

# 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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Luleå (SE) - November 6, 2019

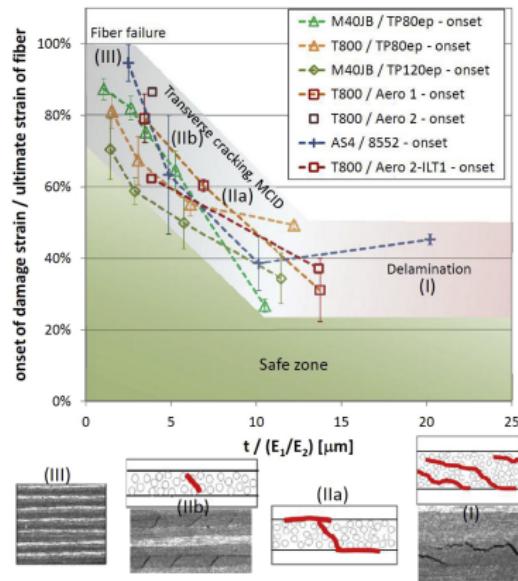


# Outline

# ➔ TRANSVERSE CRACKING IN THIN-PLIES

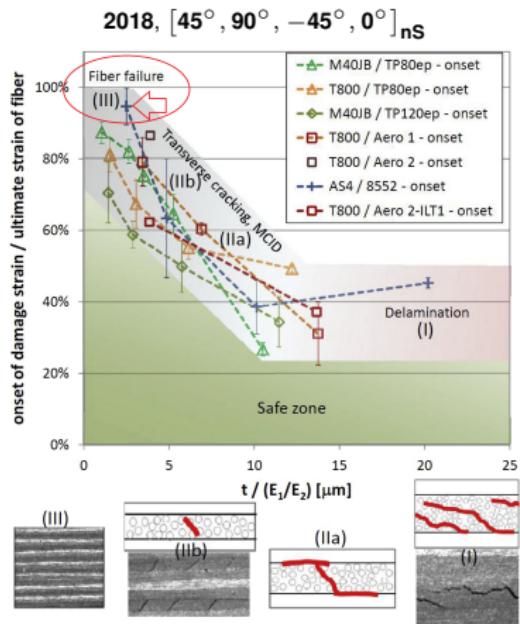
## The Thin-ply “Advantage”: new material

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



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

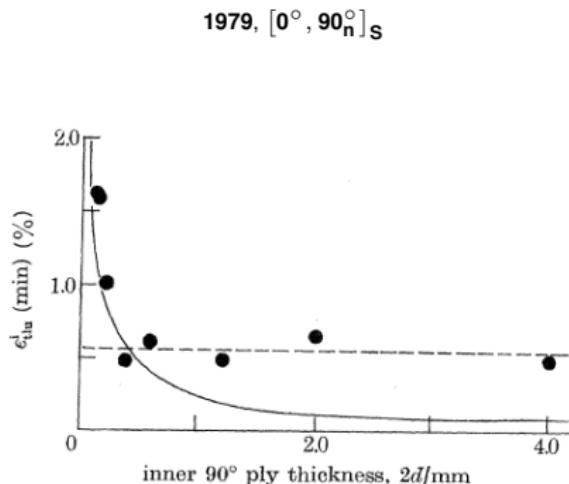
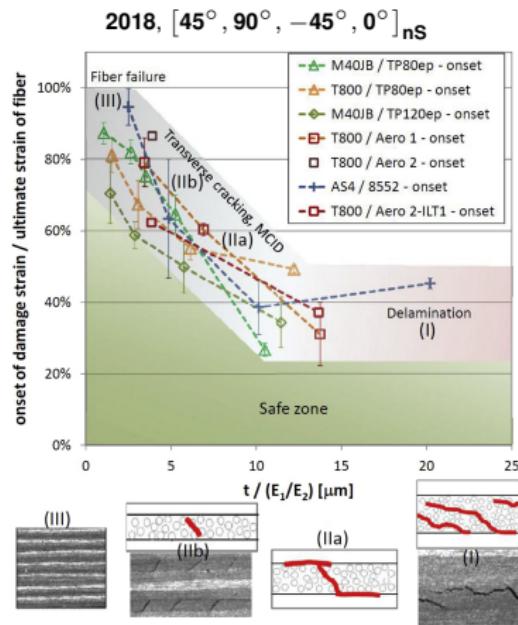
## The Thin-ply “Advantage”? New material, new problem...



- 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!

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

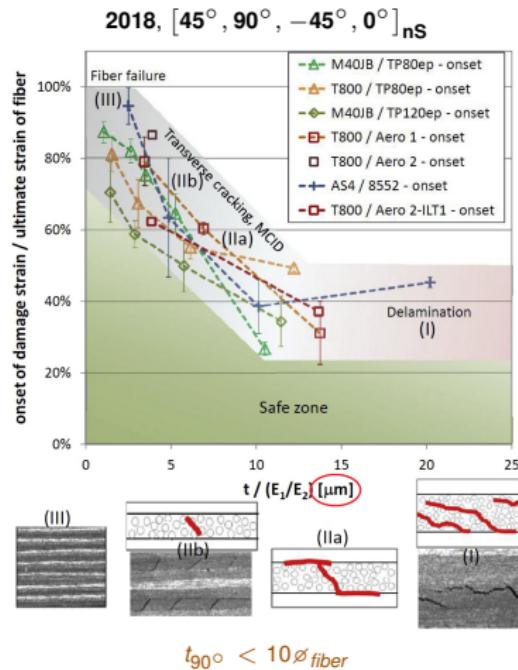
## The Thin-ply “Advantage”: new material, old result



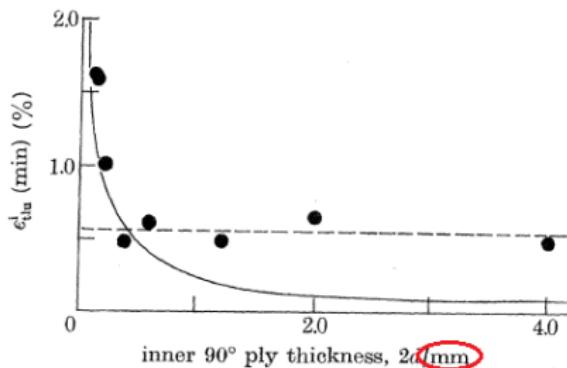
Cugnoni et al., Compos. Sci. Technol. **168**, 2018.

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

## The Thin-ply “Advantage”: new material, old result?



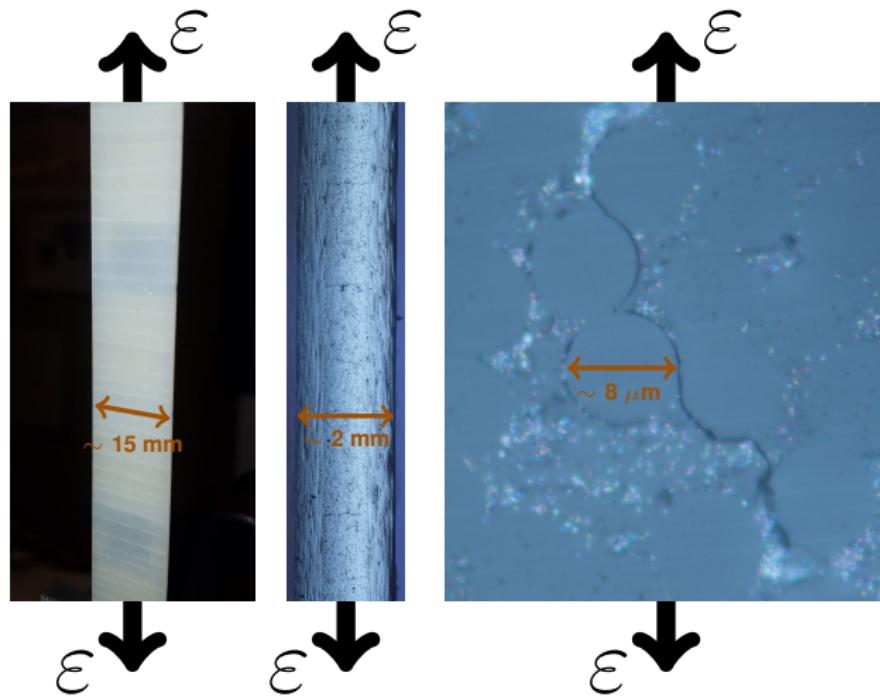
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$t_{90^\circ} > 100\phi_{fiber}$

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

## Micromechanics of Initiation



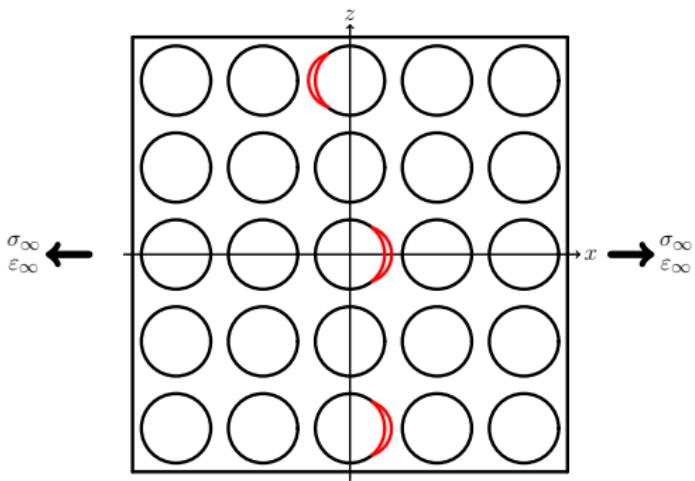
**Left:**  
front view of  $[0, 90]_S$ ,  
visual inspection.

