SAND2012-0381 C
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Glass Cracking Near Edges and Interfaces

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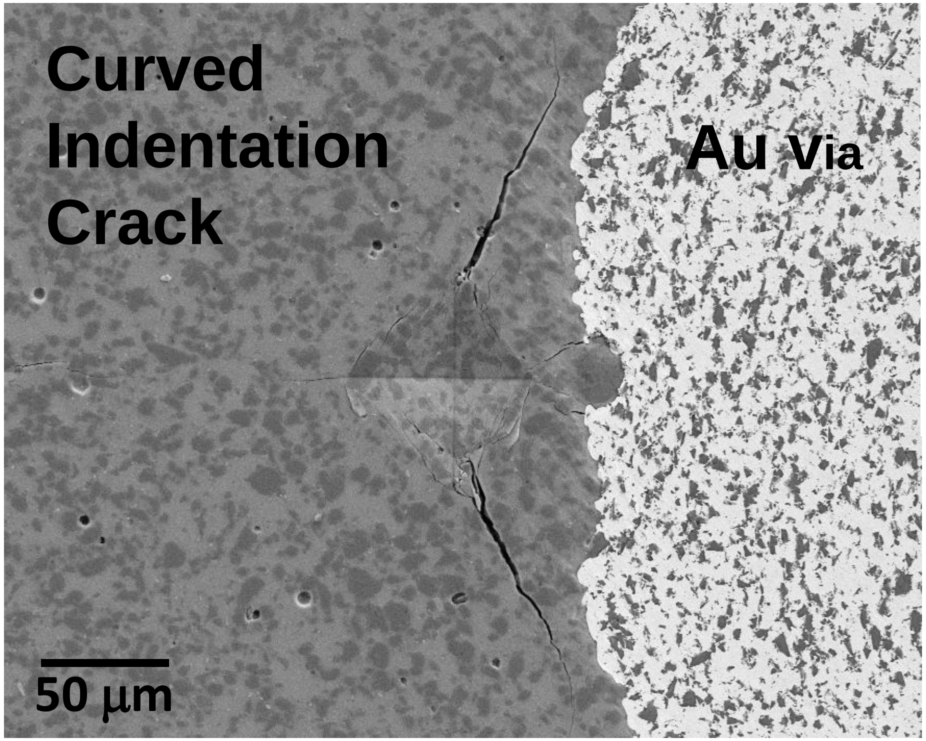
Motivation

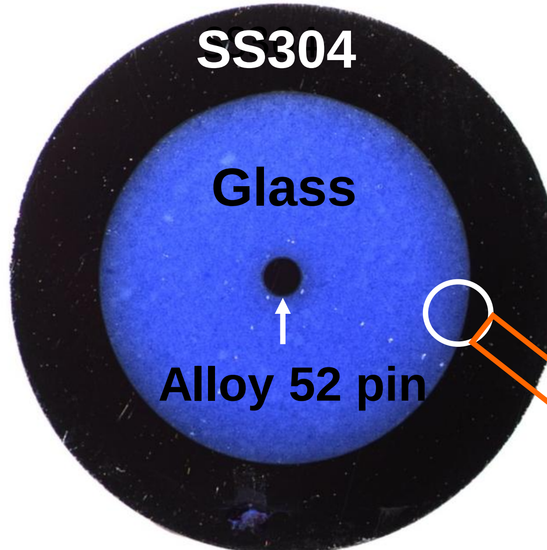
- **Glass edges are susceptible to damage**
  - **Solar panels, cell phone covers, glass-to-metal seals**

- **Indentations cracks are used to examine stress states in bulk glass.**
  - **Near interfaces, these cracks experience Mode II loading, and additional Mode I loading due to elastic mismatches**
  - **Crack length changes, and cracks curve (non-ideal shapes)**

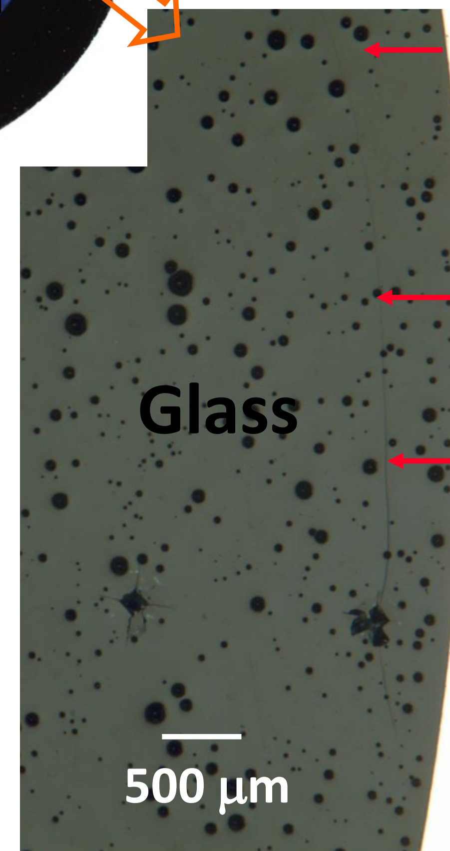
If this behavior could be well characterized near a purely elastically-mismatched interface, then we might be able to elicit stresses near interfaces that are both thermally <u>and</u> elastically mismatched

