edge crack

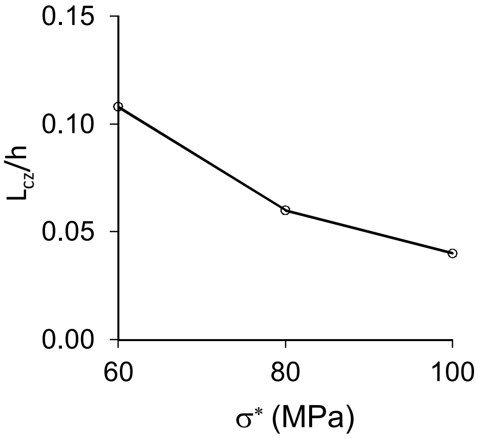




- Similar problem, but now no initial crack



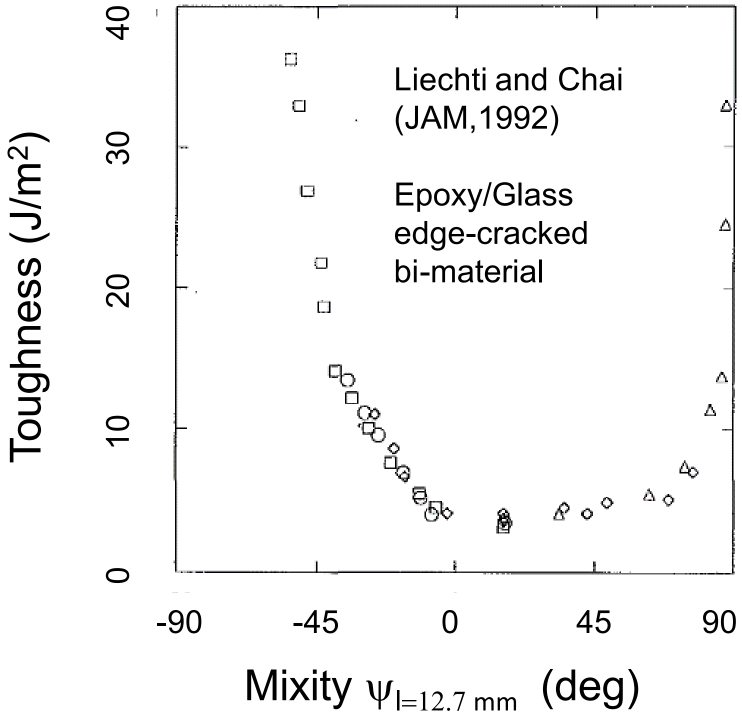
T-U relationship when a pure mode I loading



- the cohesive zone is the “initial flaw” and it depends on the details of the T-U.
  - Γ, σ^* combinations are not material properties (Reedy, IJSS, 2014).

Mode-mixity and CZMs

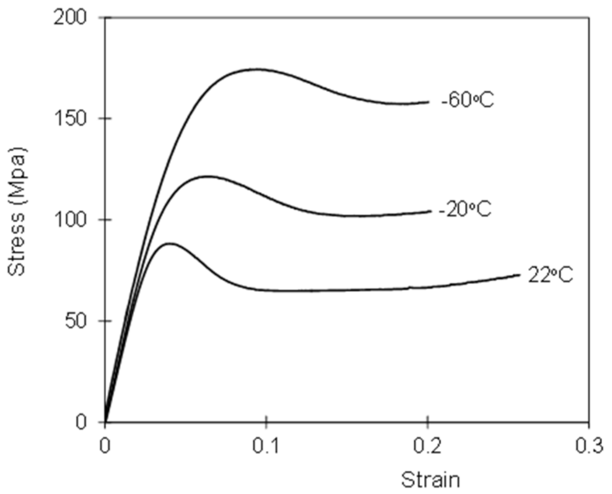
- The toughness of a polymer/solid interface increases with increasing mode-mixity.
- Many widely used CZMs do not directly incorporate a mode-mixity dependent toughness (Tvergaard and Hutchinson, 1993, Xu and Needleman, 1994).
- Extension to include a mode-mixity dependent toughness has proved difficult.
  - A polynomial-based potential formulation defined by eight fracture parameters (Park and Paulino, 2011).
  - A nonpotential-based method that defines Mode I and Mode II response independently coupled by a mixed-mode failure condition (Yang and Thouless, 2001).



Liechti, K.M. and Chai, Y.S., Journal of Applied Mechanics, 1992. 59: p. 295-304.

