

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

L. Di Stasio^{1,2}

¹ Division of Materials Science, Luleå University of Technology, Luleå, Sweden

²EEIGM & IJL, Université de Lorraine, Nancy, France

Instituto IMDEA Materiales
Getafe, Madrid (ES) - September 17, 2019



Outline

- ➔ Transverse Cracks Initiation
- ➔ Modeling
- ➔ Debond Initiation
- ➔ Debond Propagation
- ➔ Conclusions

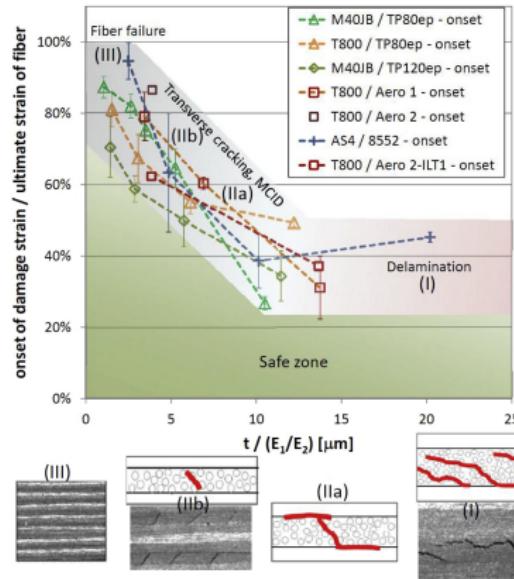
Transverse Cracks Initiation Modeling Debond Initiation Debond Propagation Conclusions
The Thin-ply "Advantage" Micromechanics of Initiation A Counter-intuitive Observation Objectives

➔ TRANSVERSE CRACKS INITIATION

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The Thin-ply "Advantage": new material

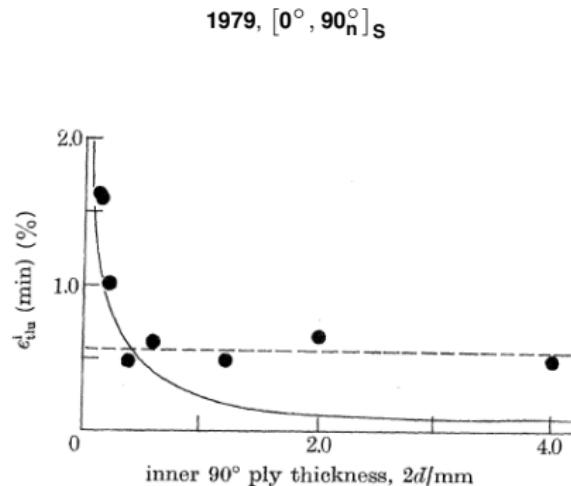
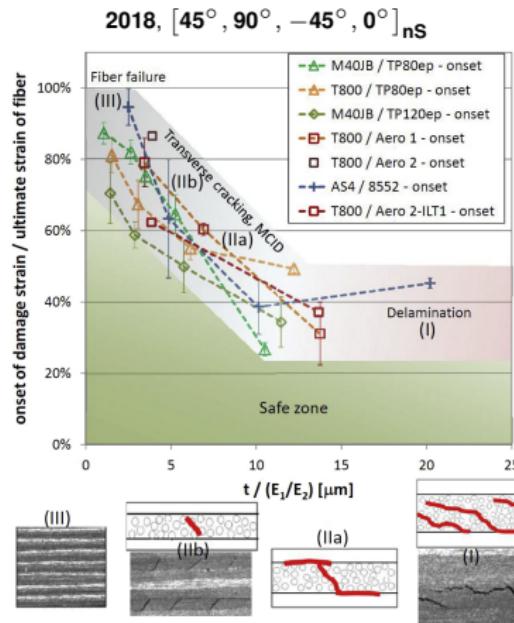
2018, $[45^\circ, 90^\circ, -45^\circ, 0^\circ]$ ns



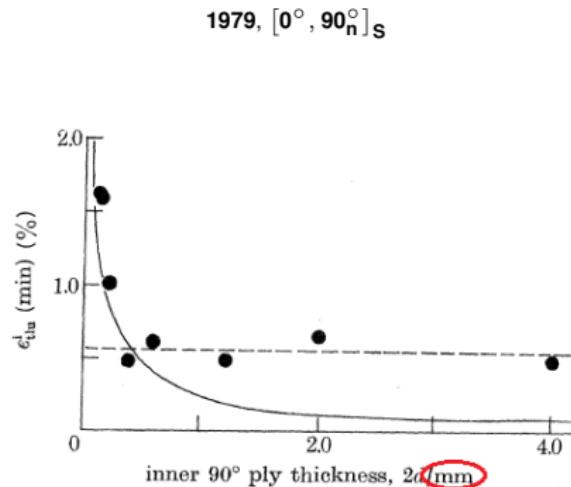
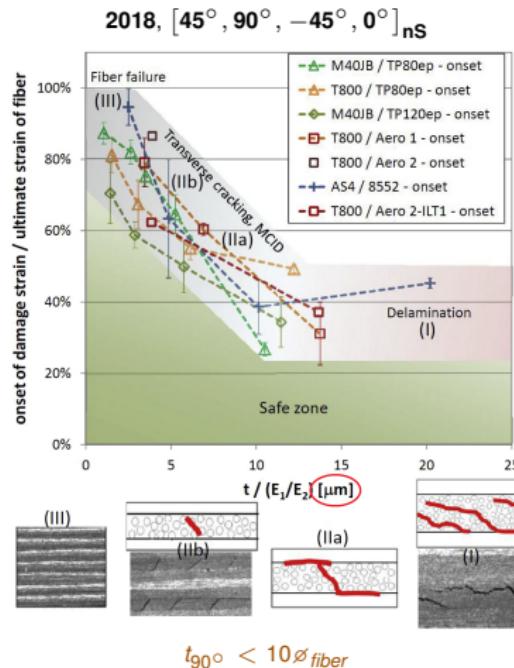
Cugnoni et al., Compos. Sci. Technol. **168**, 2018.

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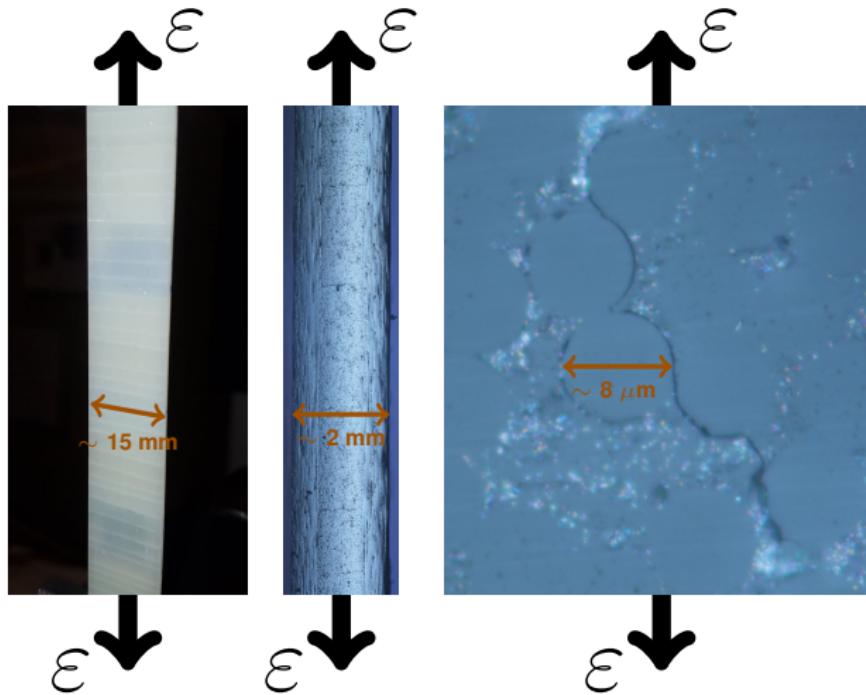
The Thin-ply "Advantage": new material, old result