Cracks near interfaces curve





Glass to metal seal



SS

Low temperature co-fired ceramic (glass-alumina composite) with Au via

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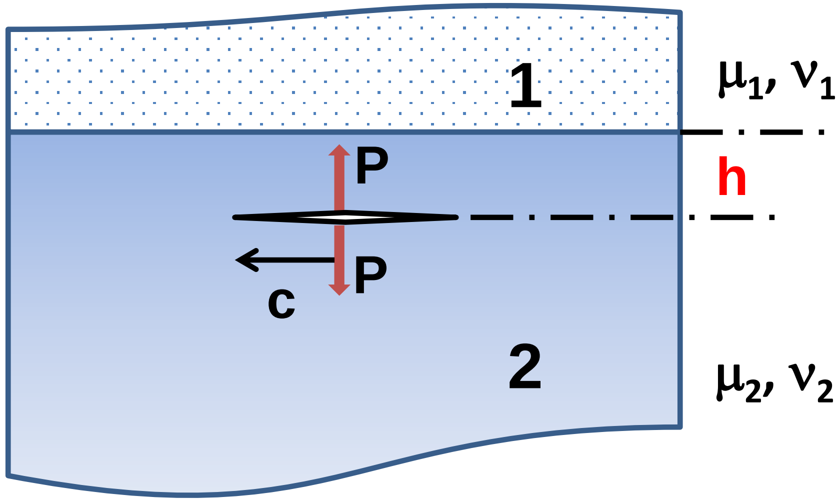
Outline

- Description of the problem, and review of known fracture mechanics results
- Experimental Approach and Assumptions (3-d vs. 2-d)
- Results for crack lengths and crack deflections
- Comparison to Max. Tangential Stress (MTS) theory
- T-stress description and Generalized MTS theory
- Results on Stressed Surfaces
- Conclusions

Sub-interface Crack Problem



Dundur's parameters, κ=f(ν)

$$\alpha = \frac{\mu_1(\kappa_2+1) - \mu_2(\kappa_1+1)}{\mu_1(\kappa_2+1) + \mu_2(\kappa_1+1)}$$

Measure of elastic mismatch, α=-1 free edge, α=0 identical, α=1 infinitely rigid

- **A center point loaded crack in a semi-infinite material 2***
- **The crack of length c is at a distance h from edge/interface**
- **When h□c**

$$K_I = K_{I,0} = \frac{\lambda P}{c^{3/2}};\ K_{II} = 0$$

*Lardner et al., Int. J. Frac., 1990,
*Lu and Lardner, Int. J. Sol. Struc., 1992

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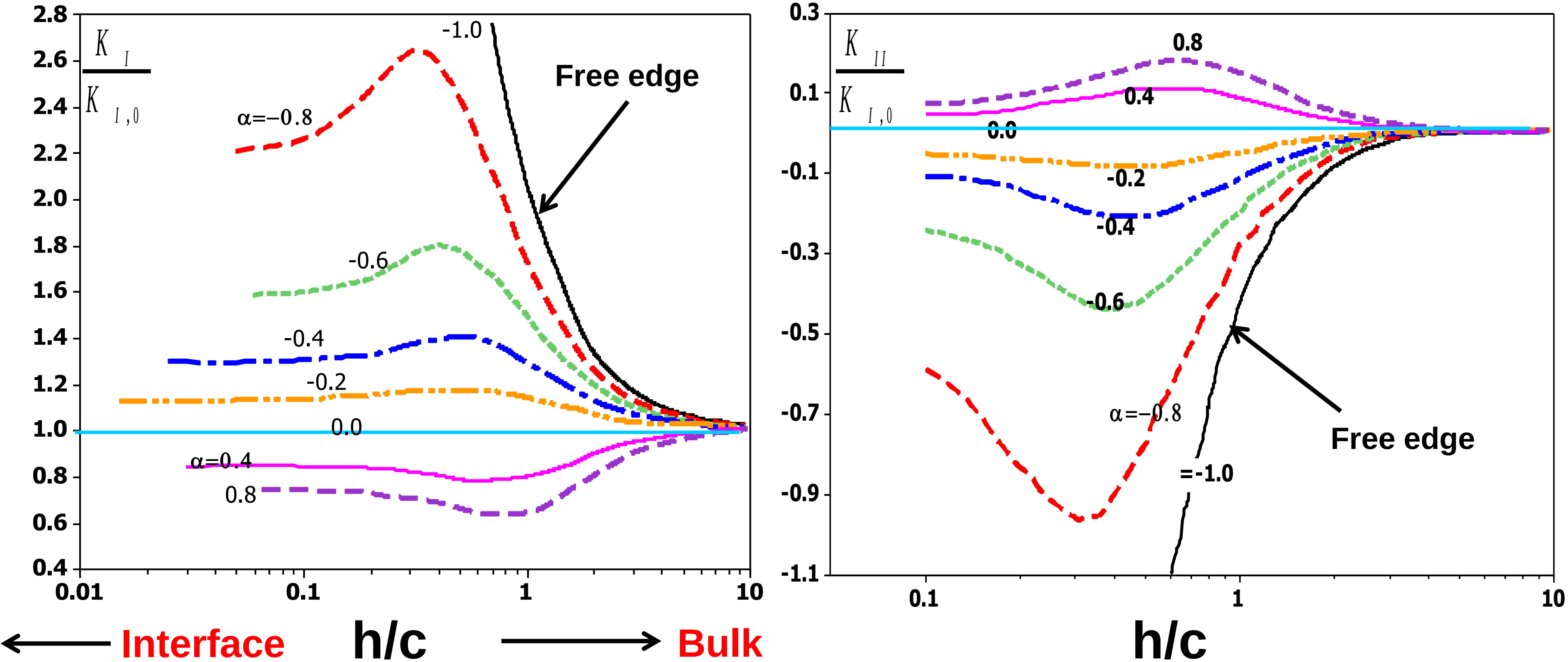
K solutions as a fn (Dundur's parameter, α)

