Ply-thickness and ply-block effect on fiber/matrix interface crack growth in cross-ply laminates under tensile loading

Insights from LEFM-based micromechanical modeling

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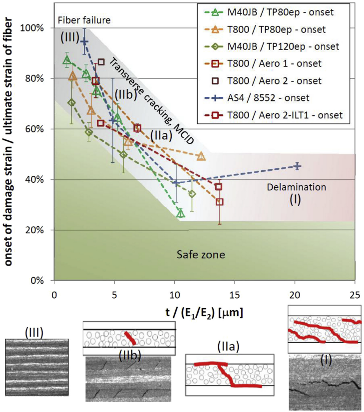
Outline

- Initiation of Transverse Cracks in Thin-plies
- Modeling the Fiber-Matrix Interface Crack
- Debond Energy Release Rate
- Conclusions

↘ INITIATION OF TRANSVERSE CRACKS IN THIN-PLIES

The Thin-ply "Advantage": new material

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



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

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

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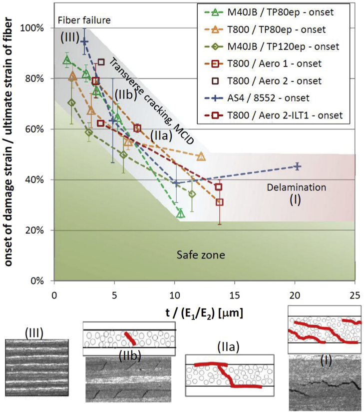

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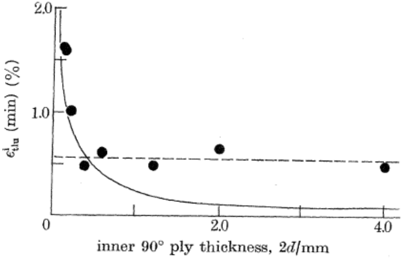
1979, $[0^{\circ}, 90^{\circ}_{n}]_S$



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

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

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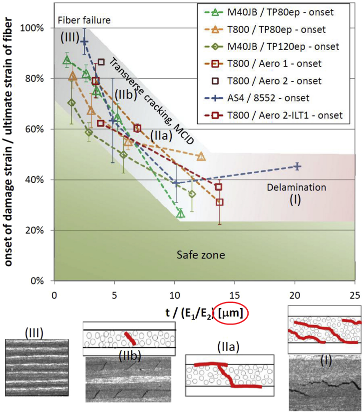
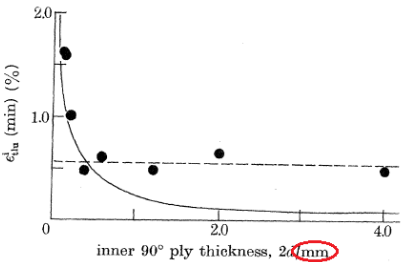


$t_{90^\circ} < 10\varnothing_{fiber}$

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

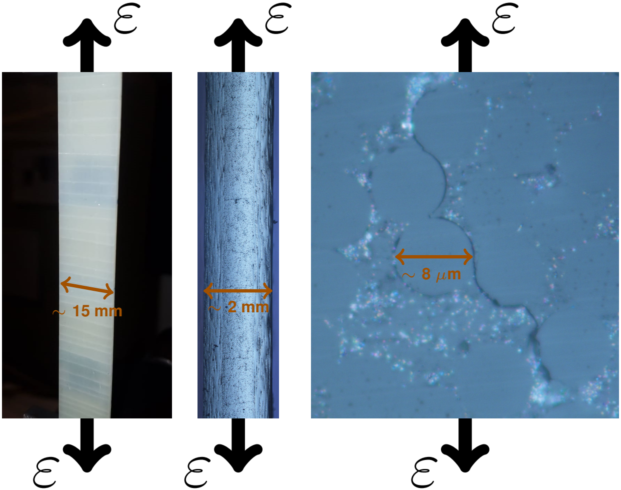
1979, $[0^\circ, 90^\circ_n]_S$



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

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

Micromechanics of Initiation



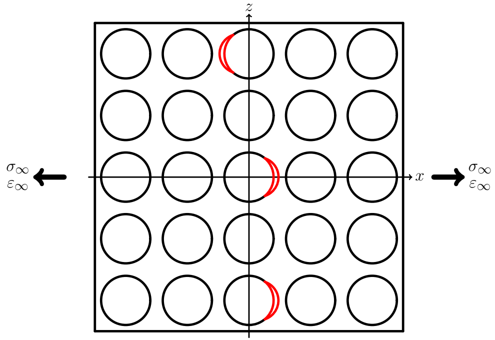
Left:
front view of $[0, 90_2]_S$,
visual inspection.

