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

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Education and Culture

Erasmus Mundus

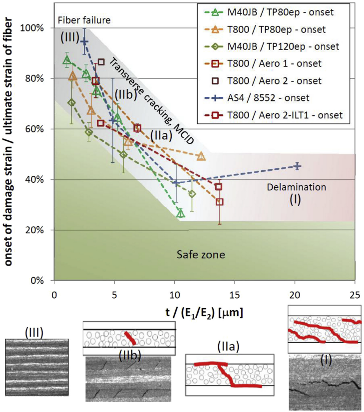
Outline

- Initiation of Transverse Cracks in Thin-plies
- Modeling
- Debond Initiation
- Debond Propagation
- Conclusions

INITIATION OF TRANSVERSE CRACKS IN THIN-PLIES

The Thin-ply “Advantage”: new material

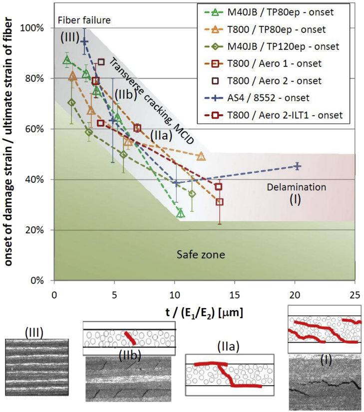
2018, $\left[45^\circ, 90^\circ, -45^\circ, 0^\circ\right]_{nS}$



Cugnoni et al., Compos. Sci. Technol. **168**, 2018.

The Thin-ply "Advantage": new material, old result

2018, $[45^\circ, 90^\circ, -45^\circ, 0^\circ]_{nS}$



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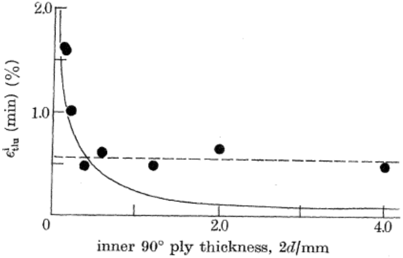
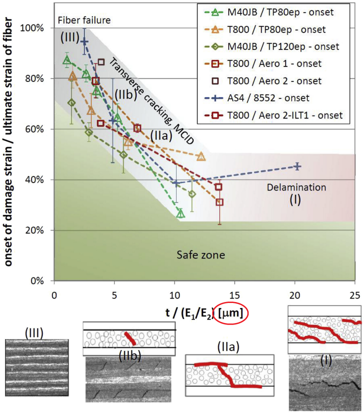
1979, $[0^\circ, 90^\circ_n]_S$



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

The Thin-ply "Advantage": new material, old result?

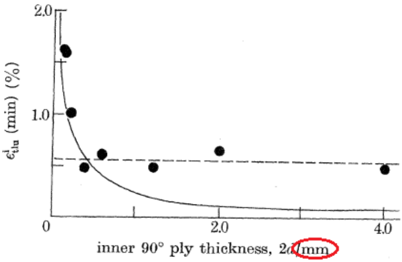
2018, $[45^\circ, 90^\circ, -45^\circ, 0^\circ]_{nS}$



$t_{90^\circ} < 10 \varnothing_{fiber}$

Cugnoni et al., Compos. Sci. Technol. **168**, 2018.