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

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

## Micromechanics of Initiation

### Stage 1: isolated debonds



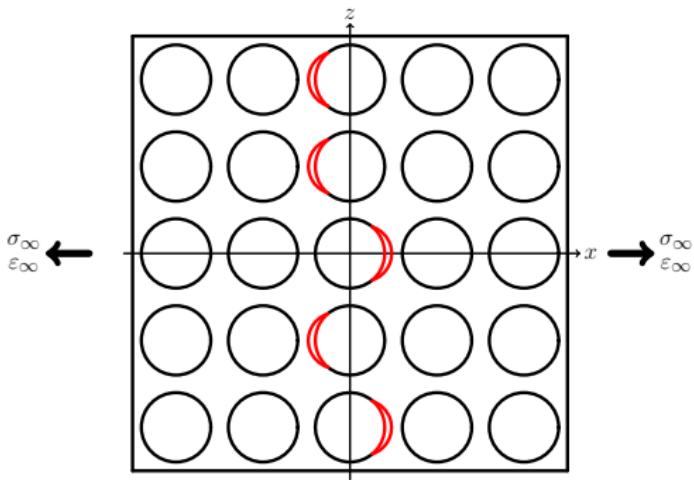
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Zhang et al., Compos. Part A-Appl. S. **28** (4), 1997.

## Micromechanics of Initiation

### Stage 2: consecutive debonds



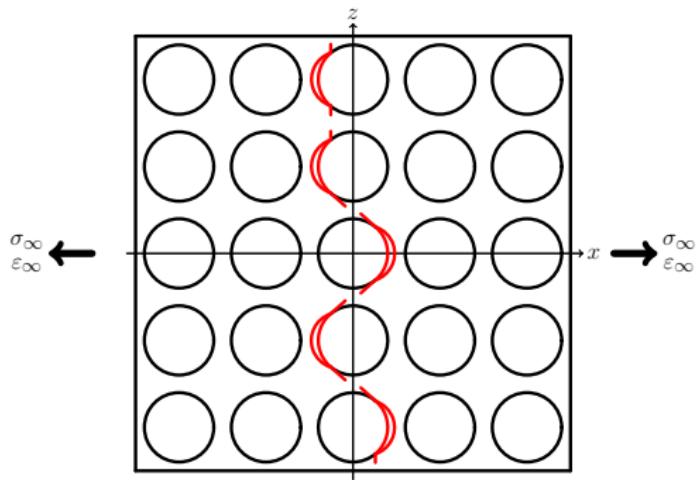
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Bailey et al., J. Mater. Sci. **16** (3), 1981.

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

## Micromechanics of Initiation

### Stage 3: kinking



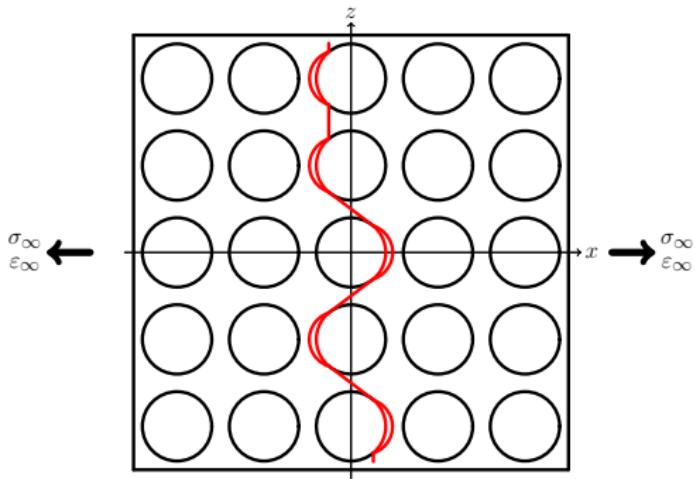
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Bailey et al., J. Mater. Sci. **16** (3), 1981.

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

## Micromechanics of Initiation

### Stage 4: coalescence



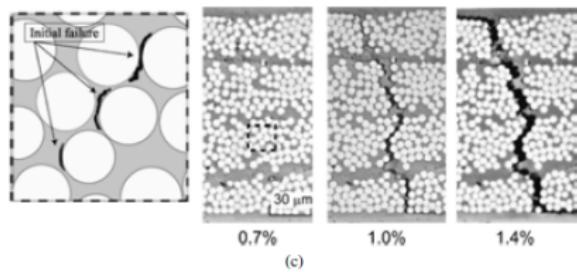
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## A Counter-intuitive Observation

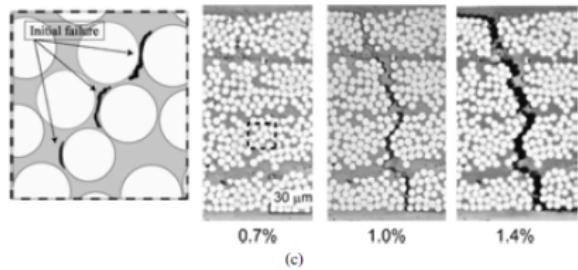
$$[0^\circ, 90_n^\circ]_S$$



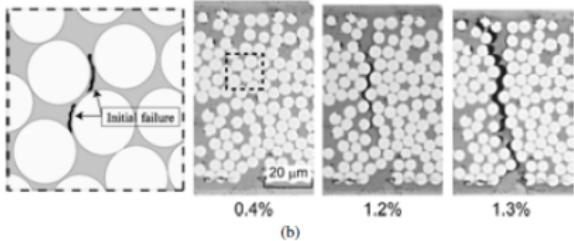
$$n = 4, t_{90^\circ} = 160 \mu m$$

## A Counter-intuitive Observation

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



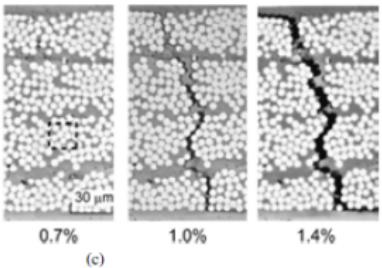
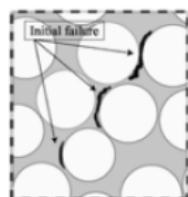
$$n = 4, t_{90^\circ} = 160 \mu m$$



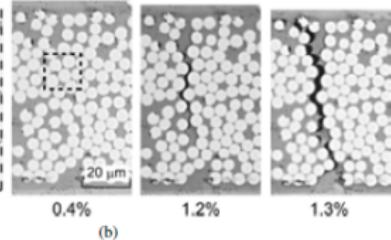
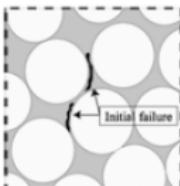
$$n = 2, t_{90^\circ} = 80 \mu m$$

## A Counter-intuitive Observation

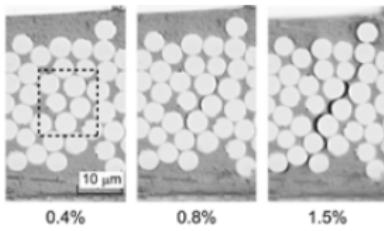
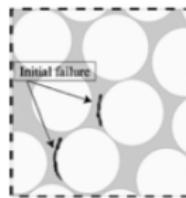
$[0^\circ, 90^\circ]_S$