Simple CZM that includes ψ-dependent toughness (MDG$_C$ CZM) Reedy & Emery, IJSS 2014

- MDG$_C$ CZM incorporates all energy dissipation mechanisms (bulk materials are linear elastic).
- Mode I energy dissipation is defined by a simple traction-separation law relating normal stress and normal opening (localized crack-tip blunting).
- Mode II (III) energy dissipation is associated with interfacial shear yielding (slip).
  - epoxy quite ductile in shear.
  - in mode II, Γ relatively high, so could expect yielding instead of shear failure.
- The amount of shear dissipation is not defined by a traction-separation law --- the extent of the slip zone is determined by the level of interfacial shear in front of the Mode I CZ.

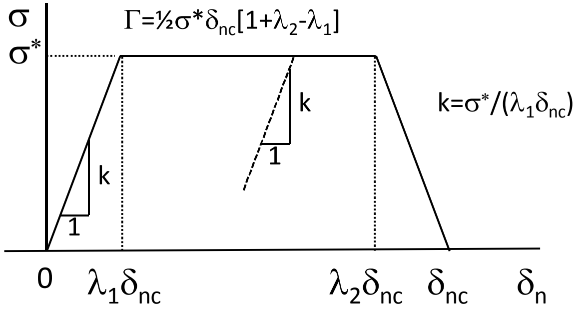


Epoxy adhesives can be quite ductile when tested in compression.

Epon 828/T403, 100:43 pbw, cured 24 hr. at 50oC followed by 24 hr. at 40oC.

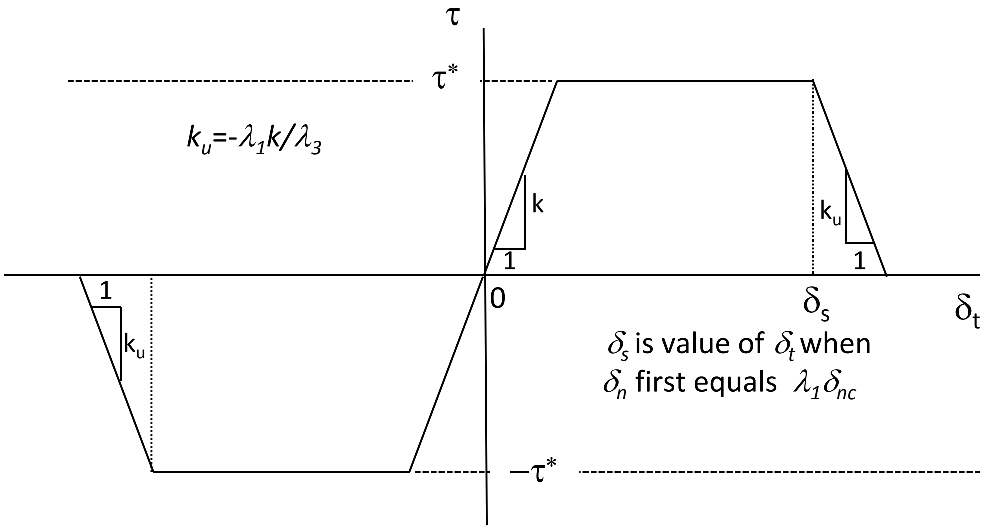
Tested at a nominal strain rate of 0.00027/s.

Mode-dependent toughness cohesive zone model (MDG$_c$ CZM)



Plane strain CZM for mode I opening (when δ_n <0; can define a multiple of *k* to penalize penetration)

Key parameters: interfacial strength σ^* and the intrinsic work of separation/unit area of interface Γ.

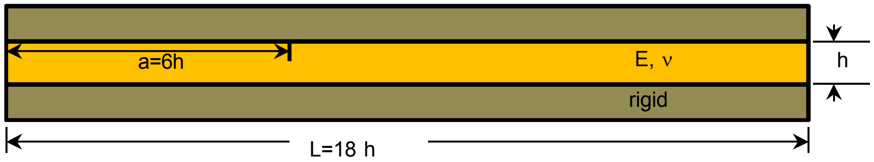


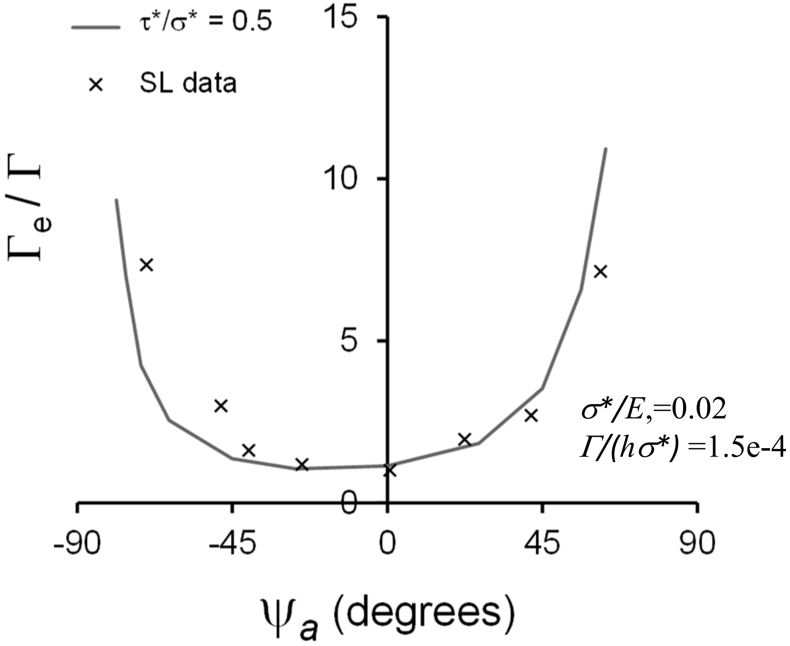
Plane strain CZM for mode II shear yielding prior to mode I separation (e.g., when $\delta_n < \lambda_1\delta_{nc}$).

