

THE FIBER-MATRIX INTERFACE CRACK PROBLEM AND ITS SOLUTION BY THE FINITE ELEMENT METHOD

L. Di Stasio^{1,2}, Z. Ayadi¹, J. Varna²

¹EEIGM & IJL, Université de Lorraine, Nancy, France

²Division of Materials Science, Luleå University of Technology, Luleå, Sweden

Mid-Term Defence - Nancy (FR), October 24, 2017



Outline

- ➔ Damage Mechanisms in Thin Ply Fiber Reinforced Polymer Laminates
- ➔ The Fiber-Matrix Interface Problem in Fiber Reinforced Polymer Laminates
- ➔ Analysis of the Infinite Reference Volume Element (RVE)
- ➔ Conclusions & Outlook
- ➔ Appendices



DAMAGE IN THIN PLY FRPC

Spread Tow Technology: Introduction

- Firstly developed for commercial use in Japan between 1995 and 1998 (Kawabe, Tomoda et al. 1997 [1], 2003 [2], 2008 [3], 2009 [4])
- In the last decade its use has been spreading, from sports' equipments to mission-critical applications as in the *Solar Impulse 2*
- Only a few producers worldwide: NTPT (USA-CH) [5], Oxeon (SE) [6], Chomarat (FR), Hexcel (USA), Technomax (JP)

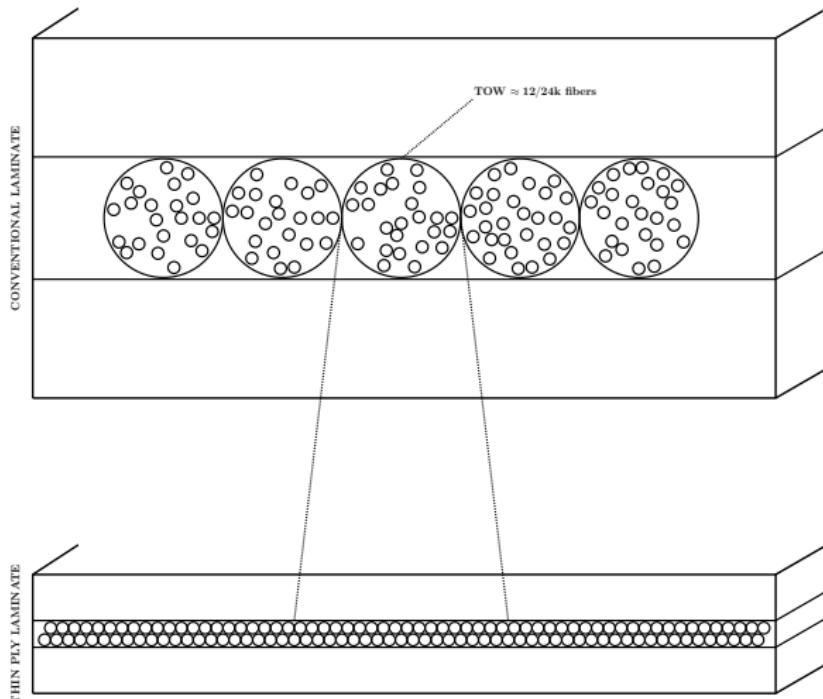


(a) By North Thin Ply Technology.

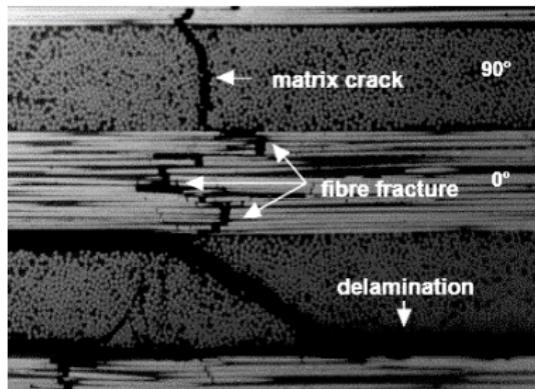


(b) By TeXtreme.