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



Micromechanics of Initiation



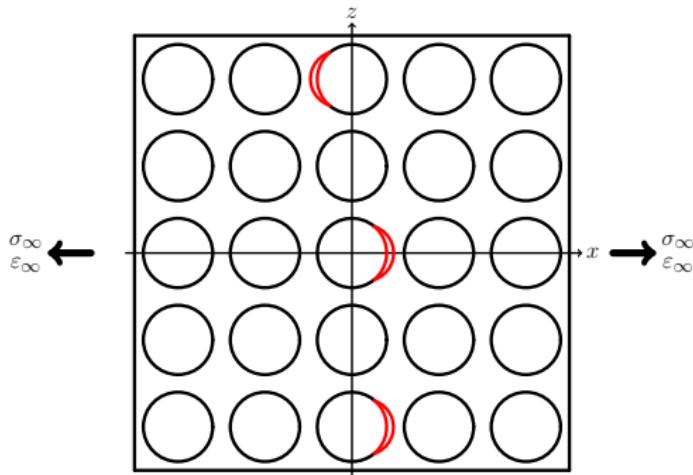
Left:
front view of [0, 90₂]_S,
visual inspection.

Center:
edge view of [0, 90₂]_S,
optical microscope.

Right:
edge view of [0, 90₂]_S,
optical microscope.

Micromechanics of Initiation

Stage 1: isolated debonds



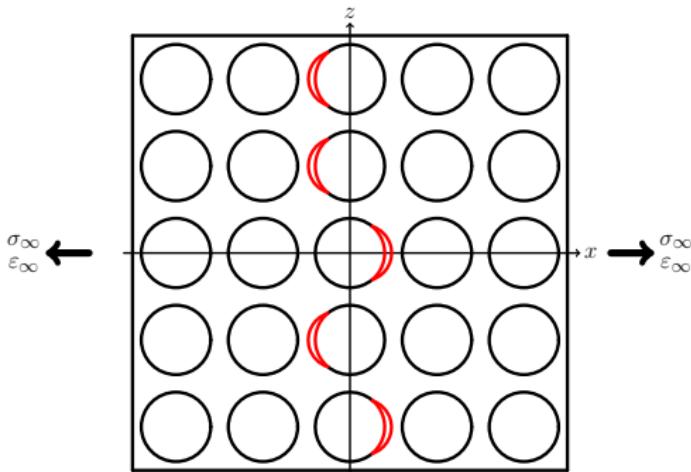
Bailey et al., P. Roy. Soc. A-Math. Phy. **366** (1727), 1979.

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

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

Micromechanics of Initiation

Stage 2: consecutive debonds



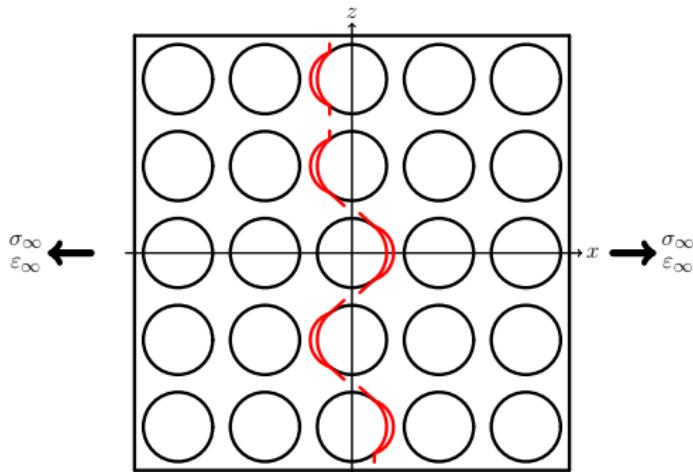
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Zhang et al., Compos. Part A-Appl. S. **28** (4), 1997.

Micromechanics of Initiation

Stage 3: kinking



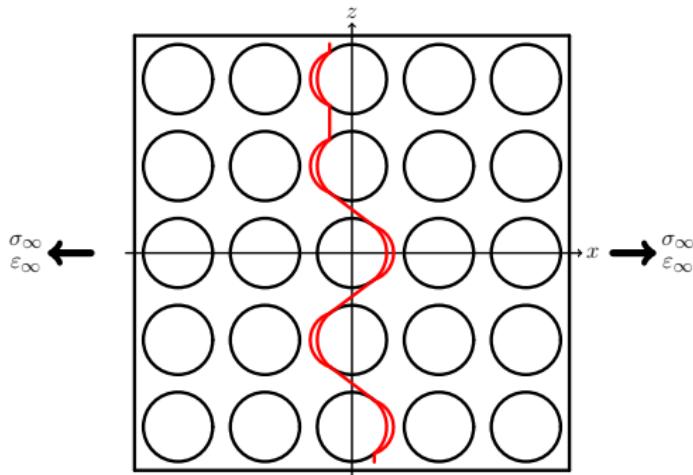
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Bailey et al., J. Mater. Sci. **16** (3), 1981.

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

Micromechanics of Initiation

Stage 4: coalescence

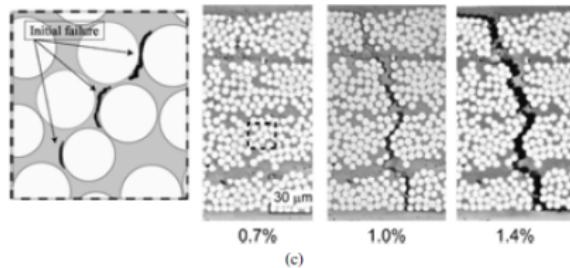


Bailey et al., P. Roy. Soc. A-Math. Phy. **366** (1727), 1979.

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

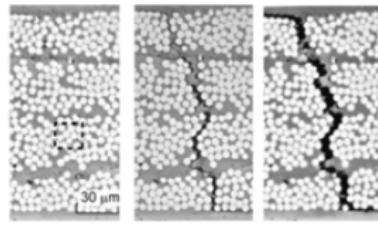
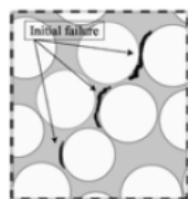
Zhang et al., Compos. Part A-Appl. S. **28** (4), 1997.