Key parameter: shear yield strength τ^*.

Comparison of analysis using MDG$_c$ CZM with experiment

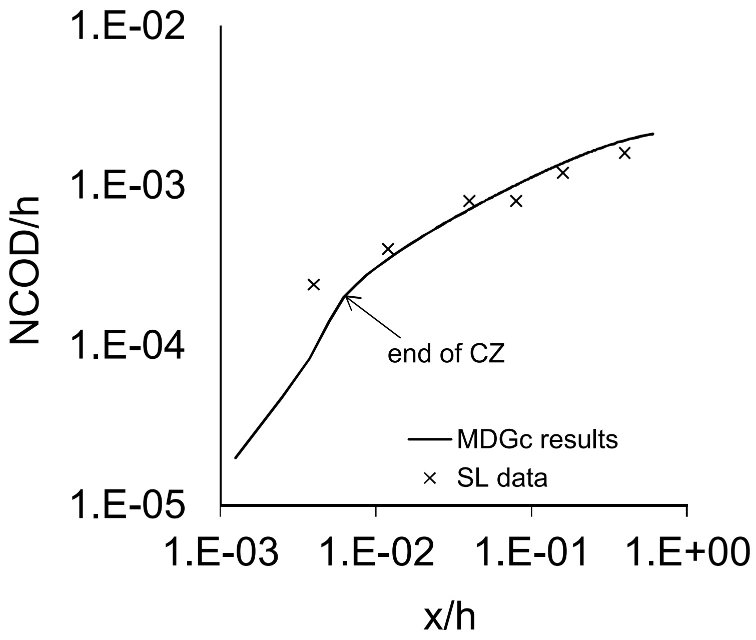
- Swadener and Liechti, measured the interfacial toughness of a glass/epoxy interface (JAM, 1998)
  - E = 2 GPa, h=0.25 mm, and Γ=1.5 J/m^2
- Calculated effective toughness Γ_e in good agreement with data
  - displays similar asymmetric response
- Shape of calculated Γ_e/Γ vs. ψ_a relationship is not predefined
- Inputs: bond elastic properties and mode I interfacial toughness



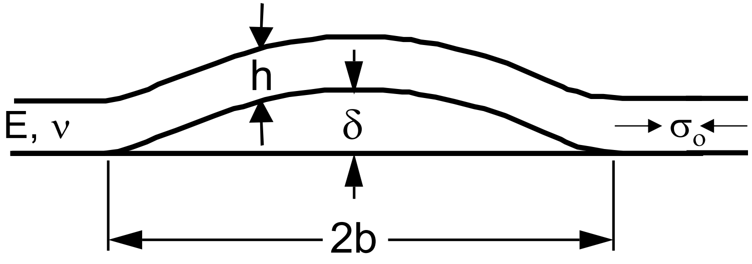


Comparison of analysis using MDG$_c$ CZM with experiment

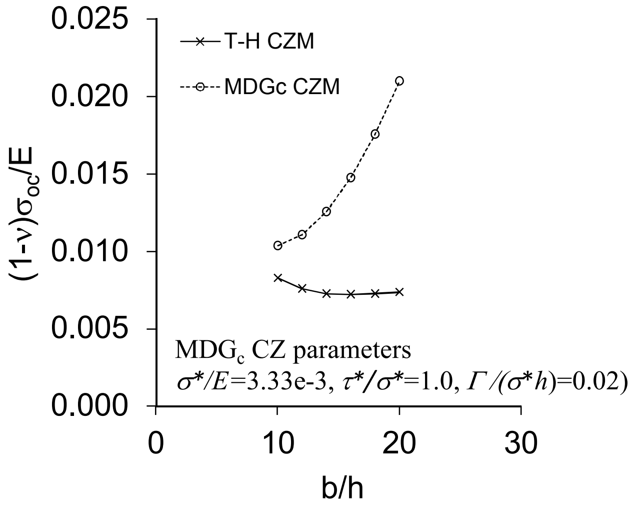
- Swadener and Liechti (SL) also reports normal crack-tip opening displacement data.
  - measured to high accuracy and precision using interferometry techniques (Liechti, 1993)
  - allows a comparison that differs from the higher level Γ_e/Γ vs. ψ_a response
- There is good agreement between analysis and the SL data.
- Demonstrates that when a MDG$_c$ CZM calculation generates a good match to Γ_e/Γ vs. ψ_a data, it also generates local crack-tip deformations that are in reasonable agreement with experimental results.