Lu and Lardner, Int. J. Sol. Struc., 1992

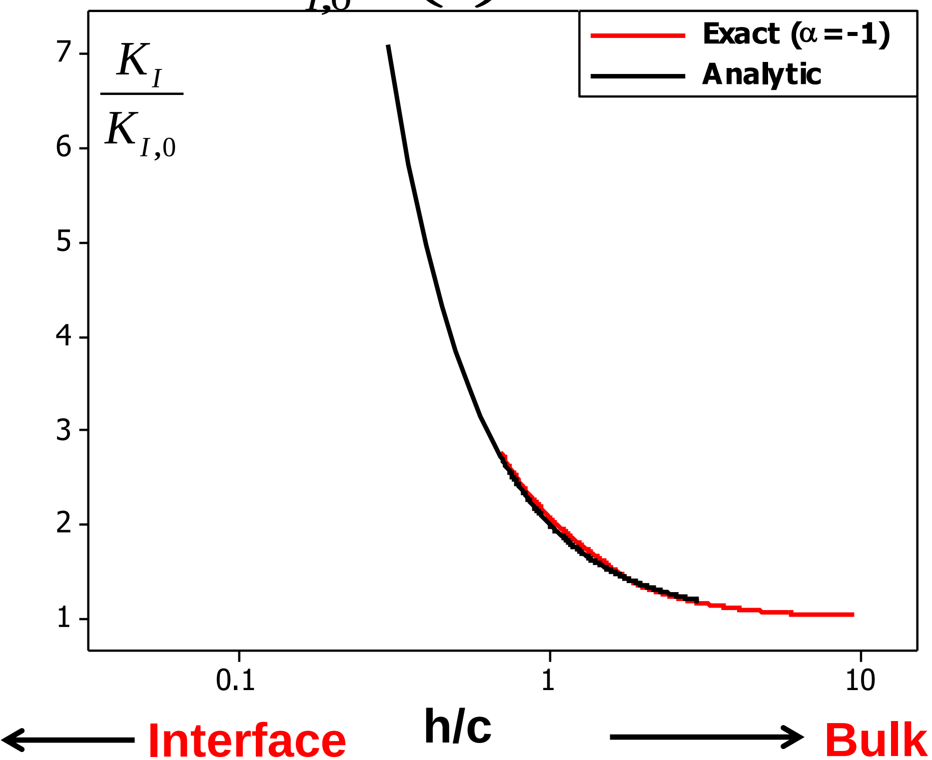
Normalized Mode I, K_I / K_{I0} Normalized Mode II, K_{II} / K_{I0}

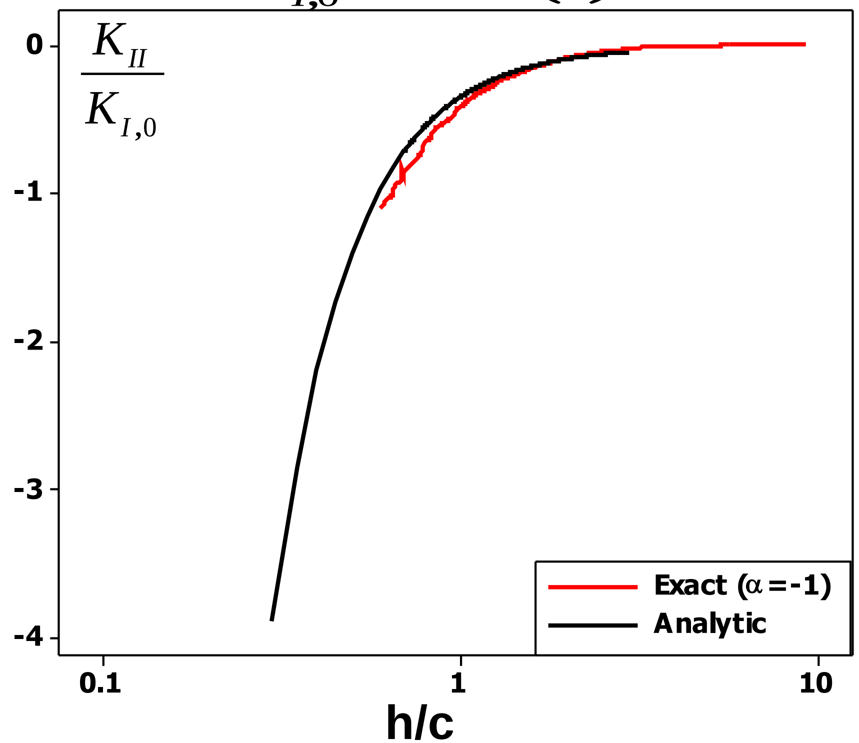


The sub-interface crack was modeled by continuously distributed edge dislocations, and using the stress field for a single dislocation the boundary value problem is solved. The K's are obtained in terms of the dislocation density functions which are calculated numerically

Free Edge Approximations

$$\frac{K_I}{K_{I,0}} = \left(\frac{h}{c}\right)^{-3/2} + 1 \qquad \frac{K_{II}}{K_{I,0}} = -0.35\left(\frac{h}{c}\right)^{-2}$$





Lardner et al., Int. J. Frac., 1990

- Palmqvist type crack has the ~ same K as half-penny crack*

*Laugier, JACS, 1987

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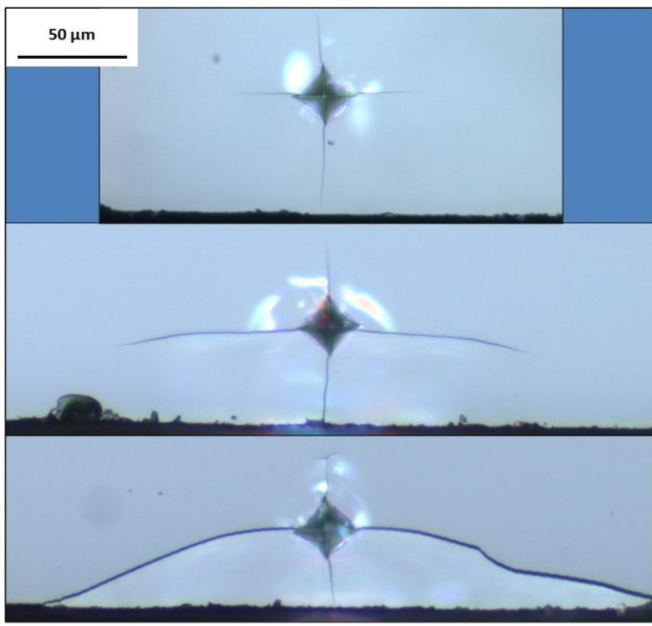
Experimental Approach