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



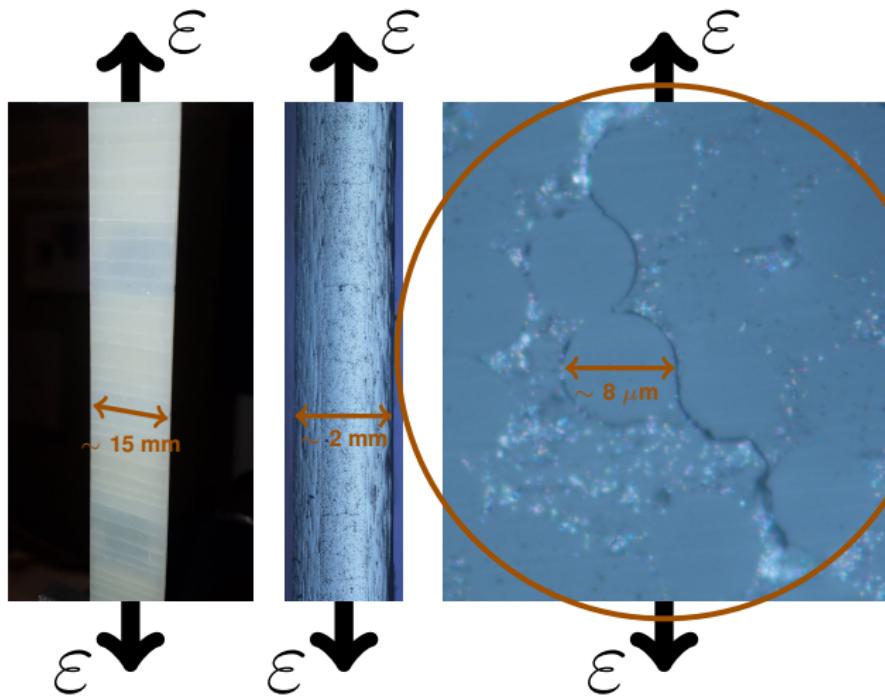
$$n = 2, t_{90^\circ} = 80 \mu m$$



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

MODELING FIBER/MATRIX  
DEBONDING

## Micromechanics of Initiation

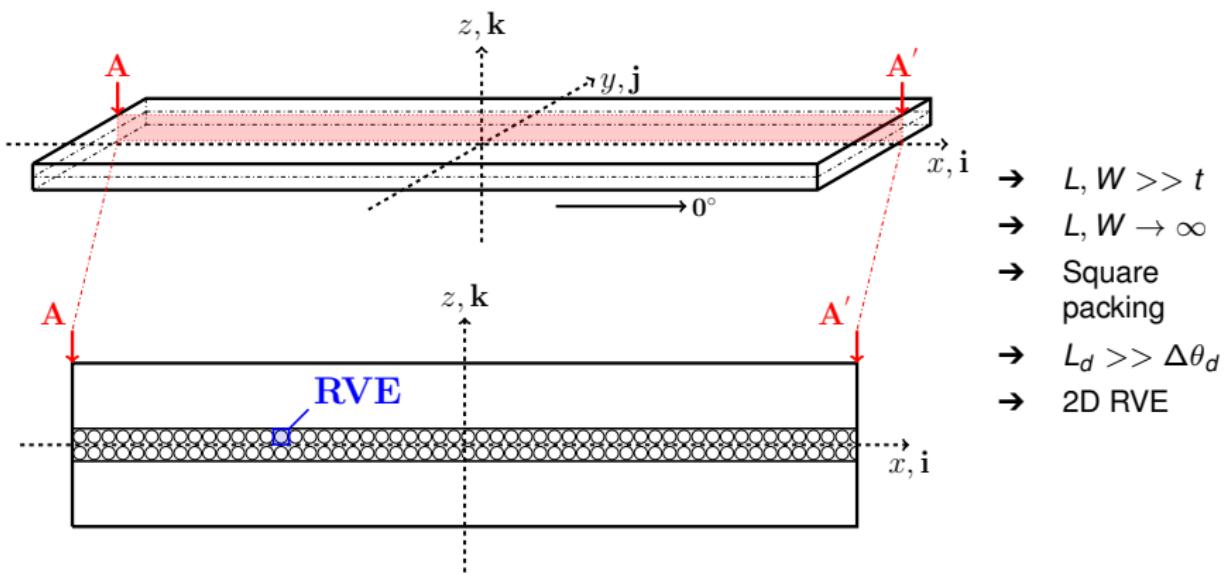


**Left:**  
front view of  $[0, 90]_S$ ,  
visual inspection.

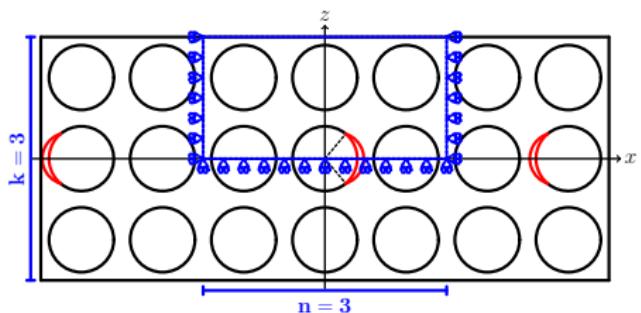
**Center:**  
edge view of  $[0, 90]_S$ ,  
optical microscope.

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

## Geometry

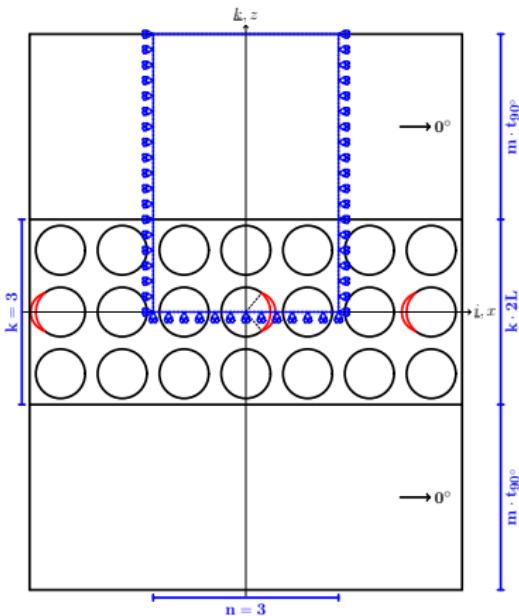


## Representative Volume Elements



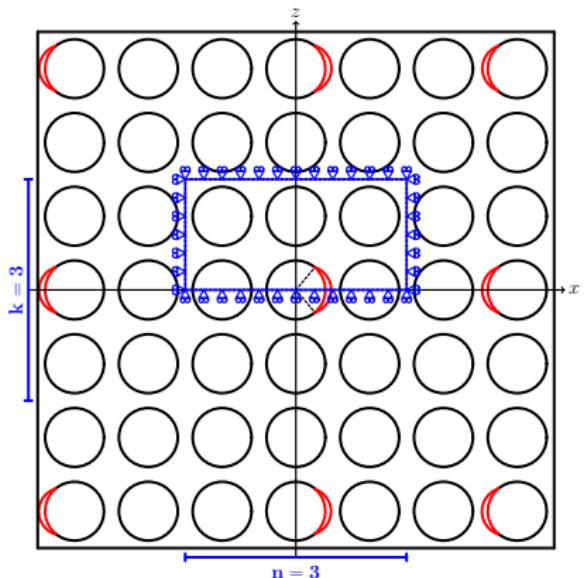
$n \times k - \text{free}$

$n \times k - H$



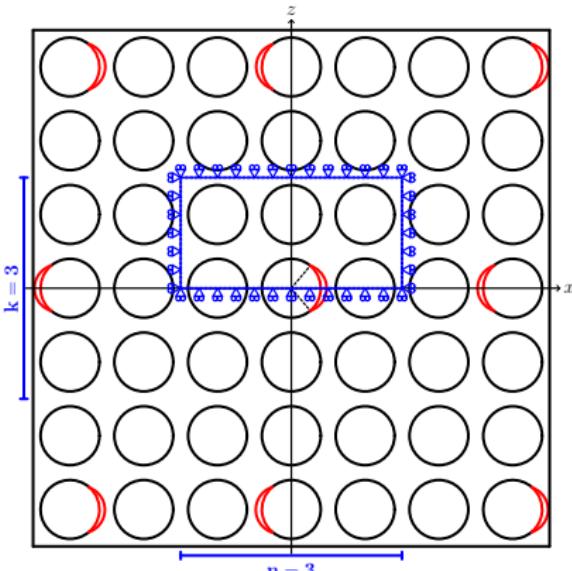
$n \times k - m \cdot t_{90^\circ}$

## Representative Volume Elements



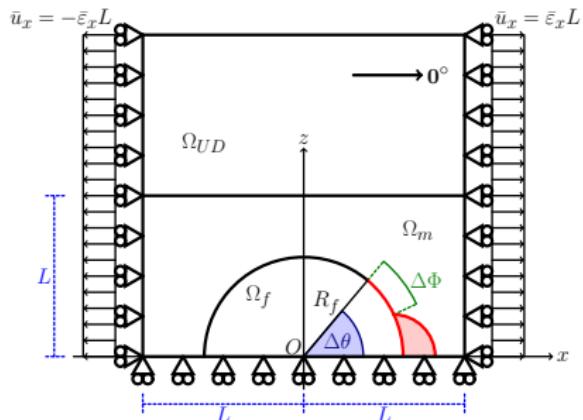
$n \times k - \text{symm (coupling)}$

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



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

## Assumptions

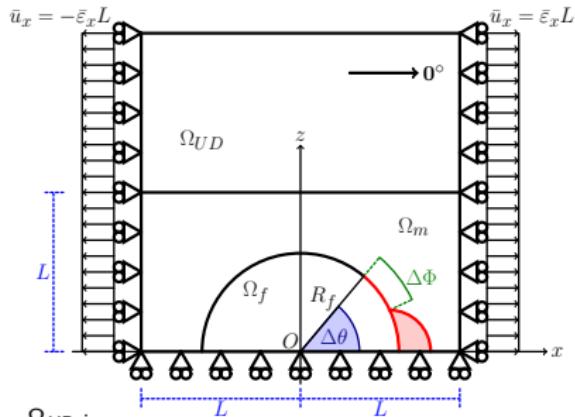


- Linear elastic, homogeneous materials
- Concentric Cylinders Assembly with Self-Consistent Shear Model for UD
- Plane strain
- Frictionless contact interaction
- Symmetric w.r.t. x-axis
- Coupling of x-displacements on left and right side (repeating unit cell)
- Applied uniaxial tensile strain  $\bar{\varepsilon}_x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

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

Material	$V_f$ [%]	$E_L$ [GPa]	$E_T$ [GPa]	$\mu_{LT}$ [GPa]	$\nu_{LT}$ [-]	$\nu_{TT}$ [-]
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  $\Omega_f, \Omega_m, \Omega_{UD}$ :

