Mode I fracture toughness and delamination of layered composites

John Botsis[1] & George A. Pappas[2]

[1]EPFL· Lausanne, Switzerland
[2]ETHZ, Zurich, Switzerland

ONLINE WORKSHOP
Mode I interlaminar fracture toughness and the factors affecting it.
MAY 2024

Objective

Characterise toughness (and traction-separation relations) of UD and MD CFRP laminates under Mode I delamination

RELEVANT QUESTIONS

1. Are the current standards appropriate for UD and MD layouts?
2. What produces the observed scale effects in delamination?

Methods

Materials & specimens

Material

Carbon/epoxy (Gurit ST™)
Autoclave curing
DCB, Initial crack 60 mm

UD Monotonic (3 mm/min)

Interlaminar & intralaminar
- **Thickness : 2,4,8,10 mm**
- **Width : 25 mm**

Angle-Ply Monotonic (3 mm/min)
(specimens with the same stiffness)

- **Interface : ±30; ±45, ±60**
- **Thickness : 4, 5.5, 6 mm**
- **Width : 25, 35, 45 mm**

Data reduction

Linear case

$$G_{total} = G_{I,i} + G_{I,b} = \frac{P^2}{2b}\frac{dC}{da}$$

Non-Linear case

$$J_{total} = J_{I,i} + J_{I,b} = \frac{P\theta}{2B}$$

Experimental techniques

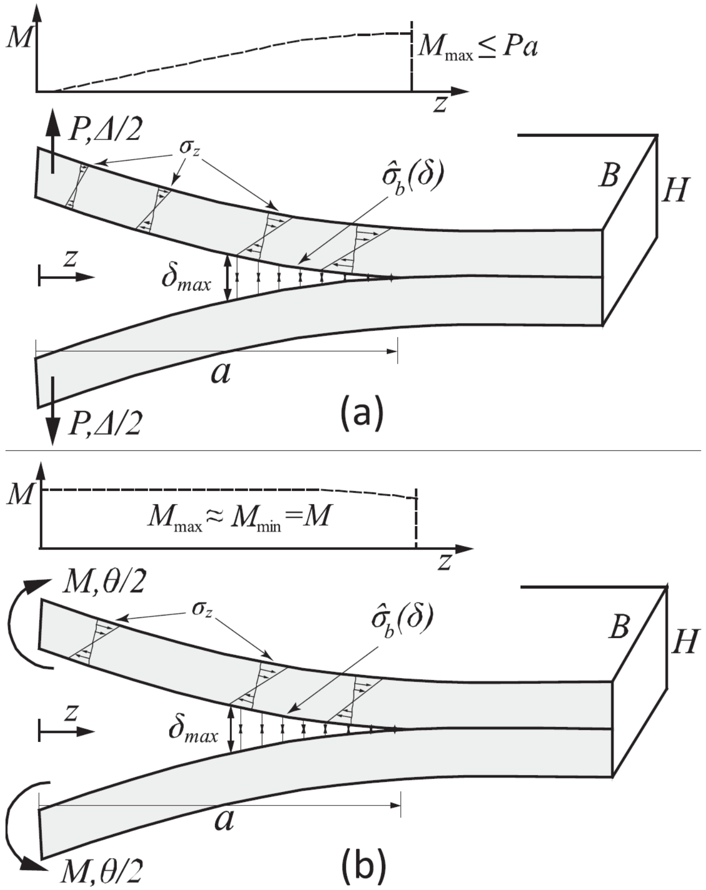
- Embedded multplexed Bragg Gratings
- Digital Image Correlation
- Traveling microscopy
- Sectioning and polishing
- Image analysis (Keyence digital microscopy)

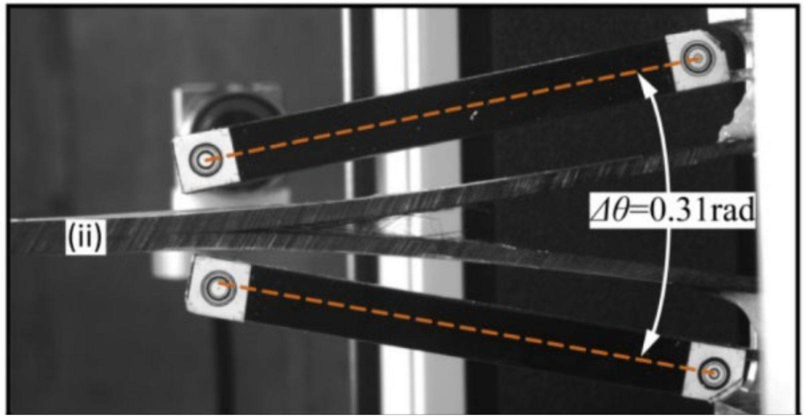
Methods

Two distinct testing configurations

End Opening Forces (EOF)

Pure Moment (PM)





$$J_{total} = J_{I,i} + J_{I,b} = \frac{P\theta}{2B}$$

PAPPAS & BOTSIS, *Int J Solids Struct* 2019; 2020.