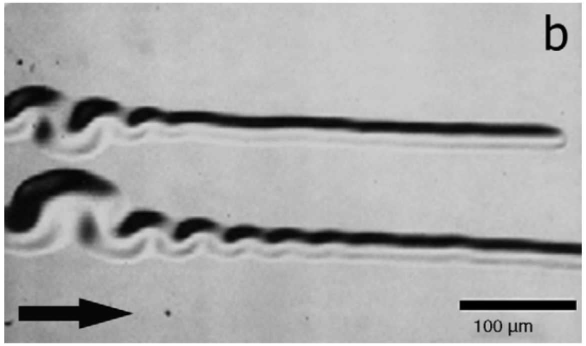


2nd Example: Buckle-driven growth of 1-D blister on rigid substrate



- Analysis subjects film to increasing biaxial compression that first buckles an initial delamination and ultimately buckled delamination extends at a critical value σ_{oc}.
- Results for mode-mixity independent T-H CZM compared to mode-mixity dependent MDG$_c$ CZM.
- MDGc CZM predictions consistent with observation: sidewalls arrest.





Cordill, M.J., et al., Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing, 2007. 443(1-2): p. 150-155.

Interfacial Fracture: Needs and Gaps

Current status:

- Sandia's Sierra/SM finite element code has a basic capability to simulate the separation of material interfaces using CZMs in conjunction with CSEs.

What can be calculated with confidence

- Growth of a preexisting interfacial crack when
  - there is small-scale yielding (bulk materials are linear elastic)
  - the crack stays on the interface

Capability needs and gaps

- Validated approach for including mode-mixity dependent toughness for different types of interfaces (refine/extend MDG_c CZM, etc.).
- Theory applicable to large-scale yielding in the bulk materials.
- Crack nucleation from geometric and material discontinuities.
- Method and criterion that allows cracks to kink out of the interface.
- Fundamental understanding of factors controlling toughness (connecting the atomistic, mesoscale, continuum-level).

Seminar series outline

https://snl-wiki.sandia.gov/display/FMSS/Fracture+Mechanics+Seminar+Series+Home

Lecture 1: **Basic Theory Part I**, Scott Grutzik (1851)	
Lecture 2: **Experimental Fracture Mechanics**, Jay Carroll (1851)	
Lecture 3: **Basic Theory Part II**, Scott Grutzik (1851)	
Lecture 4: **Fracture Resistant Design**, Jay Carroll (1851)	
Lecture 5: **Computational Methods for Brittle Fracture**, John Emery (1556)	
Lecture 6: **Computational Approaches for Resolving the Driving Force and the Resistance**, Jay Foulk (8343)	
Lecture 7: **The Materials Science of Fracture**, Brad Boyce (1881)	Nov 9, 2017
Lecture 8: **Interfacial Fracture**, Dave Reedy (1556)	Dec 14
Lecture 9: **Ductile Fracture Experiments**, Brad Boyce (1881)	Jan 11, 2018
Lecture 10: **Ductile Fracture Analysis**, Jay Foulk (8343)	Feb 8
Lecture 11: **Dynamic Fracture**, Bo Song (1528)	Mar 8
Lecture 12: **Shock/spall**, Tracy Vogler (8343)	Apr 12
Lecture 13: **Phase field fracture modeling**, Mike Tupek (1542)	May 10

List of Texts

Anderson: *Fracture mechanics* Good general reference, broad coverage

Broberg: *Cracks and Fracture* Abstract, mathematical approach to fracture

Janssen, Zuidema, Wanhill: *Fracture Mechanics* Engineering perspective, some discussion of material mechanisms

Zehnder: *Fracture Mechanics* Equivalent to a one semester masters level course

Dowling: *Mechanical Behavior of Materials* Entry level discussion of fatigue

Broek: *Elementary Engineering Fracture Mechanics* Similar to Anderson, good discussion of damage tolerance

Popelar, Kanninen: *Advanced Fracture Mechanics* General reference at a level above Anderson

Lawn: *Fracture of Brittle Solids* Theory and mechanisms for brittle fracture

Maugin: *Material Inhomogeneities in Elasticity* Mathematical background of J-integral

Ashby: *Materials Selection in Mechanical Design* Which material to use for an application

Questions?

Sandia National Laboratories is a multi-mission 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.