ESTIMATING THE AVERAGE SIZE OF FIBER/MATRIX INTERFACE CRACKS IN UD AND CROSS-PLY LAMINATES

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

7th ECCOMAS Thematic Conference on the Mechanical Response of Composites
Girona (ES) - September 18-20, 2019

Education and Culture

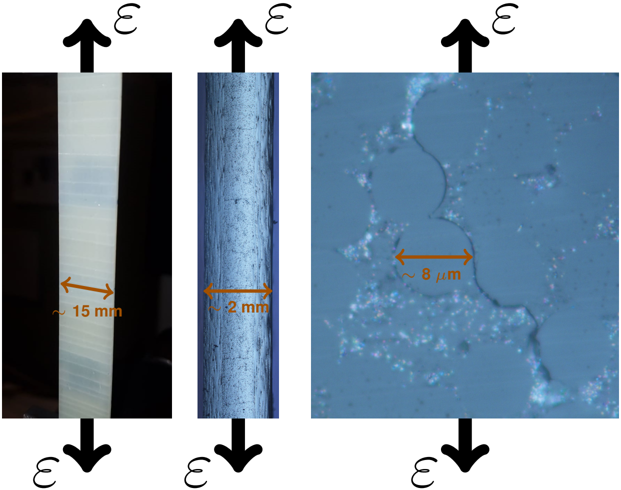
Erasmus Mundus

Outline

- Transverse Cracks Initiation in FRPC
- Modeling
- Debond Initiation
- Debond Propagation
- Conclusions

↘ TRANSVERSE CRACKS INITIATION IN FRPC

Micromechanics of Initiation: Transverse Tensile Loading



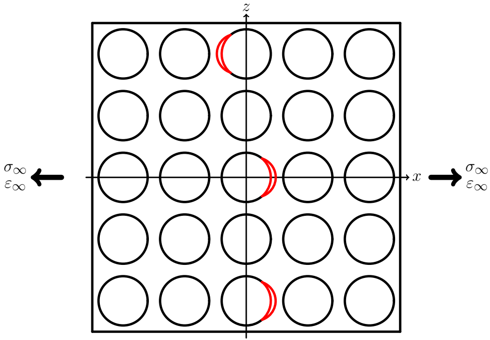
Left:
front view of $[0, 90_2]_S$, visual inspection.

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

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

Micromechanics of Initiation: Transverse Tensile Loading

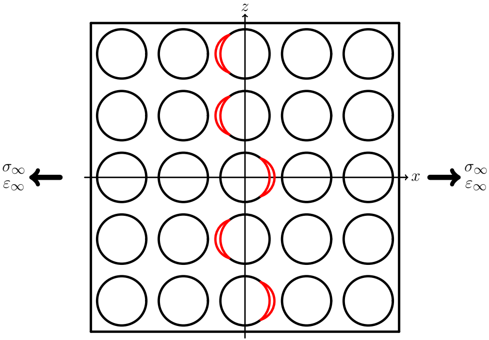
Stage 1: isolated debonds



Bailey et al., P. Roy. Soc. A-Math. Phy. **366** (1727), 1979.
Bailey et al., J. Mater. Sci. **16** (3), 1981.
Zhang et al., Compos. Part A-Appl. S. **28** (4), 1997.

Micromechanics of Initiation: Transverse Tensile Loading

Stage 2: consecutive debonds



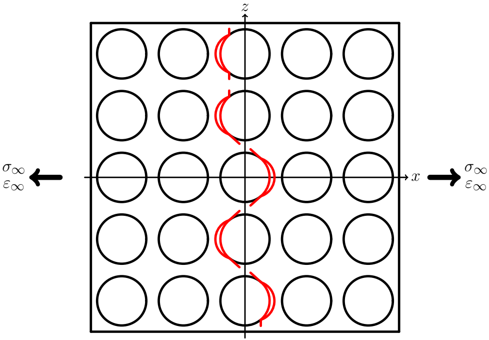
Bailey et al., P. Roy. Soc. A-Math. Phy. **366** (1727), 1979.

Bailey et al., J. Mater. Sci. **16** (3), 1981.

Zhang et al., Compos. Part A-Appl. S. **28** (4), 1997.