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

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

$$\text{for } \Delta\theta \leq \alpha \leq 180^\circ :$$

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

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

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

→ 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

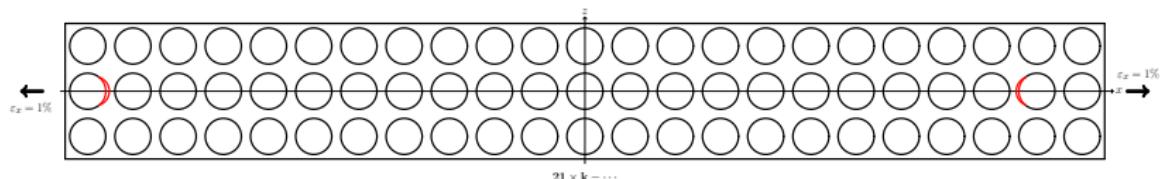
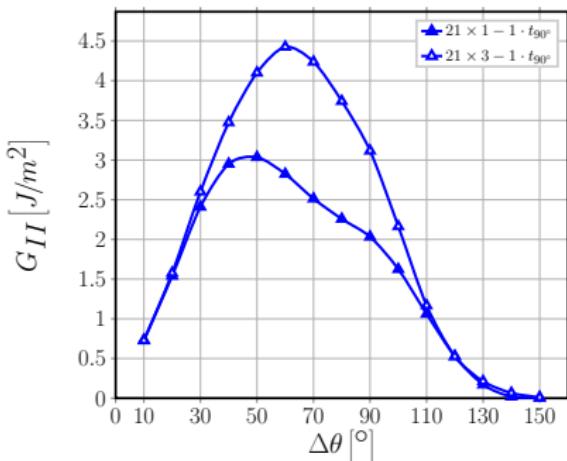
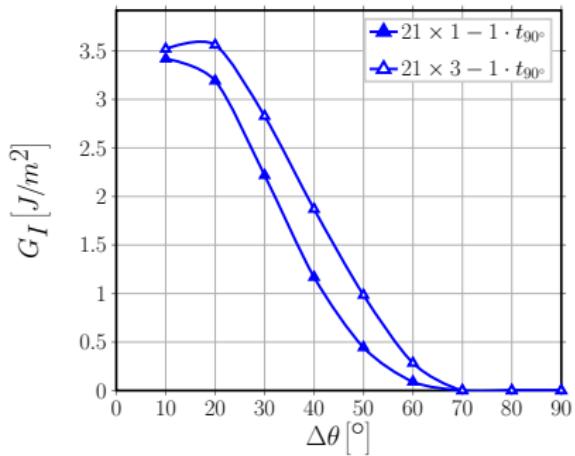
→ 2<sup>nd</sup> order shape functions

→ 6-nodes triangles & 8-nodes quadrilaterals

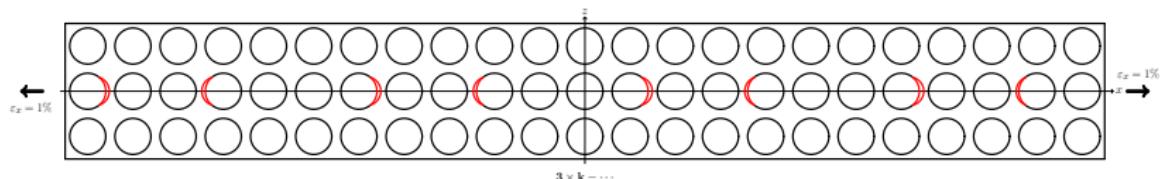
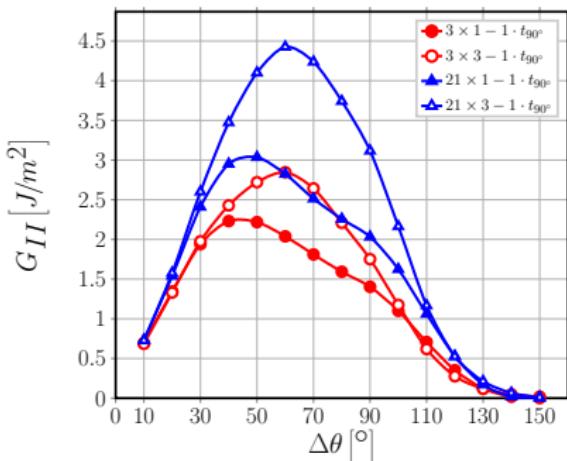
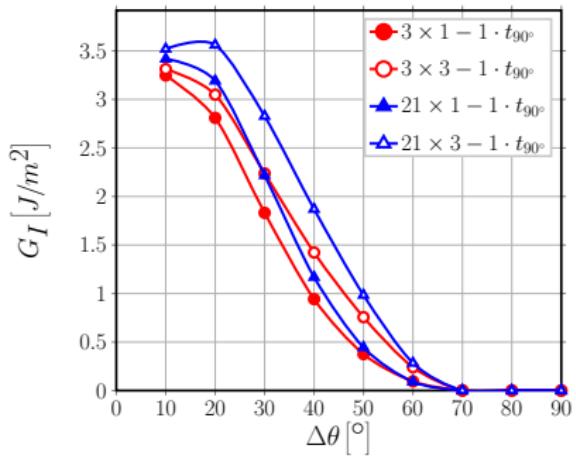
→ regular mesh of quadrilaterals  
at the crack tip:

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

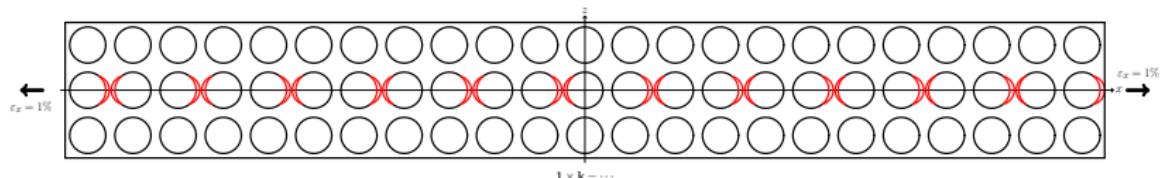
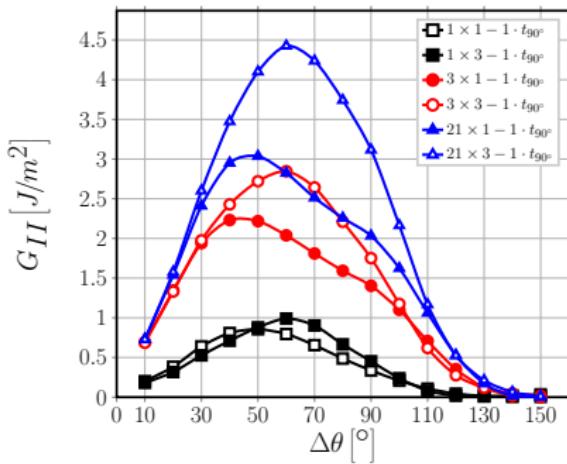
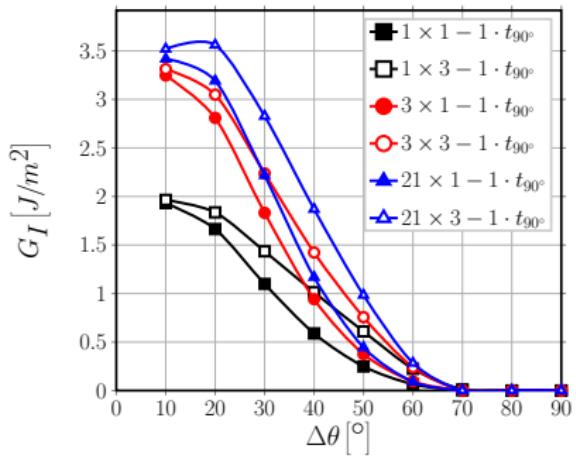
## Interaction of Debonds: Crack Shielding



