

TOWARDS TOUGH SELF-HEALING THIN-PLY LAMINATES

INSIGHTS FROM COMPUTATIONAL MICROMECHANICAL MODELING AND

HIGH-TEMPERATURE EXPERIMENTAL INVESTIGATION OF ONSET AND PROPAGATION OF
TRANSVERSE CRACKING

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Outline

- ➔ Transverse Cracking in Thin-plies
- ➔ Modeling Fiber/Matrix Debonding
- ➔ Measuring Transverse Cracks Propagation
- ➔ Design Idea

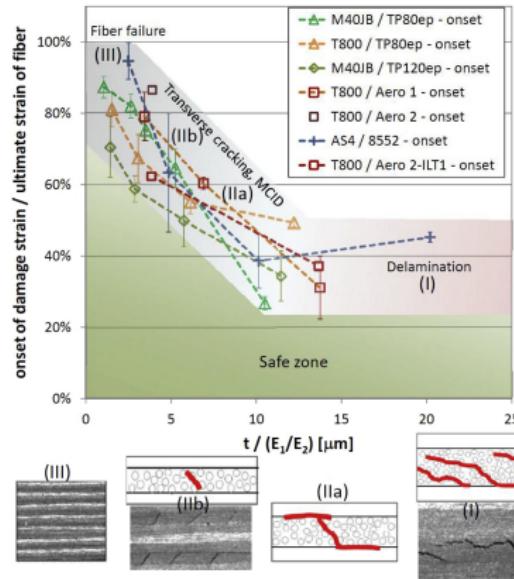
Transverse Cracking in Thin-plies Modeling Fiber/Matrix Debonding Measuring Transverse Cracks Propagation Design Idea
The Thin-ply "Advantage" Micromechanics of Initiation A Counter-intuitive Observation



TRANSVERSE CRACKING IN THIN-PLIES

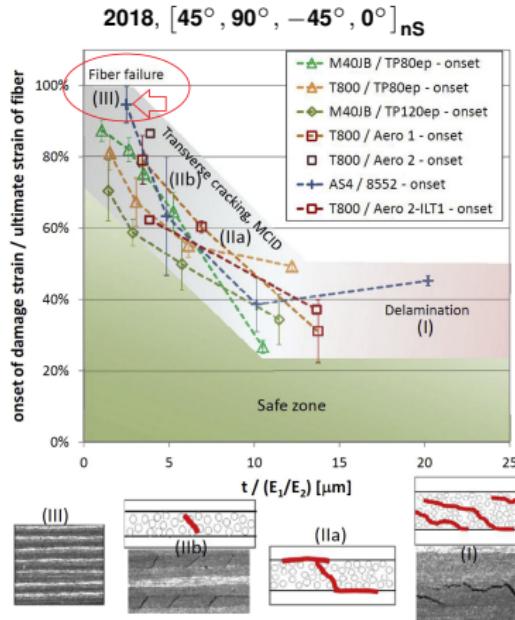
The Thin-ply "Advantage": new material

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



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

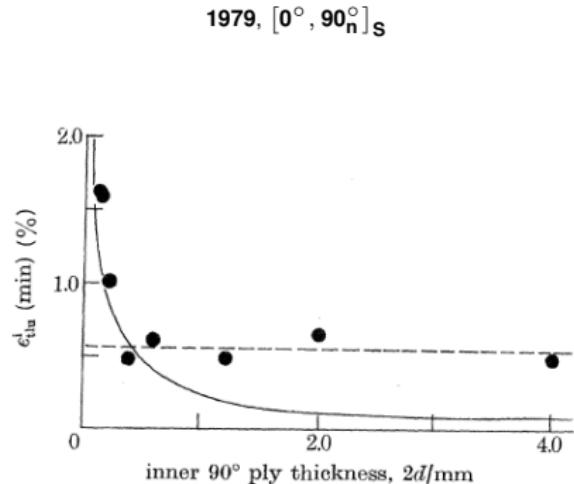
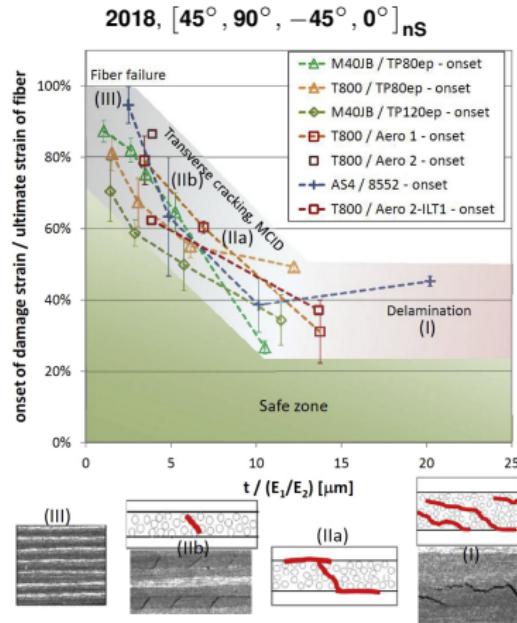
The Thin-ply "Advantage"? New material, new problem...



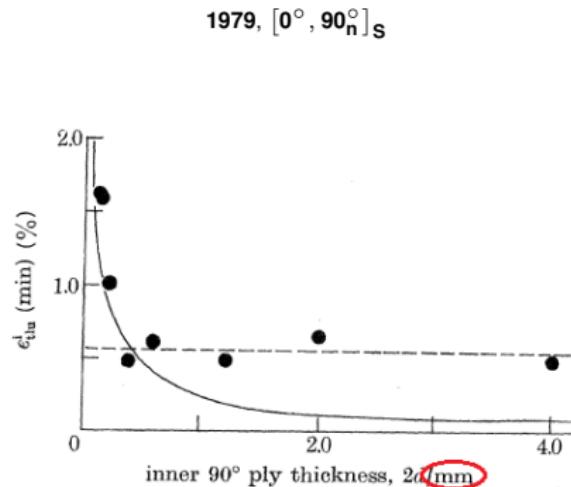
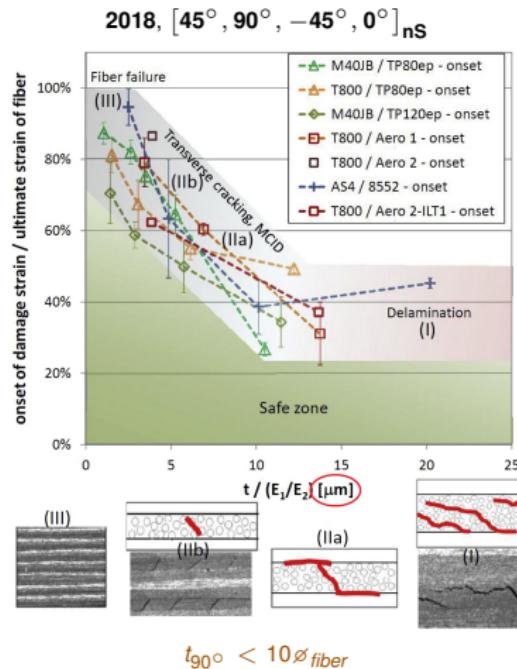
Cugnoni et al., Compos. Sci. Technol. **168**, 2018.

- material from NTPT (CH) (on the left)
- recent tests (master theses @ LTU) have shown the same behavior with material from Oxeon (SE)
- ✓ extended range of elastic behavior with no damage-induced stiffness reduction
- ✗ brittle failure of the whole laminate!
- ✗ very risky for application in safety-critical primary structures!

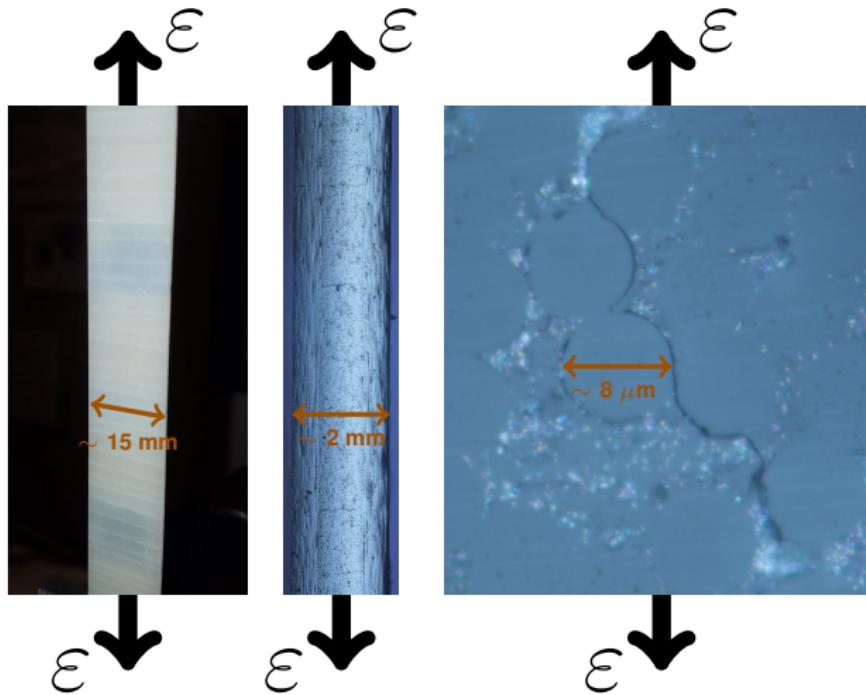
The Thin-ply "Advantage": new material, old result



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



Micromechanics of Initiation



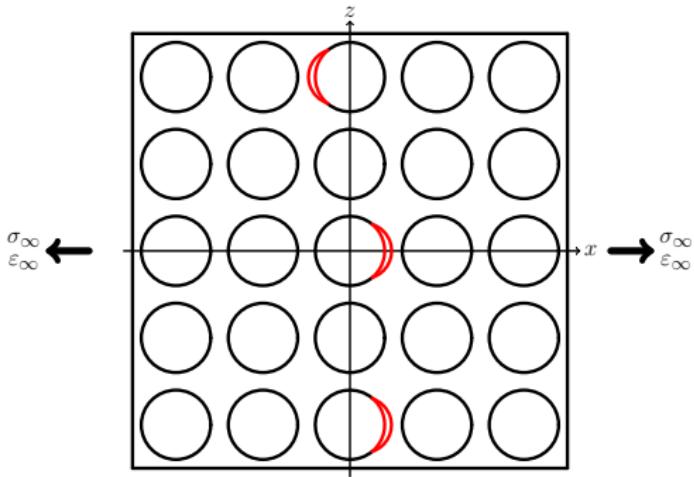
Left:
front view of $[0, 90]_S$,
visual inspection.