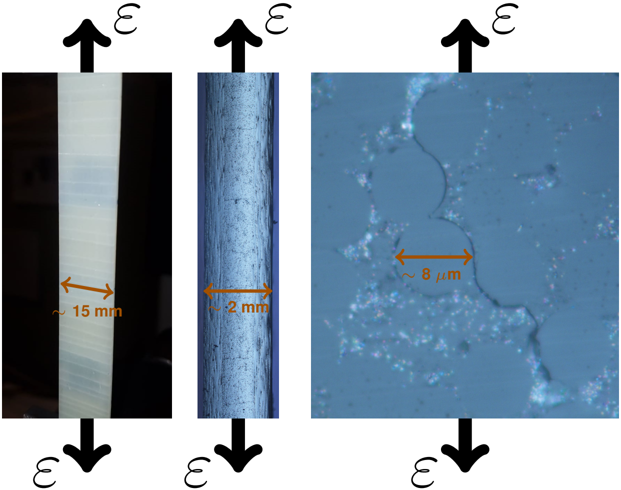
1979, $[0^\circ, 90^\circ_n]_S$



$t_{90^\circ} > 100 \varnothing_{fiber}$

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

Micromechanics of Initiation



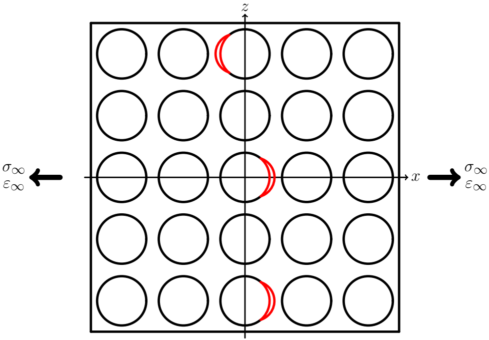
Left:
front view of $[0, 90_2]_S$,
visual inspection.

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

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

Micromechanics of Initiation

Stage 1: isolated debonds



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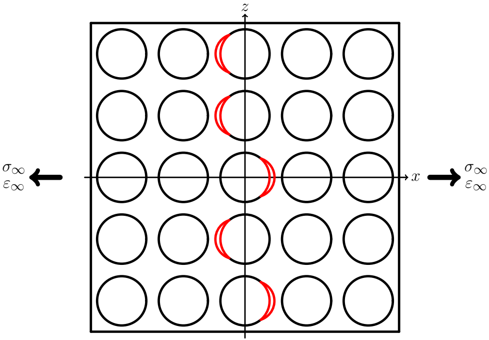
Zhang et al., Compos. Part A-Appl. S. **28** (4), 1997.

Micromechanics of Initiation

Stage 2: consecutive debonds



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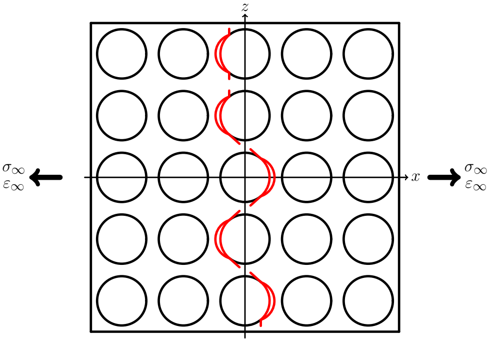
Zhang et al., Compos. Part A-Appl. S. **28** (4), 1997.

Micromechanics of Initiation

Stage 3: kinking



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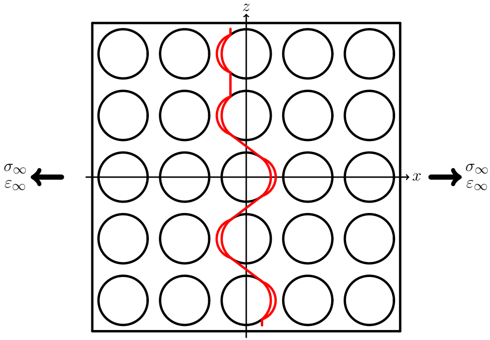
Micromechanics of Initiation

Stage 4: coalescence



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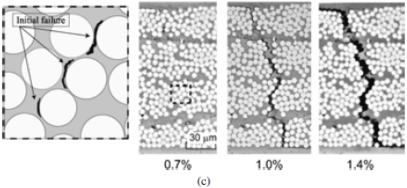
Bailey et al., J. Mater. Sci. **16** (3), 1981.

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

A Counter-intuitive Observation

$[\mathbf{0}^{\circ}, \mathbf{90}^{\circ}_{\mathbf{n}}]_{\mathbf{S}}$

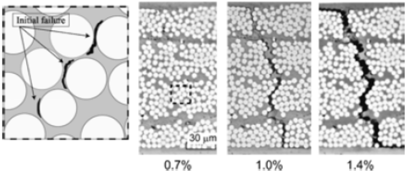


$n = 4$, $t_{90^{\circ}} = 160\mu m$

Saito et al., Adv. Compos. Mater. **21** (1), 2012.