Micromechanics of Initiation: Transverse Tensile Loading

Stage 3: kinking



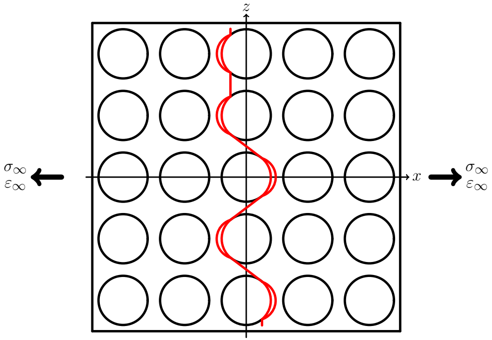
Bailey et al., P. Roy. Soc. A-Math. Phy. **366** (1727), 1979.

Bailey et al., J. Mater. Sci. **16** (3), 1981.

Zhang et al., Compos. Part A-Appl. S. **28** (4), 1997.

Micromechanics of Initiation: Transverse Tensile Loading

Stage 4: coalescence



Bailey et al., P. Roy. Soc. A-Math. Phy. **366** (1727), 1979.

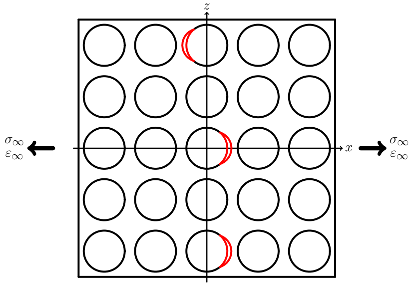
Bailey et al., J. Mater. Sci. **16** (3), 1981.

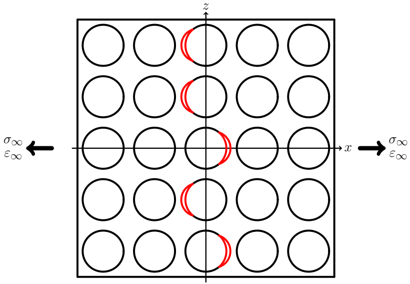
Zhang et al., Compos. Part A-Appl. S. **28** (4), 1997.

Objective of the Study

Can we talk about a ply-thickness effect for the fiber-matrix interface crack?

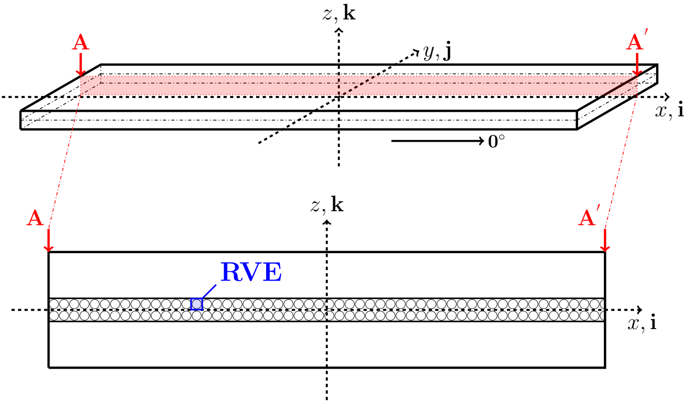
Stage 1: isolated debonds	Stage 2: consecutive debonds





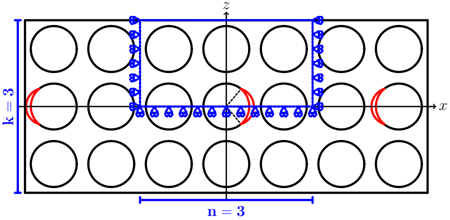
↘ MODELING

Geometry

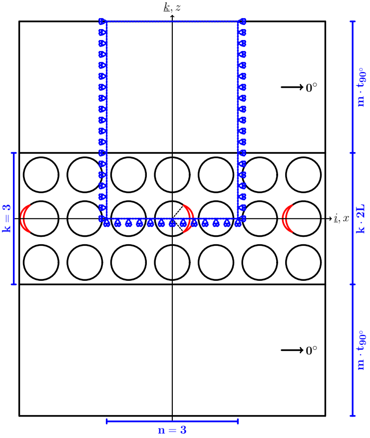


- ➔ $L, W >> t$
- ➔ $L, W \to \infty$
- ➔ Square packing
- ➔ $L_d >> \Delta\theta_d$
- ➔ 2D RVE