- Surfaces and interfaces tested:
  - Free glass edges (α=-1); Starphire SLS glass, 4 mm thick
  - Glass edges bonded to epoxy cured at room temperature (α=-0.93)
  - Free edges of heat strengthened SLS glass
  - Free edges of tempered glass

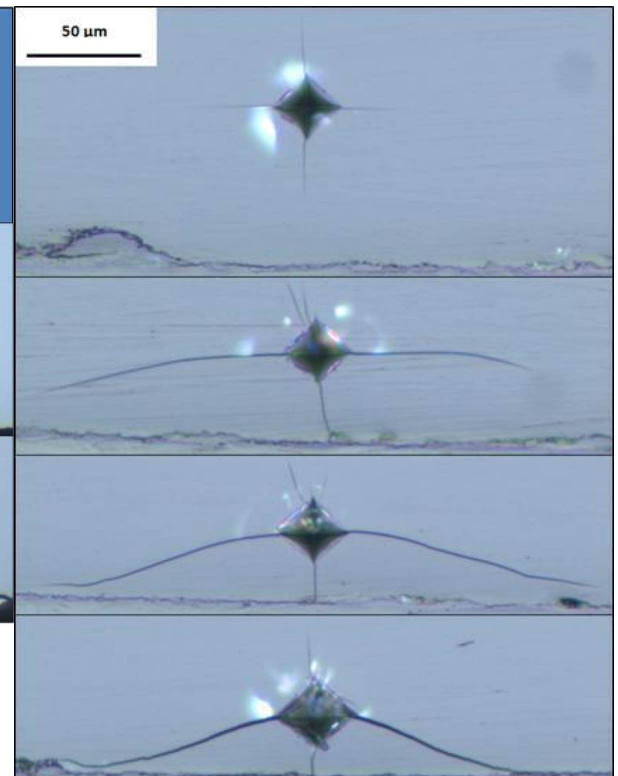
- Low load Vickers indentations tests (3N-5N loads)
  - Indentations at various values of h/c approaching the edge
  - Crack lengths and crack deflections angles measured

As-Received SLS Behavior

- SLS Crack Shape Patterns
  - Crack shape patterns emerged with respect to h/a
  - h/c > 0.75: Straight cracks
  - 0.4 < h/c < 0.75: Crack tips curved
  - h/c < 0.4: Crack curves towards then away from interface
  - Indicates changing K_{II} as crack propagates away from indent center