Center:
edge view of $[0, 90]_S$,
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Right:
edge view of $[0, 90]_S$,
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Micromechanics of Initiation

Stage 1: isolated debonds



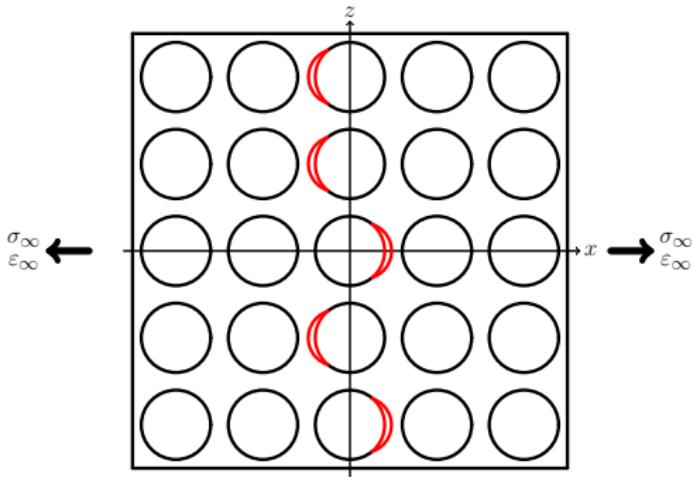
Bailey et al., P. Roy. Soc. A-Math. Phy. **366** (1727), 1979.

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



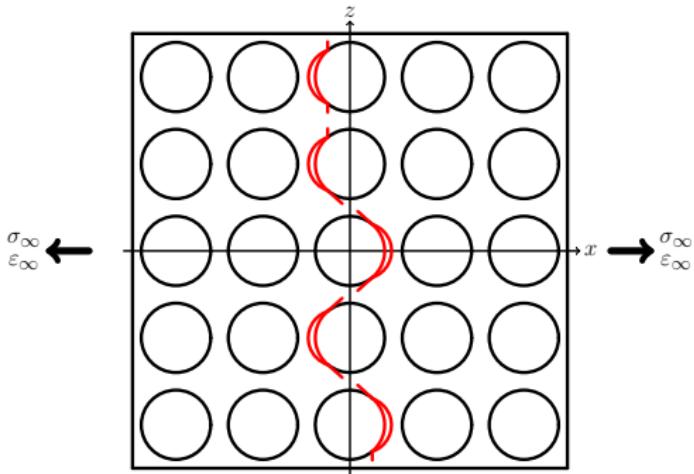
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Micromechanics of Initiation

Stage 3: kinking



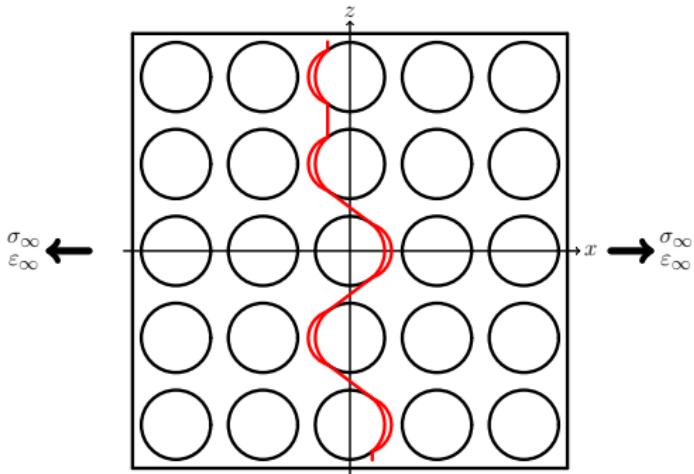
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Micromechanics of Initiation

Stage 4: coalescence



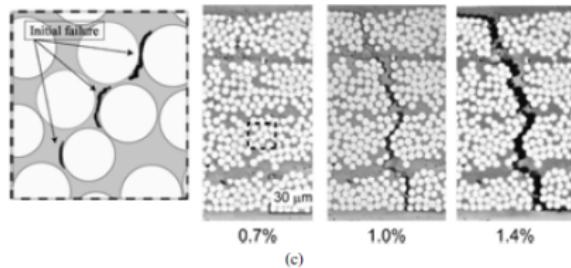
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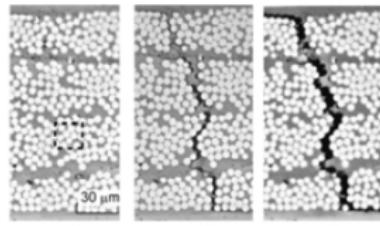
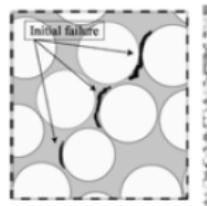
A Counter-intuitive Observation

[0°, 90°]_n

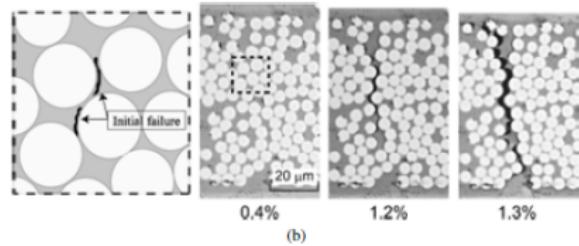


A Counter-intuitive Observation

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



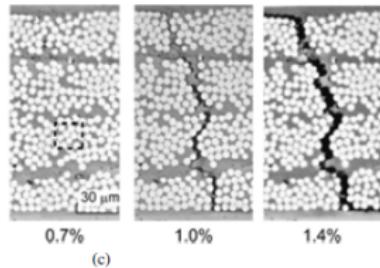
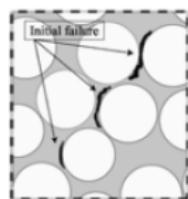
$$n = 4, t_{90^\circ} = 160 \mu m$$



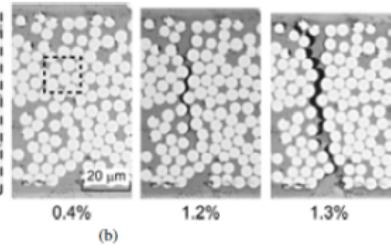
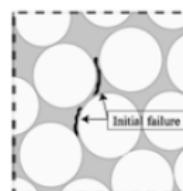
$$n = 2, t_{90^\circ} = 80 \mu m$$

A Counter-intuitive Observation

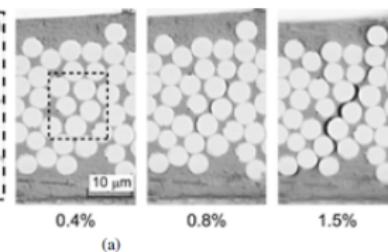
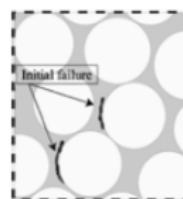
$[0^\circ, 90^\circ]_S$