Representative Volume Elements

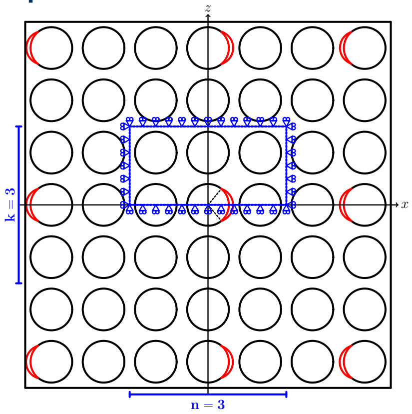


$n \times k - free$

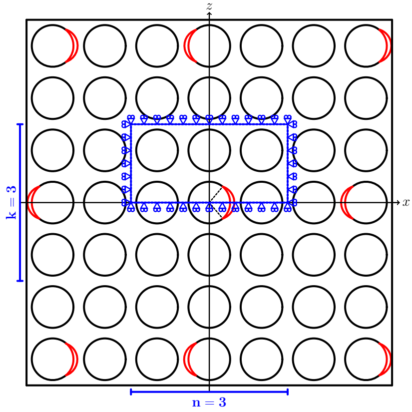


$n \times k - m \cdot t_{90^\circ}$

Representative Volume Elements

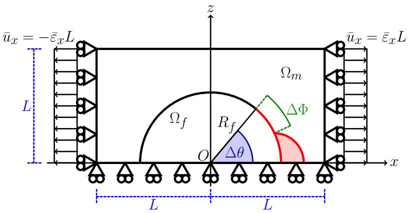


$n \times k - symm$



$n \times k - asymm$

Assumptions

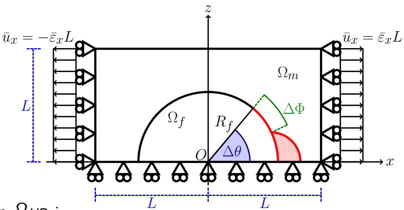


$R_f = 1 \; [\mu m] \quad L = \frac{R_f}{2}\sqrt{\frac{\pi}{V_f}}$

- ➔ Linear elastic, homogeneous materials
- ➔ Concentric Cylinders Assembly with Self-Consistent Shear Model for UD
- ➔ 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 $\bar{\varepsilon}_x = 1\%$
- ➔ $V_f = 60\%$

Material	V_f [%]	E_L [GPa]	E_T [GPa]	μ_{LT} [GPa]	ν_{LT} [$-$]	ν_{TT} [$-$]
Glass fiber	-	70.0	70.0	29.2	0.2	0.2
Epoxy	-	3.5	3.5	1.25	0.4	0.4
UD	60.0	43.442	13.714	4.315	0.273	0.465

Solution



in $\Omega_f, \Omega_m, \Omega_{UD}$:

$$\frac{\partial^2 \varepsilon_{xx}}{\partial z^2} + \frac{\partial^2 \varepsilon_{zz}}{\partial x^2} = \frac{\partial^2 \gamma_{zx}}{\partial x \partial z}$$

$$\varepsilon_y = \gamma_{xy} = \gamma_{yz} = 0$$

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{zx}}{\partial z} = 0$$

$$\frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \sigma_{zz}}{\partial z} = 0$$

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

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

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

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

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

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

$$+ BC$$

$\forall \; \Delta\theta \neq 0^\circ$

➔ oscillating singularity

$$\sigma \sim r^{-\frac{1}{2}} \sin \left(\varepsilon \log r \right), \quad V_f \to 0$$

$$\varepsilon = \frac{1}{2\pi} \log \left(\frac{1-\beta}{1+\beta} \right)$$

$$\beta = \frac{\mu_2 \left(\kappa_1 - 1 \right) - \mu_1 \left(\kappa_2 - 1 \right)}{\mu_2 \left(\kappa_1 + 1 \right) + \mu_1 \left(\kappa_2 + 1 \right)}$$

➔ receding contact

➔ $\dfrac{G\left(R_{f,2}\right)}{G\left(R_{f,1}\right)} = \dfrac{R_{f,2}}{R_{f,1}}, \; \dfrac{G\left(\bar{\varepsilon}_{x,2}\right)}{G\left(\bar{\varepsilon}_{x,1}\right)} = \dfrac{\bar{\varepsilon}^2_{x,2}}{\bar{\varepsilon}^2_{x,1}}$