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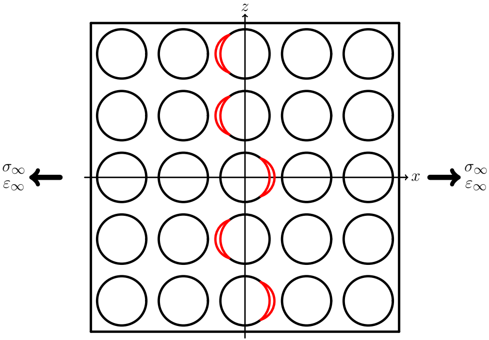
Bailey et al., J. Mater. Sci. **16** (3), 1981.

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

Micromechanics of Initiation

Stage 2: consecutive debonds



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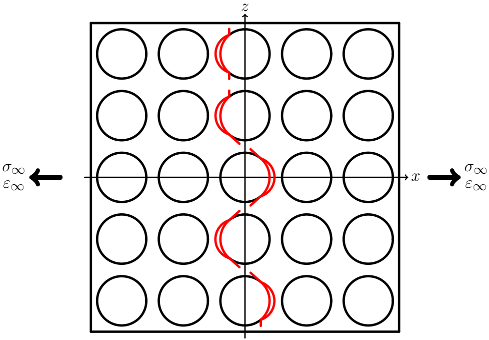
Zhang et al., Compos. Part A-Appl. S. **28** (4), 1997.

Micromechanics of Initiation

Stage 3: kinking



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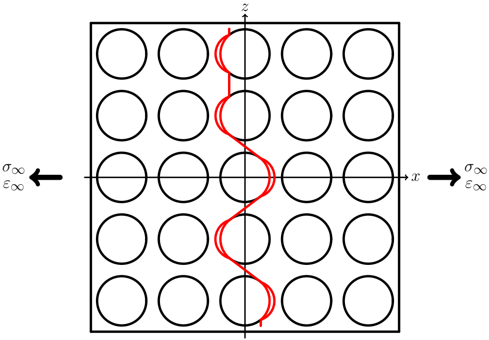
Zhang et al., Compos. Part A-Appl. S. **28** (4), 1997.

Micromechanics of Initiation

Stage 4: coalescence



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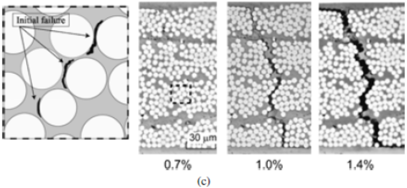
Bailey et al., J. Mater. Sci. **16** (3), 1981.

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

A Counter-intuitive Observation

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

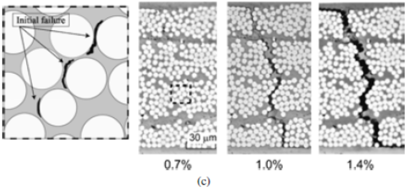


$n = 4$, $t_{90^\circ} = 160\mu m$

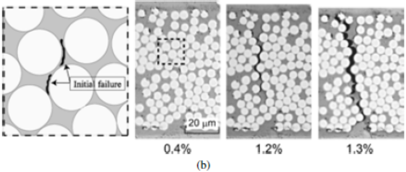
Saito et al., Adv. Compos. Mater. **21** (1), 2012.

A Counter-intuitive Observation

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



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

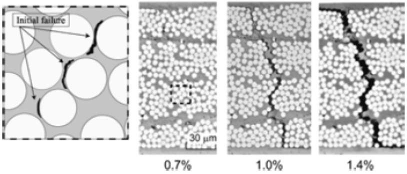


$n = 2$, $t_{90^{\circ}} = 80\mu m$

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

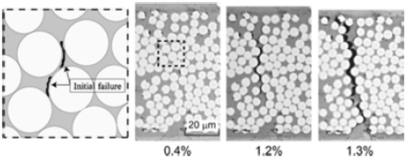
A Counter-intuitive Observation

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



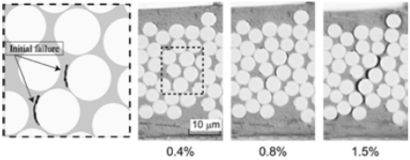
(c)