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



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

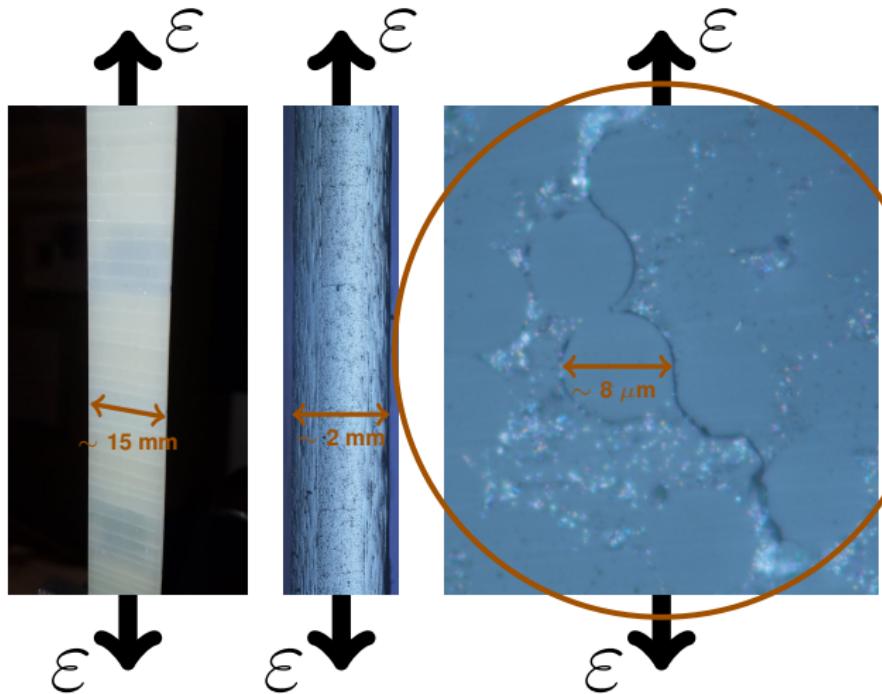


$n = 1, t_{90^\circ} = 40 \mu m$

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

MODELING FIBER/MATRIX DEBONDING

Micromechanics of Initiation

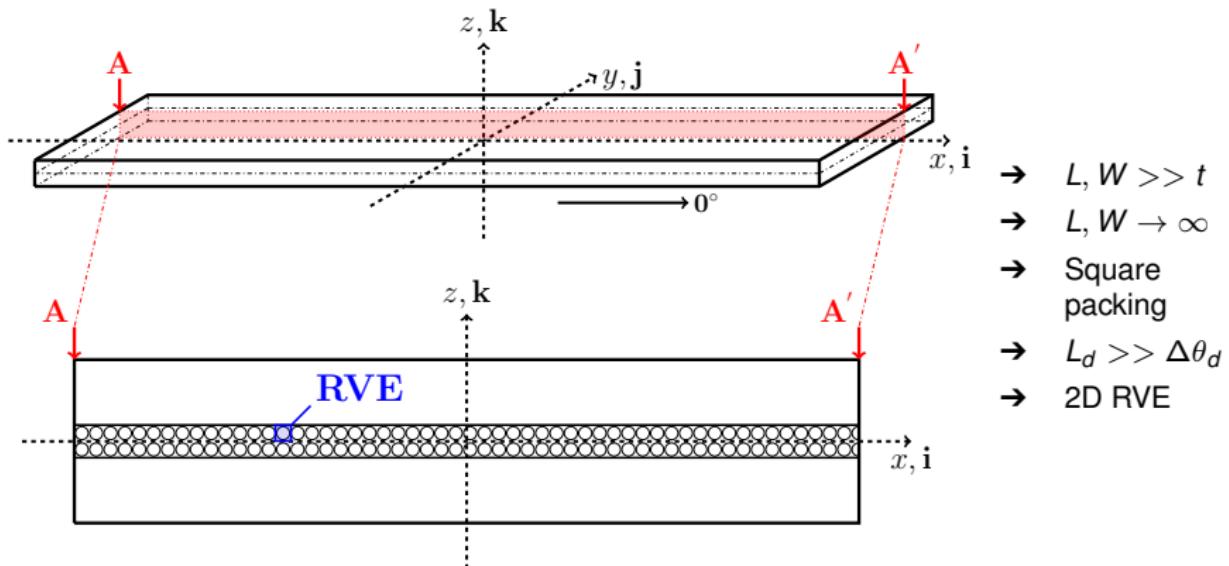


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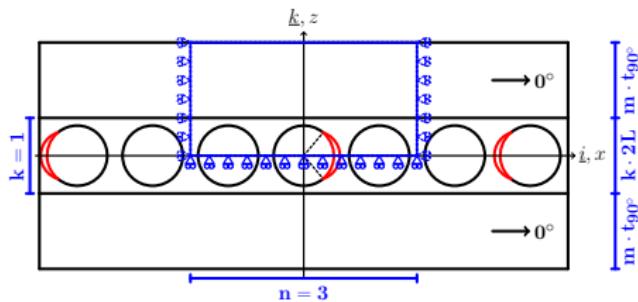
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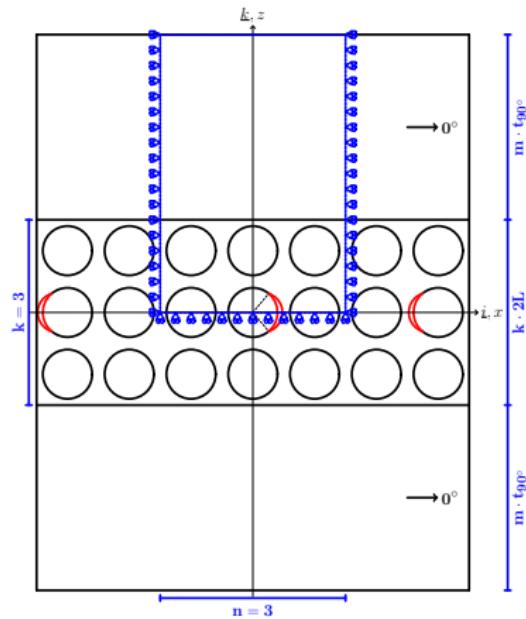
Geometry



Representative Volume Elements (RVEs)

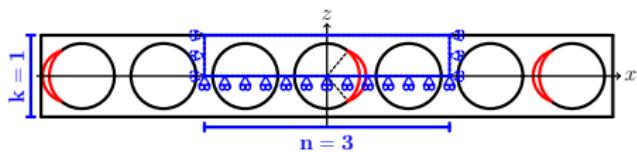


$$n \times 1 - m \cdot t_{90^\circ}$$



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

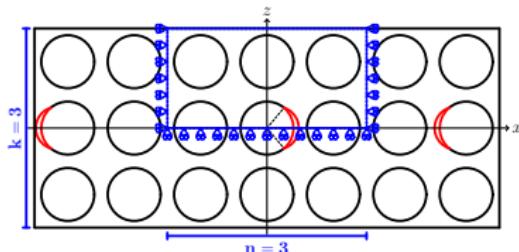
Representative Volume Elements



– free

$n \times 1$ – coupling

– coupling + H

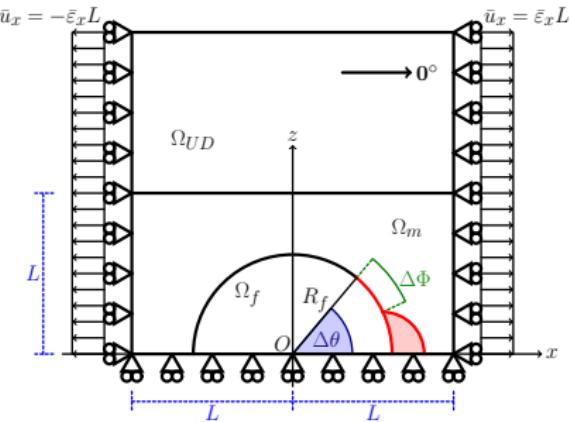


– free

$n \times k$ – coupling

– coupling + H

Assumptions

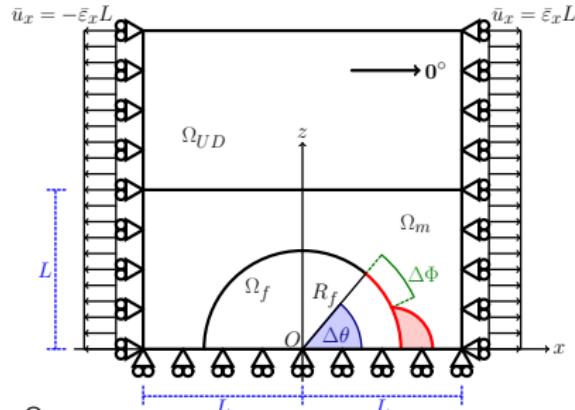


$$R_f = 1 \text{ } [\mu\text{m}] \quad L = \frac{R_f}{2} \sqrt{\frac{\pi}{V_f}}$$

- 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 Ω_f , Ω_m , Ω_{UD} :

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

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

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

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

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

→ 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 problem

→ Finite Element Method (FEM)
in Abaqus™+ VCCT

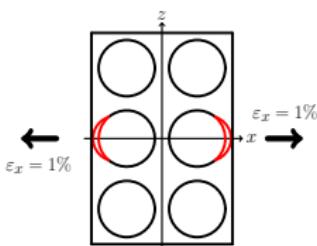
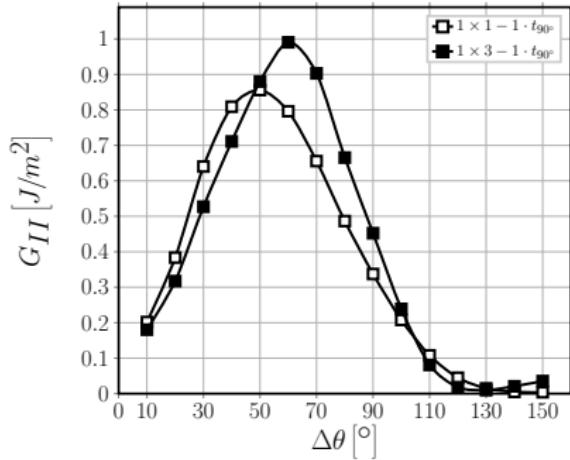
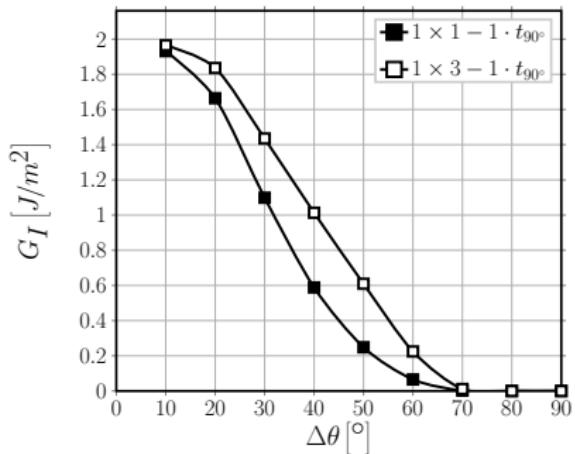
→ 2nd order shape functions

