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.

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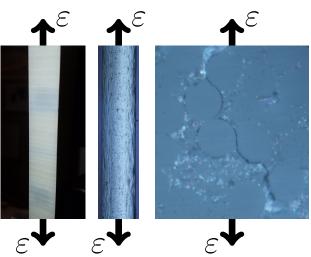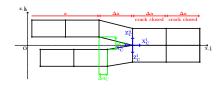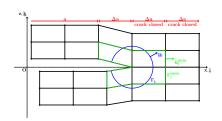
Transverse Cracking in FRPCs   The Fiber-Matrix Interface Crack Problem   Analysis of the Infinite RVE   Conclusions
Observations: From Macro to Micro   **Mathematical Modeling of Fracture**   Mathematical Modeling of Fracture

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

➜ Energy Release Rate

$$G_m = G_m\left(p_1, \ldots, p_i, \ldots, p_n\right) \quad \text{where} \quad G = \frac{\partial W}{\partial A} - \left(\frac{\partial U}{\partial A} + \frac{\partial E_k}{\partial A}\right)$$

➜ Stress Intensity Factor

$$K_m = K_m\left(p_1, \ldots, p_i, \ldots, p_n\right) \quad \text{where} \quad \sigma_m \sim K_m \frac{\alpha}{(x-a)^\beta} \quad \alpha, \beta > 0$$

➜ J-Integral

$$J = J\left(p_1, \ldots, p_i, \ldots, p_n\right) \quad \text{where} \quad J = \lim_{\varepsilon \to 0} \int_{\Gamma_\varepsilon} \left(W\left(\Gamma\right) n_i - n_j \sigma_{jk} \frac{\partial u_k\left(\Gamma, x_i\right)}{\partial x_i}\right) d\Gamma = G$$

➜ Crack Opening & Shear Displacement

$$COD = COD\left(p_1, \ldots, p_i, \ldots, p_n\right) \quad \text{and} \quad CSD = CSD\left(p_1, \ldots, p_i, \ldots, p_n\right)$$

$$p_i \in \{\text{geometry}, \text{materials}, \text{boundary conditions}, \text{loading mode}, \text{scale}\}$$
$$m \in \{I, II, III, I/II, I/III, II/III\}$$

Numerical Characterization of Fracture: VCCT & J-Integral

➜ Virtual Crack Closure Technique (VCCT)   ➜ J-Integral

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

Krueger, 2004

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

Rice, 1968

↘ THE FIBER-MATRIX INTERFACE CRACK PROBLEM

Multi-scale Decomposition of Fiber Reinforced Polymer Laminates

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

→ $\theta \left[^{\circ} \right] = 0$, angular position of debond's center

→ $2\Delta\theta \left[^{\circ} \right]$, debond's angular size

→ $\delta \left[^{\circ} \right]$, angle subtended by an element at the fiber/matrix interface

→ $VF_f \left[- \right]$, fiber volume fraction

→ $2L \left[\mu m \right]$, RVE's side length

→ $R_F \left[\mu m \right]$, fiber radius

→ $\frac{L}{R_f} = \frac{1}{2}\sqrt{\frac{\pi}{VF_f}} \left[- \right]$, RVE's aspect ratio

→ $\sigma_0 \left[MPa \right] = \frac{E_m}{1-\nu_m^2}\varepsilon_{xx}$, reaction stress of undamaged infinite RVE

→ $G_0 \left[\frac{J}{m^2} \right] = \pi R_f \sigma_R^2 \frac{1+(3-4nu_m)}{8Gm}$, 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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