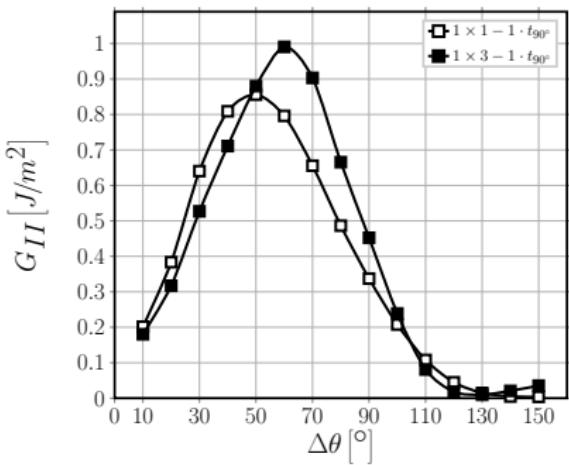
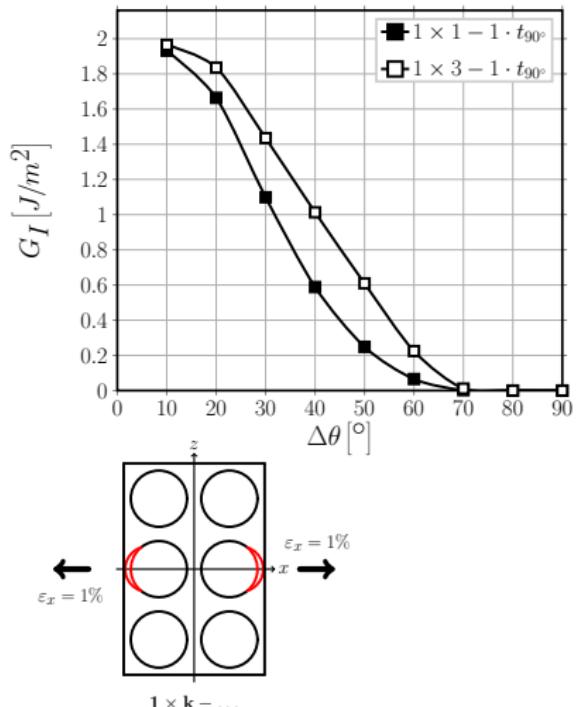
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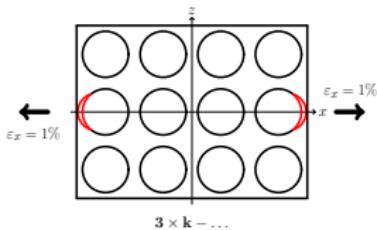
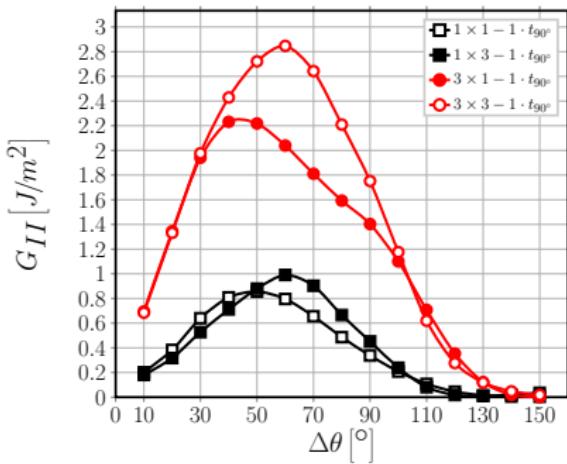
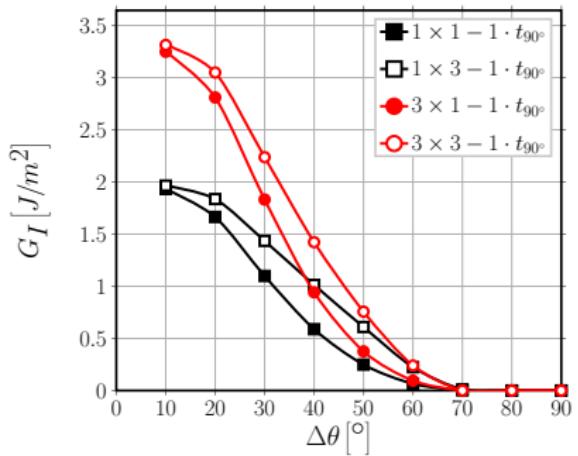
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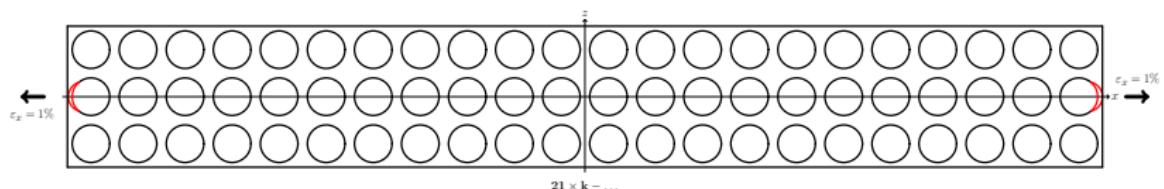
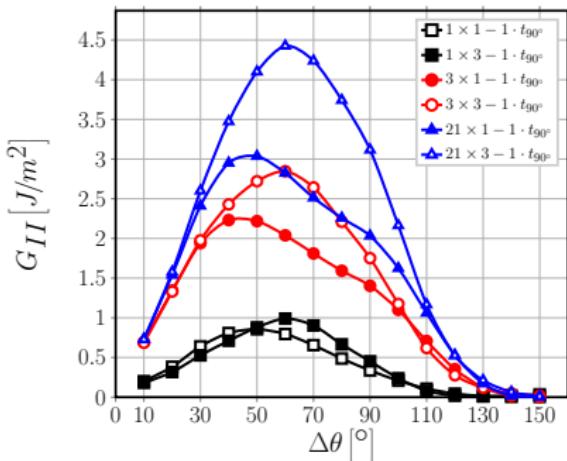
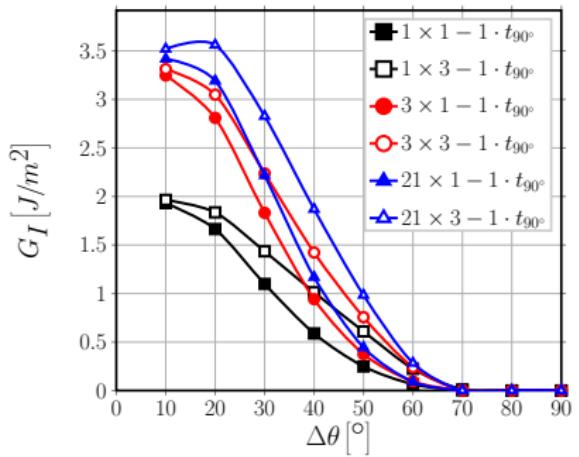
## Interaction of Debonds: Strain Magnification



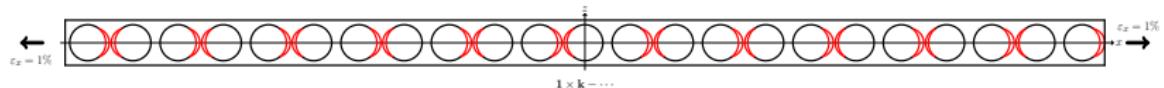
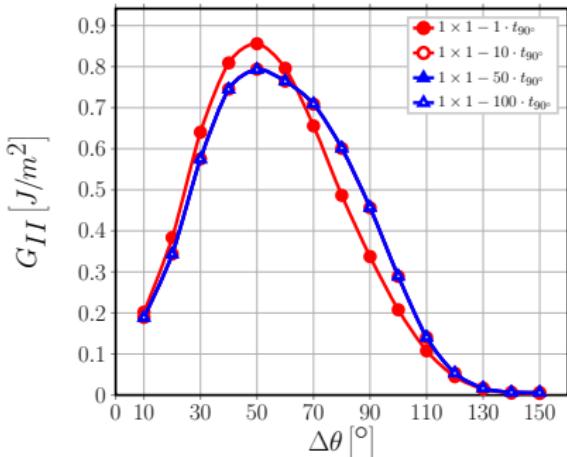
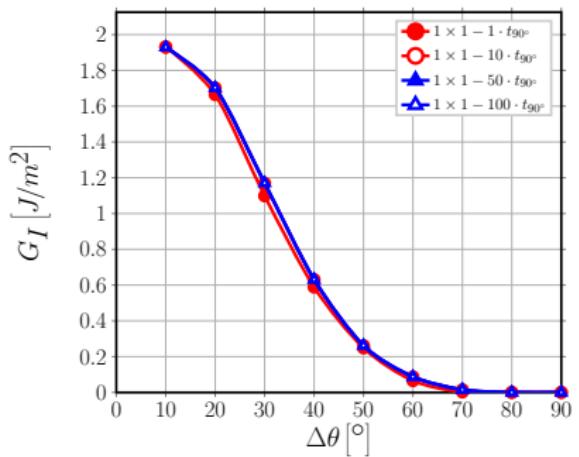
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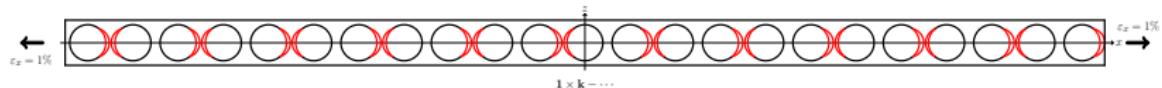
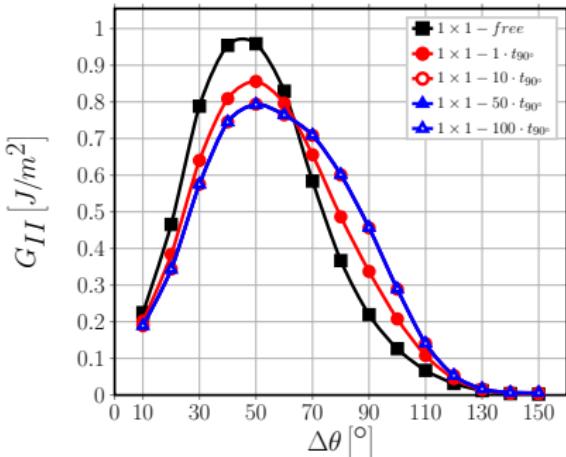
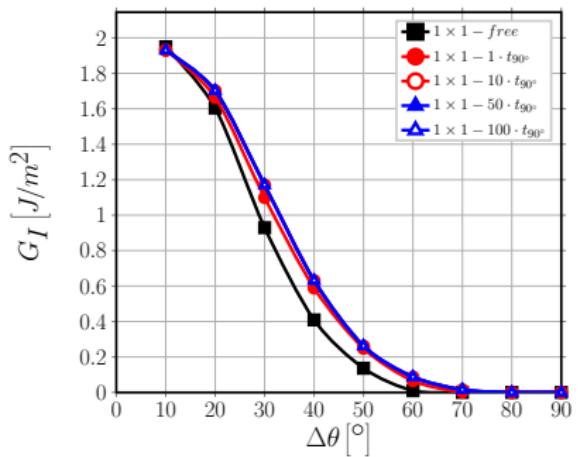
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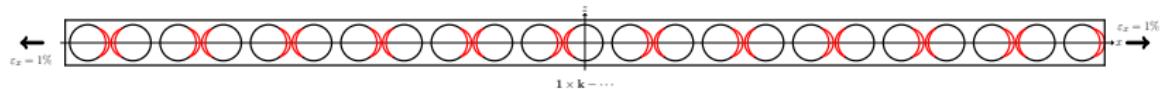
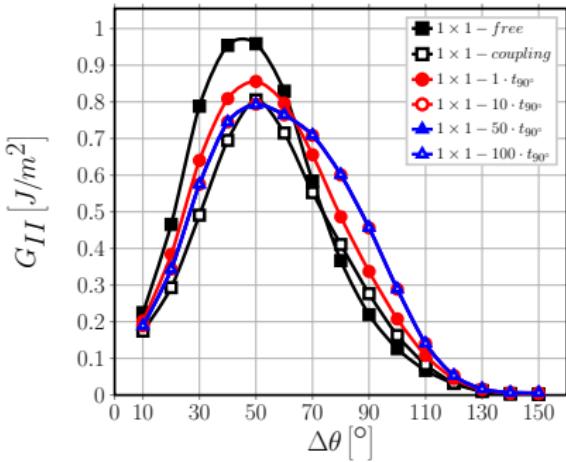
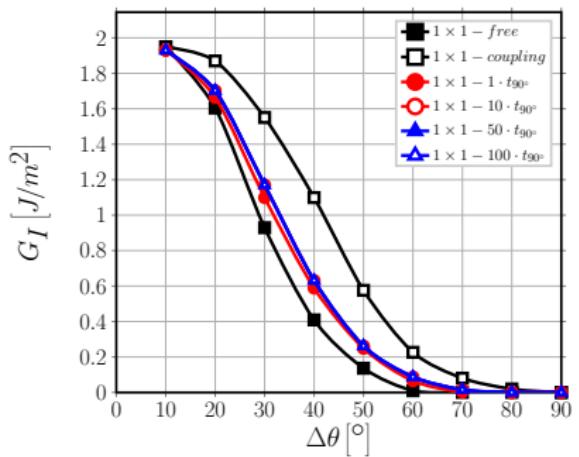
## Effect of 0° ply thickness