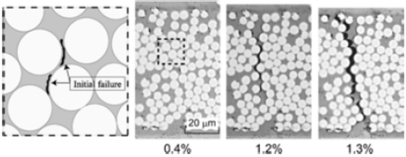
A Counter-intuitive Observation

$[0^\circ, 90^\circ_n]_S$



(c)

$n = 4$, $t_{90^\circ} = 160\mu m$



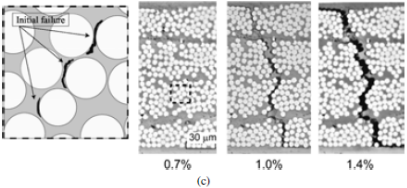
(b)

$n = 2$, $t_{90^\circ} = 80\mu m$

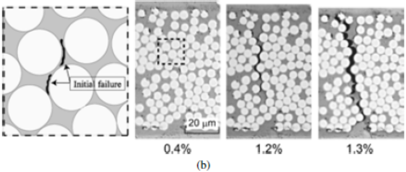
Saito et al., Adv. Compos. Mater. **21** (1), 2012.

A Counter-intuitive Observation

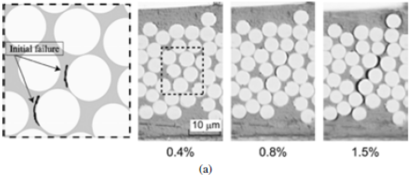
$$[\mathbf{0}^{\circ}, \mathbf{90}^{\circ}_{\mathbf{n}}]_{\mathbf{S}}$$



$n = 4$, $t_{90^{\circ}} = 160\mu m$



$n = 2$, $t_{90^{\circ}} = 80\mu m$



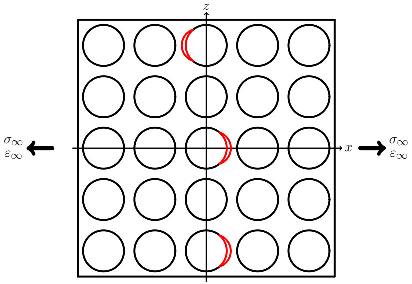
$n = 1$, $t_{90^{\circ}} = 40\mu m$

Saito et al., Adv. Compos. Mater. **21** (1), 2012.

Objective of the Study

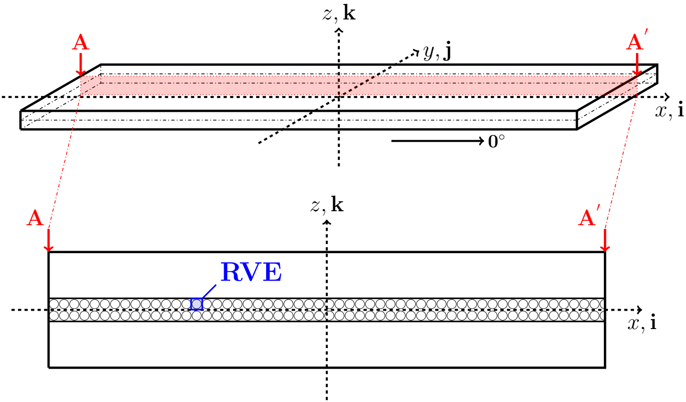
Can we talk about a ply-thickness effect for the fiber-matrix interface crack?

Stage 1: isolated debonds



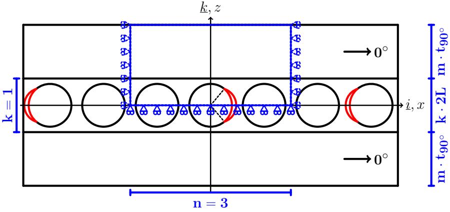
↘ MODELING

Geometry

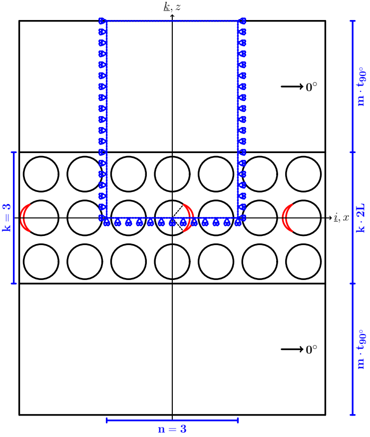


- ➔ $L, W >> t$
- ➔ $L, W \to \infty$
- ➔ Square packing
- ➔ $L_d >> \Delta\theta_d$
- ➔ 2D RVE