Methods

Fracture toughness/resistance measurements

For UD composites in DCB configuration:

ASTM Standard D5528-01

- Modified Beam Theory (MBT)
- Compliance Calibration (CC)
- Modified Compliance Calibration (MCC)

Initiation load at:

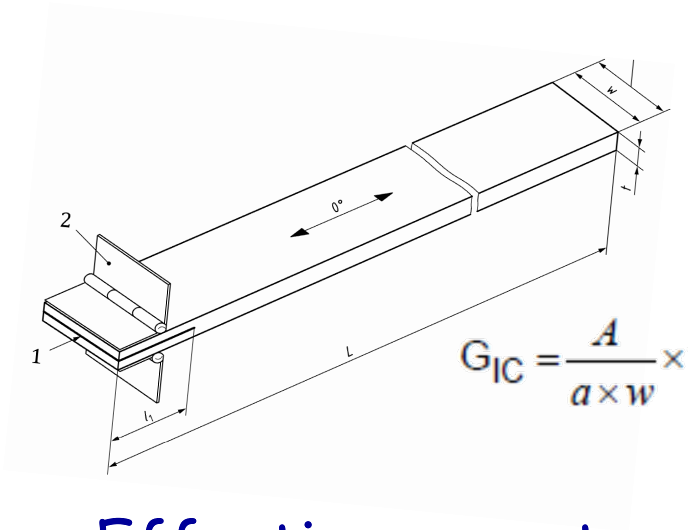
1. Non-linearity
2. Visual observation of Δa
3. Load off-set 5%

Potential Problems:

-inaccuracies in measuring Δa
-non-linearities
-crack front geometry
-Bias in compliance fitting

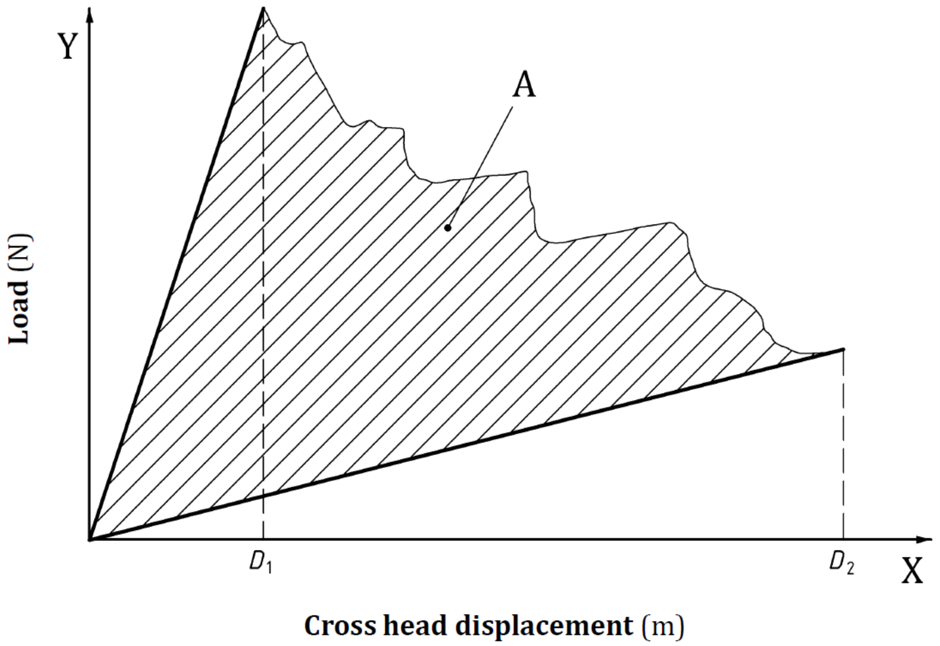
Methods

DIN EN 6033 : Interlaminar fracture toughness energy (UD tape or woven fabric)



$$G_{IC} = \frac{A}{a \times w} \times 10^6$$

- Effective mean toughness over $\Delta a = D_2 - D_1 \sim 90mm$



Problems:

- Scale effects (specimen thickness/width)

Methods

Reported data in the literature on toughness on angle-ply are not consistent/conclusive.

The ASTM standard does not work well for fracture toughness of angle-ply specimens because of:

- Inaccuracies in crack length measurements
- Compliance fitting
- Geometric and/or material non-linearities

$$G_{total} = G_{I,i} + G_{I,b} = \frac{P^2}{2b}\frac{dC}{da}$$

The J-integral based method overcomes these shortcomings:

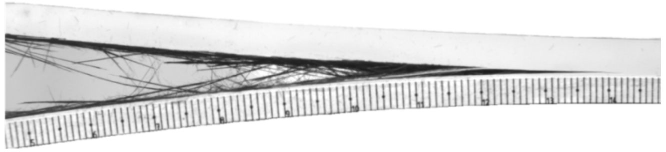
$$J_{total} = J_{I,i} + J_{I,b} = \frac{P\theta}{2B}$$

