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

L. Di Stasio[1,2], J. Varna[1], Z. Ayadi[2]

[1] Division of Materials Science, Luleå University of Technology, Luleå, Sweden

[2] EEIGM & IJL, Université de Lorraine, Nancy, France

10th EEIGM International Conference on Advanced Materials Research

Moscow (RU), April 25-26, 2019

Education and Culture

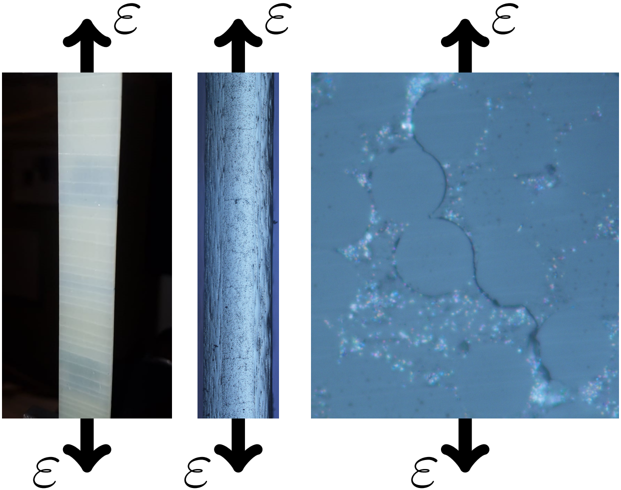
Erasmus Mundus

Outline

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

↘ 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.

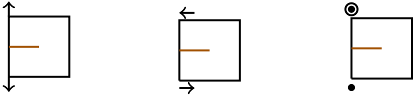
Right:
edge view of $[0, 90]_S$, optical microscope.

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

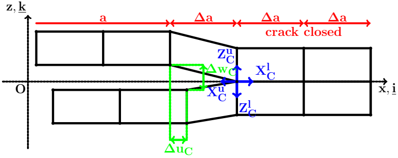
$$J = \lim_{\delta \to 0} \int_{\Gamma_\delta} \left(W - n_j \sigma_{jk} \frac{\partial u_k}{\partial x_i}\right) d\Gamma$$

➔ 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

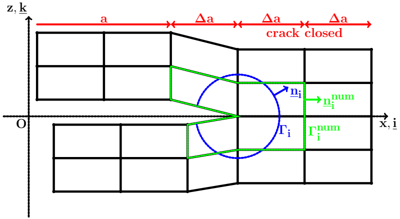
Virtual Crack Closure Technique (VCCT)



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

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

J-Integral

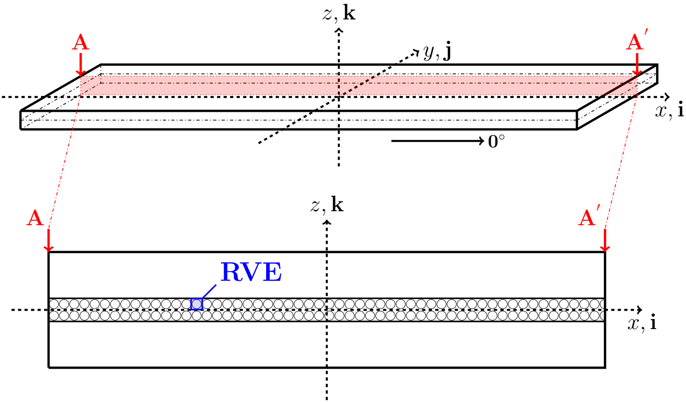


$$J_i = \sum_{k=1}^{n_{segments}} \sum_{j=1}^{n_{nodes}} \left[w_j \left(W - n_j \sigma_{jk} \frac{\partial u_k}{\partial x_i} \right) \bigg|_{(x_{kj}, y_{kj})} \right]$$

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.