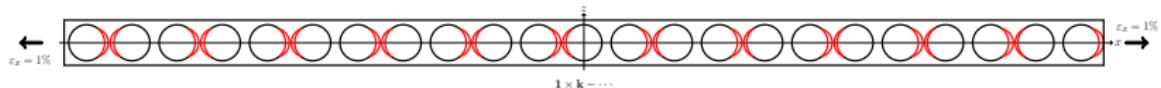
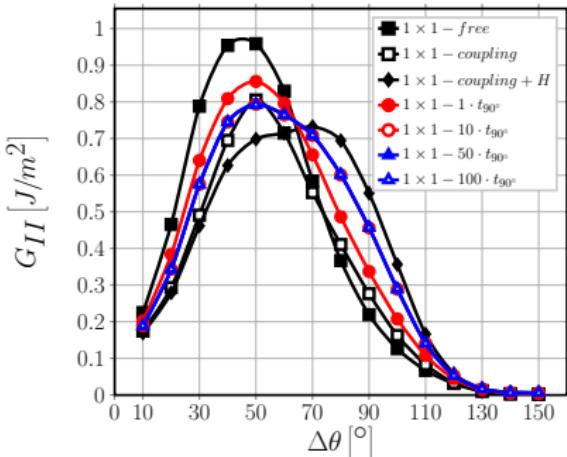
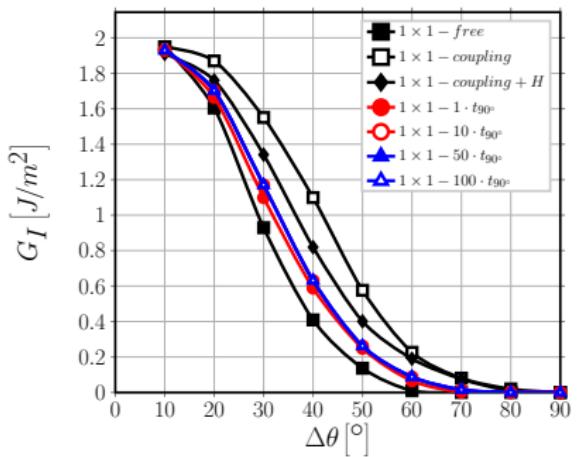
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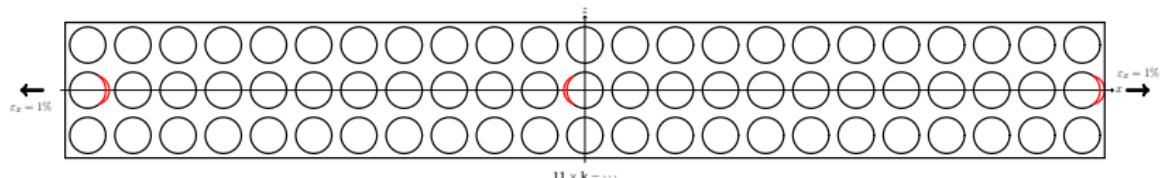
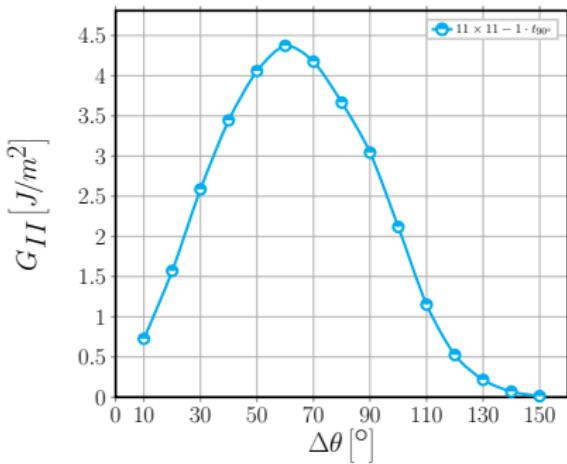
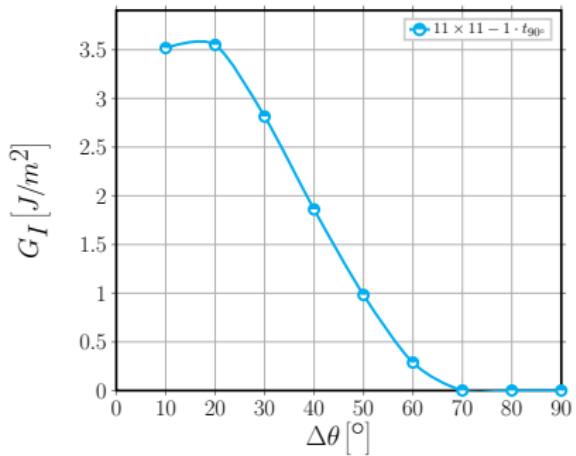
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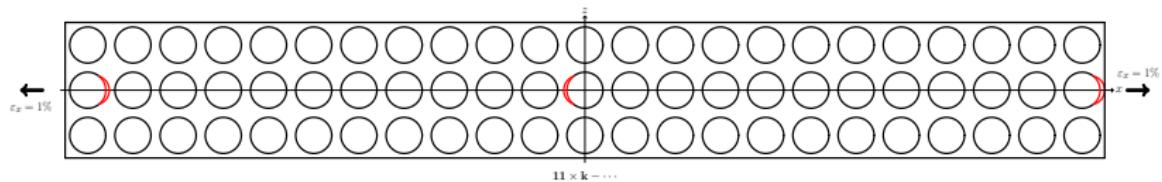
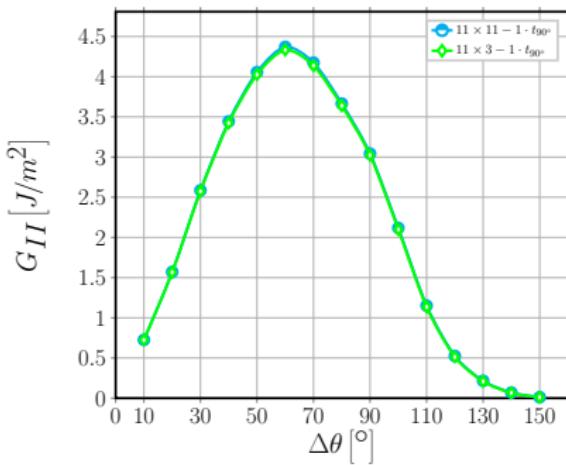
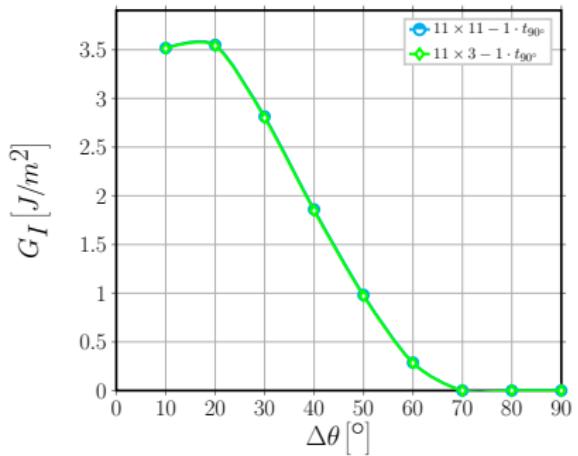
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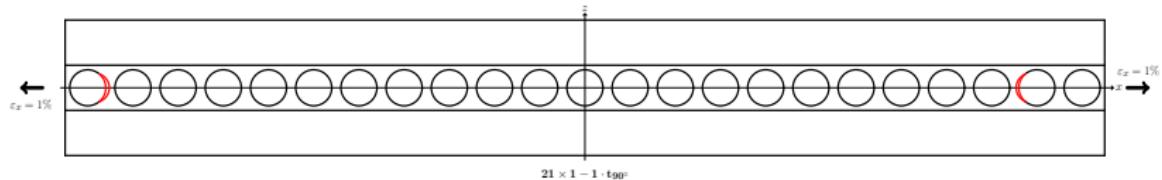
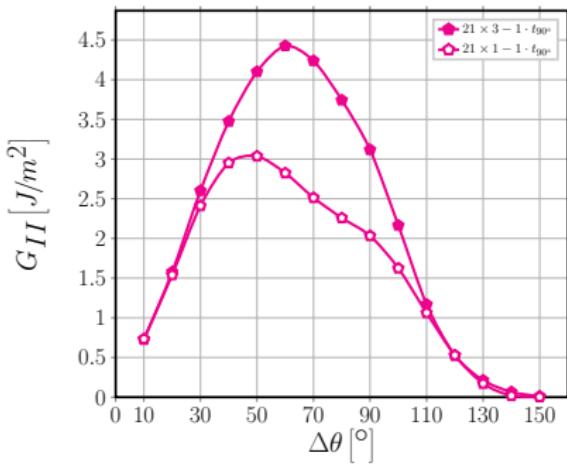
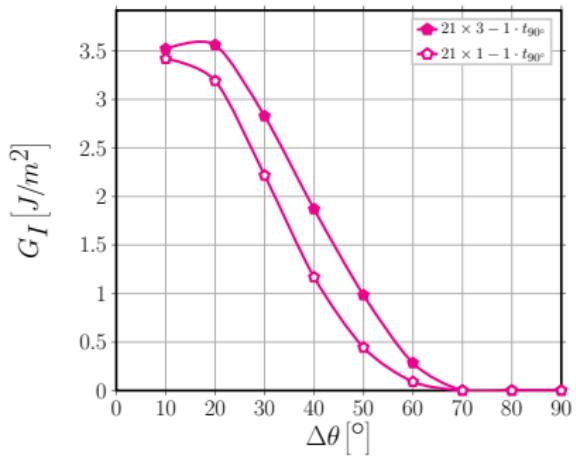
## Effect of 90° ply thickness