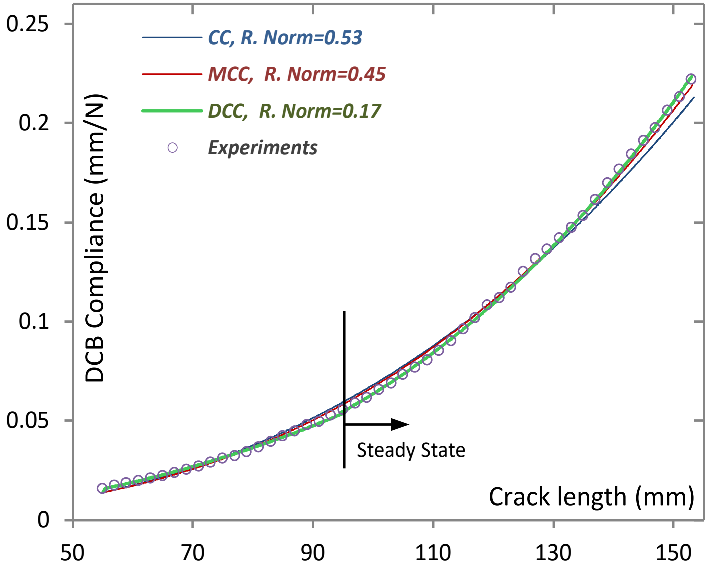
Results on UD CFRP

The ASTM standard works well for the fracture toughness at initiation of UD specimens.

$$G_{I,i} = \frac{P^2}{2b}\frac{dC}{da}$$

For long delamination cracks (Large Scale Bridging), the standard is not always appropriate: Problems appear in compliance calibration and nonlinearities when are present.



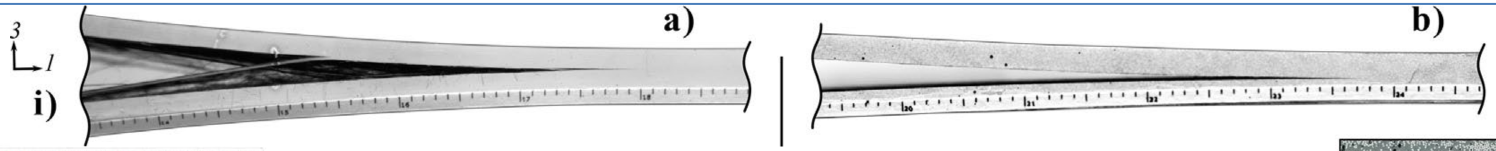


$$G_{total} = G_{I,i} + G_{I,b} = \frac{P^2}{2b}\frac{dC}{da}$$

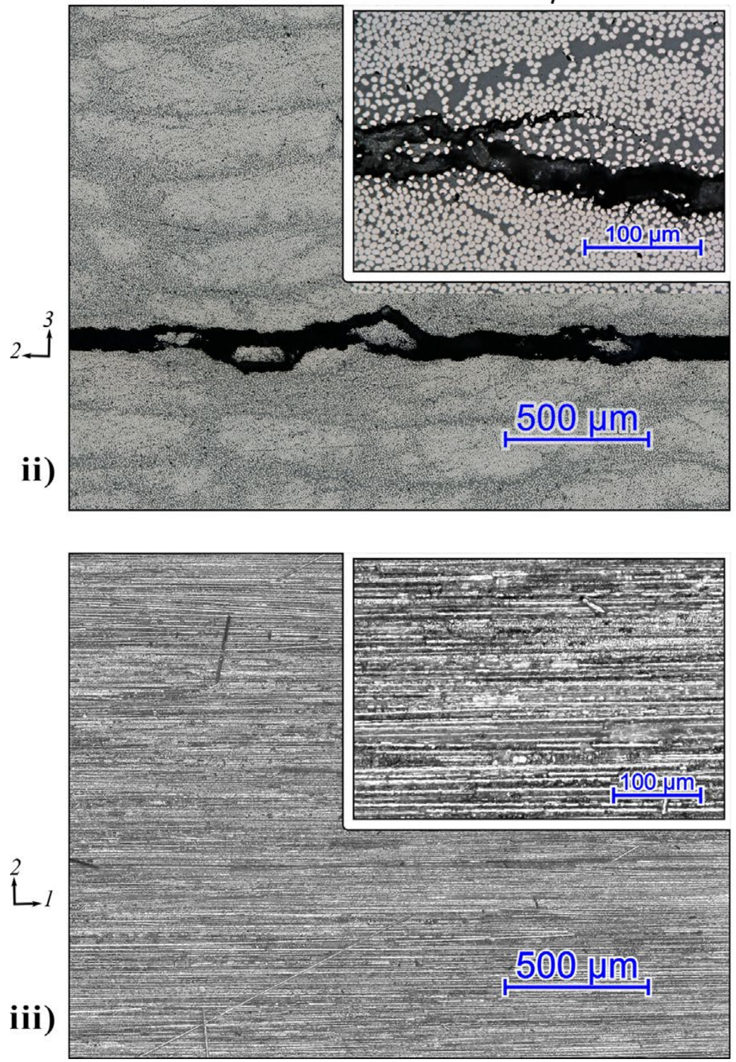
PAPPAS & BOTSIS, *Int J Solids Struct* 2016