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



(b)

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



(a)

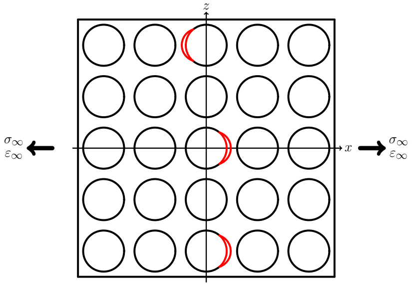
$n = 1,\ t_{90^{\circ}} = 40\mu m$

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

Objective of the Study

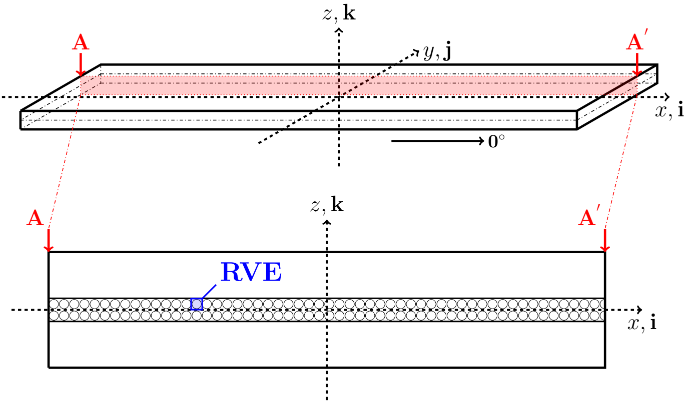
Can we talk about a ply-thickness effect for the fiber-matrix interface crack?

Stage 1: isolated debonds



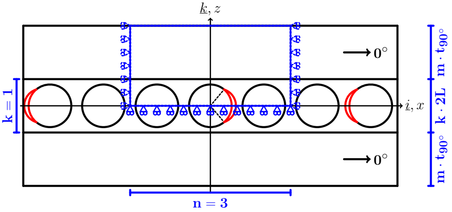
Modeling the Fiber-Matrix Interface Crack

Geometry

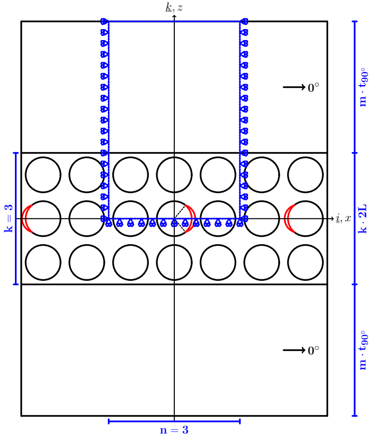


- ➔ $L, W >> t$
- ➔ $L, W \to \infty$
- ➔ Square packing
- ➔ $L_d >> \Delta\theta_d$
- ➔ 2D RVE

Representative Volume Elements

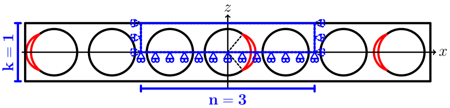


$n \times 1 - m \cdot t_{90^\circ}$

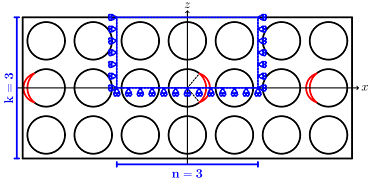


$n \times k - m \cdot t_{90^\circ}$

Representative Volume Elements

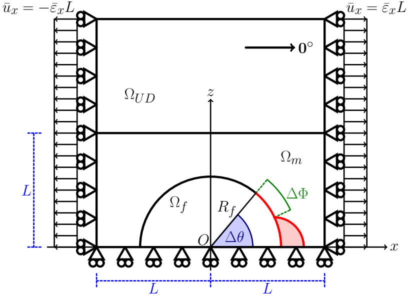


$$n \times 1 \begin{array}{l} - \textit{free} \\ - \textit{coupling} \\ - \textit{coupling} + H \end{array}$$