➔ FEM + LEFM (VCCT)

➔ regular mesh of quadrilaterals at the crack tip:

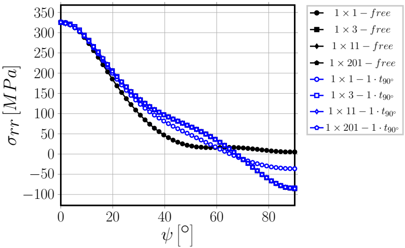
- $AR \sim 1, \quad \delta = 0.05^\circ$

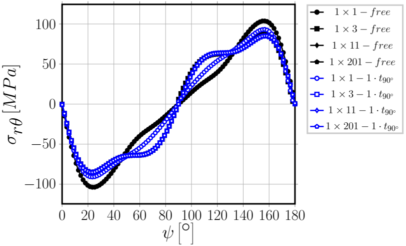
$\forall \; \Delta\theta$

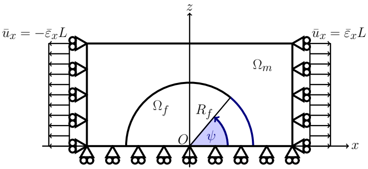
➔ 2nd order shape functions

↘ Debond Initiation

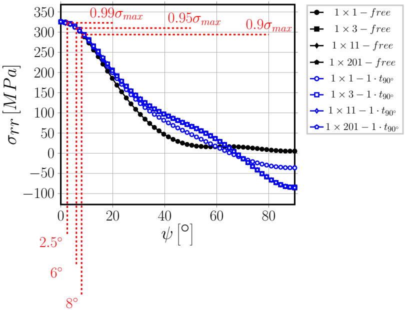
σ_{rr} vs $\tau_{r\theta}$: radial stress vs tangential shear at the interface

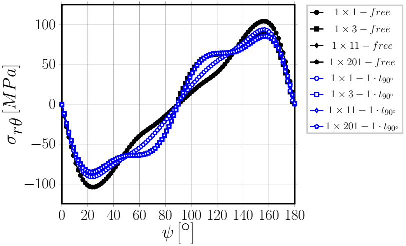


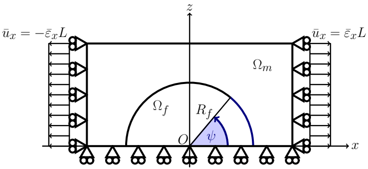




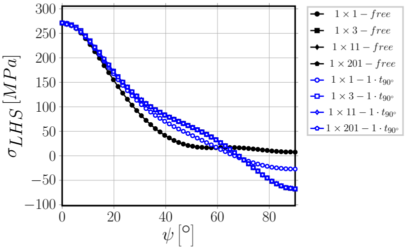
σ_{rr} vs $\tau_{r\theta}$: radial stress vs tangential shear at the interface

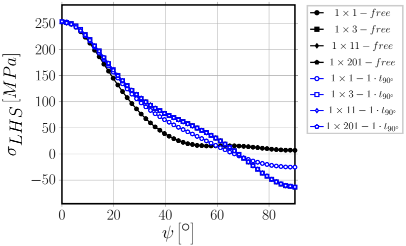






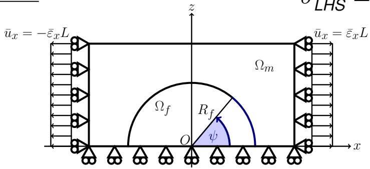
σ_{LHS}: local hydrostatic stress at the interface



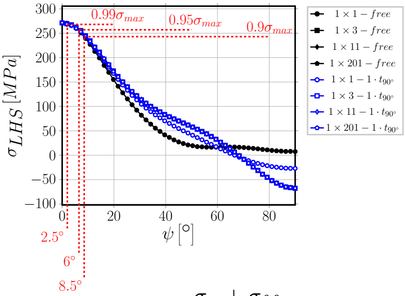


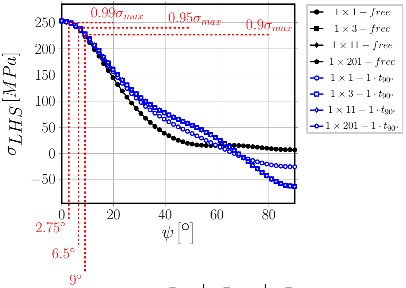
$$\sigma^{2D}_{LHS} = \frac{\sigma_{rr} + \sigma_{\theta\theta}}{2}$$

$$\sigma^{3D}_{LHS} = \frac{\sigma_{rr} + \sigma_{\theta\theta} + \sigma_{yy}}{3}$$