Representative Volume Elements

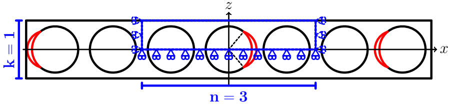


$$n \times 1 - m \cdot t_{90^\circ}$$

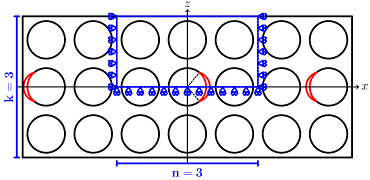


$$n \times k - m \cdot t_{90^\circ}$$

Representative Volume Elements

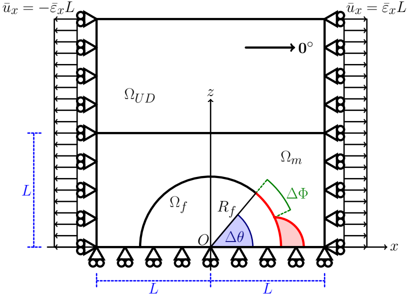


$$n \times 1 - \begin{cases} \textit{free} \\ \textit{coupling} \\ \textit{coupling} + H \end{cases}$$



$$n \times k - \begin{cases} \textit{free} \\ \textit{coupling} \\ \textit{coupling} + H \end{cases}$$

Assumptions

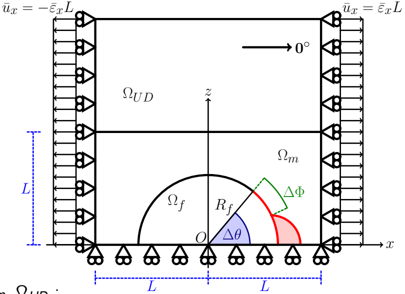


$R_f = 1\ [\mu m]$ $\quad L = \dfrac{R_f}{2}\sqrt{\dfrac{\pi}{V_f}}$

- ➔ 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 $0^\circ \leq \alpha \leq \Delta\theta$:

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

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

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

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

$$+ BC$$

➔ 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

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

➔ FEM + LEFM (VCCT)

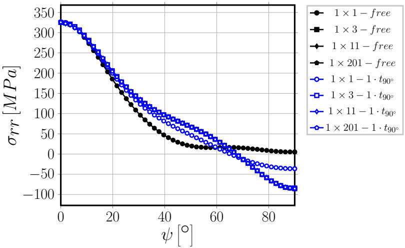
➔ 2^{nd} order shape functions

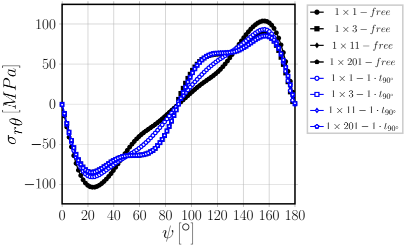
➔ regular mesh of quadrilaterals at the crack tip:

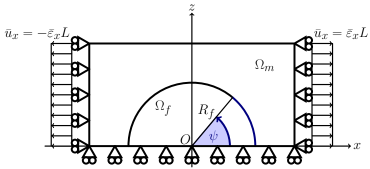
- $AR \sim 1, \quad \delta = 0.05^\circ$

↘ Debond Initiation

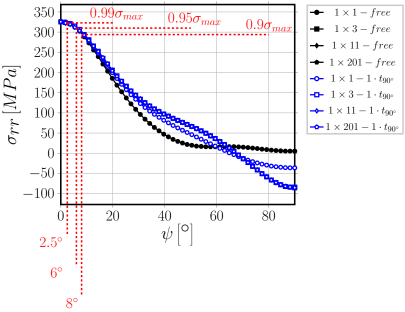
σ_{rr} vs $\tau_{r\theta}$: radial stress vs tangential shear at the interface