→ 6-nodes triangles & 8-nodes quadrilaterals

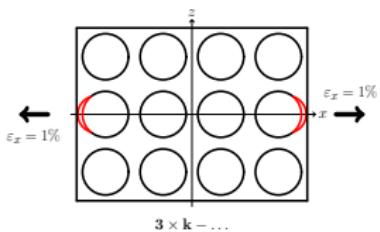
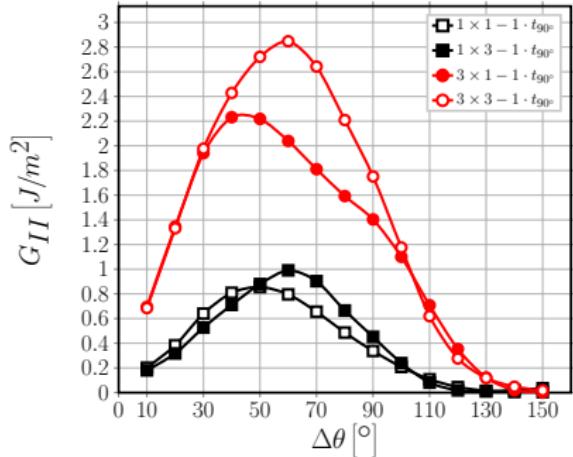
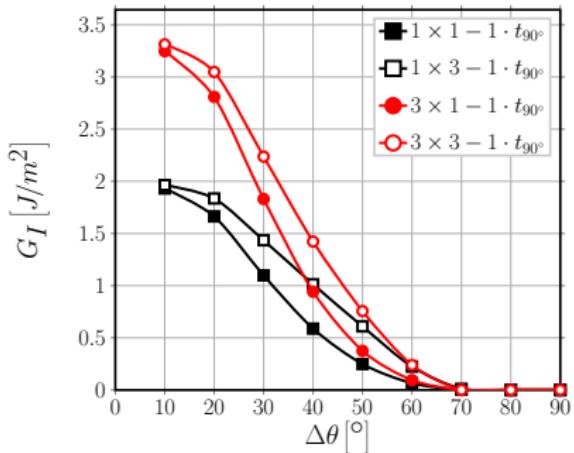
→ regular mesh of quadrilaterals
at the crack tip:

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

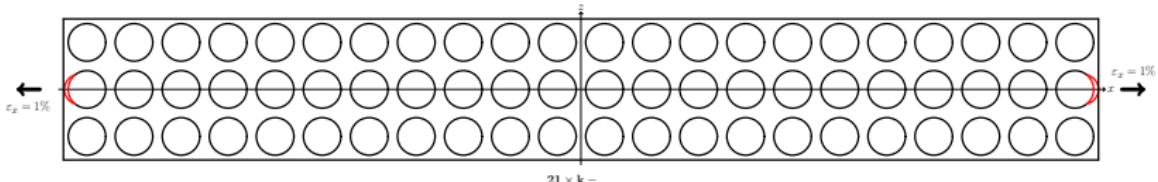
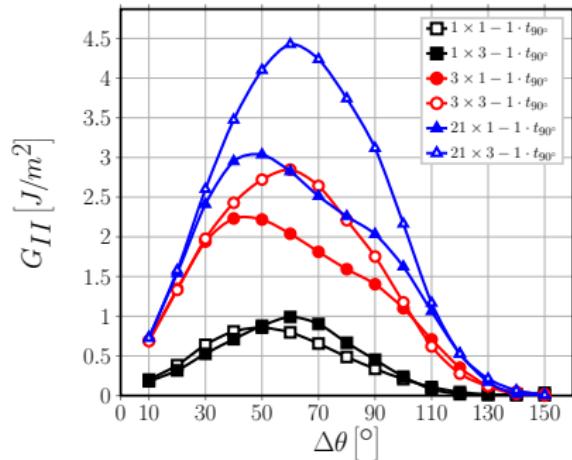
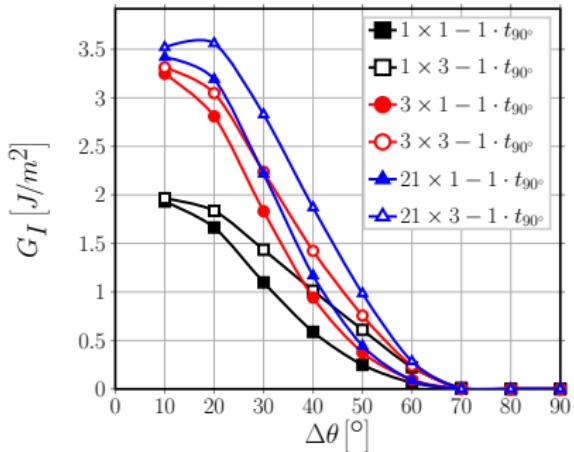
Interaction of Debonds: Strain Magnification



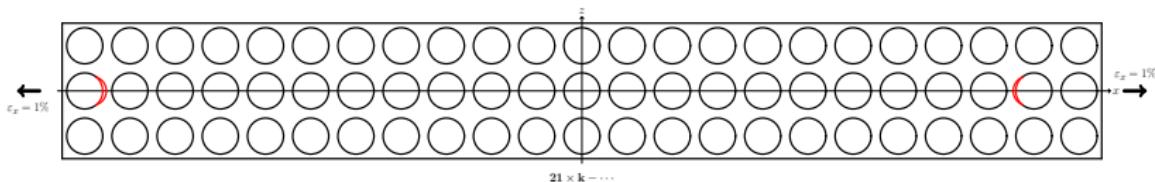
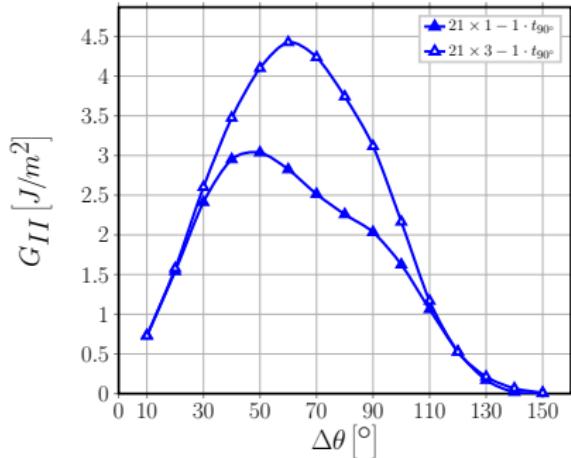
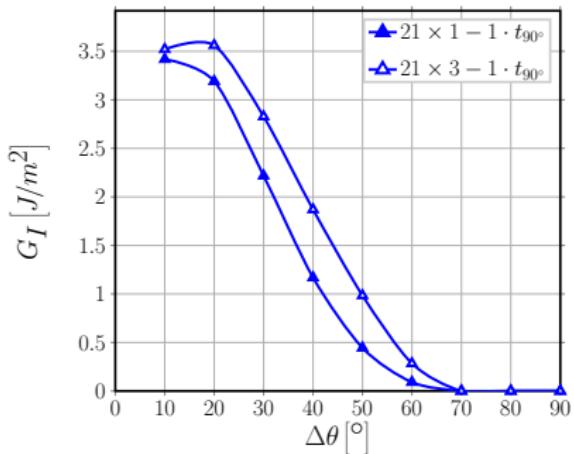
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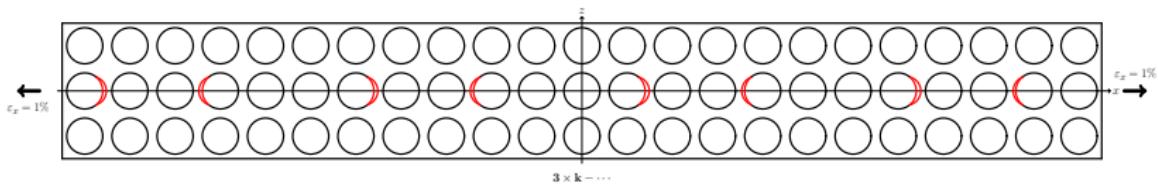
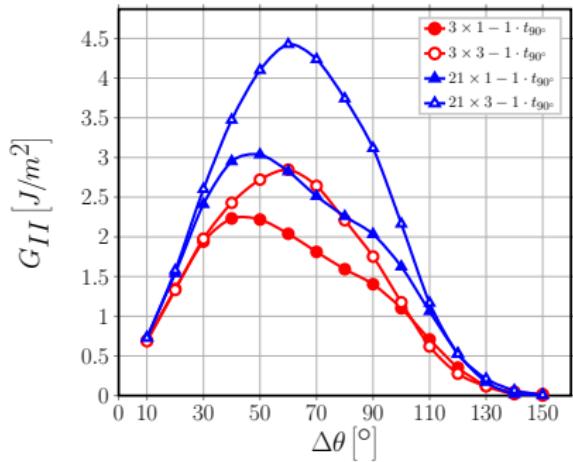
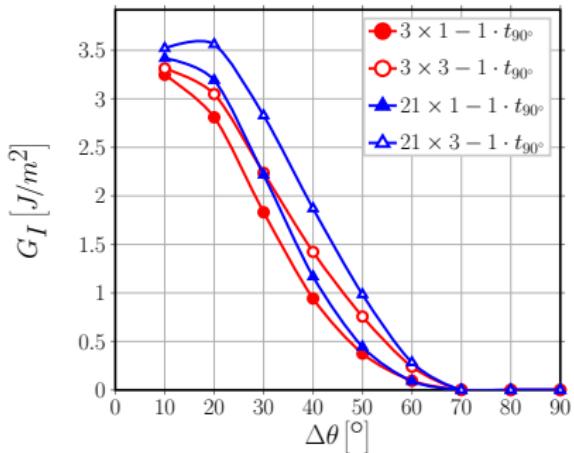
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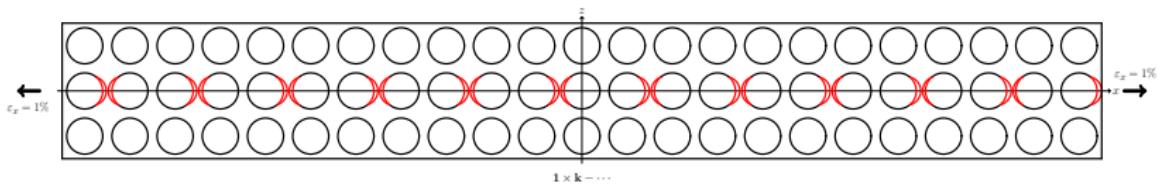
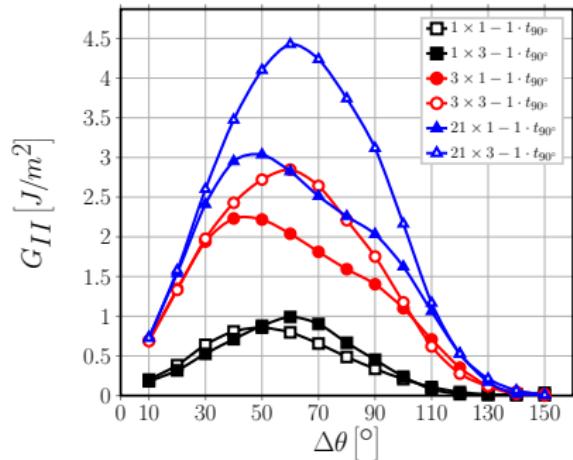
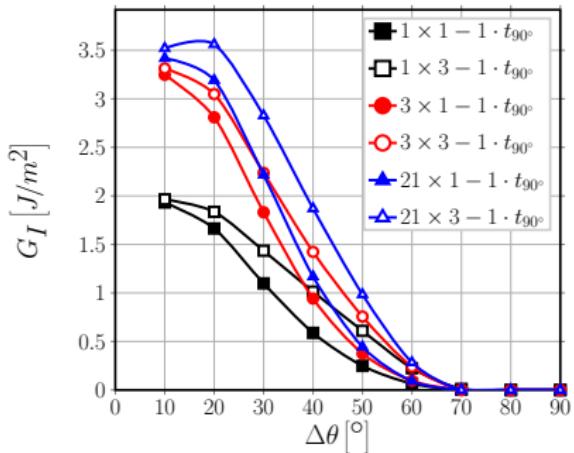
Interaction of Debonds: Crack Shielding