Origin of fiber bridging

High Fiber-Bridging

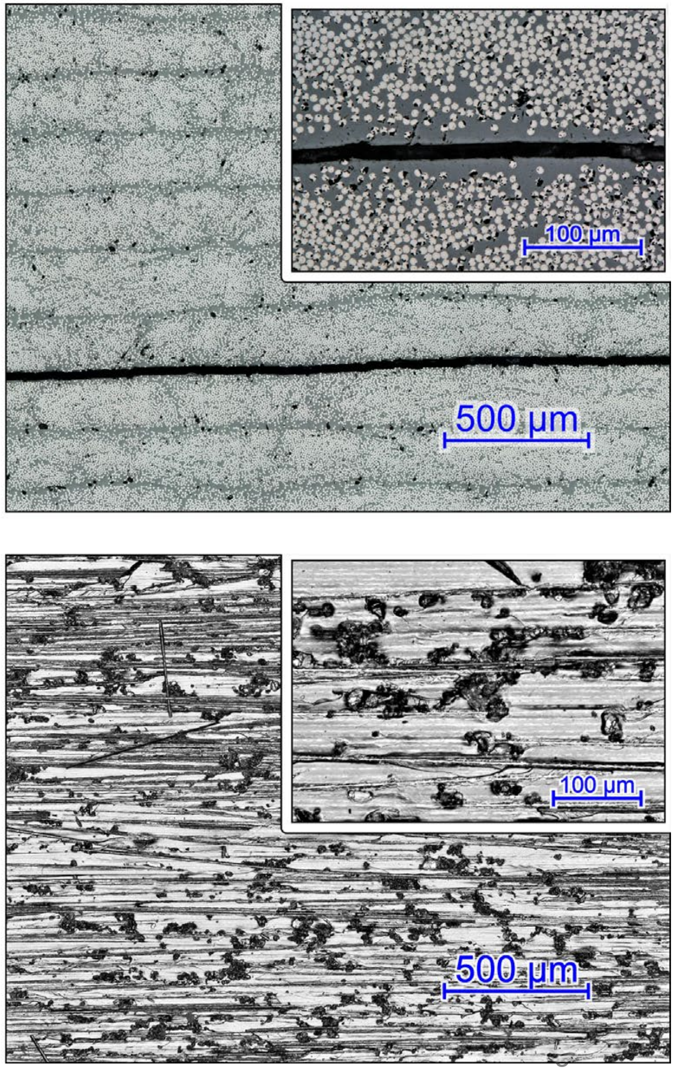


No Fiber-Bridging



- On “brittle” matrix systems: Cracks will potentially stay with matrix-rich zones

- On tough matrix systems: Cracks will follow fiber rich zones

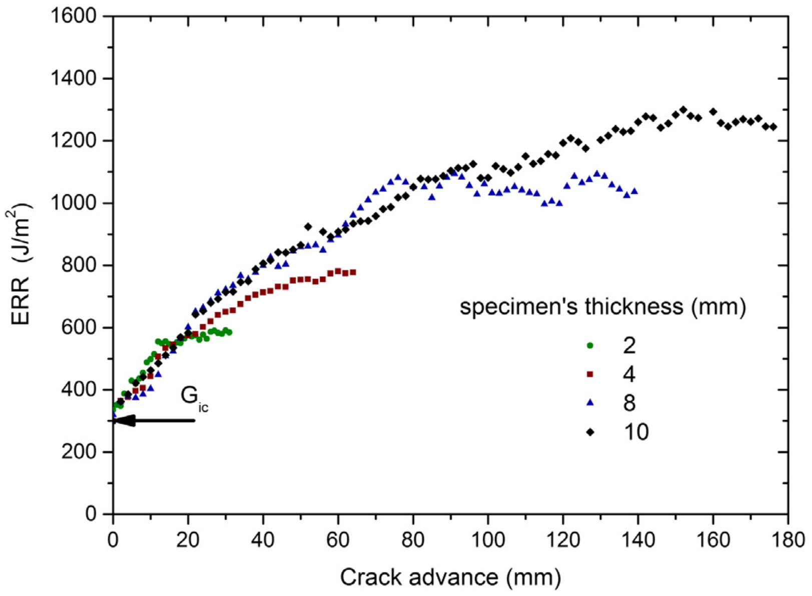


What else can affect toughening?

BLONDEAU, PAPPAS & BOTSIS, *Compos Struct* 2021.