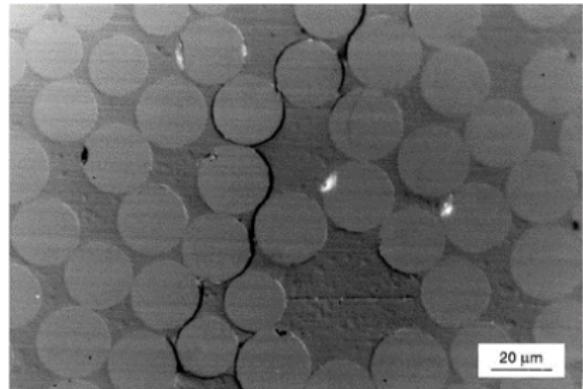
Spread Tow Technology: Foundations



Damage Onset and Propagation



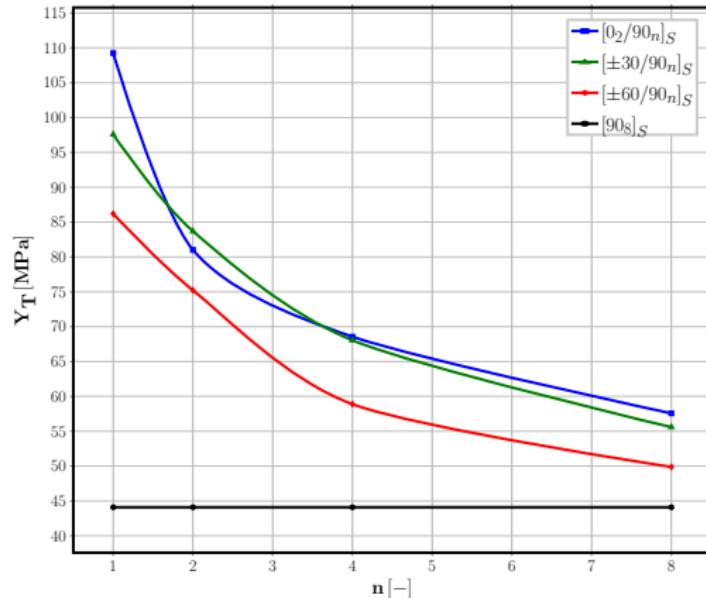
(c) By Dr. R. Olsson, Swerea, SE.



(d) By Prof. Dr. E. K. Gamstedt, KTH, SE.

For a visual definition of intralaminar transverse cracking.

The Thin Ply Effect

In situ transverse lamina strength Y_T as a function of thickness and ply orientation

Measurements of in-situ transverse strength from D. L. Flaggs & M. H. Kural, 1982 [7].

Characterization of the Fracture Process

- Energy Release Rate

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

- Stress Intensity Factor

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

- J-Integral

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

- Crack Opening & Shear Displacement

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

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

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

Evaluation of Fracture Parameters

→ Analytical

- ✓ Closed form
- ✓ Every material scale can be studied

- ✗ Particular configurations, often infinite in size
- ✗ Complex geometries cannot be studied

→ Numerical

- ✓ Complex geometries can be studied
- ✓ Every material scale can be studied

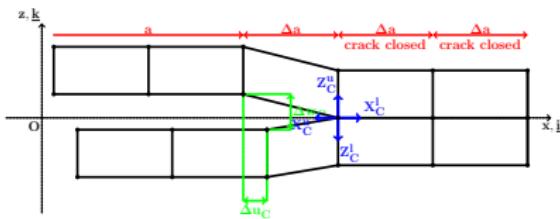
- ✗ Discretization
- ✗ Finite domains

→ Experimental

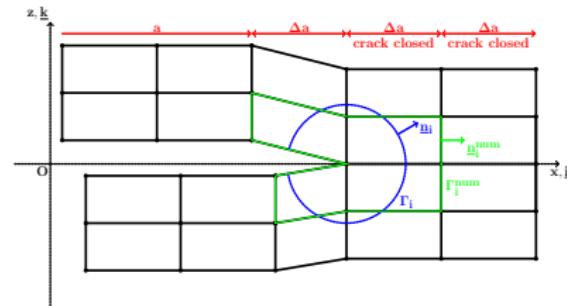
- ✓ Complex geometries can be studied
- ✗ Not every material scale is accessible