## Effect of 90° ply thickness



## Effect of 90° ply thickness

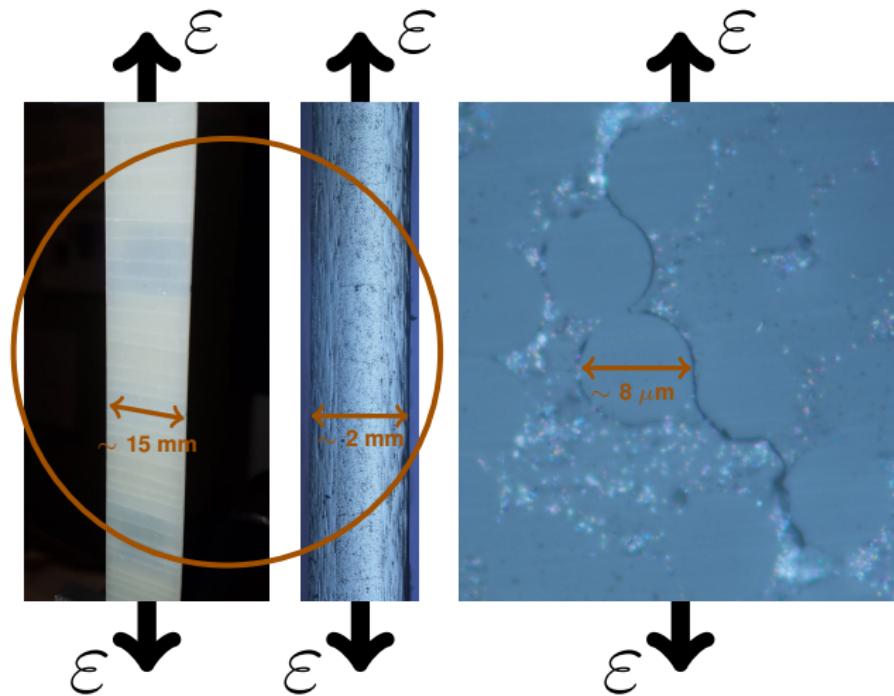


## Summary

- No effect of  $90^\circ$  ply thickness can be observed when  $t_{90^\circ}$  is at least  $\sim 3\varnothing_{fiber}$
- Only if  $t_{90^\circ}$  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 ( $G \sim \varepsilon_{applied}^2$ )
- No effect of  $0^\circ$  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  $0^\circ$  layer

MEASURING TRANSVERSE  
CRACKS PROPAGATION

## Micromechanics of Initiation

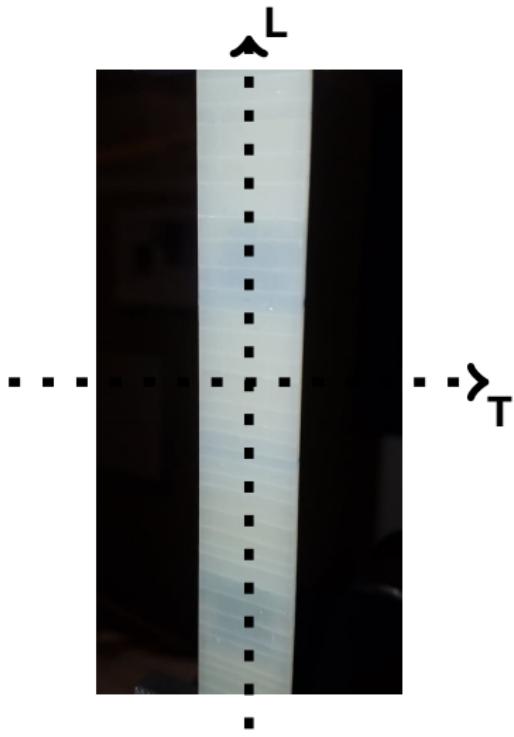


**Left:**  
front view of  $[0, 90]_S$ ,  
visual inspection.

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

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

## Materials

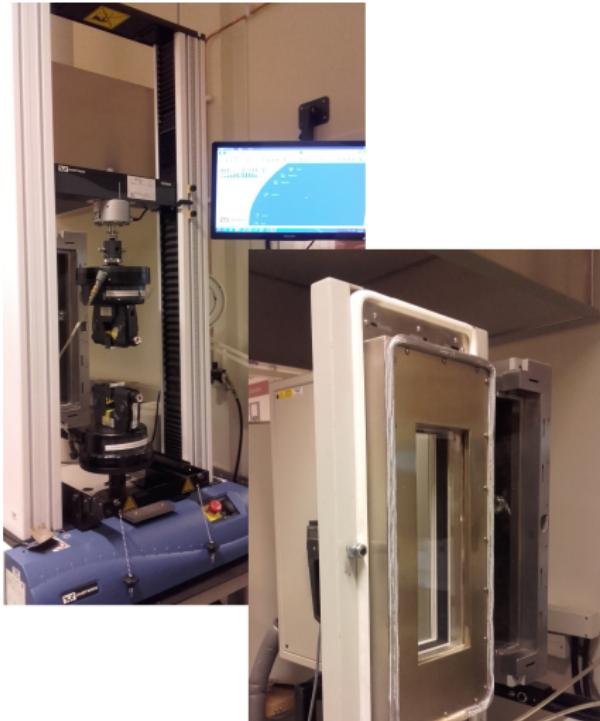


- Glass fiber/epoxy prepreg
- $V_f \sim 50 - 55\%$
- Lay-up  $[0^\circ, 90^\circ]$
- Manufacturing: manual lay-up + vacuum bag + hot press
- Cutting and polishing of specimens
- Specimen size (nominal):  
 $200\text{ mm} \times 15\text{ mm} \times 1.85\text{ mm}$

UD properties (measured)

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

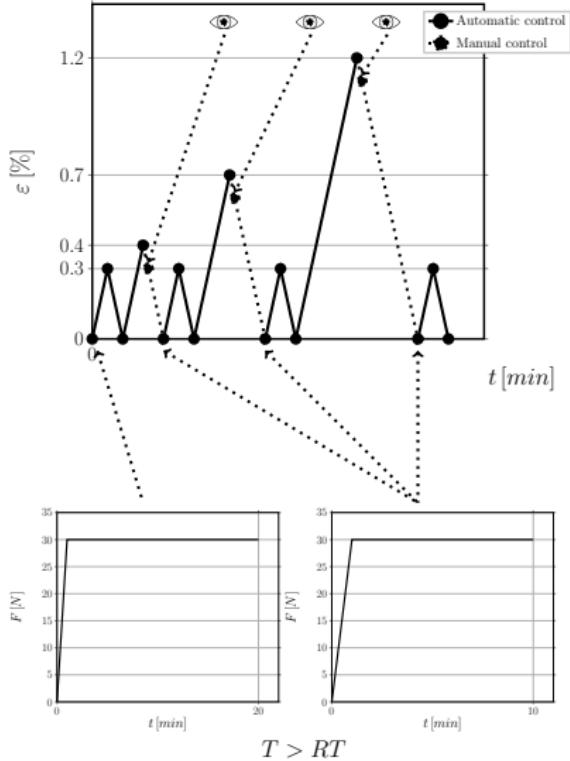
## Equipment



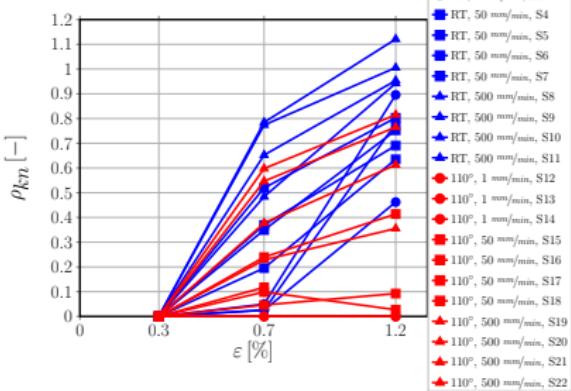
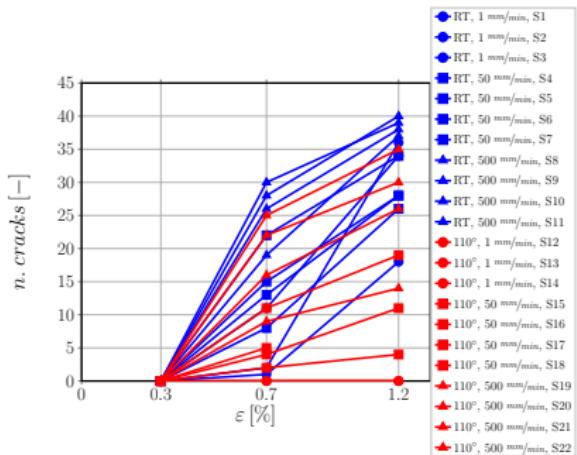
- Universal electro-mechanical testing machine (Instron 3366)
- Environmental chamber (Instron), temperature range:  $-100^\circ$  to  $+350^\circ C$
- Extensometer (Instron), gauge length: 50 mm

## Testing procedure

	RT	110°C
1 mm/min	3 sp.	3 sp.
50 mm/min	4 sp.	4 sp.
500 mm/min	4 sp.	4 sp.