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

Assumptions

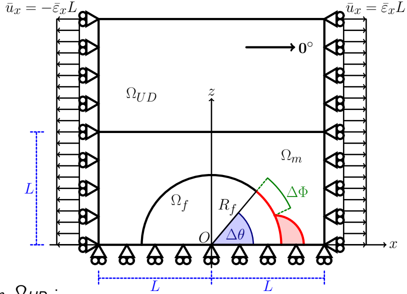


$R_f = 1\ [\mu m]$ $\quad L = \frac{R_f}{2}\sqrt{\frac{\pi}{V_f}}$

- ➔ 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 $0° \leq \alpha \leq \Delta\theta$:

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

for $\Delta\theta \leq \alpha \leq 180°$:

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

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

$$+ BC$$

- ➔ Oscillating singularity

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

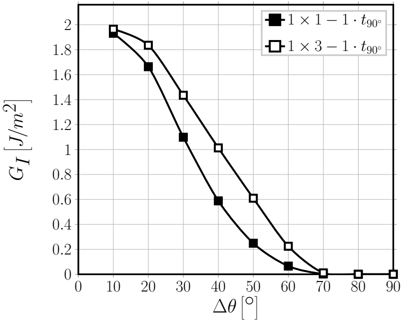
$$\varepsilon = \frac{1}{2\pi} \log\left(\frac{1-\beta}{1+\beta}\right)$$

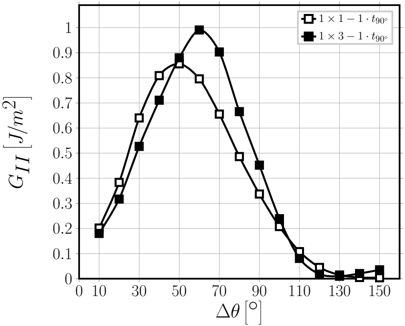
$$\beta = \frac{\mu_2 (\kappa_1 - 1) - \mu_1 (\kappa_2 - 1)}{\mu_2 (\kappa_1 + 1) + \mu_1 (\kappa_2 + 1)}$$

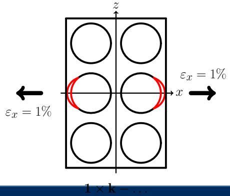
- ➔ $G = \frac{\partial W}{\partial A} - \left(\frac{\partial U}{\partial A} + \frac{\partial E_k}{\partial A} \right)$
- ➔ Finite Element Method (FEM) in Abaqus™
- ➔ 2^{nd} order shape functions
- ➔ 6-nodes triangles & 8-nodes quadrilaterals
- ➔ regular mesh of quadrilaterals at the crack tip:
  - $AR \sim 1$
  - $\delta = 0.05°$

↘ DEBOND ENERGY RELEASE RATE

Interaction of Debonds: Strain Magnification







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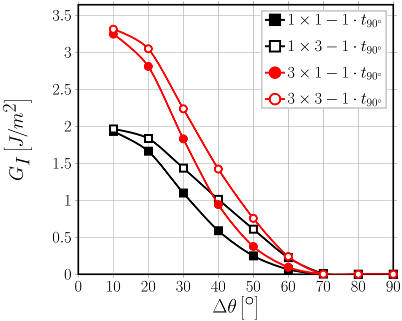