Starphire Free Edge



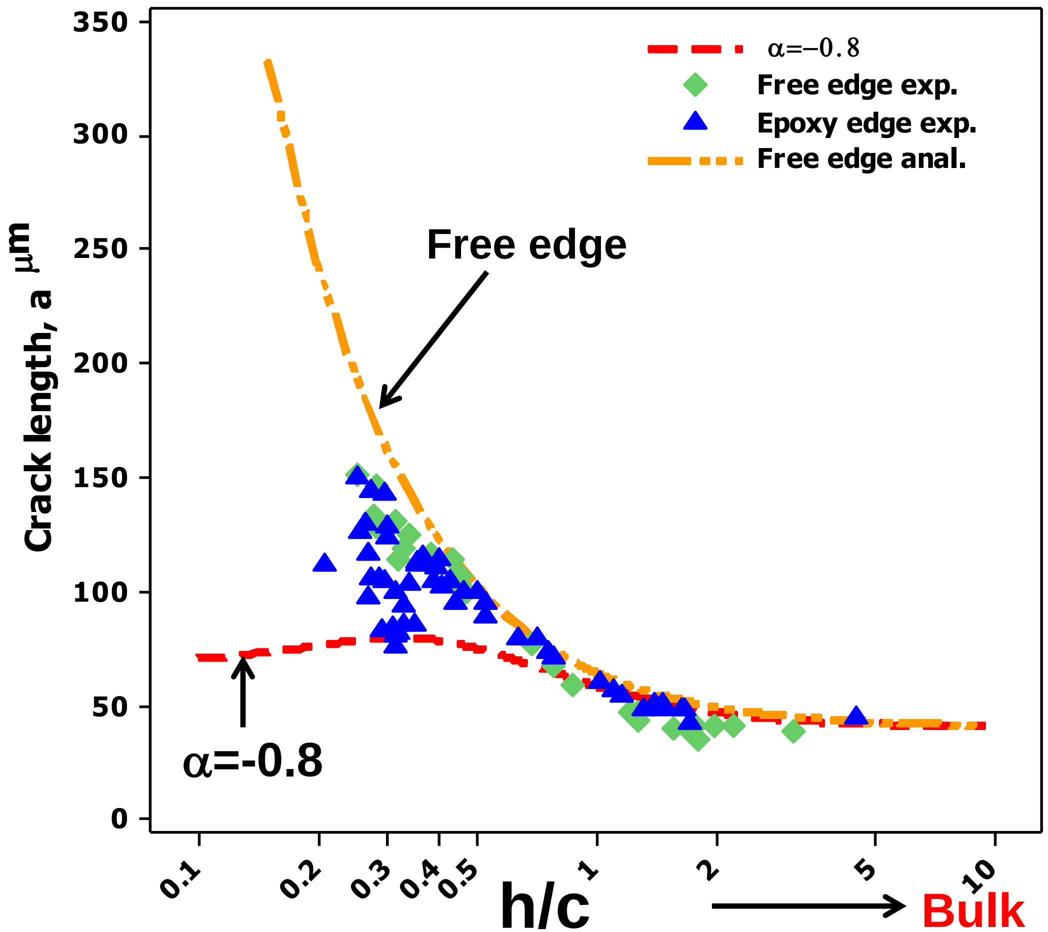
Starphire/Epoxy Interface

Crack Lengths Comparisons

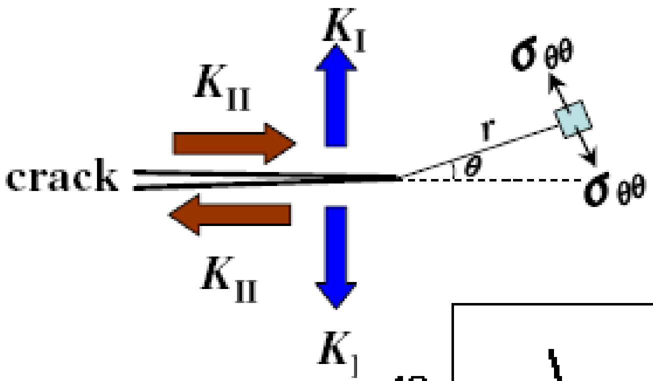
Knowing G_c, K_I/K_{I0}, and K_{II}/K_{I0}, K_{I0} is calculated

$$G_c = \left(\frac{1-\nu^2}{2\mu}\right)\left(\frac{K_I^2+K_{II}^2}{K_{I0}^2}\right)K_{Ic}^2$$

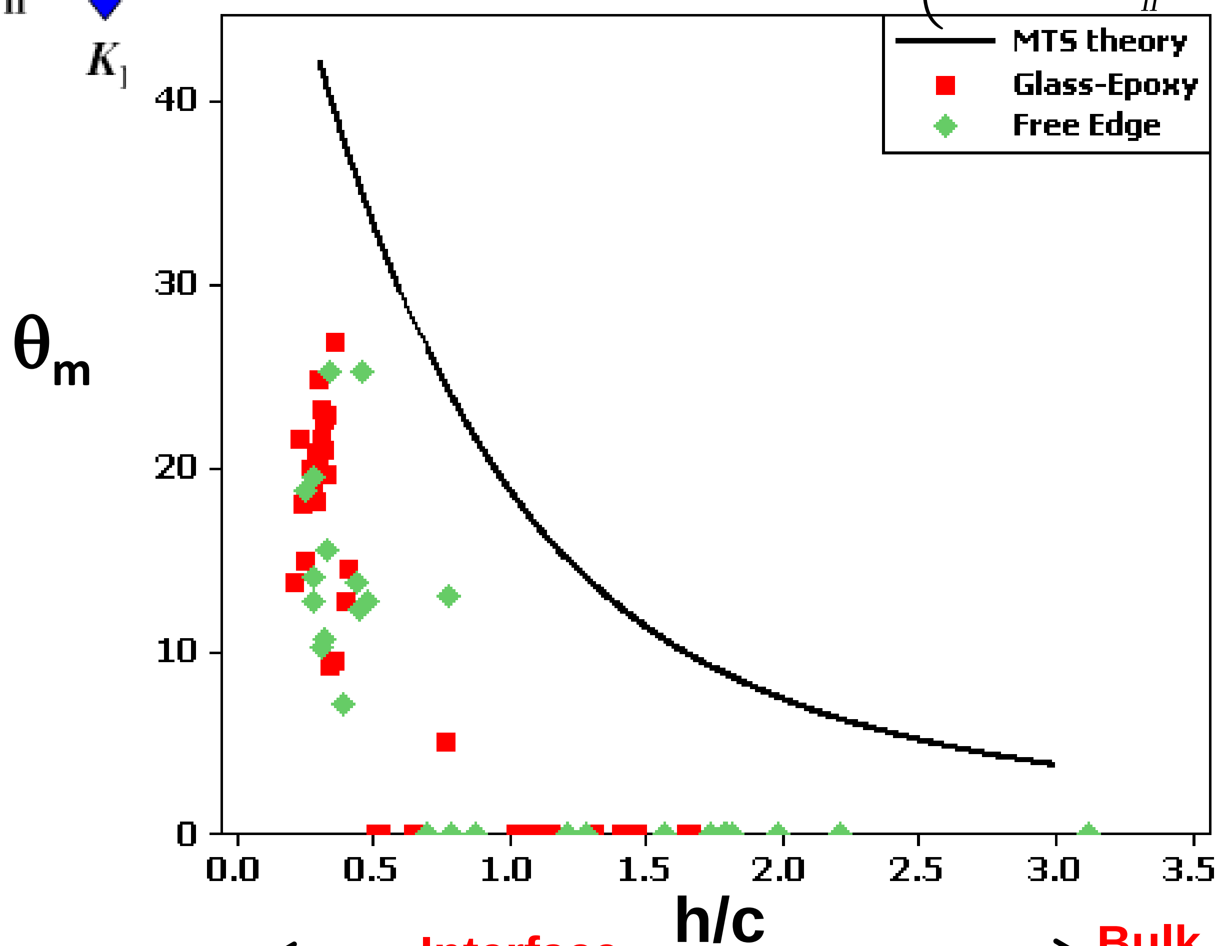
Crack lengths are then calculated from $K_{I,0} = \frac{\chi P}{c^{3/2}}$