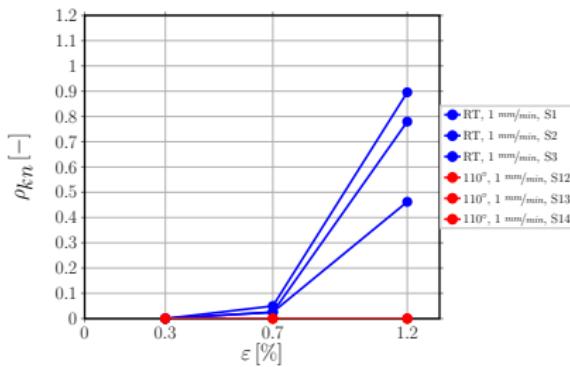
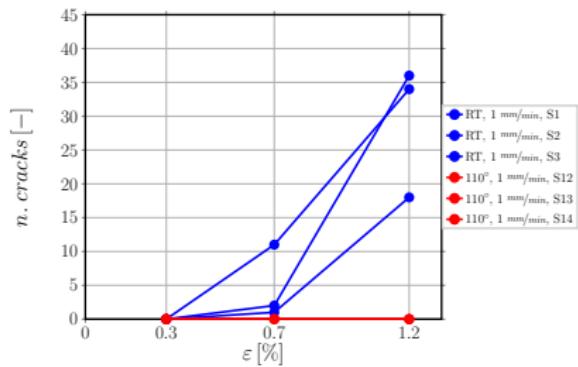


## Crack density



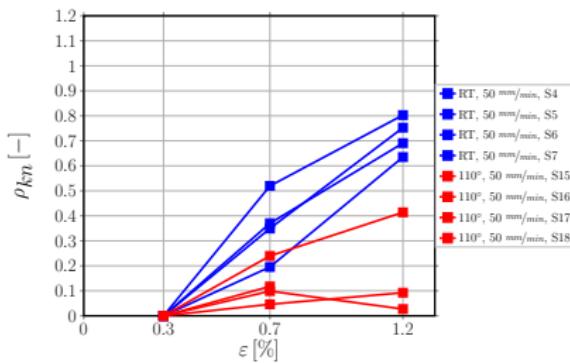
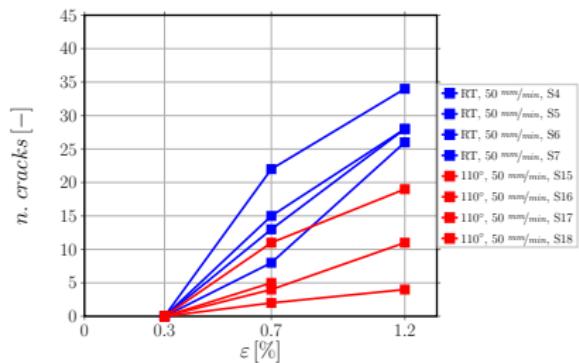
$$\rho_{kn} = \frac{n \text{ cracks}}{L_{gauge}} t_{90^\circ}$$

## Crack density



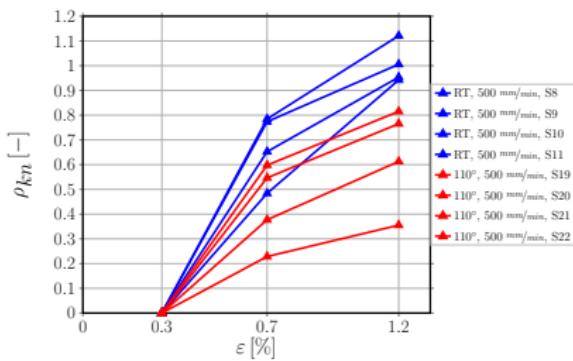
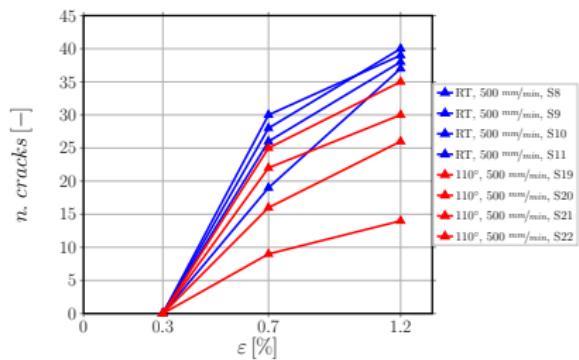
$$\rho_{kn} = \frac{n \text{ cracks}}{L_{gauge}} t_{90^\circ}$$

## Crack density



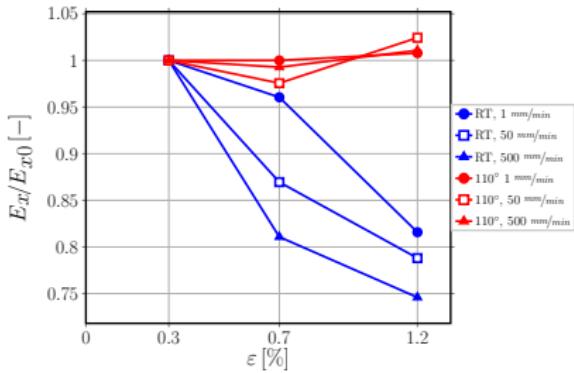
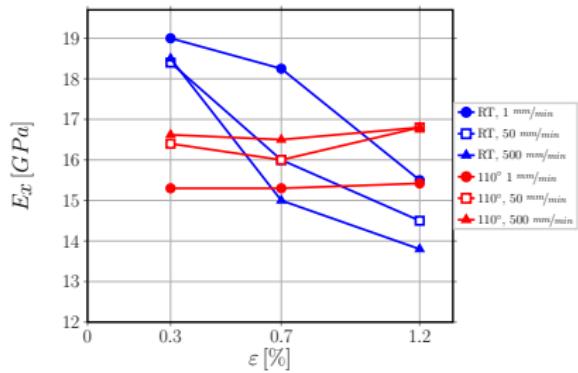
$$\rho_{kn} = \frac{n \text{ cracks}}{L_{gauge}} t_{90^\circ}$$

## Crack density

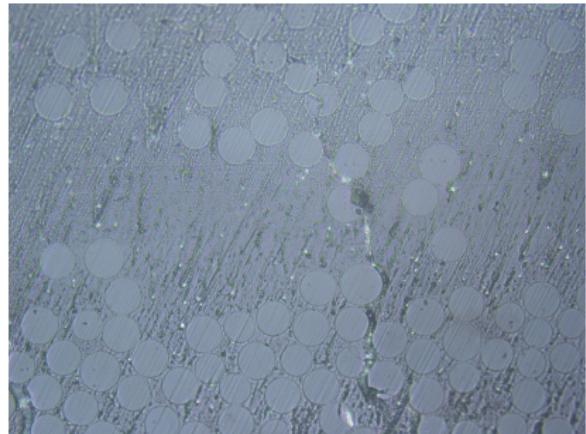


$$\rho_{kn} = \frac{n \text{ cracks}}{L_{gauge}} t_{90^\circ}$$

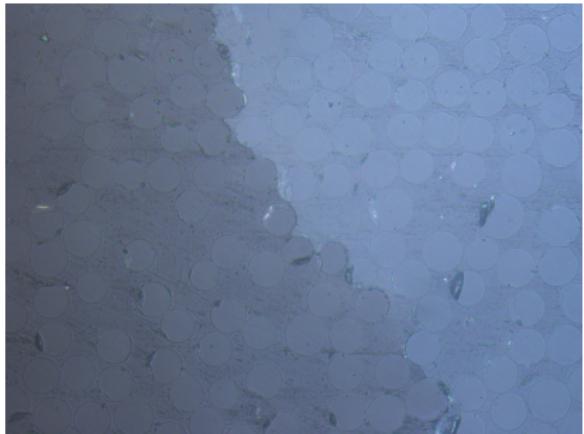
## Young's modulus



## Re-bonding?



RT



110°

DESIGN IDEA

## Design Idea

- ☞ Use weak fiber/matrix interfaces + microstructure → dissipate energy through diffuse debonding + lower stiffness reduction
- ☞ Use microstructure (*ply-thickness effect*) → prevent transverse cracking = significant stiffness reduction
- ☞ Use partially reacted interfaces *and/or* locally partially cured matrix *and/or* nanoparticles-based local control of degree of reaction → re-bonding @  $T \sim T_{\text{stress free}}$  in unloaded state = stiffness recovery