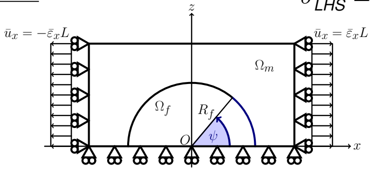
σ_{LHS}: local hydrostatic stress at the interface



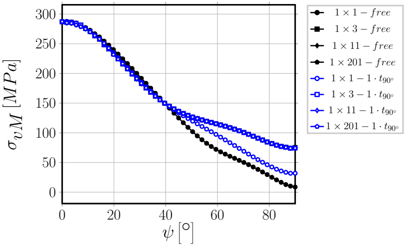


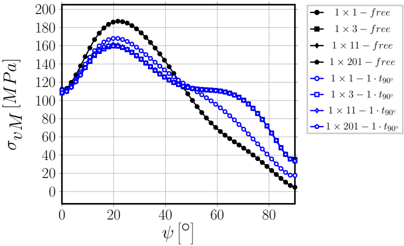
$$\sigma_{LHS}^{2D} = \frac{\sigma_{rr} + \sigma_{\theta\theta}}{2}$$

$$\sigma_{LHS}^{3D} = \frac{\sigma_{rr} + \sigma_{\theta\theta} + \sigma_{yy}}{3}$$



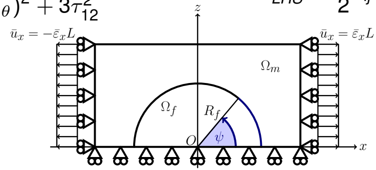
$\sigma_{\mathbf{vM}}$: von Mises stress at the interface



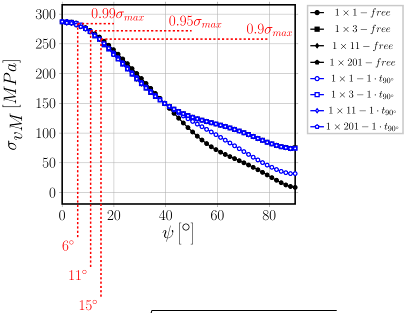


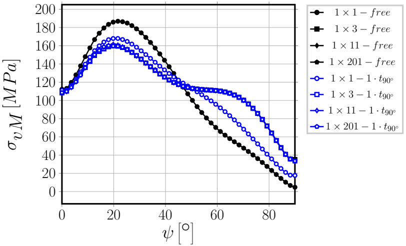
$$\sigma_{vM}^{2D} = \sqrt{(\sigma_{rr} - \sigma_{\theta\theta})^2 + 3\tau_{12}^2}$$

$$\sigma_{LHS}^{3D} = \frac{3}{2} s_{ij} s_{ij} \quad s_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij}$$



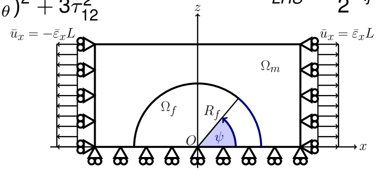
σ_{vM}: von Mises stress at the interface



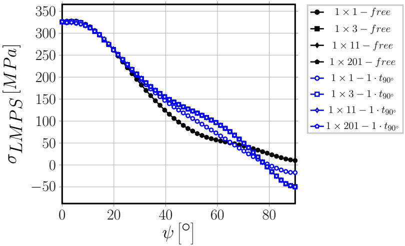


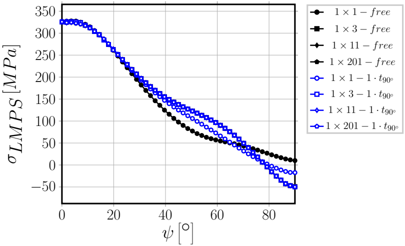
$$\sigma_{vM}^{2D} = \sqrt{(\sigma_{rr} - \sigma_{\theta\theta})^2 + 3\tau_{12}^2}$$