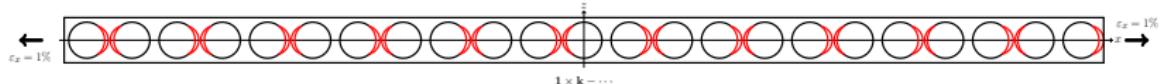
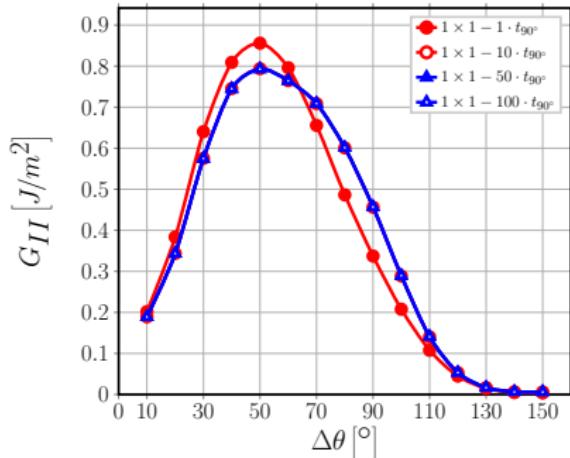
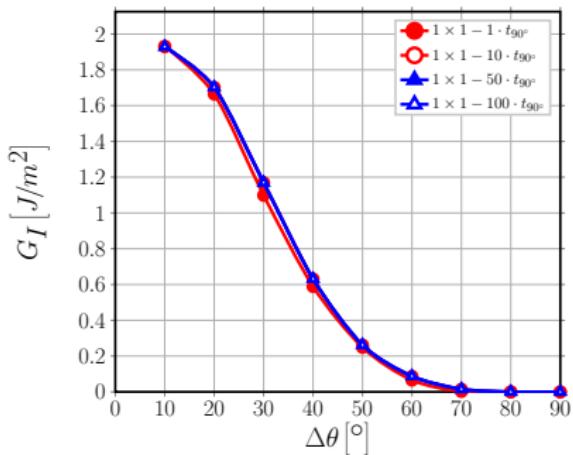
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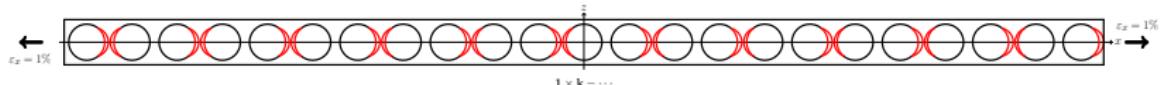
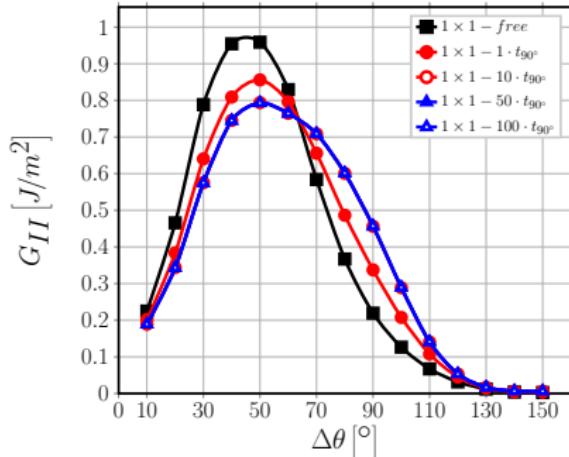
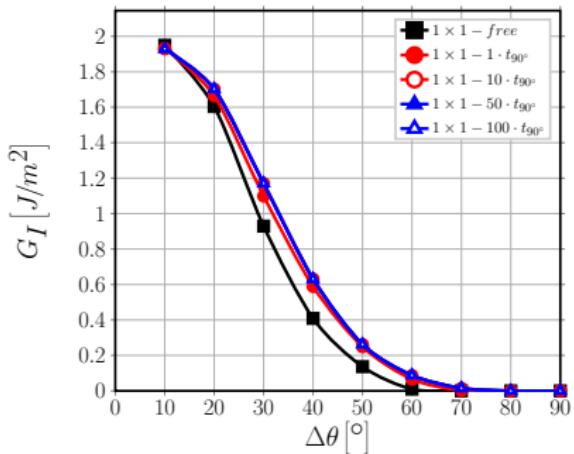
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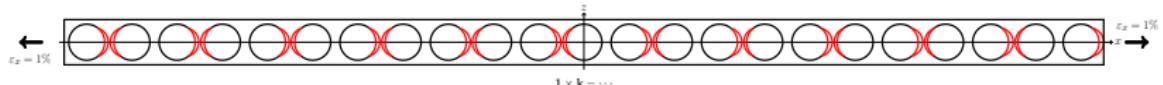
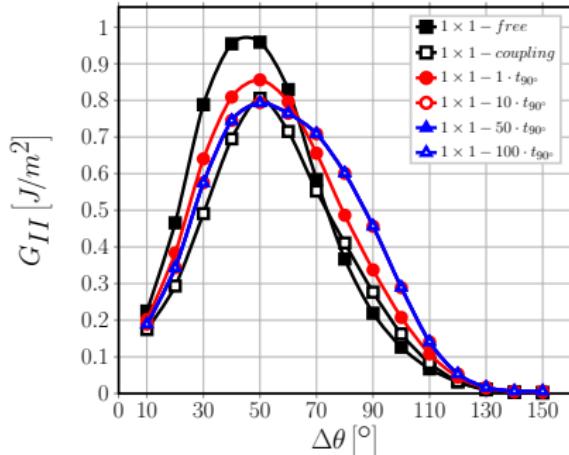
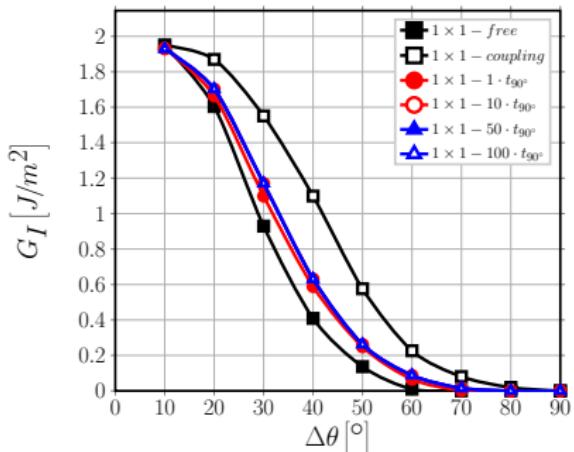
Effect of 0° ply thickness