Numerical Estimation of Energy Release Rates

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



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



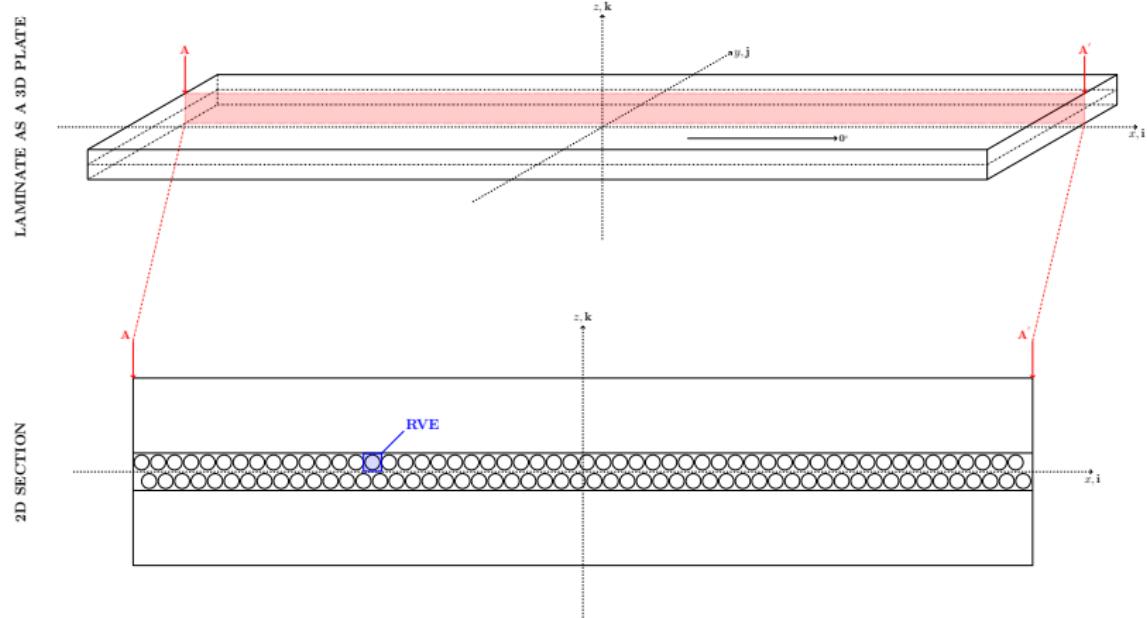
Krueger, 2004

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

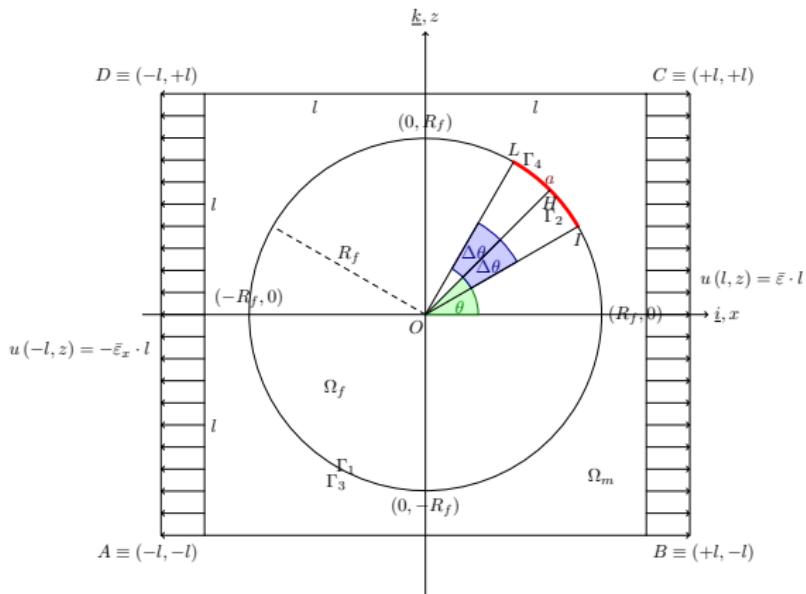
Rice, 1968

THE FIBER-MATRIX INTERFACE PROBLEM IN FRPC

Multi-scale Decomposition of Fiber Reinforced Polymer Laminates



The Fiber-Matrix Interface Crack Problem: Statement



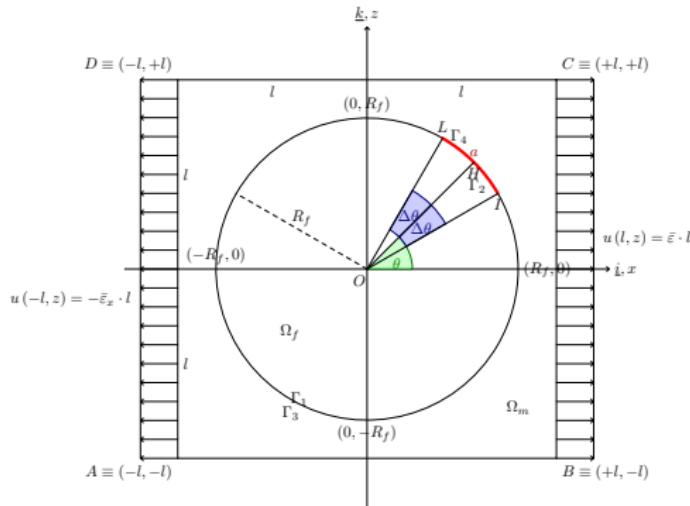
- 2D space
- Linear elastic homogeneous isotropic materials
- Mismatching elastic properties
- Plane state (strain or stress)