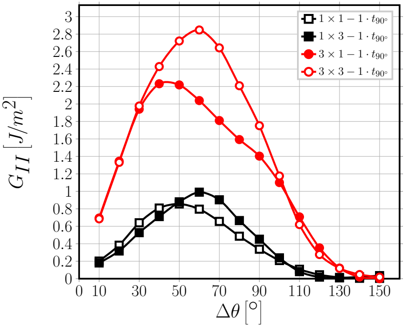

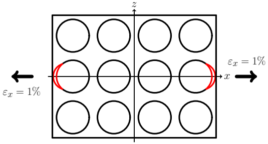

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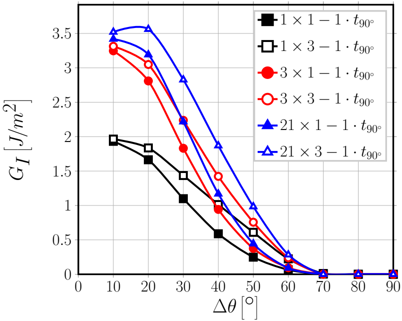
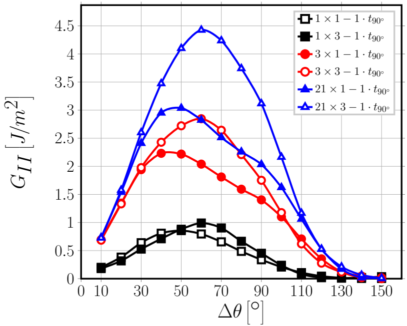
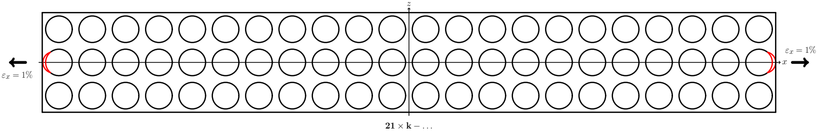
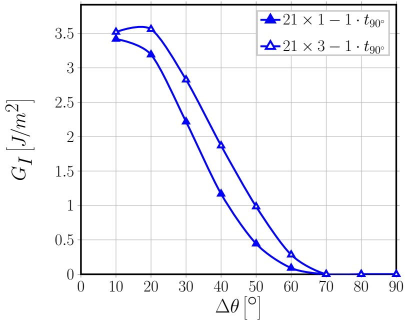
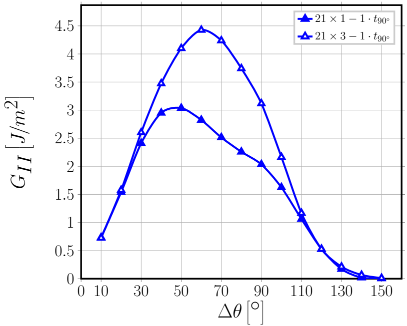


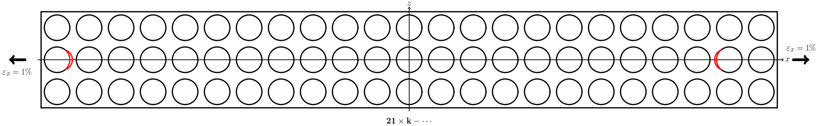




Interaction of Debonds: Crack Shielding







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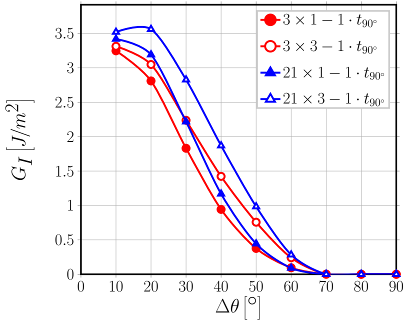

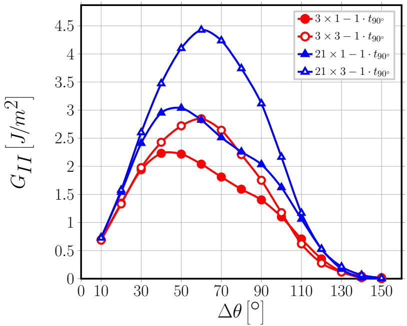

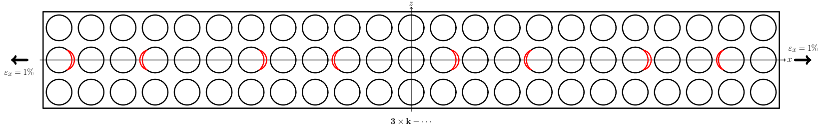

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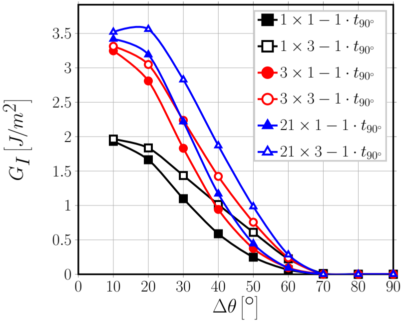
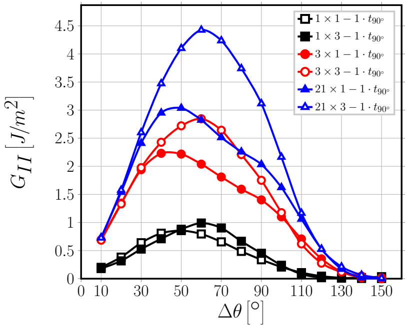
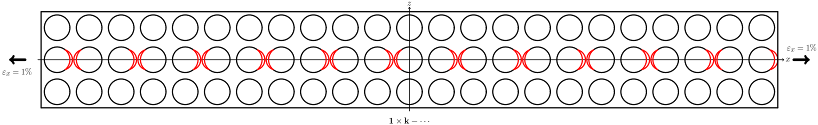
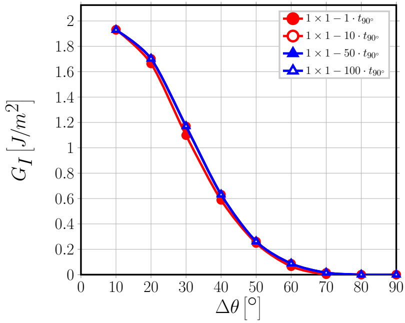
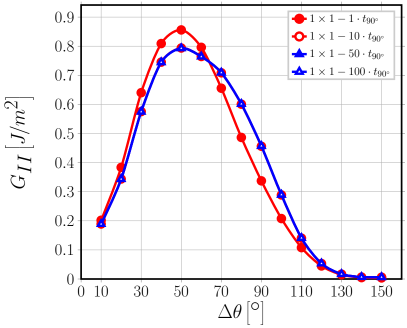


