INVESTIGATION OF SCALING LAWS OF THE FIBER/MATRIX INTERFACE CRACK IN POLYMER COMPOSITES THROUGH FINITE ELEMENT-BASED MICROMECHANICAL MODELING

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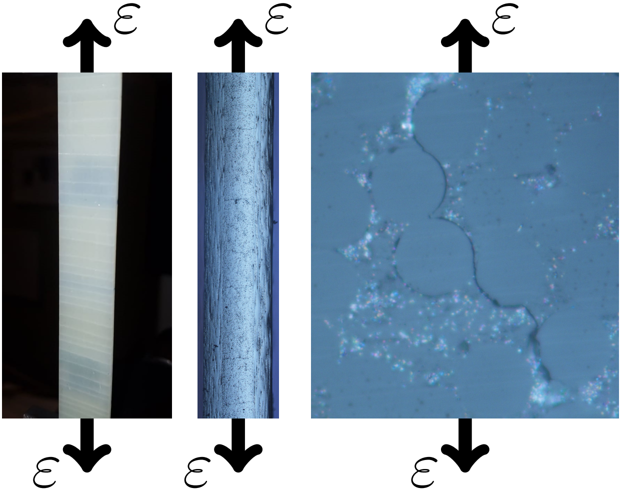
Outline

- Initiation of Transverse Cracking in Fiber Reinforced Polymer Composites (FRPCs): Microscopic Observations & Modeling
- The Fiber-Matrix Interface Crack Problem
- Analysis of the Infinite Reference Volume Element (RVE)
- Conclusions & Outlook

↘ TRANSVERSE CRACKING IN FRPCs

Observations: From Macro to Micro



Left:
front view of $[0, 90_2]_S$, visual inspection.

Center:
edge view of $[0, 90]_S$, optical microscope.

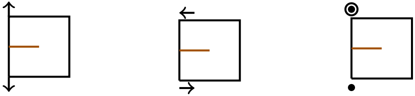
Right:
edge view of $[0, 90]_S$, optical microscope.

Mathematical Modeling of Fracture: Linear Elastic Fracture Mechanics (LEFM)

Fracture Mode

$I, II, III, I/II, I/III, II/III$

Mode I Mode II Mode III



➔ Energy Release Rate: $G\ \left[\frac{J}{m^2} = \frac{N}{m}\right]$

$$G = \frac{\partial W}{\partial A} - \left(\frac{\partial U}{\partial A} + \frac{\partial E_k}{\partial A}\right)$$

➔ Stress Intensity Factor: $K\ \left[Pa\sqrt{m}\right]$

$$K_{I/II/III} = \lim_{r \to 0} \sqrt{2\pi r} \cdot \sigma_{I/II/III}(r, 0)$$

Variables

geometry
materials
boundary conditions
loading mode
scale

➔ J-Integral: $J\ \left[\frac{J}{m^2} = \frac{N}{m}\right]$

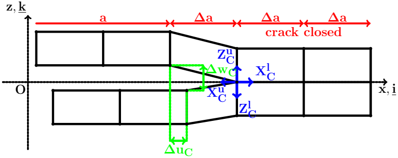
$$J = \lim_{\delta \to 0} \int_{\Gamma_\delta} \left(W - n_j \sigma_{jk} \frac{\partial u_k}{\partial x_i}\right) d\Gamma$$

➔ Average Crack Opening & Shear Displacement: COD, $CSD_{II/III}$ $[m]$

$$\begin{Bmatrix} COD \\ CSD_{II} \\ CSD_{III} \end{Bmatrix} = \frac{1}{S_C} \int_{S_C} \overrightarrow{\Delta u_C} \cdot \begin{Bmatrix} \overrightarrow{n_I} \\ \overrightarrow{n_{II}} \\ \overrightarrow{n_{III}} \end{Bmatrix} dS$$

Numerical Characterization of Fracture: VCCT & J-Integral

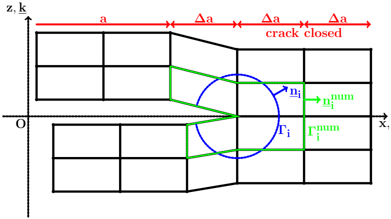
Virtual Crack Closure Technique (VCCT)



$$G_I = \frac{Z_C \Delta w_C}{2B\Delta a} \qquad G_{II} = \frac{X_C \Delta u_C}{2B\Delta a}$$

Krueger R.; *Virtual crack closure technique: History, approach, and applications. Appl. Mech. Rev.* **57** (2) 109–143, 2004.

J-Integral

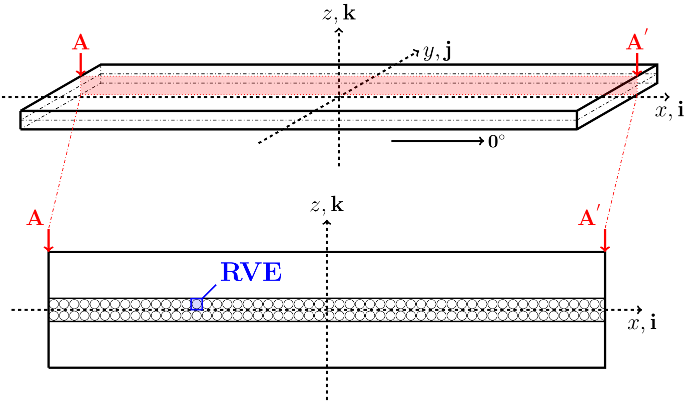


$$J_i = \sum_{k=1}^{n_{segments}} \sum_{j=1}^{n_{nodes}} \left[w_j \left(W - n_j \sigma_{jk} \frac{\partial u_k}{\partial x_i} \right) \bigg|_{(x_{kj}, y_{kj})} \right]$$

Rice J. R.; *A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks. J. Appl. Mech.* **35** (2) 379–386, 1968.