Results on UD CFRP

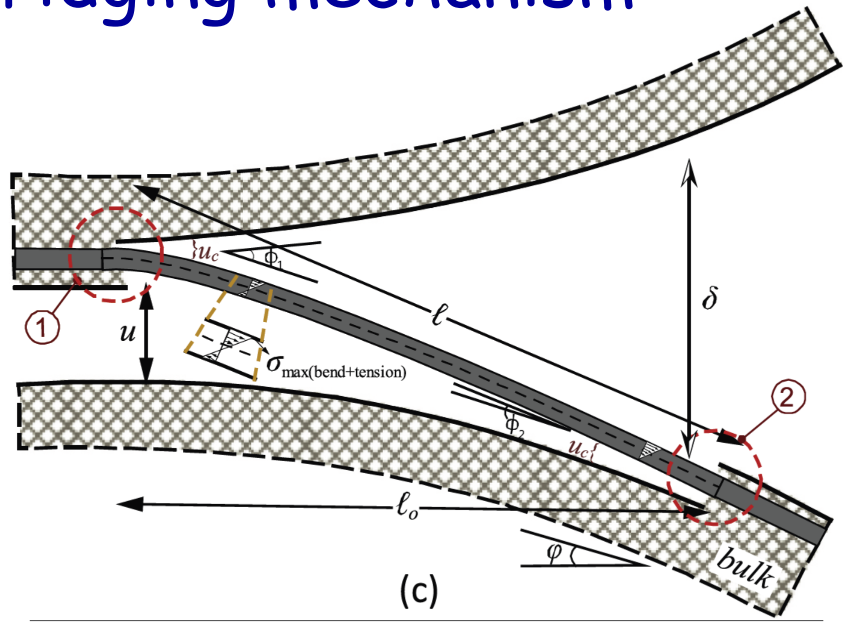
Scale effects



Intitiation toughness is the same. Resistnace during delamination is geometry-dependent.

FARMAND-ASHTIANI, ET AL, *Int J Solids Struct* 2015

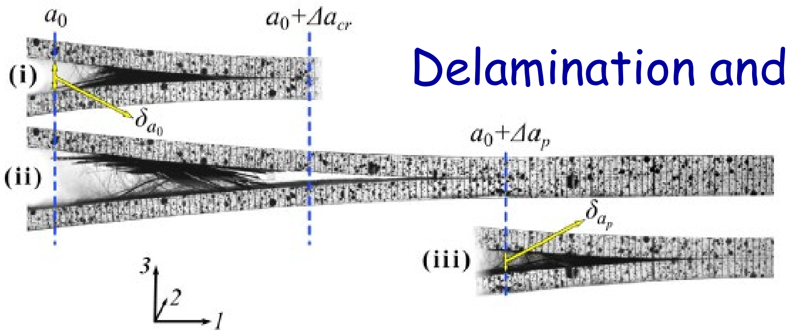
Bridging mechanism



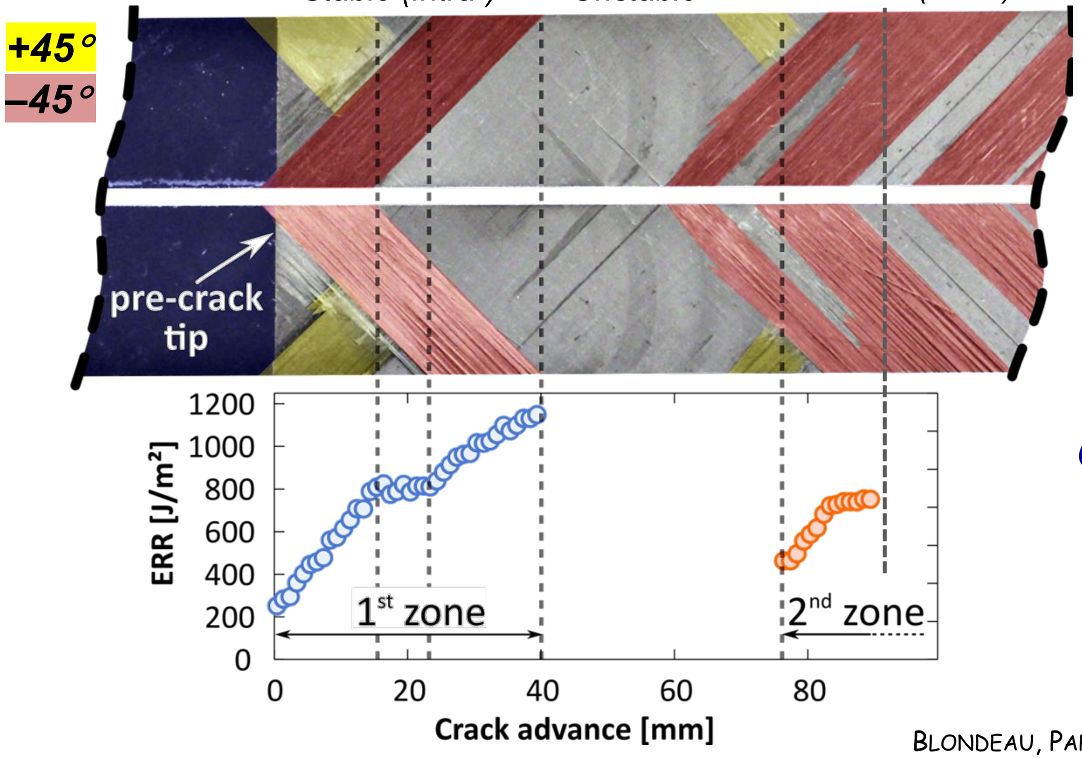
The arm's stiffness matters because the fiber bundles in the bridging zone support bending.