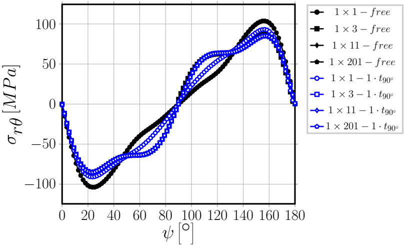


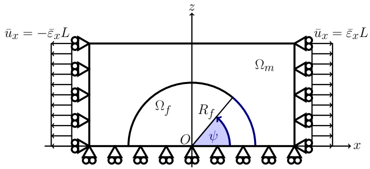




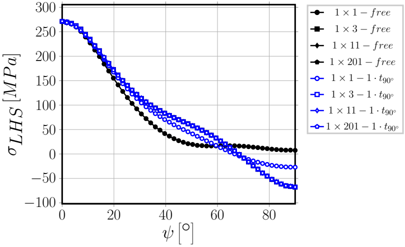
σ_{rr} vs $\tau_{r\theta}$: radial stress vs tangential shear at the interface

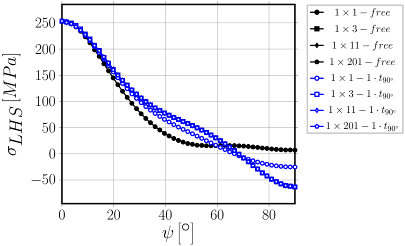






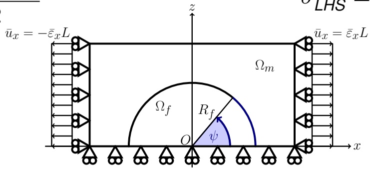
σ_{LHS}: local hydrostatic stress at the interface





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

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



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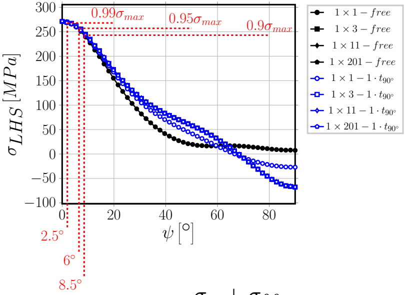

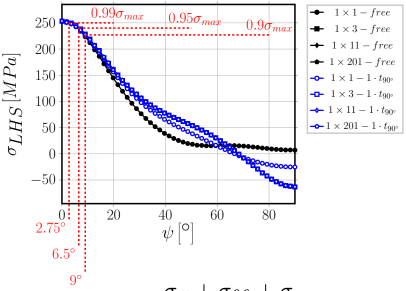

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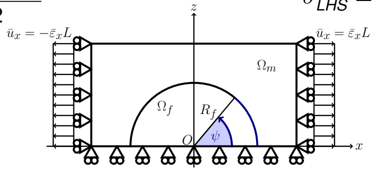
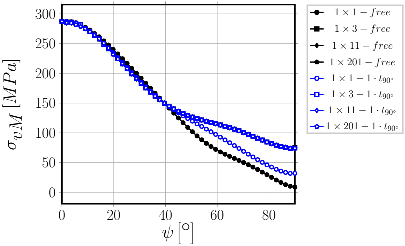
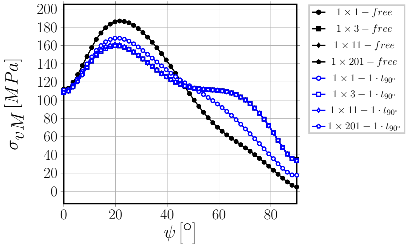


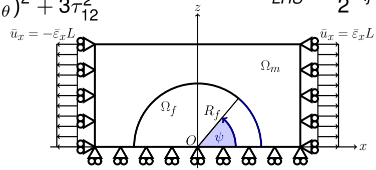
$\sigma_{\mathbf{vM}}$: von Mises stress at the interface