A Counter-intuitive Observation

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

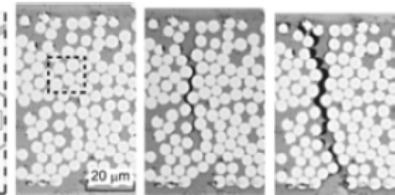
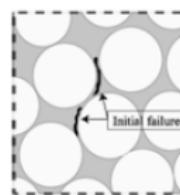
$$n = 4, t_{90^\circ} = 160 \mu m$$

A Counter-intuitive Observation

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

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

(c)

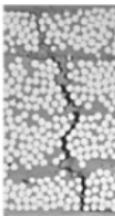
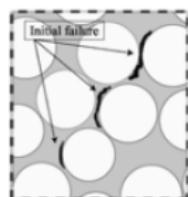


$$n = 2, t_{90^\circ} = 80 \mu m$$

(b)

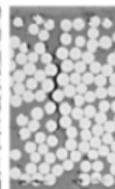
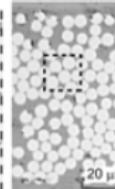
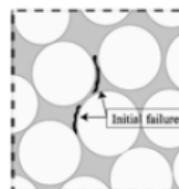
A Counter-intuitive Observation

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



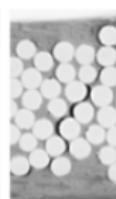
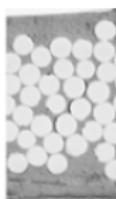
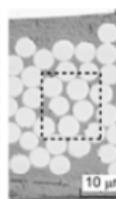
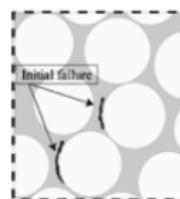
(c)

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



(b)

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



(a)

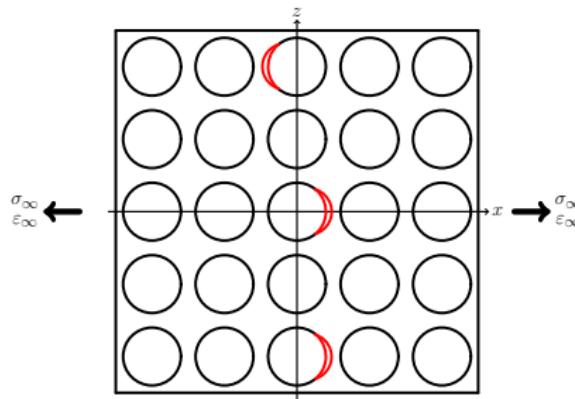
$n = 1, t_{90^\circ} = 40 \mu m$

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

Objectives

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

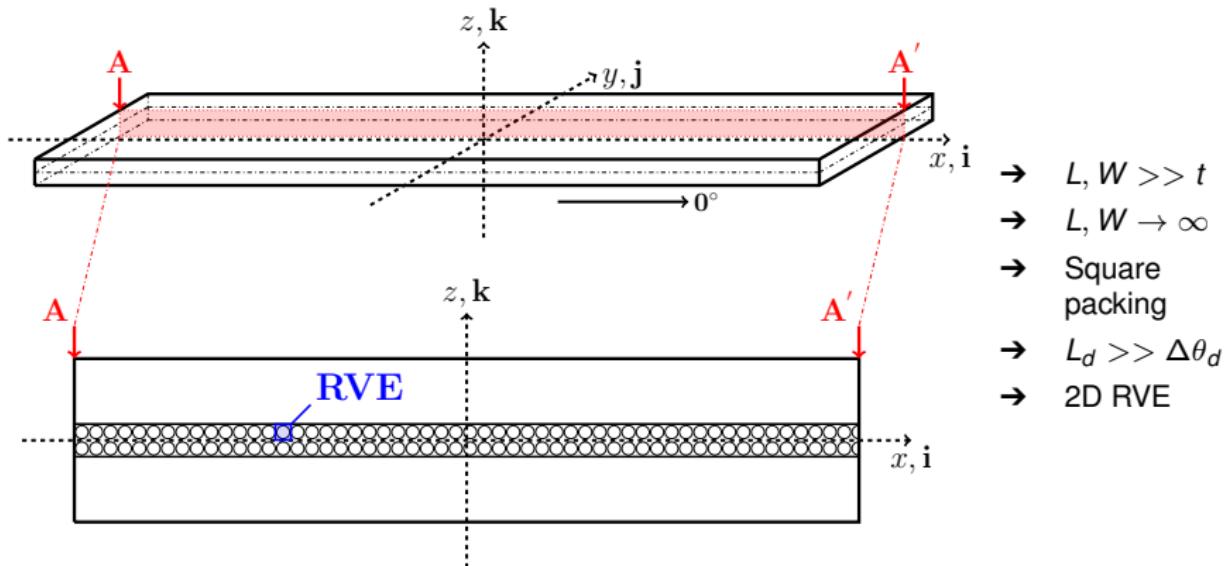
Stage 1: isolated debonds



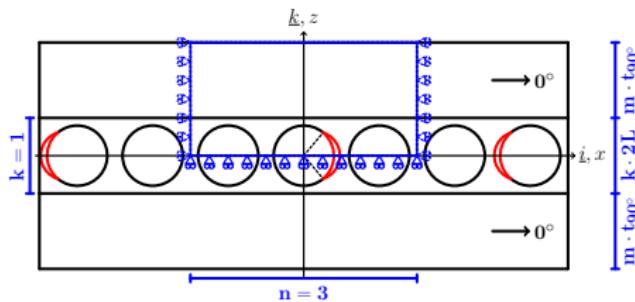
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Geometry Representative Volume Elements Assumptions Solution

MODELING

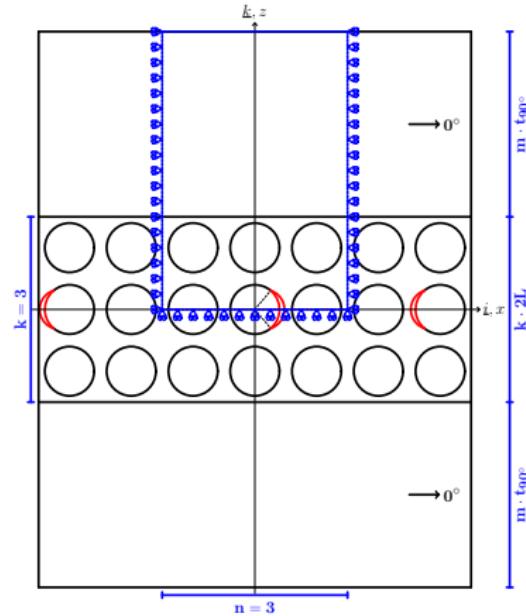
Geometry



Representative Volume Elements

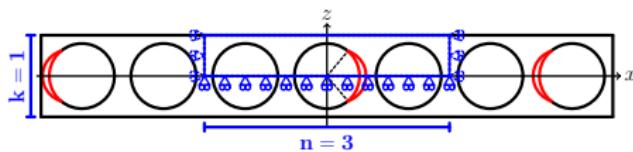


$$n \times 1 - m \cdot t_{90^\circ}$$



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

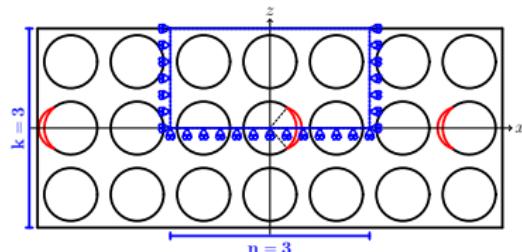
Representative Volume Elements



– free

$n \times 1 - \text{coupling}$

– coupling + H

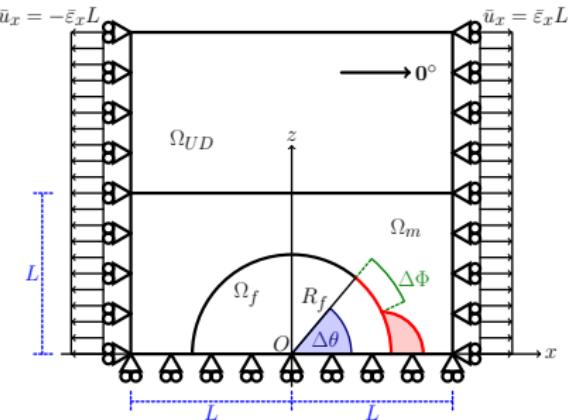


– free

$n \times k - \text{coupling}$

– coupling + H

Assumptions

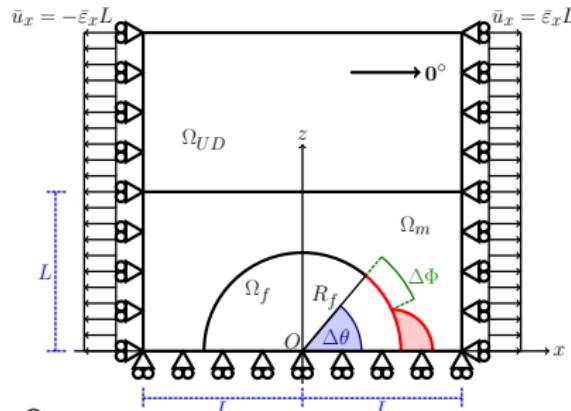


- Linear elastic, homogeneous materials
- Concentric Cylinders Assembly with Self-Consistent Shear Model for UD
- Plane strain
- Frictionless contact interaction
- Symmetric w.r.t. x-axis
- Coupling of x-displacements on left and right side (repeating unit cell)
- Applied uniaxial tensile strain $\bar{\varepsilon}_x = 1\%$
- $V_f = 60\%$