Crack Deflection Angles Based on MTS theory



$$\theta_m = 2\tan^{-1}\left(\frac{K_I - \sqrt{K_I^{\,2} + 8K_{II}^{\,2}}}{4K_{II}}\right)$$

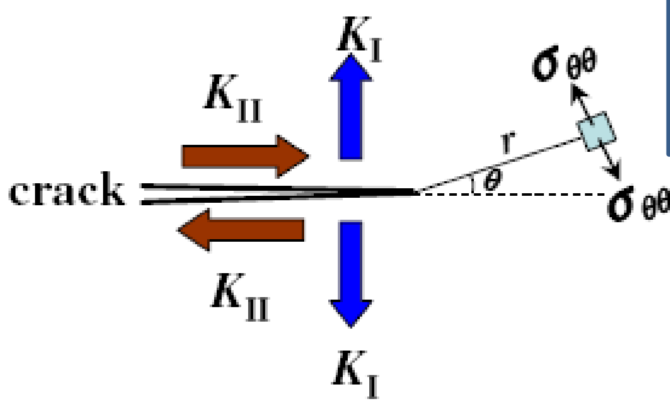


← **Interface** **Bulk** →

Generalized MTS theory

$$\sigma_{\theta\theta} = \frac{1}{\sqrt{2\pi r}}\cos\frac{\theta}{2}\left[K_I\cos^2\frac{\theta}{2} - \frac{3}{2}K_{II}\sin\theta\right] + T\sin^2\theta$$

- **T is a constant non-singular stress parallel to the crack which is independent of the distance from the crack tip, r**
- **T is dependent on the geometry and loading configuration**
- **To evaluate the direction of the maximum tangential stress, $\sigma_{\theta\theta}$ which now includes the T-term, is considered**
- **This maximum is evaluated at a certain distance, r_c, from the crack tip (r_c/c ~0.01-0.02)**



Williams, J. Appl. Mech. , 1957
Williams, Ewing, IJF, 1972
Finnie, Saith, IJF, 1973
Smith et al, PRS, 2006
Ayatollahi, Aliha, IJSS 2009

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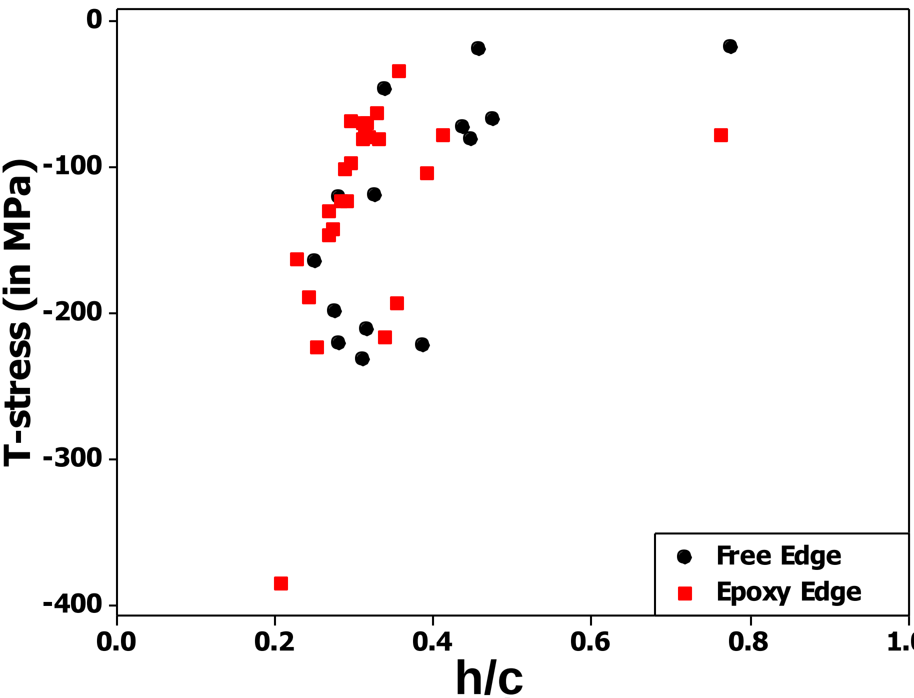
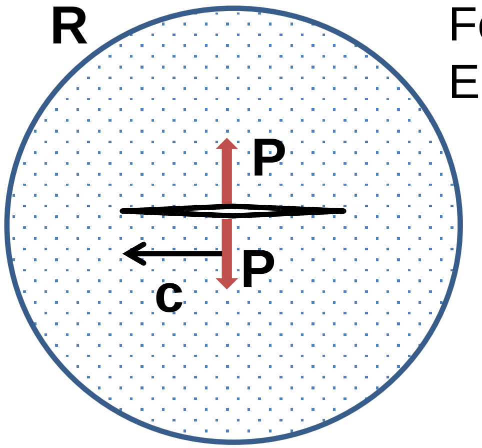
T-stresses for a point loaded crack