PAPPAS & BOTSIS, *Compos Sci Tech* 2020

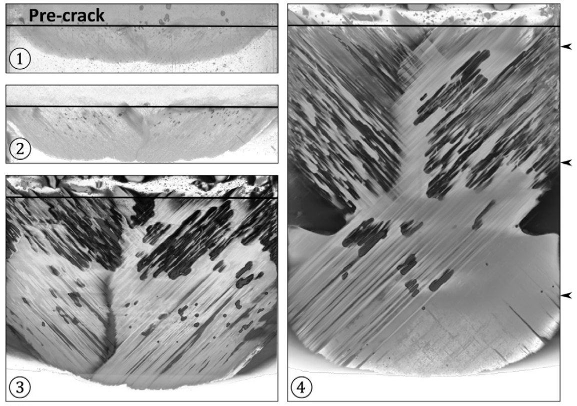
Results on MD angle-ply

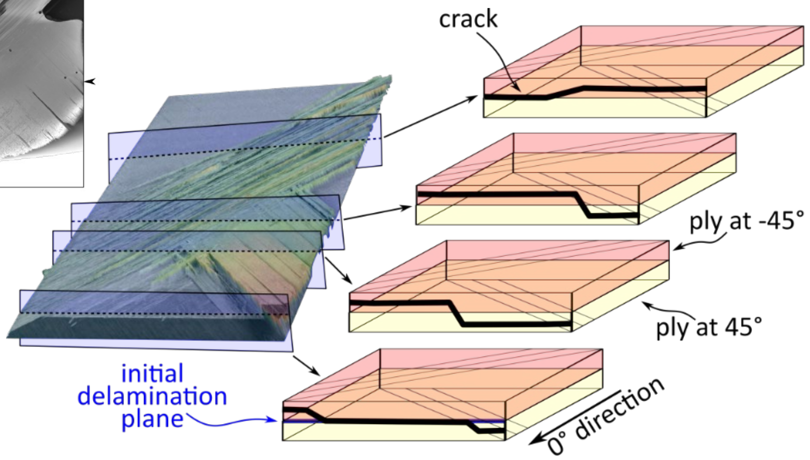


Delamination and bridging



X-ray Computer Tomography and Interpretation





Crack propagation & growth leads to migrations amongst:

i) Intra- (stable with LSB)

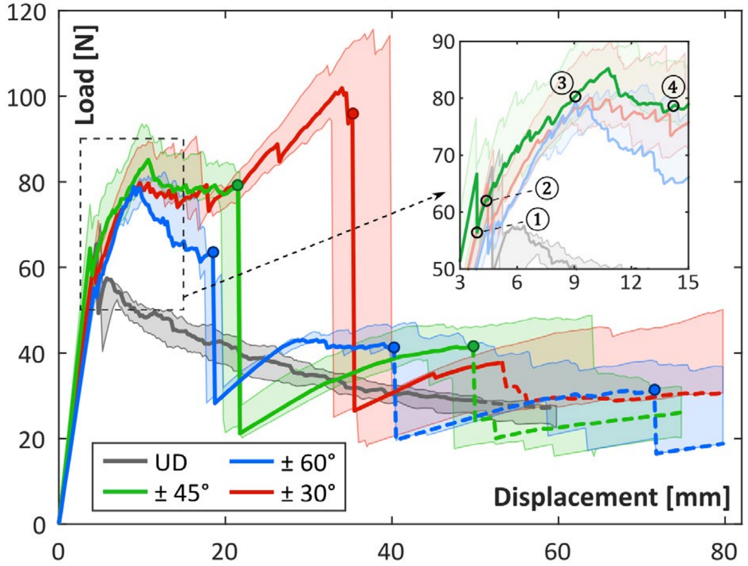
ii) Inter- (unstable) laminar plane.