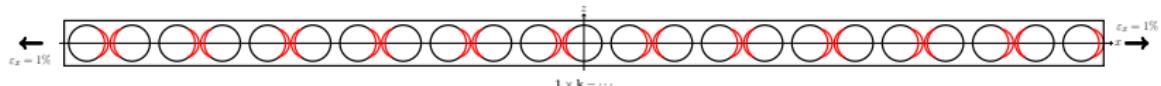
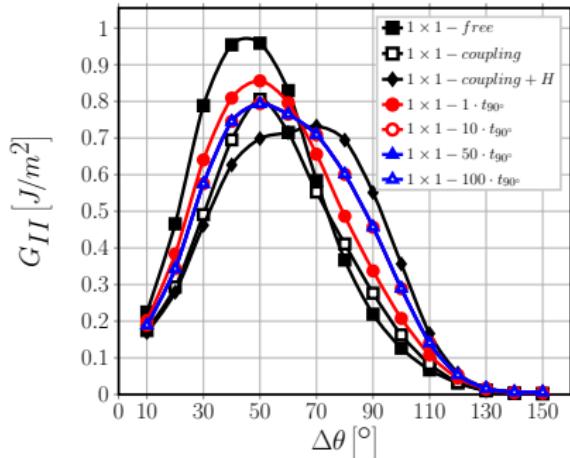
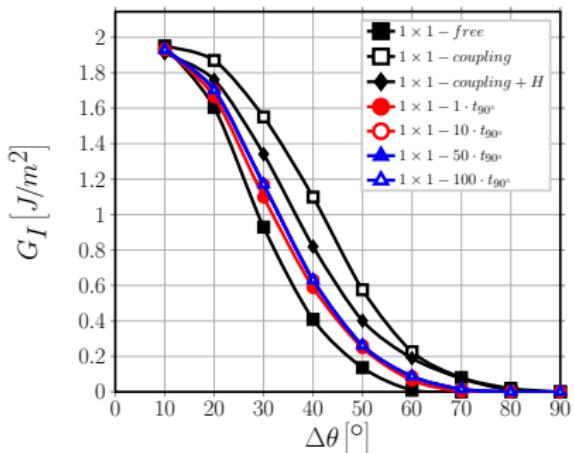
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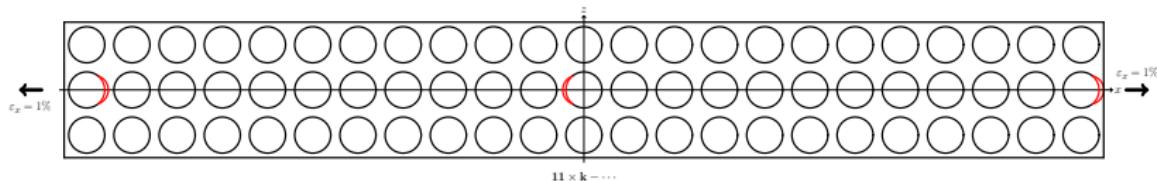
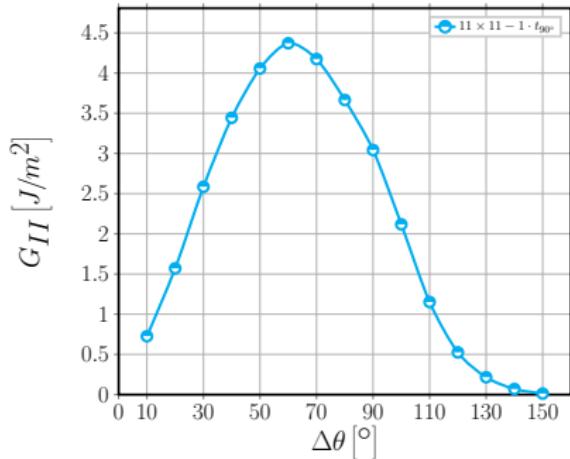
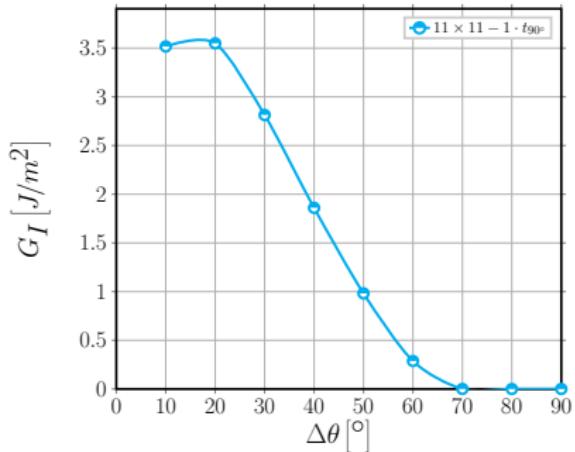
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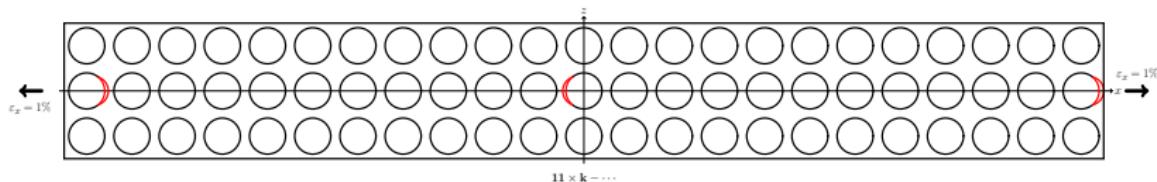
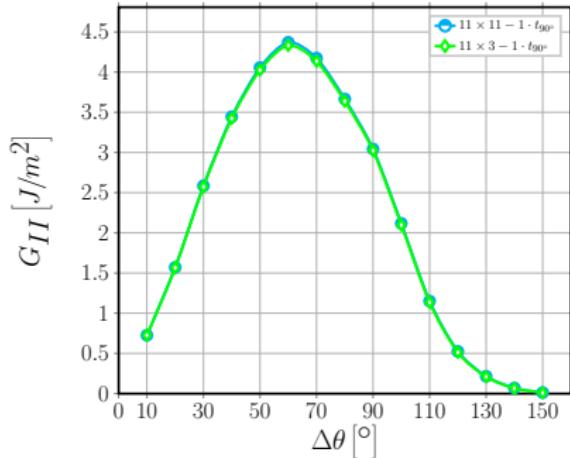
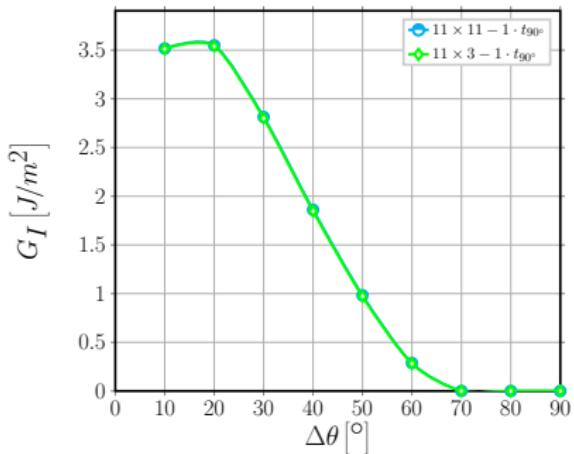
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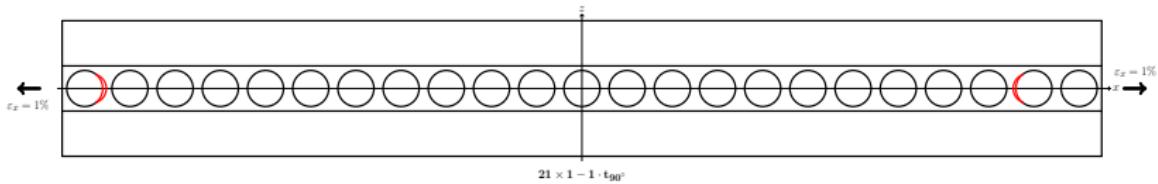
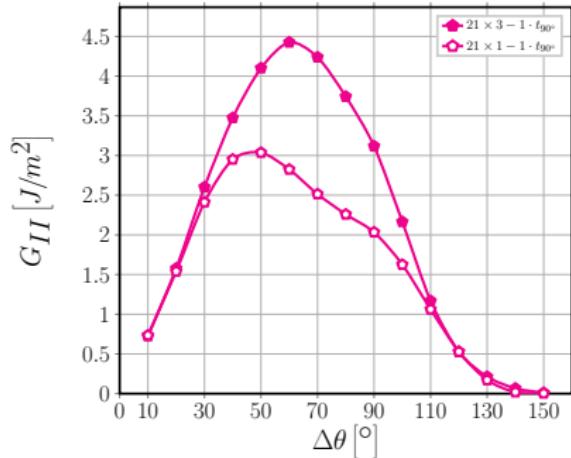
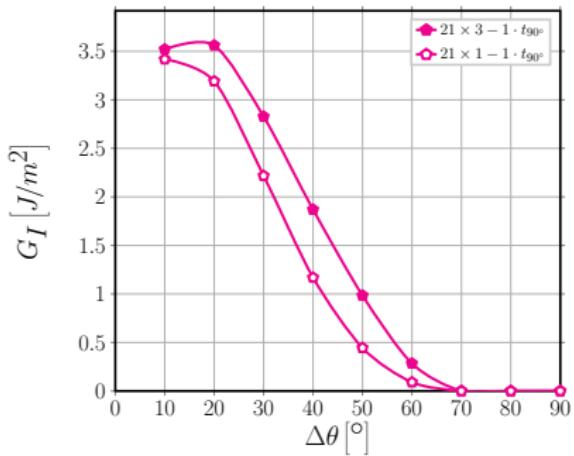
Effect of 90° ply thickness