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

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

$$\frac{\partial^2 \varepsilon_{xx}}{\partial z^2} + \frac{\partial^2 \varepsilon_{zz}}{\partial x^2} = \frac{\partial^2 \gamma_{zx}}{\partial x \partial z} \quad \text{for } 0^\circ \leq \alpha \leq \Delta\theta : \\ (\vec{u}_m(R_f, \alpha) - \vec{u}_f(R_f, \alpha)) \cdot \vec{n}_\alpha \geq 0$$

$$\varepsilon_y = \gamma_{xy} = \gamma_{yz} = 0 \quad \text{for } \Delta\theta \leq \alpha \leq 180^\circ :$$

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{zx}}{\partial z} = 0 \quad \vec{u}_m(R_f, \alpha) - \vec{u}_f(R_f, \alpha) = 0$$

$$\frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \sigma_{zz}}{\partial z} = 0 \quad \sigma_{ij} = E_{ijkl} \varepsilon_{kl}$$

$$\sigma_{yy} = \nu (\sigma_{xx} + \sigma_{zz}) \quad + BC$$

→ Oscillating singularity

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

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

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

→ receding contact

→ Finite Element Method (FEM)
in Abaqus™

→ 2nd order shape functions

→ 6-nodes triangles & 8-nodes quadrilaterals

→ regular mesh of quadrilaterals
at the crack tip:

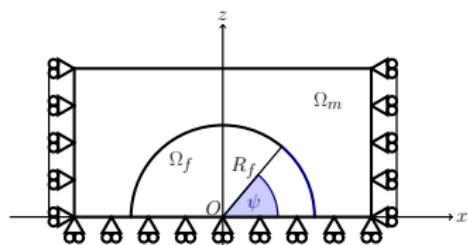
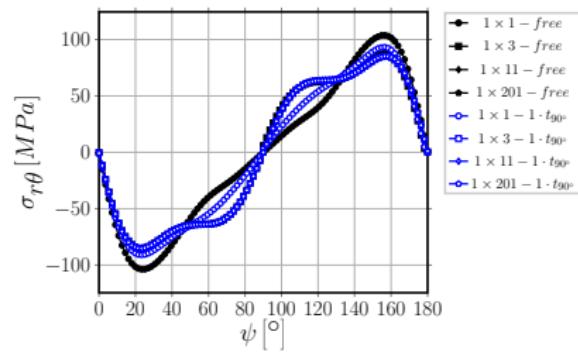
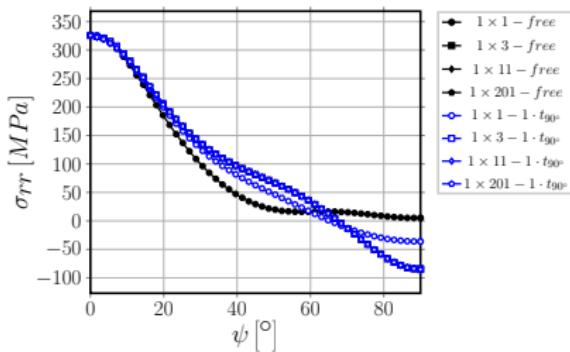
- $AR \sim 1$
- $\delta = 0.05^\circ$

Transverse Cracks Initiation Modeling Debond Initiation Debond Propagation Conclusions

σ_{rr} vs $\tau_{r\theta}$

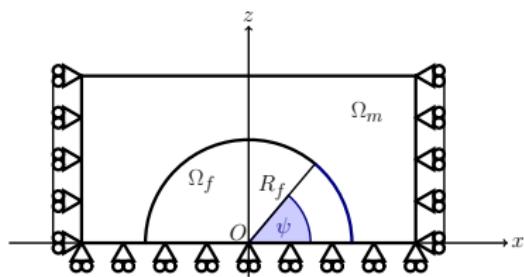
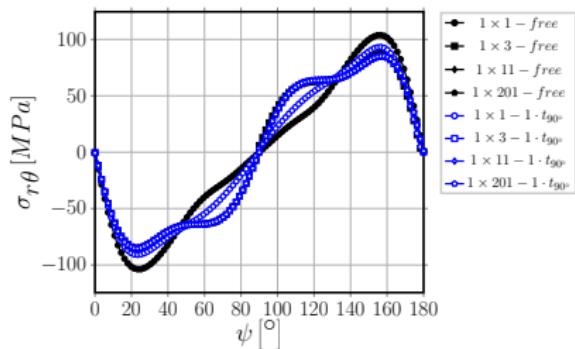
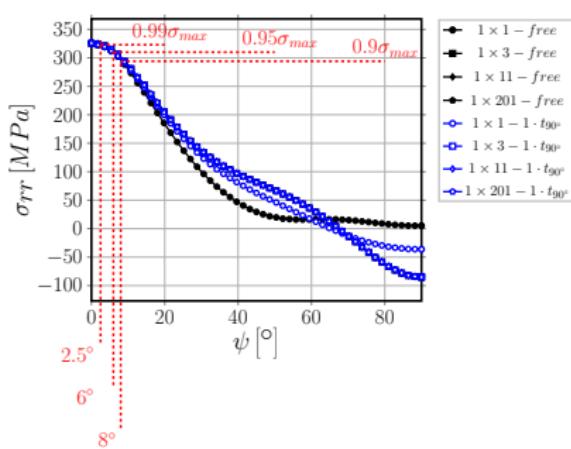
DEBOND INITIATION