- Dirichlet-type BC
- Linear Fracture Mechanics
- Contact interaction
- Applied uniaxial traction
- ? SIF, ERR, mode ratio, stress and displacement distribution at the interface

The Fiber-Matrix Interface Crack Problem: Solution

Method	Domain	Natural Variable	Conjugate Variable	Dirichlet BC
Analytical functions	(complex) 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

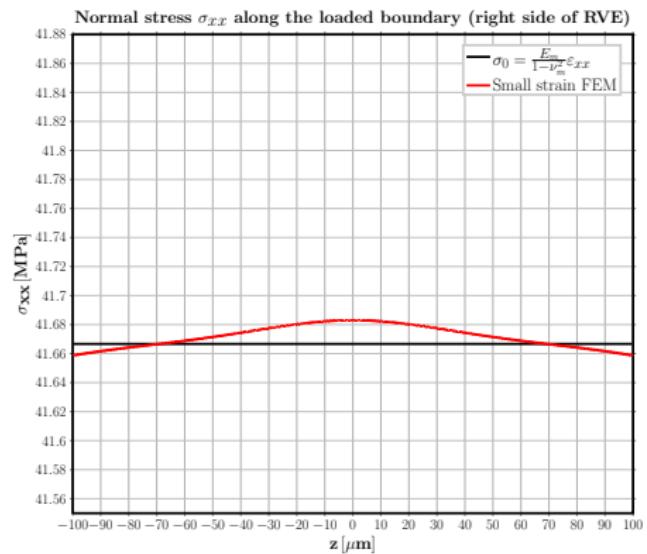
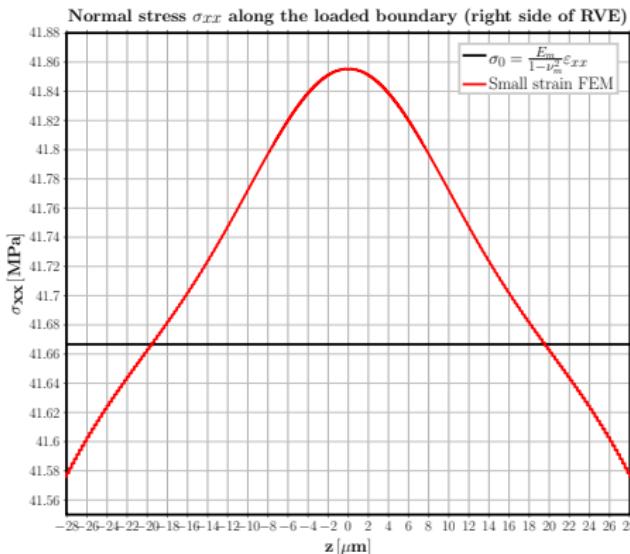
ANALYSIS OF THE INFINITE RVE

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
- $\frac{L}{R_f} = \frac{1}{2} \sqrt{\frac{\pi}{Vf}}$, 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