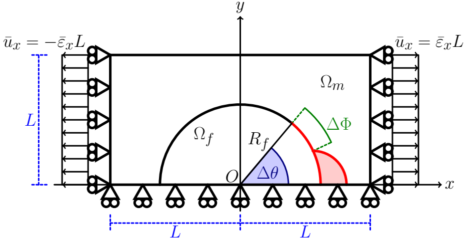
↘ THE FIBER-MATRIX INTERFACE CRACK PROBLEM

The Fiber-Matrix Interface Crack Problem: Geometry



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

The Fiber-Matrix Interface Crack Problem: Assumptions

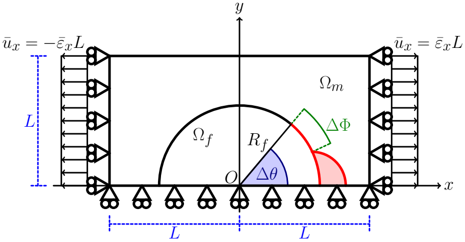


$$R_f = 1 \ [\mu m] \qquad L = \frac{R_f}{2}\sqrt{\frac{\pi}{V_f}}$$

Material	E_1	ν_{12}
glass fiber	70.0	0.2
epoxy	3.5	0.4

- ➔ Linear elastic, homogeneous and isotropic materials
- ➔ Plane strain
- ➔ Frictionless contact interaction
- ➔ Symmetric w.r.t. x-axis
- ➔ Coupling of x-displacements on left and right side (repeating unit cell)
- ➔ Applied uniaxial tensile strain $\bar{\varepsilon}_x = 1\%$

The Fiber-Matrix Interface Crack Problem: Solution



in Ω_f, Ω_m :

$$\frac{\partial^2 \varepsilon_{xx}}{\partial y^2} + \frac{\partial^2 \varepsilon_{yy}}{\partial x^2} = \frac{\partial^2 \gamma_{xy}}{\partial x \partial y}$$

$$\varepsilon_z = \gamma_{zx} = \gamma_{yz} = 0$$

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} = 0$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} = 0$$

$$\sigma_{zz} = \nu \left(\sigma_{xx} + \sigma_{yy}\right)$$

for $0^\circ \leq \alpha \leq \Delta\theta$:

$$\left(\vec{u}_m(R_f, \alpha) - \vec{u}_f(R_f, \alpha)\right) \cdot \vec{n}_\alpha \geq 0$$

for $\Delta\theta \leq \alpha \leq 180^\circ$:

$$\vec{u}_m(R_f, \alpha) - \vec{u}_f(R_f, \alpha) = 0$$

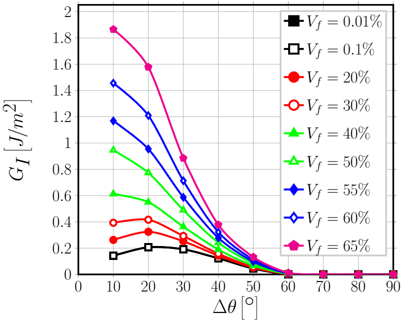
$$\sigma_{ij} = E_{ijkl}\varepsilon_{kl}$$

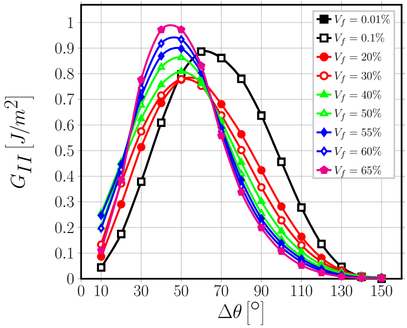
$$+ BC$$

- ➔ Finite Element Method (FEM) in Abaqus^{TM}
- ➔ 2^{nd} order shape functions
- ➔ 6-nodes triangles & 8-nodes quadrilaterals
- ➔ regular mesh of quadrilaterals at the crack tip:
  - $AR \sim 1$
  - $\delta = 0.05^\circ$

The Fiber-Matrix Interface Crack Problem: Normalization & Scaling

➔ $G_I = G_0\left(V_f, E_f, \nu_f, E_m, \nu_m, \bar{\varepsilon}_x\right) g_{\Delta\theta}\left(\Delta\theta, BC, microstructure\right)$





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.

DocMASE

UNIVERSITÉ DE LORRAINE

EEIGM

LULEÅ UNIVERSITY OF TECHNOLOGY

Education and Culture

Erasmus Mundus