σ_{rr} VS $\tau_{r\theta}$



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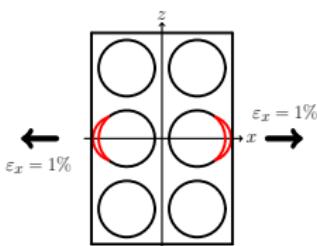
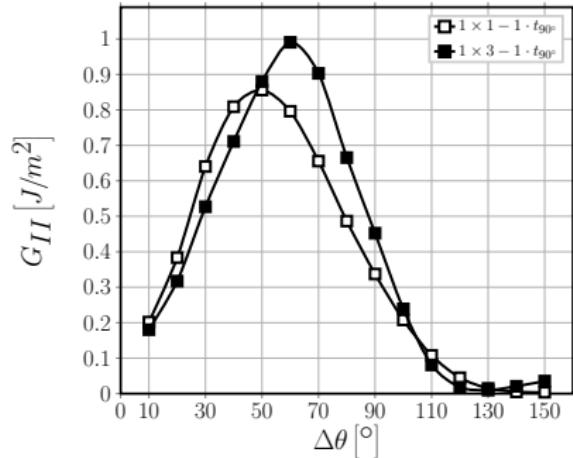
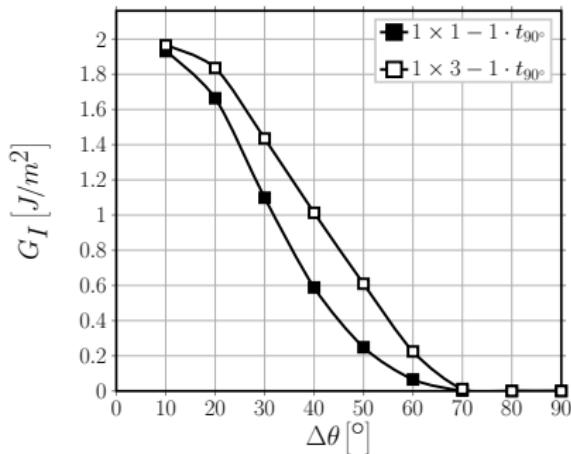
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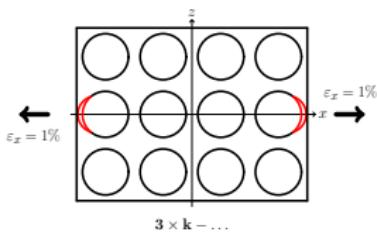
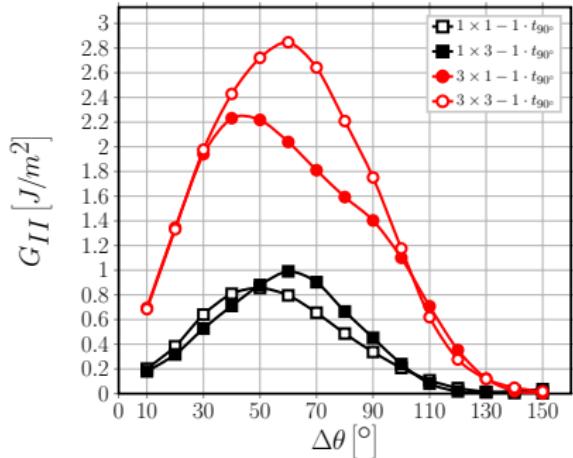
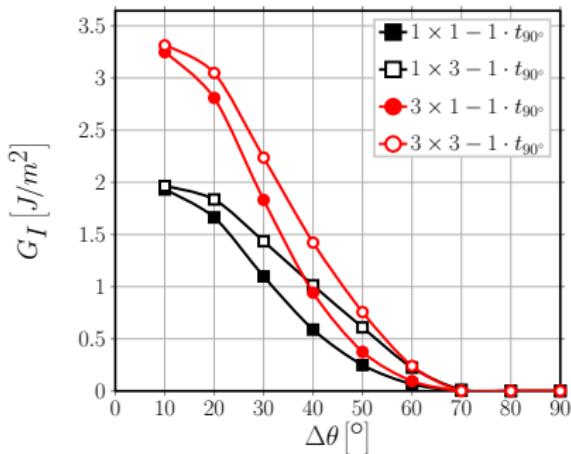
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DEBOND PROPAGATION

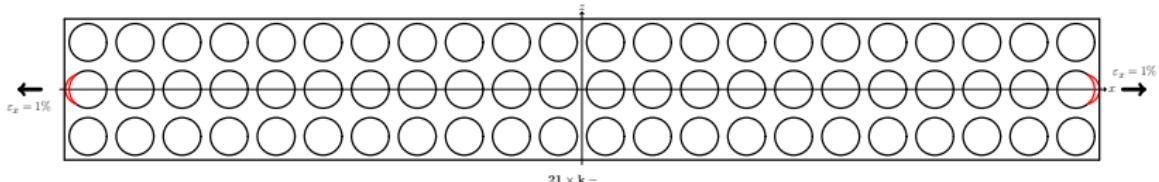
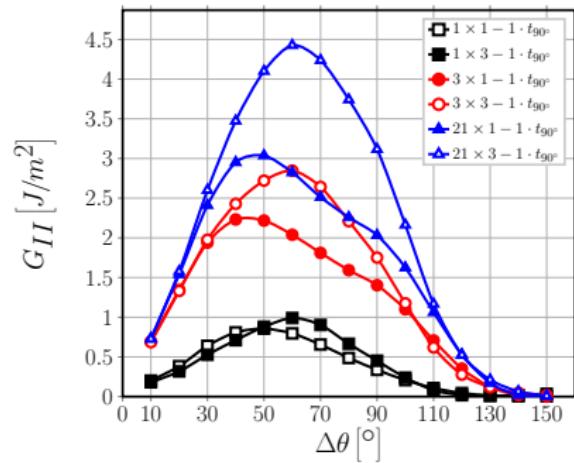
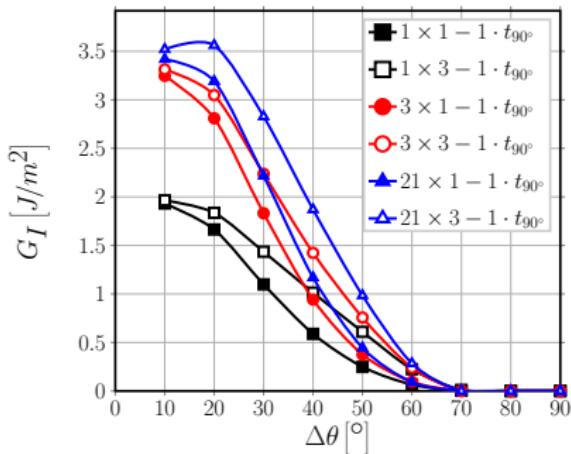
Interaction of Debonds: Strain Magnification