BLONDEAU, PAPPAS & BOTSIS, *Compos Struct* 2019

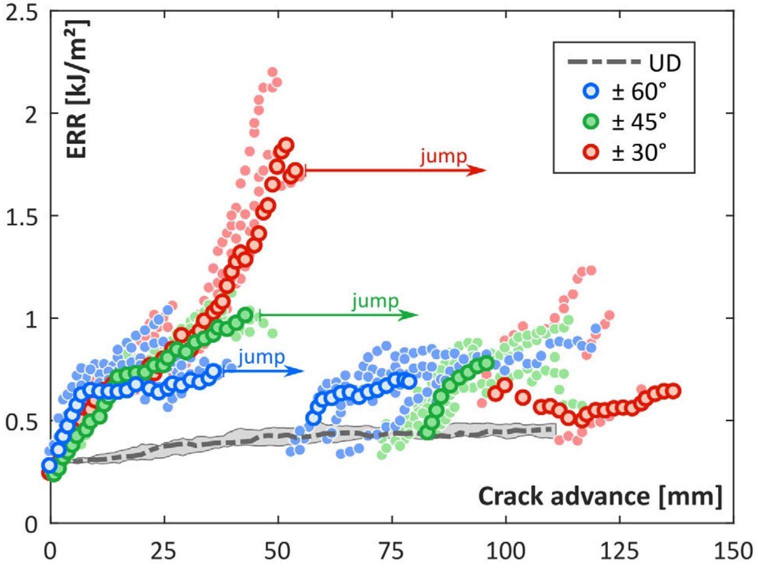
Results on MD angle-ply

Stacking sequence	Abbr.	B [mm]	J_{pop-in} [kJ/m^2]	$J_{I,i}$ [kJ/m^2]
$[0_{10}//S]$	UD	25.2	0.32 ± 0.04	0.27 ± 0.01
$[-60/60/-60/0_9/60/-60/60//AS]$	± 60°	25.15	0.29 ± 0.03	0.31 ± 0.03
$[-45/45/-45/0_9/45/-45/45//AS]$	± 45°	25.0	0.27 ± 0.02	0.26 ± 0.02
$[-30/30/-30/90/0_5/90/30/-30/30//AS]$	± 30°	25.1	0.29 ± 0.03	0.28 ± 0.03
$[-60/60/-60/0_8/60/-60/60//AS]$	$\pm 60^\circ_{35}$	34.95	0.27 ± 0.02	0.30 ± 0.02
$[-60/60/-60/0_7/60/-60/60//AS]$	$\pm 60^\circ_{45}$	44.95	0.29 ± 0.01	0.32 ± 0.02

Load-Displacement Response



R-Curve Behavior



initiation toughness (independent of interface angle)

$$J_{I,i} = \frac{P\theta}{2B}$$

propagation toughness (strong dependence on interface angle)

$$J_{total} = J_{I,i} + J_{I,b} = \frac{P\theta}{2B}$$

Blondeau, Pappas & Botsis, *Compos Struct* 2019

EPFL

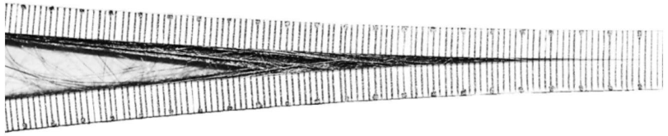
Summary

1. The ASTM standards give good results on toughness at initiation of UD laminates.
2. For long crack lengths, fracture resistance mesurements can be challenging due to bias when fitting the compliance to crack length data.
3. In the MD laminates, the standards are not generally appropriate due to bowing, non-symmetric crack front, non-planar crack, etc.
4. An efficient method to overcome these issues is to calculate the J-integral at initiation and propagation. Our results show that consistent data are obtained in anti-symmetric interfaces. The data show that toughness at initiation is independent of interface angle (UD, CP, angle-ply), loading condition (PM or EOF) and intra- or inter-
5. The specimen geometry effects on fracture resistance are due to the bending of the bridging bundles and they interaction with the spacemen's arms.
6. The delamination response of DCB under end-opening-forces and pure moments of CFRP is different and attributed to the bending stiffness of the bridging bundles.