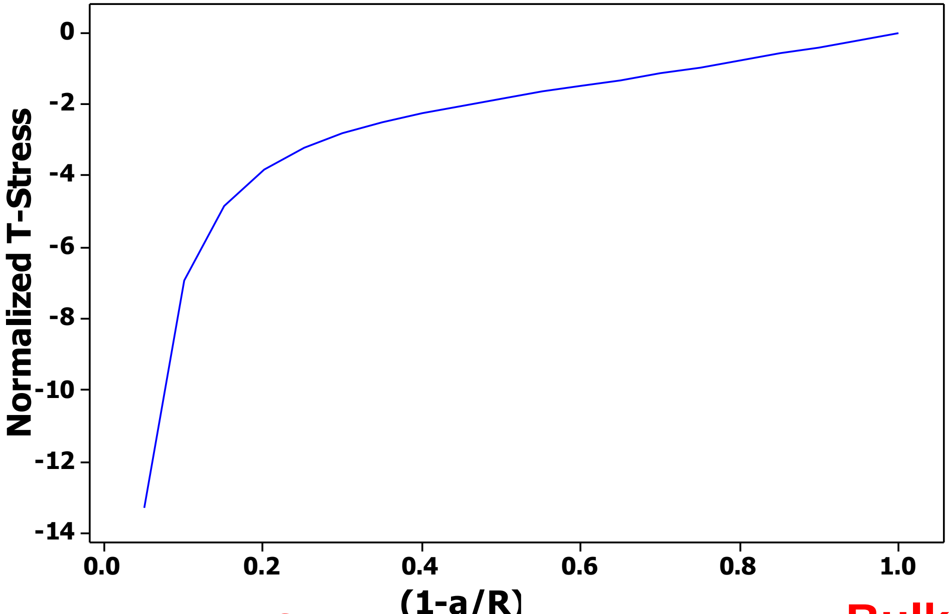
Computed T-stresses based on GMTS, and measured crack deflection angles



r_c value chosen ~ 230 micron based on Ayatollahi, Alahi, Int. J. Sol. Struc. , 2009



Fett,
Eng. Frac. Mech.1998



Interface ← → **Bulk**

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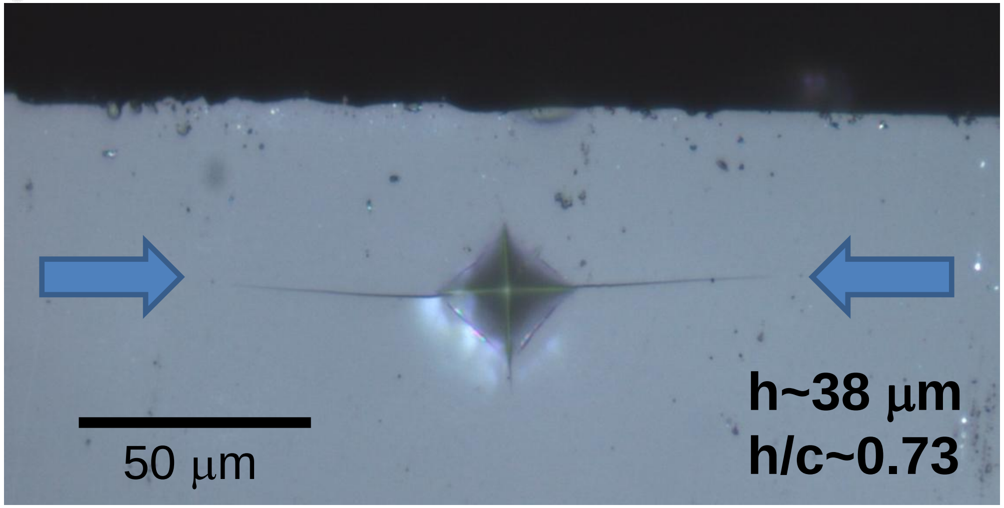
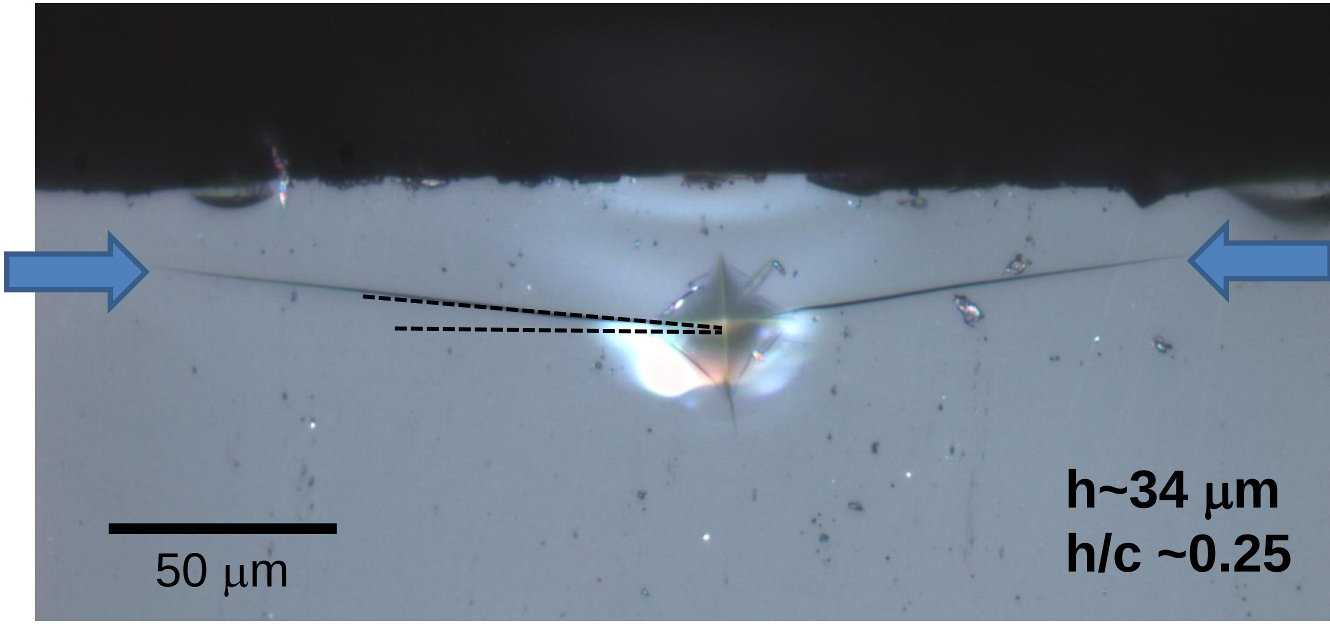
Crack Stability On Stressed Surfaces