Effect of 90° ply thickness



Effect of 90° ply thickness



Summary

- 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

Transverse Cracking in Thin-plies

Modeling Fiber/Matrix Debonding

Measuring Transverse Cracks Propagation

Design Idea

Prelude Materials Equipment

Testing procedure

Crack density

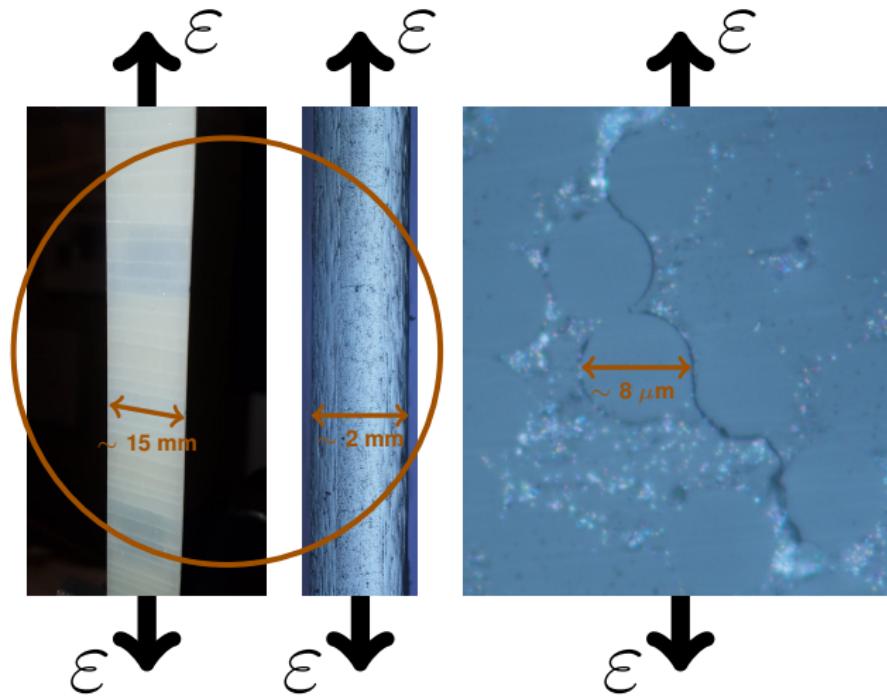
Young's modulus

Re-bonding?



MEASURING TRANSVERSE CRACKS PROPAGATION

Micromechanics of Initiation

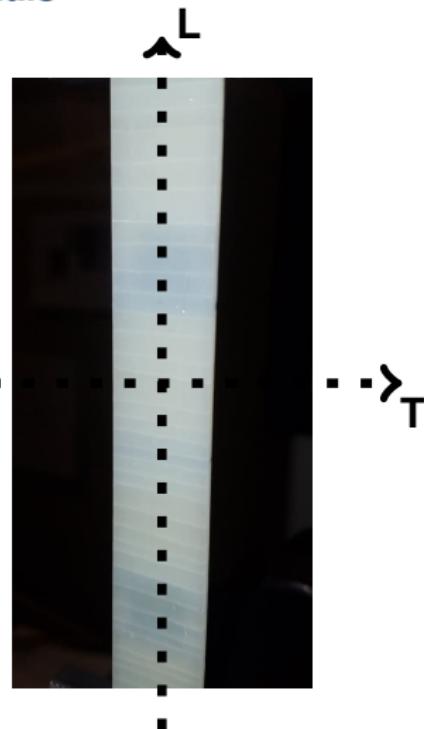


Left:
front view of $[0, 90]_S$,
visual inspection.

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

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

Materials

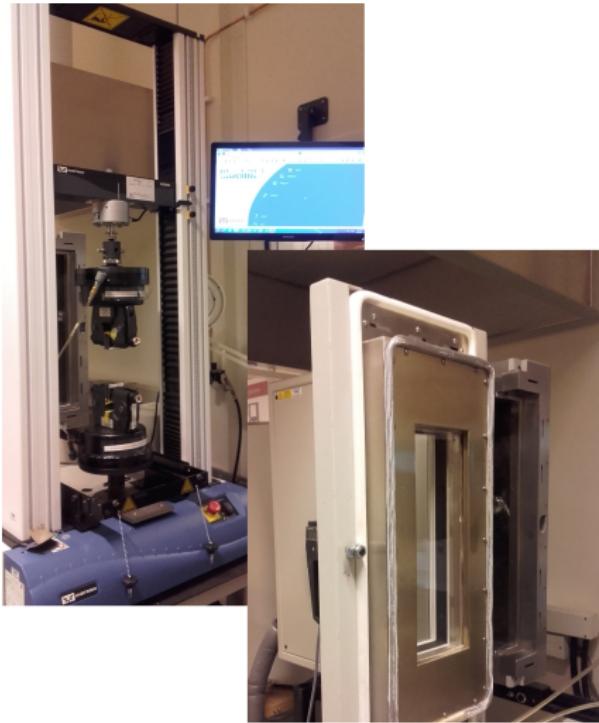


- Glass fiber/epoxy prepreg
- $V_f \sim 50 - 55\%$
- Lay-up $[0^\circ, 90^\circ]$
- Manufacturing: manual lay-up + vacuum bag + hot press
- Cutting and polishing of specimens
- Specimen size (nominal):
 $200 \text{ mm} \times 15 \text{ mm} \times 1.85 \text{ mm}$

UD properties (measured)

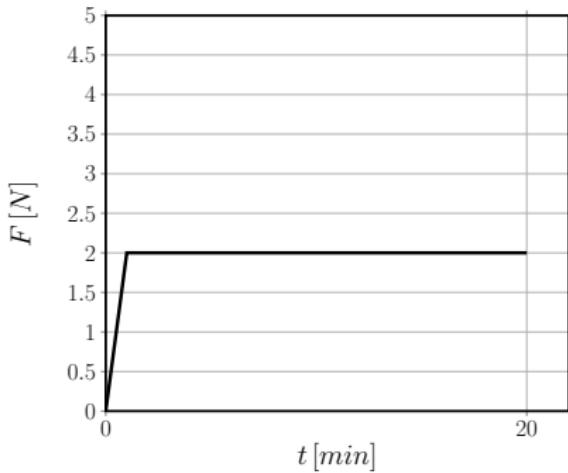
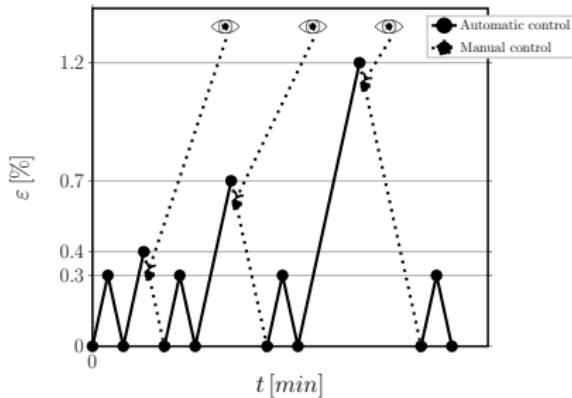
E_L [GPa]	38.5
E_T [GPa]	15.3
ν_{LT} [-]	0.3
G_{LT} [GPa]	3.5
$\varepsilon_T^{\text{lim}}$ [%]	0.43
σ_T^{lim} [MPa]	60
$T_{\text{stress free}}$ [$^\circ\text{C}$]	116.3

Equipment



- Universal electro-mechanical testing machine (Instron 3366)
- Environmental chamber (Instron), temperature range: -100° to $+350^\circ C$
- Extensometer (Instron), gauge length: 50 mm