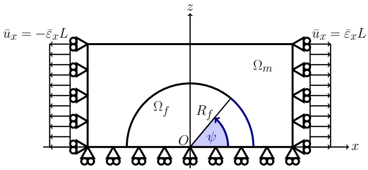
$$\sigma_{LHS}^{3D} = \frac{3}{2} s_{ij} s_{ij} \quad s_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij}$$



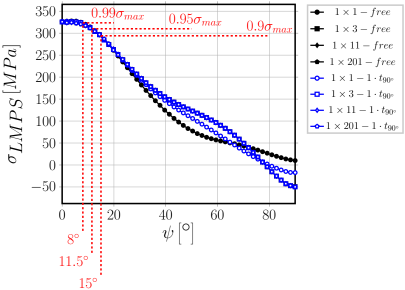
σ_{I}: maximum principal stress at the interface

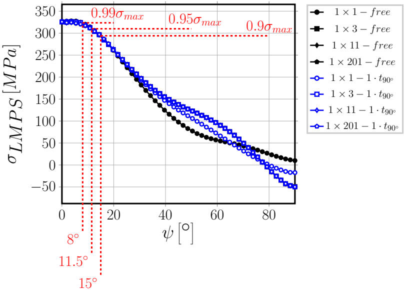


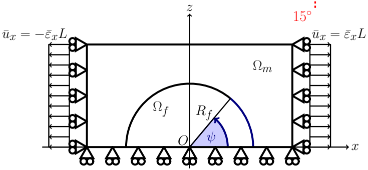




σ_{I}: maximum principal stress at the interface





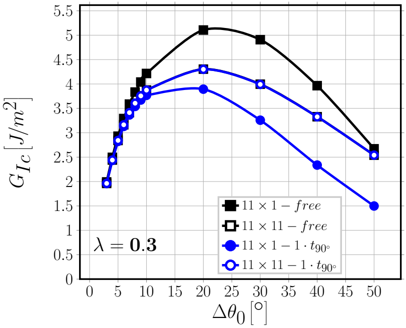


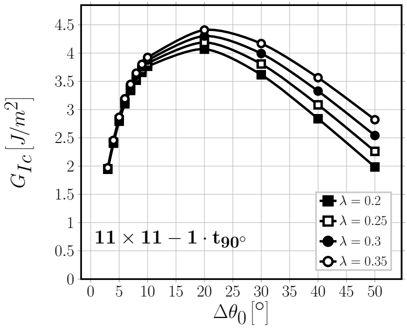
Summary

➔

↘ Debond Propagation

Estimation of G_{Ic}

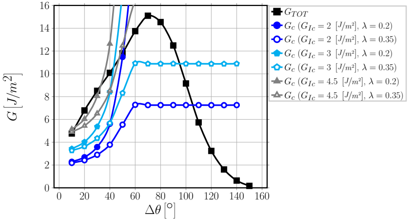




$$G_{Ic} = \left.\frac{G_c}{1+\tan^2\left(\left(1-\lambda\right)\Psi_G\right)}\right|_{G_c=G_{TOT}(\Delta\theta_0)}, \quad \Psi_G = tan^{-1}\left.\left(\sqrt{\frac{G_{II}}{G_I}}\right)\right|_{\Delta\theta_0}$$

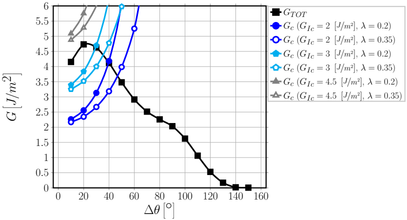
Estimation of $\Delta\theta_{max}$

$21 \times 1 - free$



$\Delta\theta_{max} \in (30^\circ - 105^\circ)$

$21 \times 1 - 1 \cdot t_{90^\circ}$

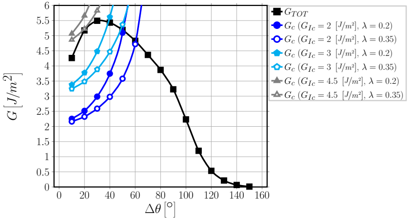


$\Delta\theta_{max} \in (30^\circ - 50^\circ)$

$$G_{TOT}(\Delta\theta) > G_c = G_{Ic}\left(1 + \tan^2\left((1-\lambda)\Psi_G\right)\right), \quad \Psi_G = tan^{-1}\left(\sqrt{\frac{G_{II}}{G_I}}\right)\Bigg|_{\Delta\theta}$$