Compressive stress adds on to the T-stress and prevents crack curvature



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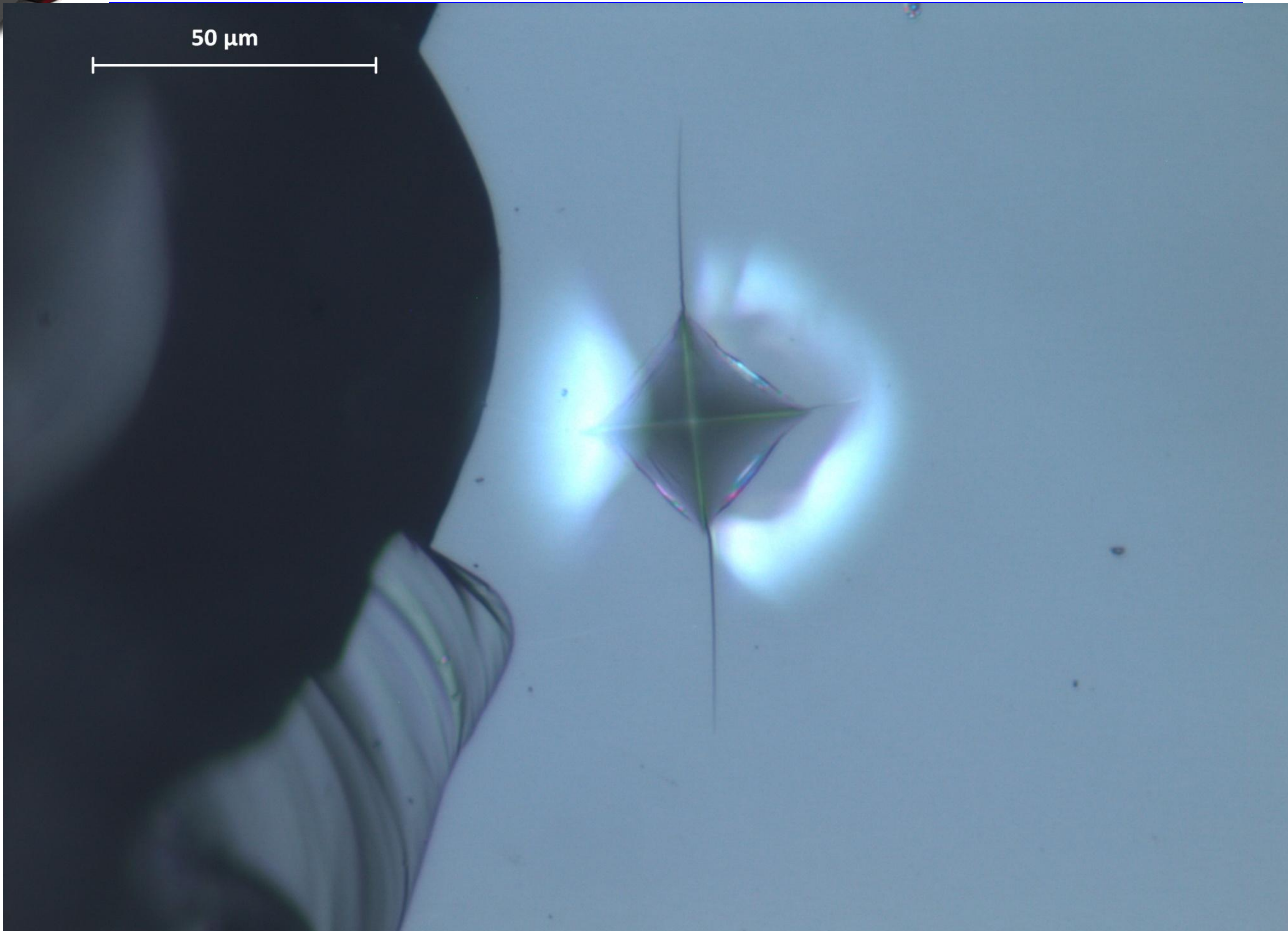
Crack Stability on Stressed Surfaces



Conclusions

- **In glasses, for a free edge, and for a "soft" interface, the crack lengths are predicted reasonably well using a mixed mode fracture criterion. Therefore it might be possible to study stress effects near such interfaces even with highly non-ideal crack shapes**

- **MTS theory over-predicts the crack deflection angles**

- **Trends in T-stresses for a point loaded crack are qualitatively consistent with T-stress values calculated using GMTS**

- **Compressive surface stresses tend to stabilize cracks near interfaces, in a manner similar to negative T-stress.**

Additional Slides

Glass Cracking Near Edges and Interfaces

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Understanding and mitigating cracking near free or constrained edges of glass is a technologically important problem. Vickers indentation is an extremely useful tool to study the behavior of glasses, and has been used to estimate toughness, residual stresses and gain insight into materials behavior. When used to probe the behavior of cracks near edges, indentation cracks are subjected to an additional loading: that due to the elastic mismatch between the glass and the free/constrained edge. Here, we use a fracture mechanics solution that treats indentation cracks as point-loaded 2-d cracks to understand the cracking behavior of soda-lime silicate glass at free edges and at glass-epoxy interface. Crack lengths are measured as the crack progressively nears the interface, and the results are reasonably close to the predictions based on the mechanics model. The curvature of the crack path is correlated to the mixed-modity of the loading, and the effect of compressive stresses parallel to the crack path on its "curving" behavior is examined. The mechanics model may be useful in studying crack behavior along other material interfaces and different edge conditions.

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Generalized MTS theory

[illegible]

$(2r_c/a)$^0.5=0.1

2rc/a=0.01

a=100 micron

Rc=0.5 micron

$$T \le \frac{1}{8}\frac{K_I}{\left(2\pi r_c\right)^{1/2}}$$