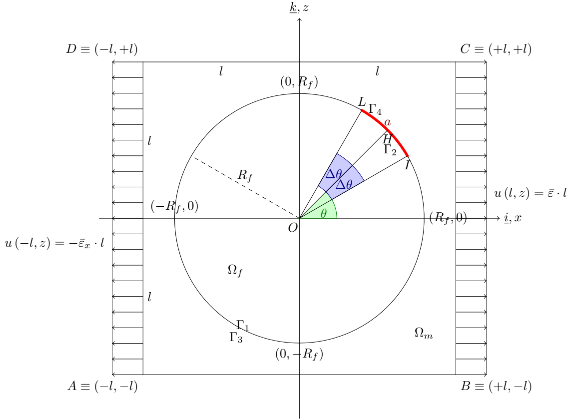
↘ The Fiber-Matrix Interface Crack Problem

The Fiber-Matrix Interface Crack Problem: Geometry



- ➔ $L, W >> t$
- ➔ $L, W \rightarrow \infty$
- ➔ 2D RVE

The Fiber-Matrix Interface Crack Problem: Statement



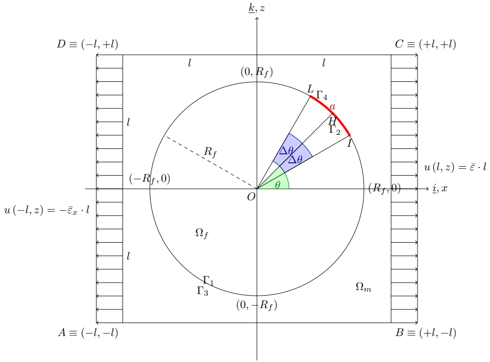
- ➔ 2D space
- ➔ Linear elastic homogeneous isotropic materials
- ➔ Mismatching elastic properties
- ➔ Plane state (strain or stress)
- ➔ Dirichlet-type BC
- ➔ Linear Fracture Mechanics
- ➔ Contact interaction
- ➔ Applied uniaxial traction
- ? SIF, ERR, mode ratio, stress and displacement distribution at the interface

The Fiber-Matrix Interface Crack Problem: Solution

Method	**Domain**	**Natural Variable**	**Conjugate Variable**	**Dirichlet BC**
Analytical (complex) functions	2D, continuous, infinite	Airy stress potential & stress	Displacement & strain	In stress
	M. Toya (1975), A Crack Along the Interface of a Circular Inclusion Embedded in an Infinite Solid [10].			
Boundary Element Method (BEM)	1D, discrete, finite	Stress, by using Green's potentials or Betti's influence functions	Displacement & strain	In stress
	F. París et al. (1996), The fiber-matrix interface crack - A numerical analysis using Boundary Elements [11].			
Finite Element Method (FEM)	2D, discrete, finite	Displacement	Stress	In displacement

ANALYSIS OF THE INFINITE RVE

The Finite Element Model



- ➔ $\theta\ [^\circ] = 0$, angular position of debond's center
- ➔ $2\Delta\theta\ [^\circ]$, debond's angular size
- ➔ $\delta\ [^\circ]$, angle subtended by an element at the fiber/matrix interface
- ➔ $VF_f\ [-]$, fiber volume fraction
- ➔ $2L\ [\mu m]$, RVE's side length
- ➔ $R_F\ [\mu m]$, fiber radius
- ➔ $\frac{L}{R_f} = \frac{1}{2}\sqrt{\frac{\pi}{VF_f}}\ [-]$, RVE's aspect ratio
- ➔ $\sigma_0\ [MPa] = \frac{E_m}{1-\nu_m^2}\varepsilon_{xx}$, reaction stress of undamaged infinite RVE
- ➔ $G_0\left[\frac{J}{m^2}\right] = \pi R_f \sigma_R^2 \frac{1+(3-4nu_m)}{8G_m}$, normalization G following Toya [10] and París [11]
- ➔ Small displacement formulation

↘ Conclusions

Conclusions & Outlook

Conclusions

- ➔ There is a limiting value of $\frac{L}{R_f}$ after which models are effectively infinite
- ➔ For models larger than this value, domain size and mesh refinement at the interface has a similar effect on the energy release rate
- ➔ The discrepancy in modes with the use of linear elements might be linked to the deformed shape of crack faces

Outlook

- ➔ Modeling extreme ply geometries, for example a ply with a single layer of fibers bounded by stiffer plies
- ➔ Investigate the effect of clusters of fibers in thin plies
- ➔ Analyzing the effect of complex stress and deformation states, thermal loads, different sets of boundary conditions

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