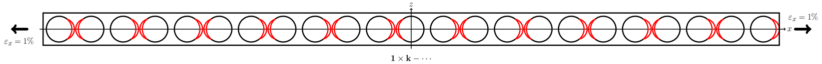




Effect of 0° ply thickness







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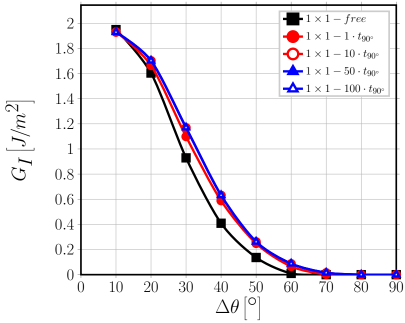

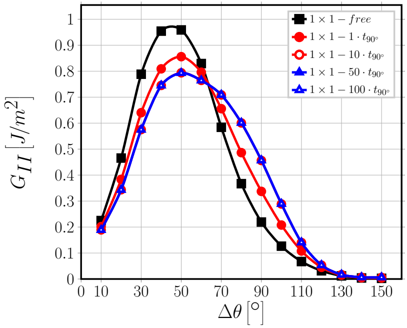

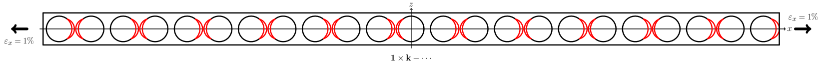

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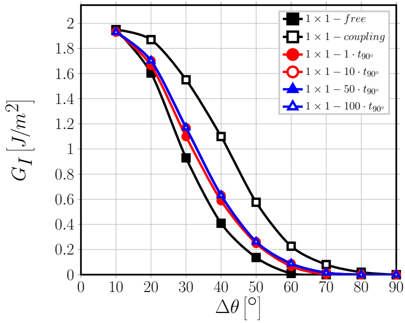
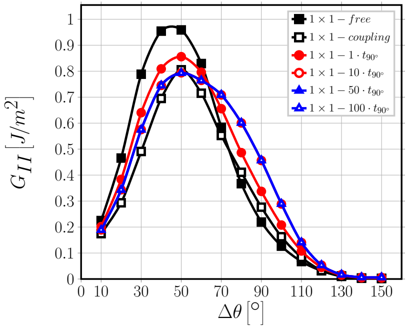
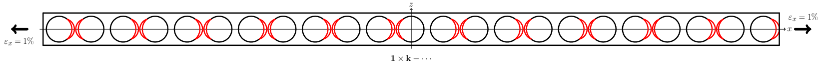
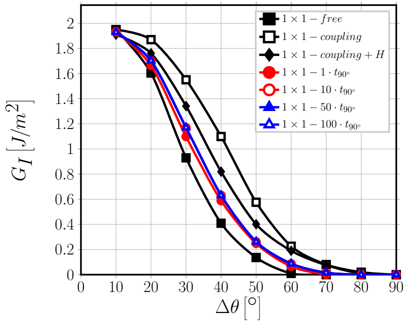
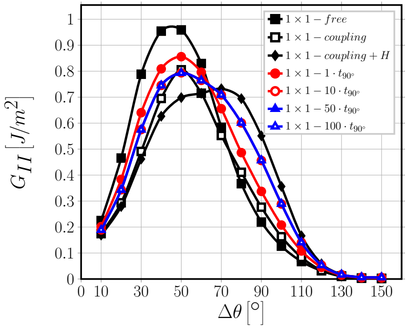