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

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



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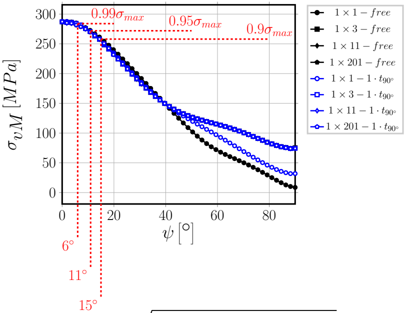

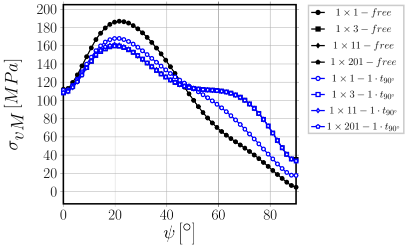

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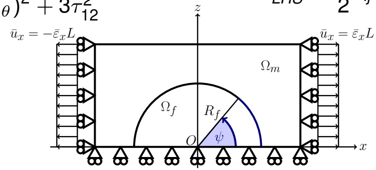
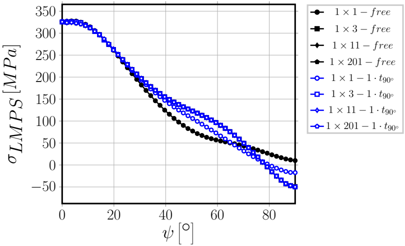
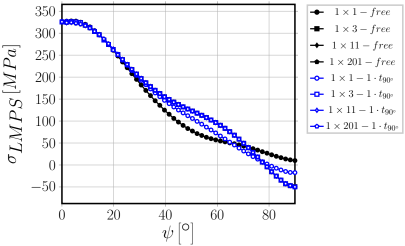
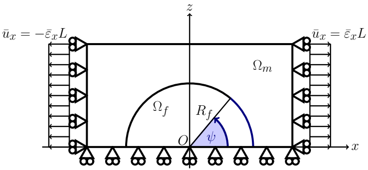


σ_{I}: maximum principal stress at the interface







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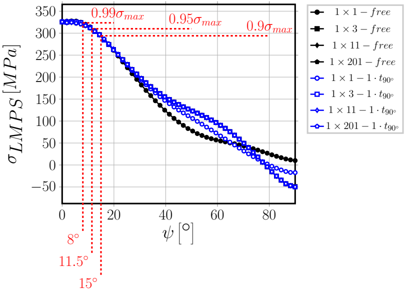
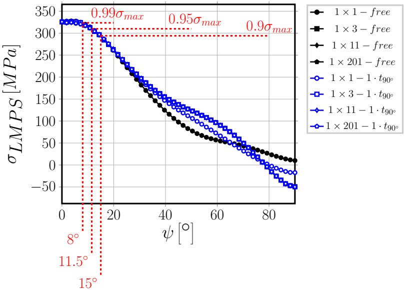
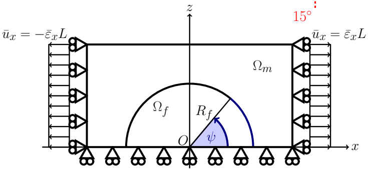




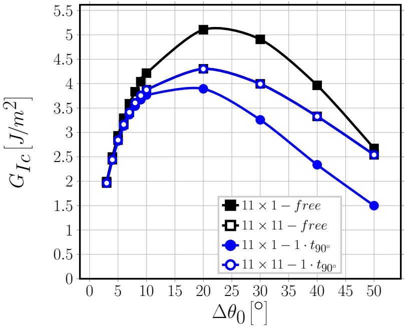


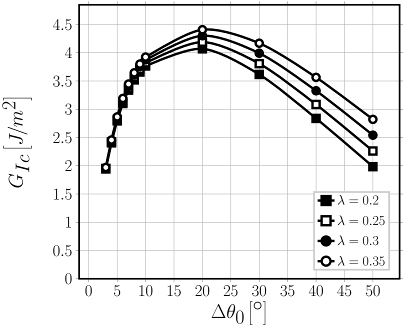
Summary

➔

↘ DEBOND PROPAGATION

Estimation of G_{Ic}





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

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

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