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

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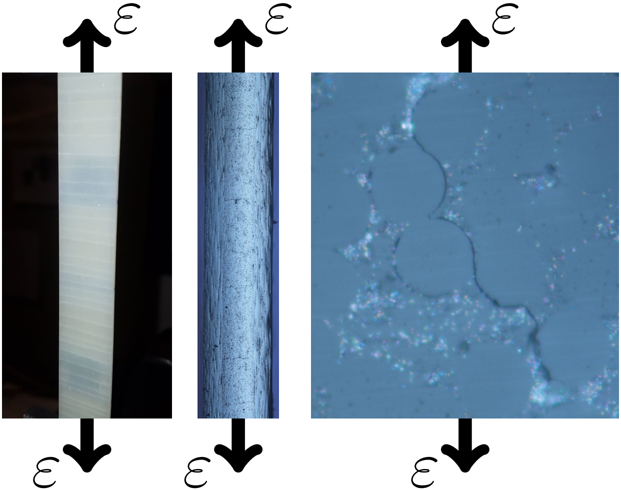
Outline

- Initiation of Transverse Cracking in Fiber Reinforced Polymer Composites (FRPCs): Microscopic Observations & Modeling
- The Fiber-Matrix Interface Problem in Fiber Reinforced Polymer Laminates
- 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.

Characterization of the Fracture Process

- 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

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

- 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

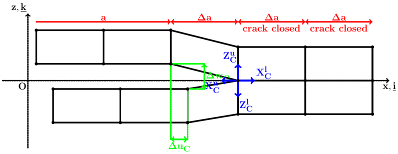
$$COD = COD\left(p_1, \ldots, p_i, \ldots, p_n\right) \quad \text{and} \quad CSD = CSD\left(p_1, \ldots, p_i, \ldots, p_n\right)$$

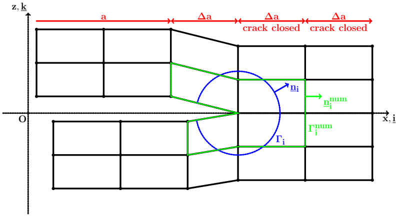
$$p_i \in \{\text{geometry}, \text{materials}, \text{boundary conditions}, \text{loading mode}, \text{scale}\}$$

$$m \in \{I, II, III, I/II, I/III, II/III\}$$

Numerical Estimation of Energy Release Rates

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





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

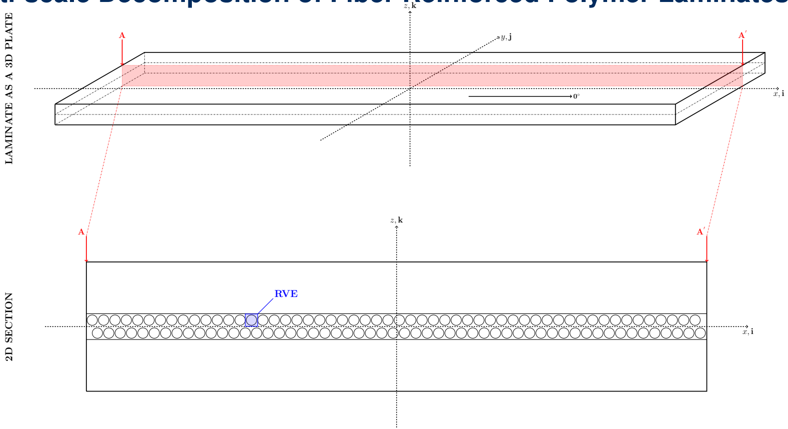
Krueger, 2004

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

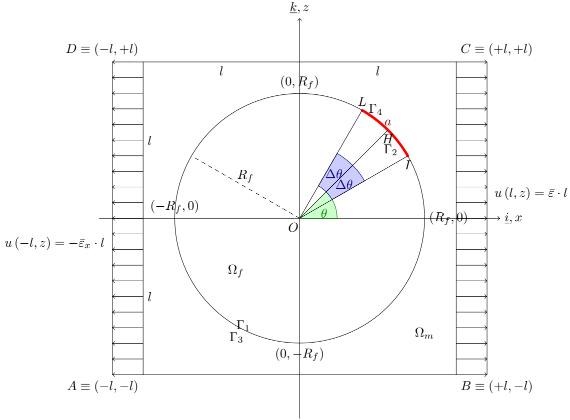
Rice, 1968

THE FIBER-MATRIX INTERFACE PROBLEM IN FRPC

Multi-scale Decomposition of Fiber Reinforced Polymer Laminates



The Fiber-Matrix Interface Crack Problem: Statement



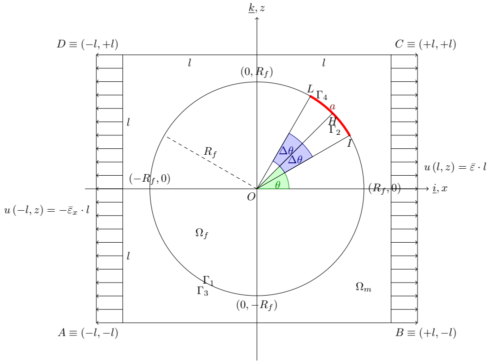
- ➔ 2D space
- ➔ Linear elastic homogeneous isotropic materials
- ➔ Mismatching elastic properties
- ➔ Plane state (strain or stress)
- ➔ Dirichlet-type BC
- ➔ Linear Fracture Mechanics
- ➔ Contact interaction
- ➔ Applied uniaxial traction
- ? SIF, ERR, mode ratio, stress and displacement distribution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



- $\theta\ [^\circ] = 0$, 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

References

- Kawabe K., Tomoda S. and Matsuo T.; *A pneumatic process for spreading reinforcing fiber tow Proc. 42nd Int. SAMPE USA (Anaheim, CA, USA)* 6576, 1997.
- Kawabe K., Tomoda S.; *Method of producing a spread multi-filament bundle and an apparatus used in the same.* Japan: Fukui Prefectural Government; 2003. JP 2003-193895, 2003.
- Kawabe K.; *New Spreading Technology for Carbon Fiber Tow and Its Application to Composite Materials Sen'i Gakkaishi* **64** (8) 262–267, 2008 [in Japanese].

References

- Sasayama H. and Tomoda S.; *New Carbon Fiber Tow-Spread Technology and Applications to Advanced Composite Materials S.A.M.P.E. journal* **45** (2) 6–17, 2009.
- Meijer A.; *NTPT makes worlds thinnest prepeg even thinner [Internet] [cited 30 April 2017]* North Thin Ply Technology (NTPT) press release 2015. Available from http://www.thinplytechnology.com/mesimages/Press_Release_N 16JUN2015.pdf.
- *oXeon TECHNOLOGIES 2014 [Internet] [cited 30 April 2017]* Available from http://oxeon.se/technologies/.

References

- Donald L. Flaggs, Murat H. Kural; *Experimental Determination of the In Situ Transverse Lamina Strength in Graphite/Epoxy Laminates. J. Comp. Mat.* **16** 2, 1982.
- Krueger R.; *Virtual crack closure technique: History, approach, and applications Appl. Mech. Rev.* **57** (2) 109–143, 2004.
- Rice J. R.; *A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks J. Appl. Mech.* **35** 379–386, 1968.

References

- Toya M.; *A Crack Along the Interface of a Circular Inclusion Embedded in an Infinite Solid J. Mech. Phys.* **22** 325–348, 1975.
- París F., Caño J. C., Varna J.; *The fiber-matrix interface crack - A numerical analysis using Boundary Elements Int. J. Fract.* **82** 1 11–29, 1996.

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