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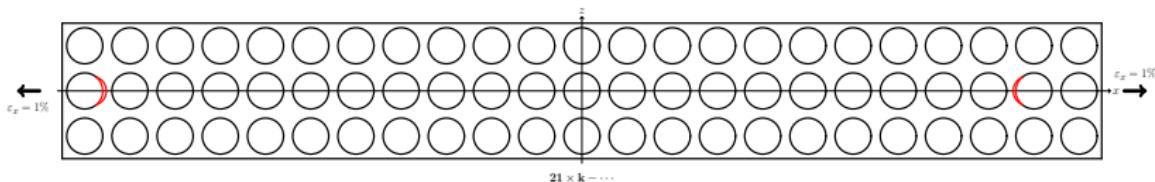
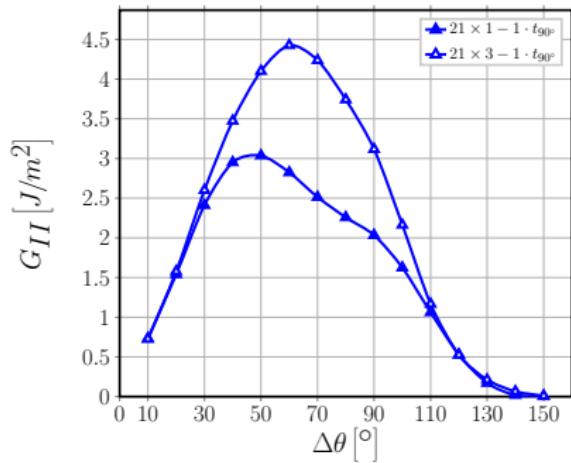
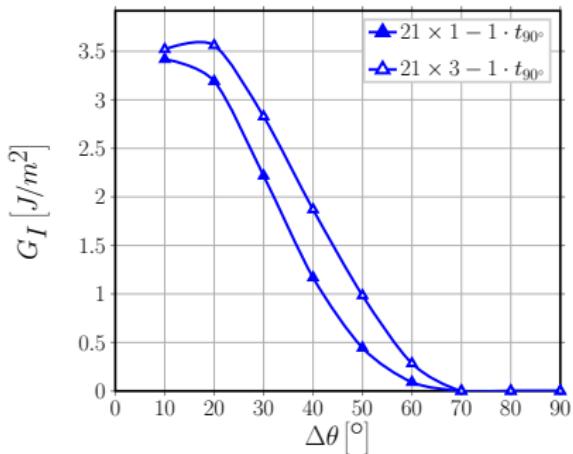
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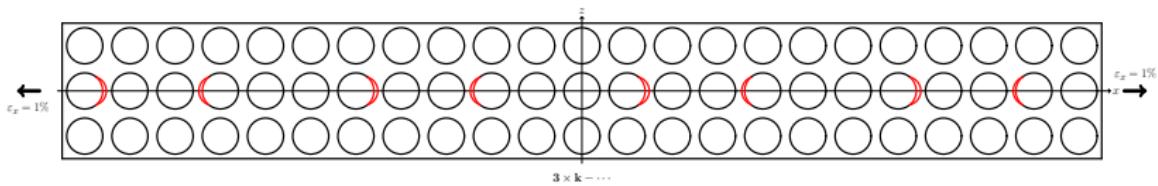
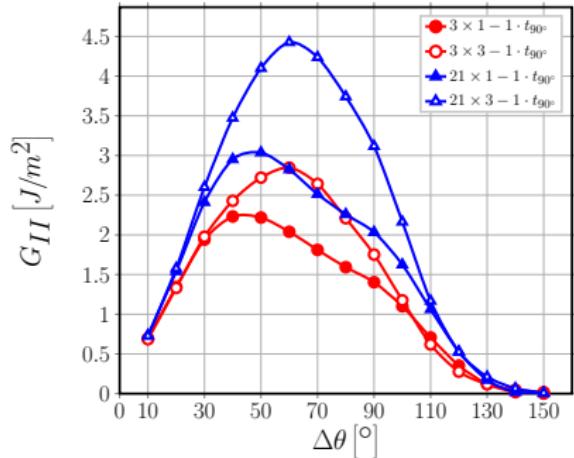
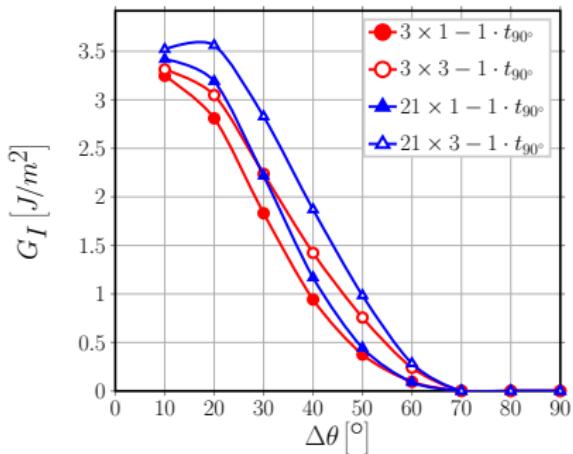
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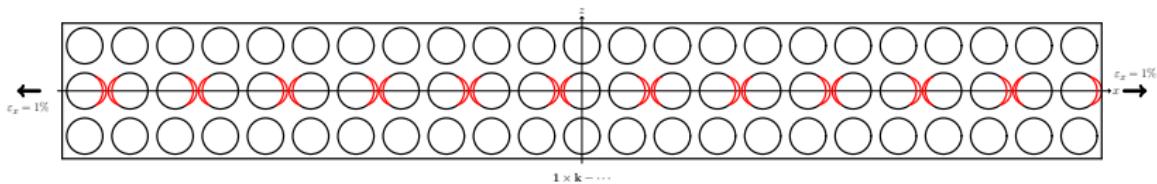
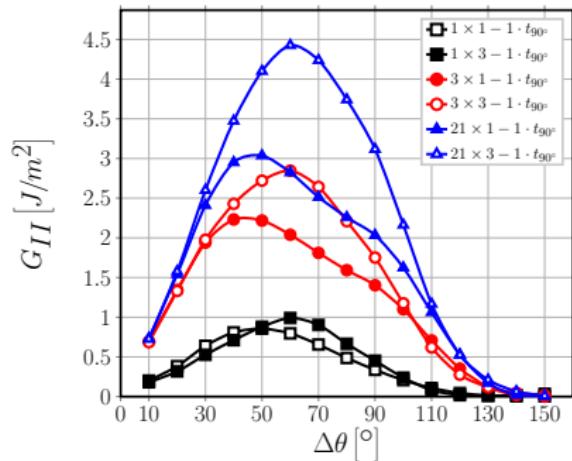
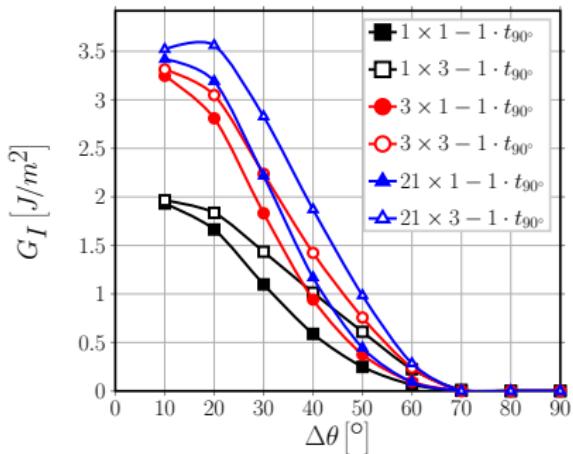
Interaction of Debonds: Crack Shielding



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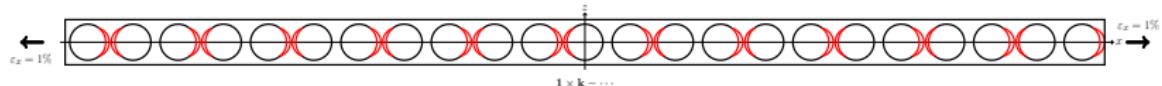
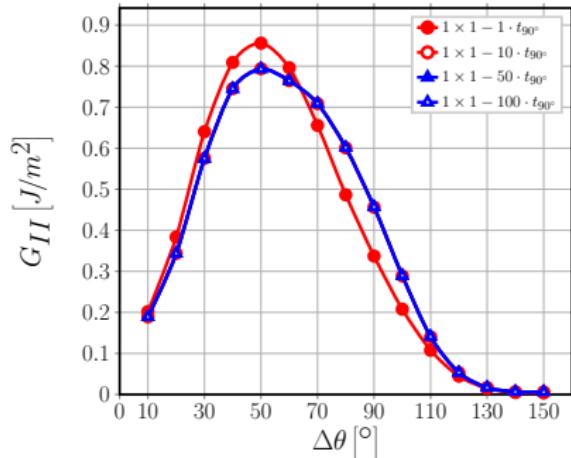
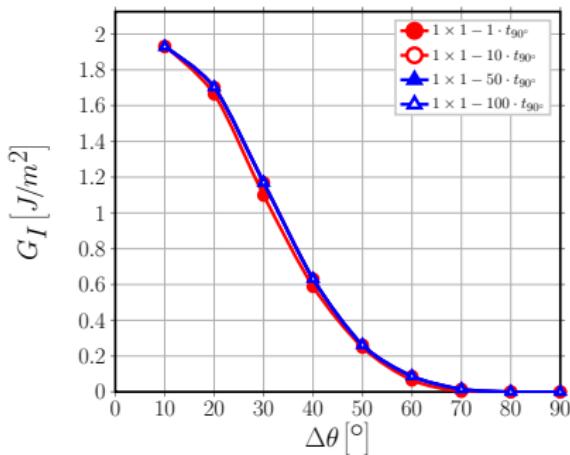