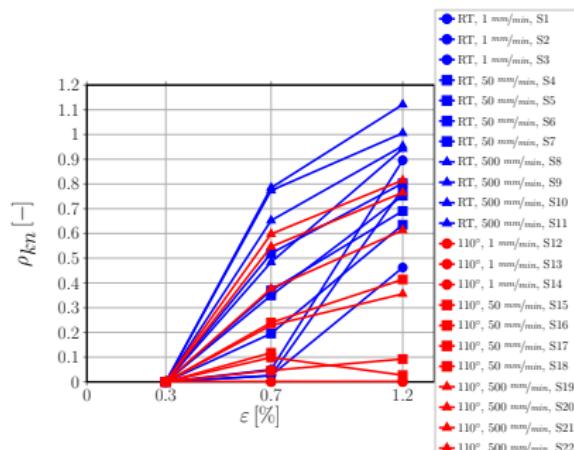
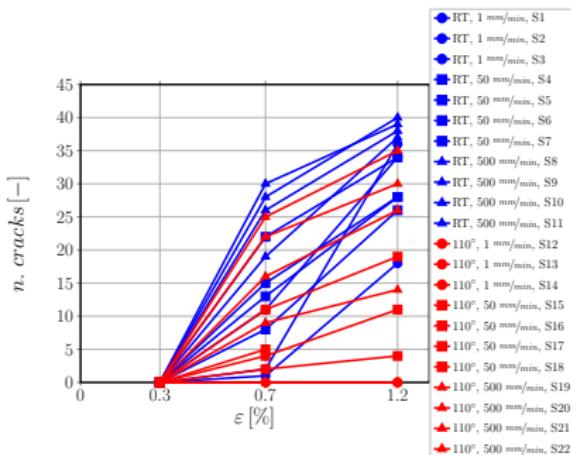
Testing procedure



Cross-head speed

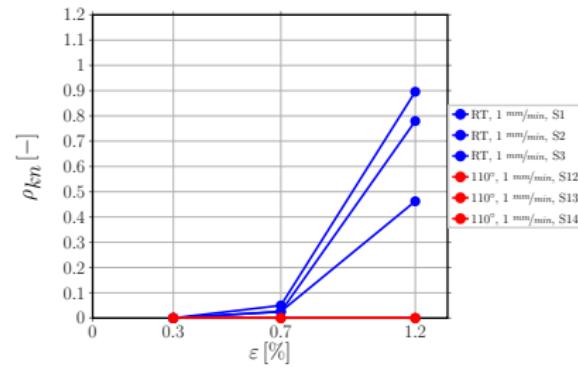
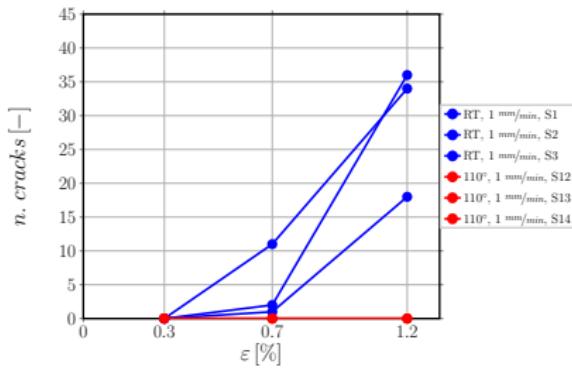
T	1 [mm/min]	50 [mm/min]	500 [mm/min]
room	3 sp.	4 sp.	4 sp.
110[°]	3 sp.	4 sp.	4 sp.

Crack density



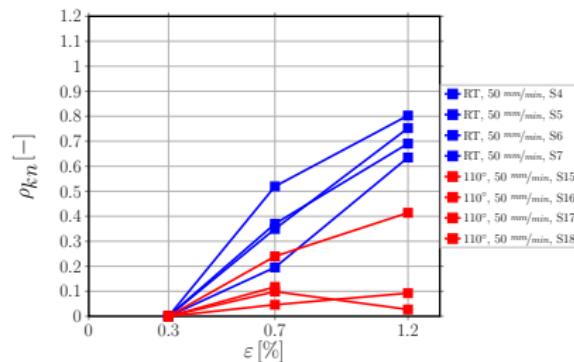
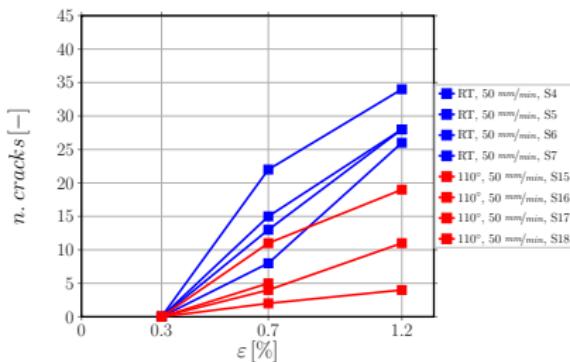
$$\rho_{kn} = \frac{n \text{ cracks}}{L_{gauge}} t_{90^\circ}$$

Crack density



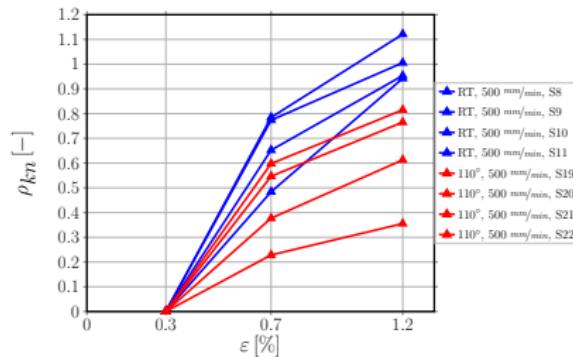
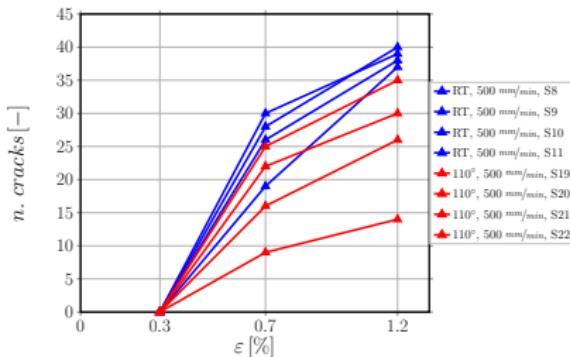
$$\rho_{kn} = \frac{n_{cracks}}{L_{gauge}} t_{90^\circ}$$

Crack density



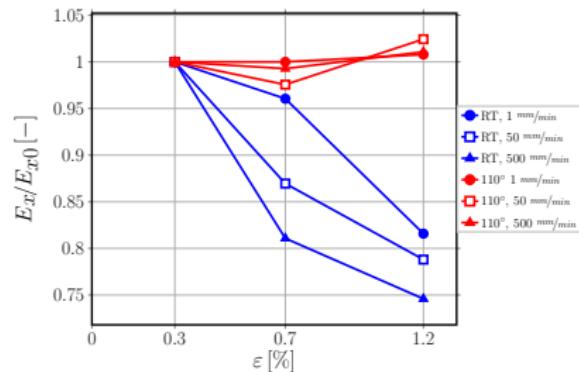
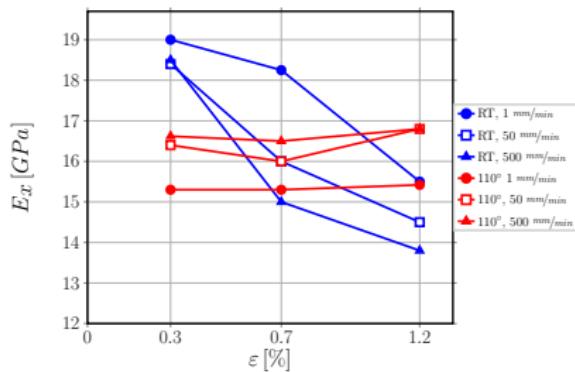
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Crack density

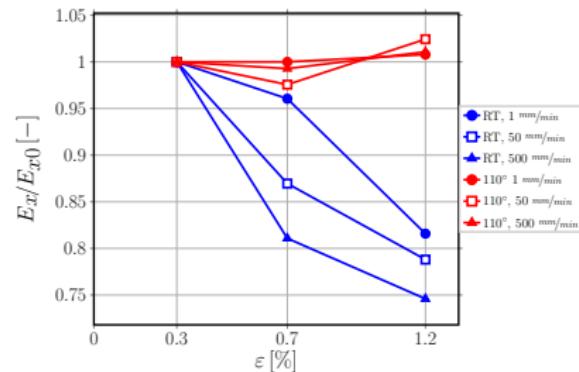
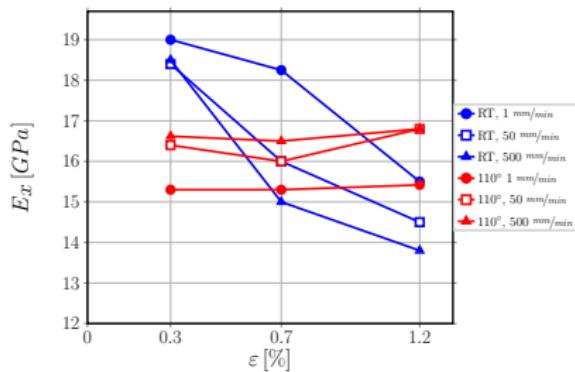


$$\rho_{kn} = \frac{n \text{ cracks}}{L_{gauge}} t_{90^\circ}$$

Young's modulus



Re-bonding?



 **DESIGN IDEA**

Transverse Cracking in Thin-plies

Modeling Fiber/Matrix Debonding

Measuring Transverse Cracks Propagation

Design Idea

Design Idea



LULEÅ
UNIVERSITY
OF TECHNOLOGY



Education and Culture

Erasmus Mundus