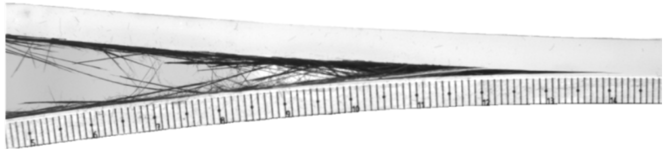
Experimental evidence

Monotonic or fatigue DCB testing of CFRP

Unidirectional interlaminar

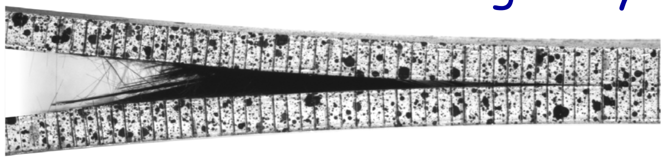


Unidirectional intralaminar

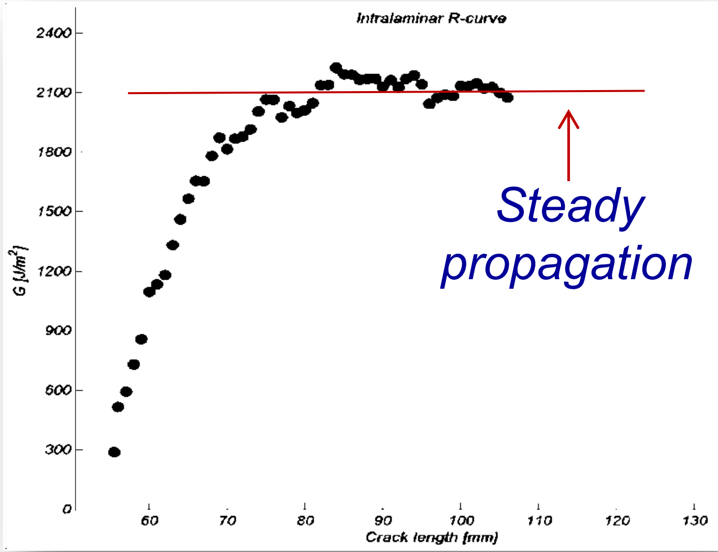


Cross-Ply

Angle-Ply



Large Scale Bridging

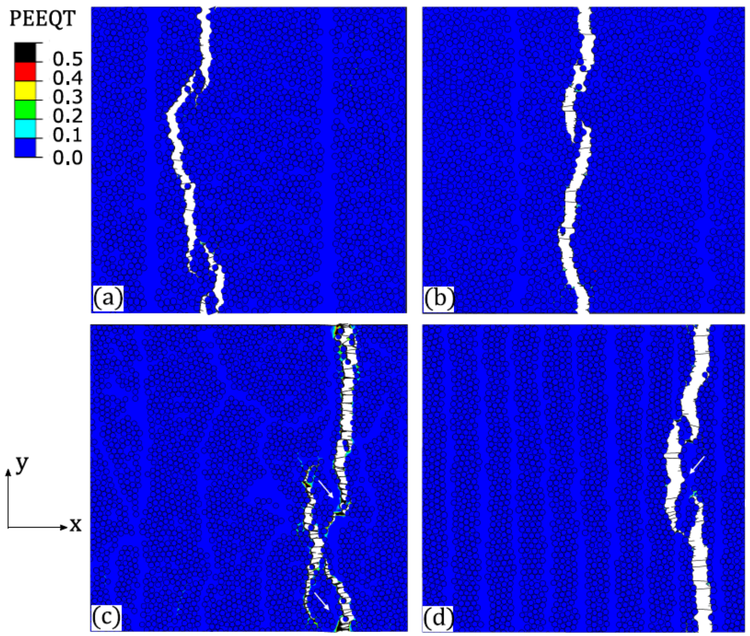


Strong influence of geometry and interface angle.

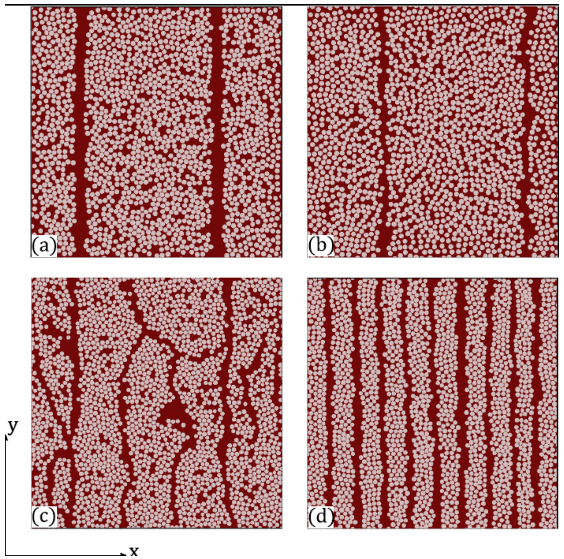
BOTSIS & CO. 2005-2021

Origin of fiber bridging

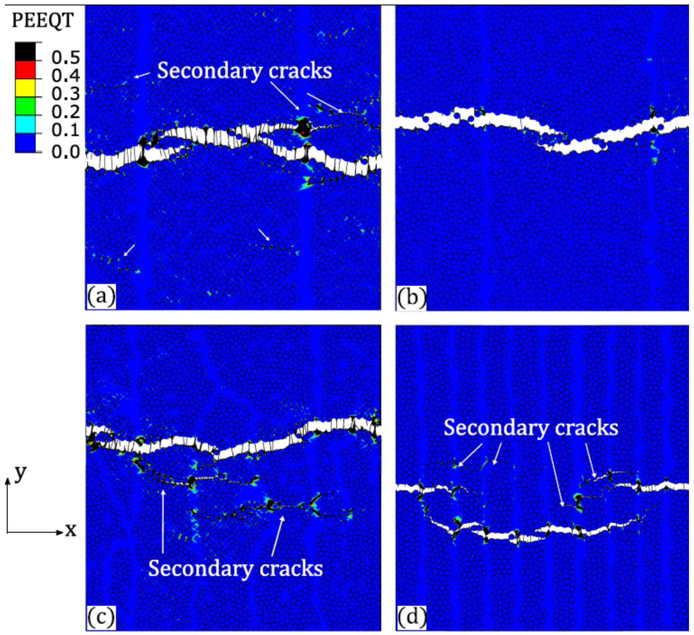
Interlaminar
Load direction : Horizontal



Investigated RVEs
(a) & (b) Batch 2
(c) Batch 1
(d) "Optimized"



Intralaminar
Load direction : Vertical



- Cracks begin on fiber rich zones
- Matrix-rich zones act as crack arresting barriers
- 'Random' microstructures allow for higher damage dissipation

NAYA, PAPPAS & BOTSIS, *Compos Struct* 2019.