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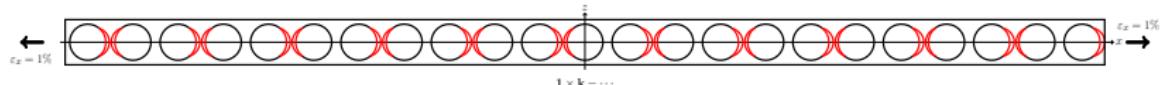
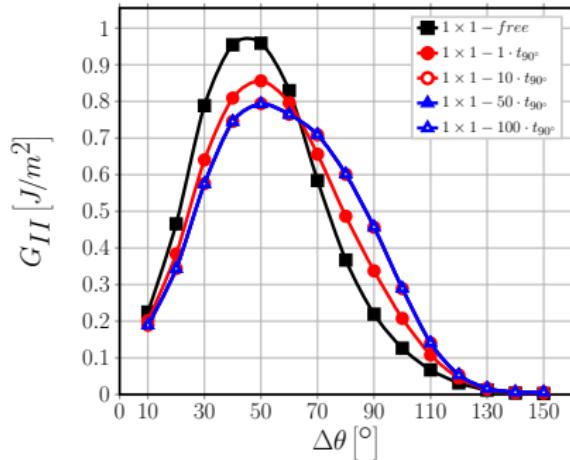
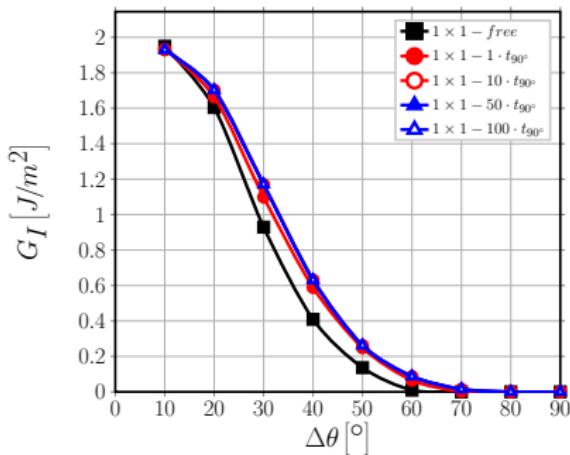
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Effect of 0° ply thickness



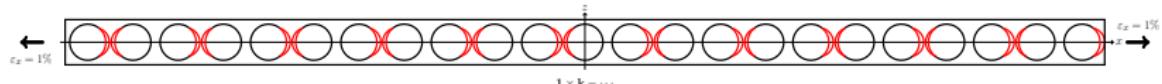
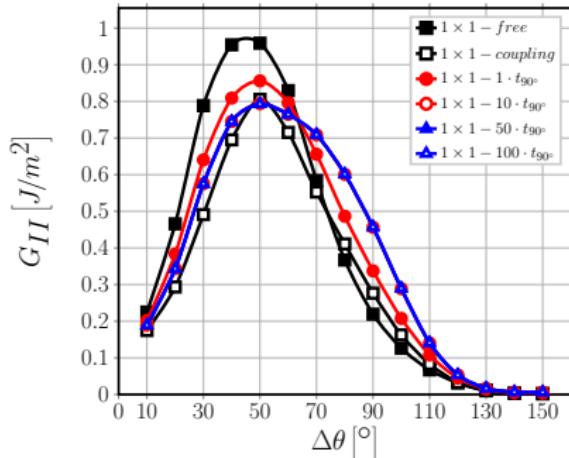
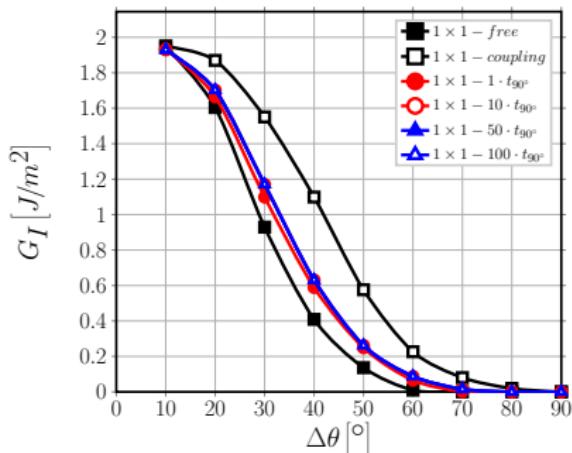
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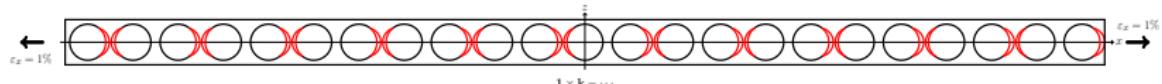
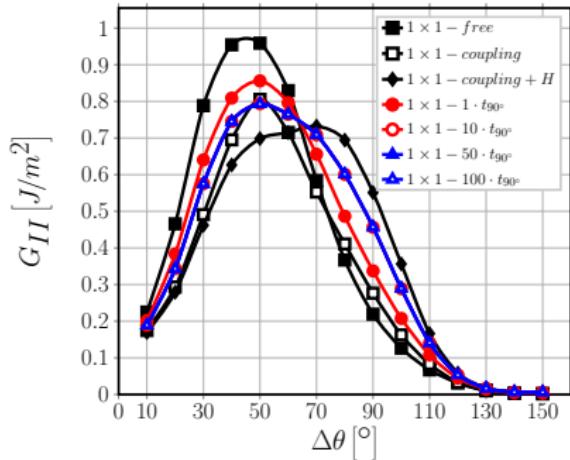
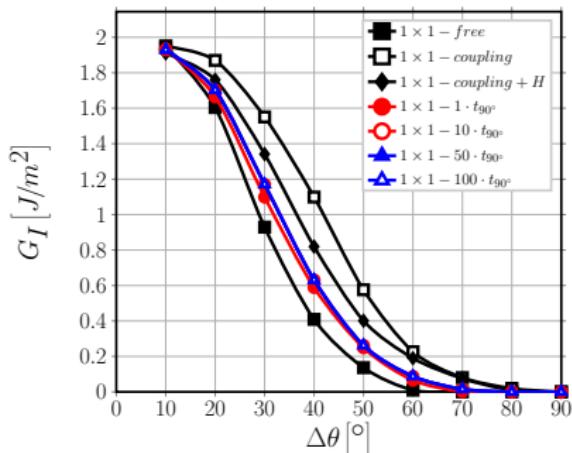


Transverse Cracks Initiation Modeling Debond Initiation Debond Propagation Conclusions
Interaction of Debonds Effect of 0° ply thickness Effect of 90° ply thickness