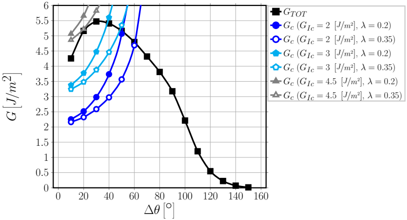
Estimation of $\Delta\theta_{max}$

$21 \times 3 - \mathit{free}$



$$\Delta\theta_{max} \in (40^\circ - 60^\circ)$$

$21 \times 3 - 1 \cdot t_{90^\circ}$

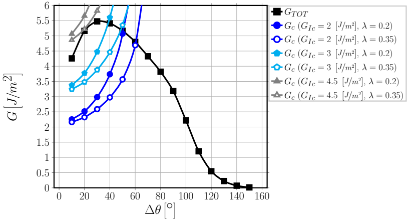


$$\Delta\theta_{max} \in (40^\circ - 60^\circ)$$

$$G_{TOT}(\Delta\theta) > G_c = G_{Ic}\left(1 + \tan^2\left((1-\lambda)\,\Psi_G\right)\right), \quad \Psi_G = \tan^{-1}\left(\sqrt{\frac{G_{II}}{G_I}}\right)\Bigg|_{\Delta\theta}$$

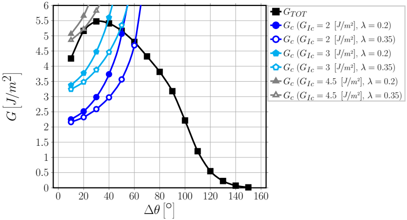
Estimation of $\Delta\theta_{max}$

$21 \times 21 - \textit{free}$



$\Delta\theta_{max} \in (40^\circ - 60^\circ)$

$21 \times 21 - 1 \cdot t_{90^\circ}$

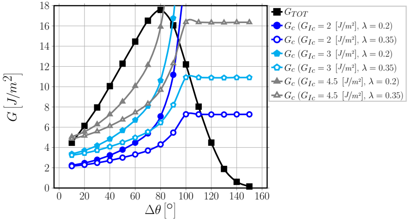


$\Delta\theta_{max} \in (40^\circ - 60^\circ)$

$$G_{TOT}\left(\Delta\theta\right) > G_c = G_{Ic}\left(1 + \tan^2\left(\left(1-\lambda\right)\Psi_G\right)\right), \quad \Psi_G = tan^{-1}\left(\sqrt{\frac{G_{II}}{G_I}}\right)\Bigg|_{\Delta\theta}$$

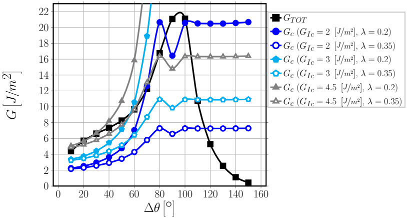
Estimation of $\Delta\theta_{max}$

$21 \times 21 - symm$



$$\Delta\theta_{max} \in (80° - 110°)$$

$21 \times 21 - asymm$



$$\Delta\theta_{max} \in (55° - 115°)$$

$$G_{TOT}(\Delta\theta) > G_c = G_{Ic}\left(1 + \tan^2\left(\left(1-\lambda\right)\Psi_G\right)\right), \quad \Psi_G = tan^{-1}\left(\sqrt{\frac{G_{II}}{G_I}}\right)\Bigg|_{\Delta\theta}$$

Conclusions

Conclusions

- ➔ No effect of 90° ply thickness can be observed when t_{90° is at least $\sim 3\varnothing_{fiber}$
- ➔ Only if t_{90° is reduced to $1\varnothing_{fiber}$, ERR is reduced for a given level of applied strain, i.e. debond growth is delayed to higher levels of applied strain ($G \sim \varepsilon^2_{applied}$)
- ➔ No effect of 0° ply thickness can be observed when $t_{0^\circ}/t_{90^\circ} > 1$
- ➔ A small difference can be observed when $t_{0^\circ} = t_{90^\circ}$, due to the smaller bending stiffness of a thinner 0° layer

DocMASE

UNIVERSITÉ DE LORRAINE

EEIGM

LULEÅ UNIVERSITY OF TECHNOLOGY

Education and Culture

Erasmus Mundus