Reaction Stress at the Boundary



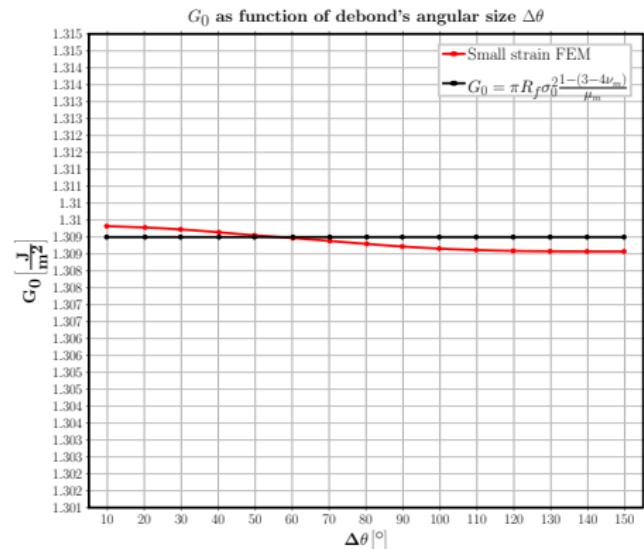
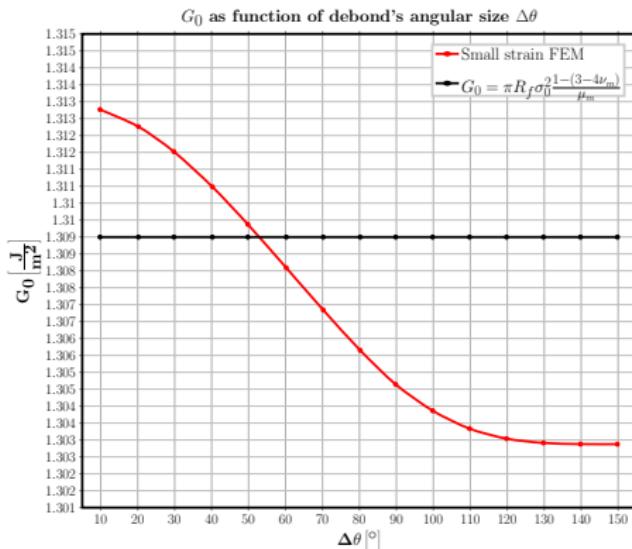
$$VF_f = 0.001, \frac{L}{R_f} \sim 28, \delta = 0.4^\circ,$$

$$\frac{\sigma_{max} - \sigma_{mean}}{\sigma_{mean}} = 0.34\%$$

$$VF_f = 0.000079, \frac{L}{R_f} \sim 100, \delta = 0.4^\circ,$$

$$\frac{\sigma_{max} - \sigma_{mean}}{\sigma_{mean}} = 0.03\%$$

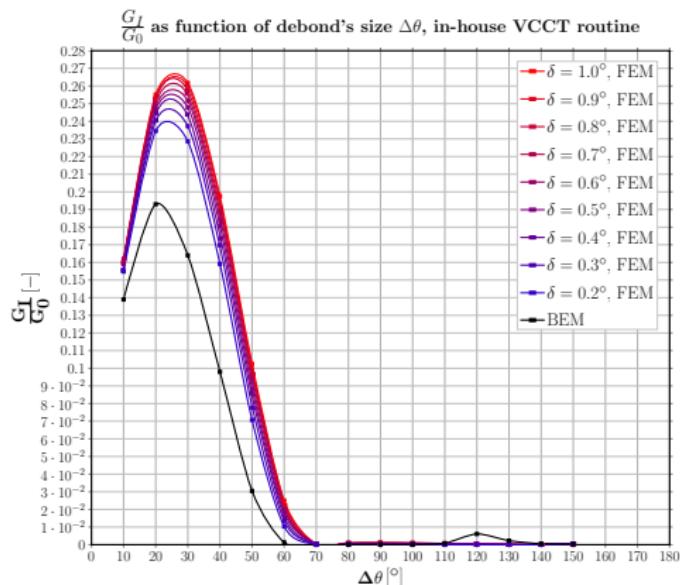
Normalization G_0 as a function of $\Delta\theta$