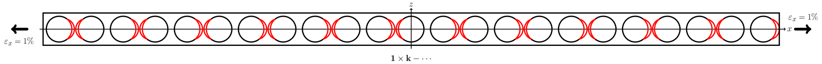




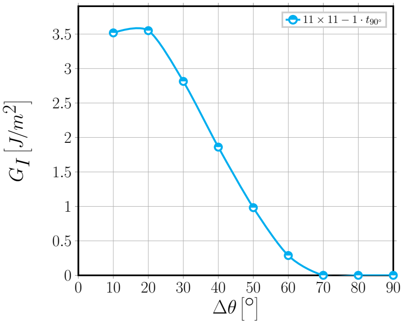
Effect of 0° ply thickness

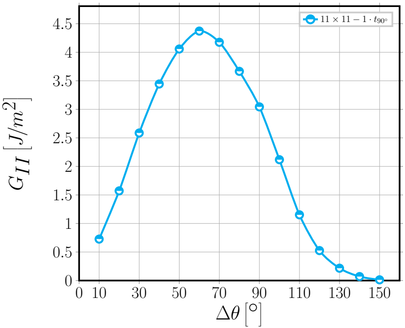


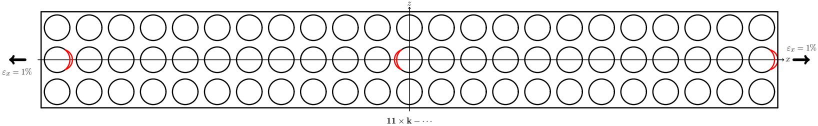




Effect of 90° ply thickness







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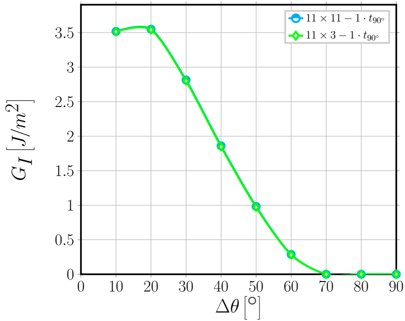
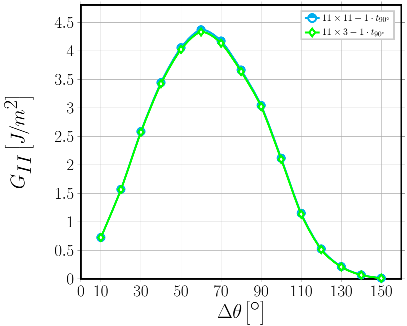
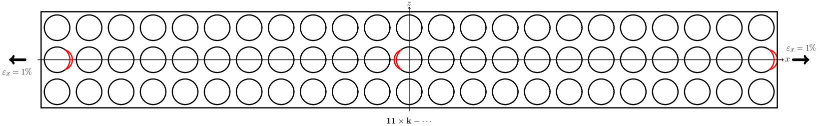
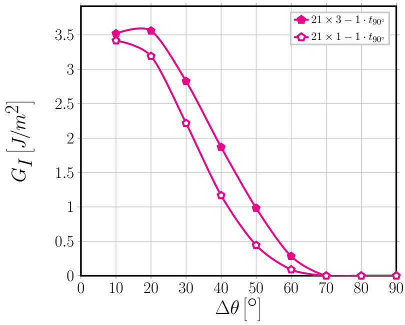
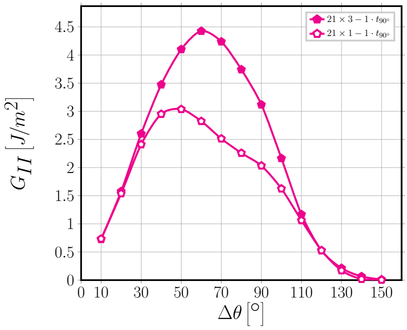


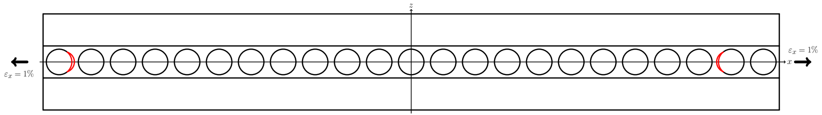




Effect of 90° ply thickness







$\mathbf{21 \times 1 - 1 \cdot t_{90°}}$

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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