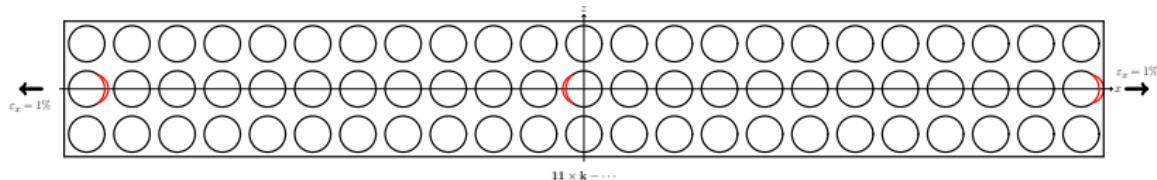
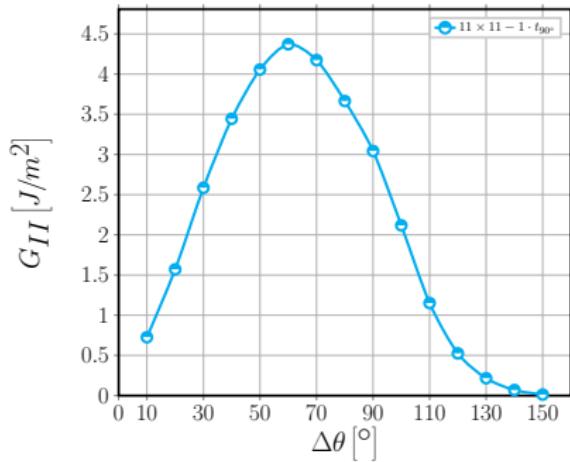
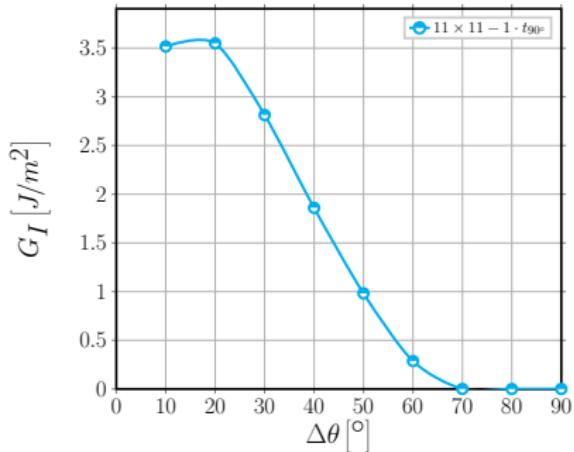
Effect of 0° ply thickness



Effect of 0° ply thickness

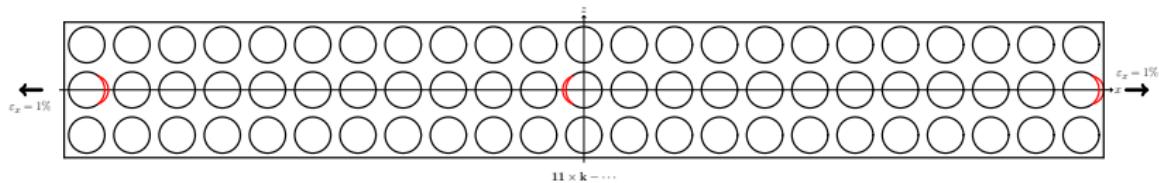
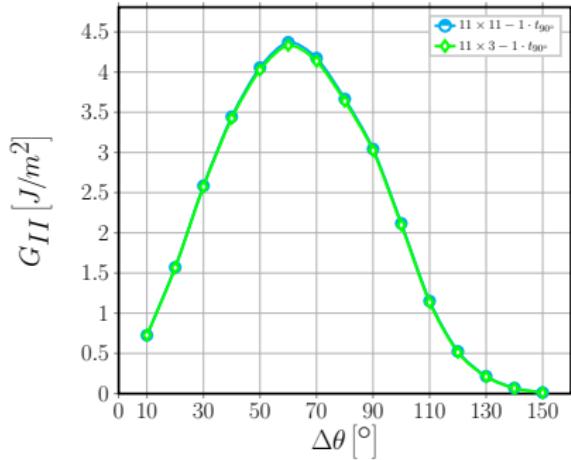
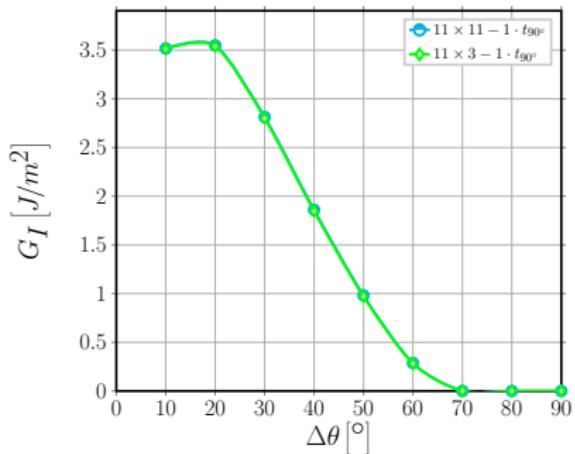


Effect of 90° ply thickness

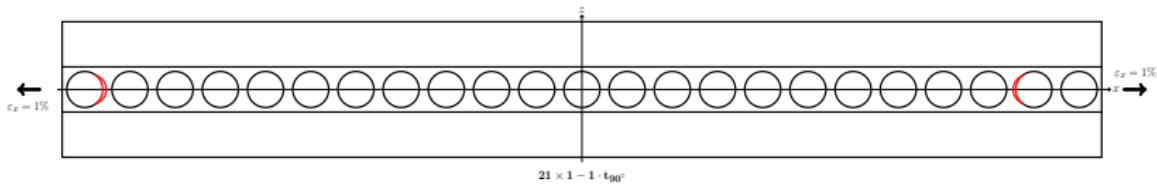
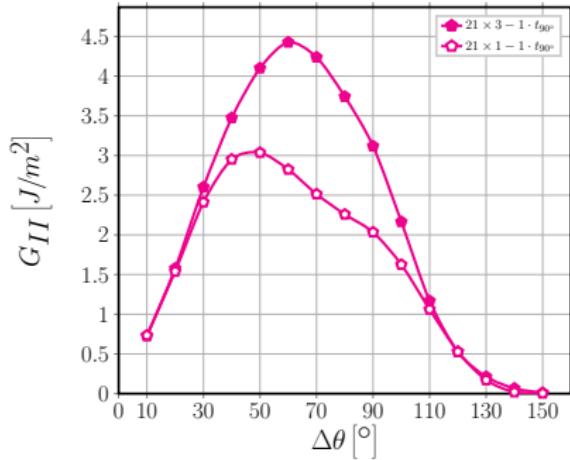
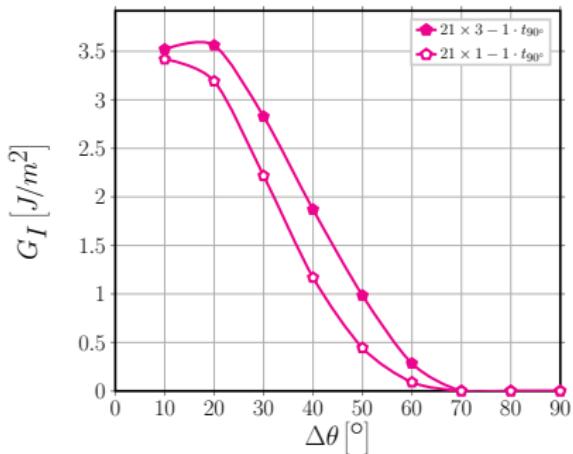


Transverse Cracks Initiation Modeling Debond Initiation Debond Propagation Conclusions
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Effect of 90° ply thickness



Effect of 90° ply thickness



CONCLUSIONS

Conclusions

- No effect of 90° ply thickness can be observed when t_{90° is at least $\sim 3\phi_{fiber}$
- Only if t_{90° is reduced to $1\phi_{fiber}$, ERR is reduced for a given level of applied strain, i.e. debond growth is delayed to higher levels of applied strain ($G \sim \varepsilon_{applied}^2$)
- 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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