$$VF_f = 0.001, \frac{L}{R_f} \sim 28, \delta = 0.4^\circ$$

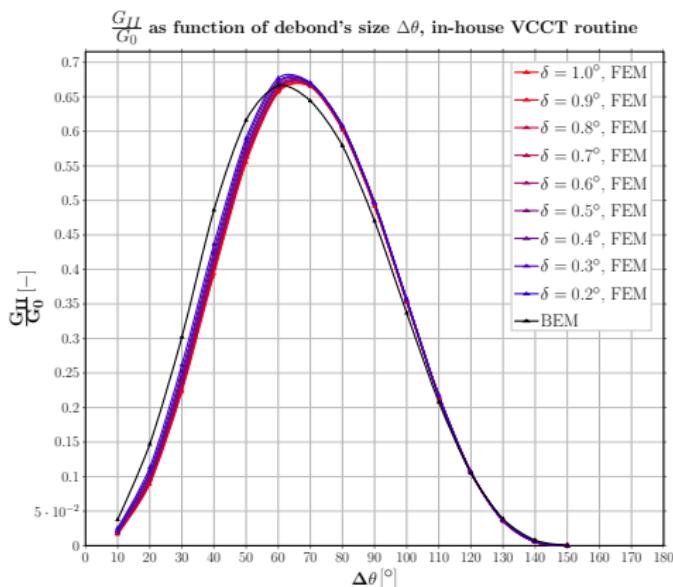
$$VF_f = 0.000079, \frac{L}{R_f} \sim 100, \delta = 0.4^\circ$$

Mode I Energy Release Rate G_I from VCCT



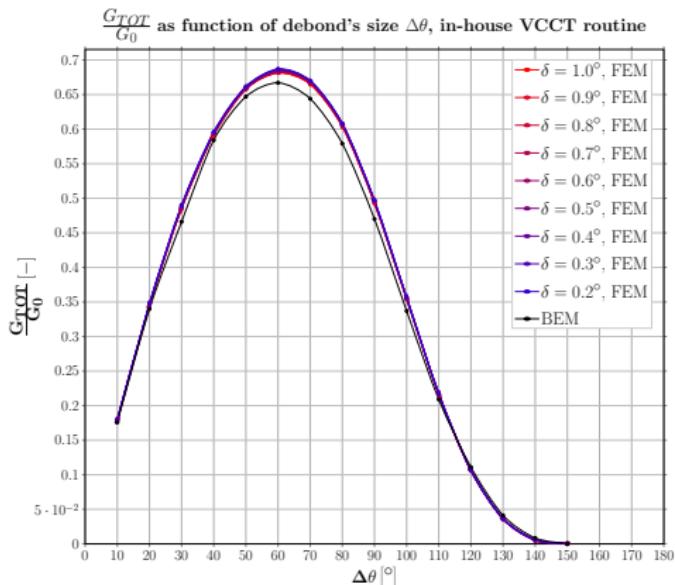
$Vf_f = 0.000079$, $\frac{L}{R_f} \sim 100$; fading from red to blue for decreasing size of elements at the interface, VCCT from FEM results; in black BEM results.

Mode II Energy Release Rate G_{II} from VCCT



$Vf_f = 0.000079$, $\frac{L}{R_f} \sim 100$; fading from red to blue for decreasing size of elements at the interface, VCCT from FEM results; in black BEM results.

Total Energy Release Rate G_{TOT} from VCCT



$Vf_f = 0.000079$, $\frac{L}{R_f} \sim 100$; fading from red to blue for decreasing size of elements at the interface, VCCT from FEM results; in black BEM results.

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

APPENDICES

Timeline

- Oct. 2015 - Dec. 2017: research in Nancy, FR
- Jan. 2018 - Dec. 2019: research in Luleå, SE

- May - June 2016: DocMASE Summer School 2016, Luleå, SE; presentation
- June 2016: quarter-term auto-evaluation report, Nancy, FR
- April 2017: International Materials Research Meeting of the Greater Region, Sarrebrücken, DE; presentation
- May 2017: EMMA doctoral school seminar, Nancy, FR; poster
- July 2017: seminar day of the Research Group 304, Nancy, FR; presentation (in French)
- October 2017: mid-term defence, Nancy, FR
- September 2018: mid-term defence, Luleå, SE
- December 2019: doctoral defence, Nancy, FR - Luleå, FR

Courses & Training

- ✓ Scientific courses (40h or 8 ECTS credits)
- ✓ Transverse courses (40h or 8 ECTS credits)
- ✓ Seminars & Conferences (at least 15 seminars)
- ✓ EMMA seminar (at least 1)
- ✓ Portfolio of competences (regular updates)
- ✓ Quarter-term assessment
- Mid-term assessment
- Doctoriales

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_NT16JUN2015.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.



LULEÅ
UNIVERSITY
OF TECHNOLOGY



Education and Culture

Erasmus Mundus