

# 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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Fundación para la Investigación, Desarrollo y Aplicación de Materiales Compuestos (FIDAMC)

Getafe, Madrid (ES) - September 16, 2019



## Outline

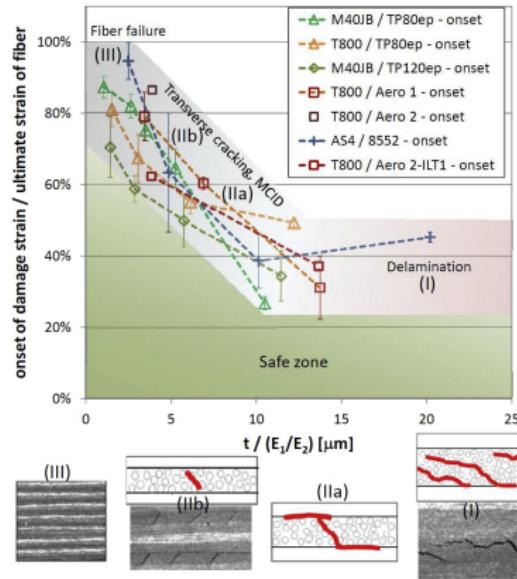
- ➔ Transverse Cracking in Thin-plies
- ➔ Modeling Fiber/Matrix Debonding
- ➔ Measuring Transverse Cracks Propagation

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

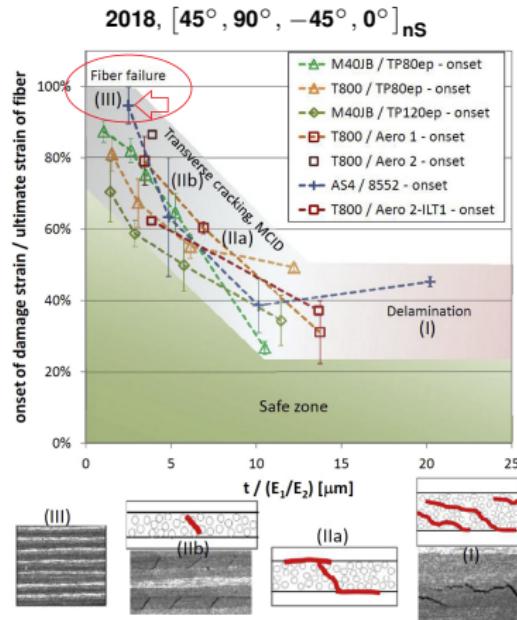


# TRANSVERSE CRACKING IN THIN-PLIES

## The Thin-ply "Advantage": new material

2018,  $[45^\circ, 90^\circ, -45^\circ, 0^\circ]$  nsCugnoni et al., Compos. Sci. Technol. **168**, 2018.

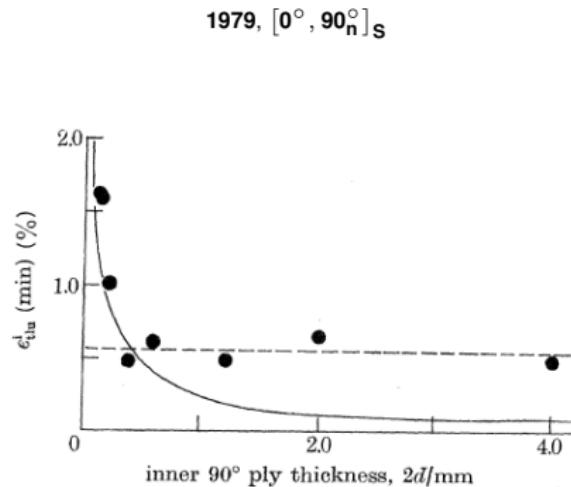
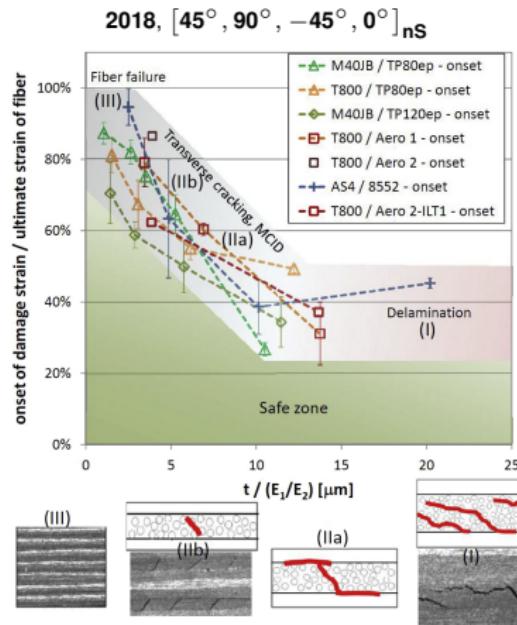
## The Thin-ply "Advantage"? New material, new problem...



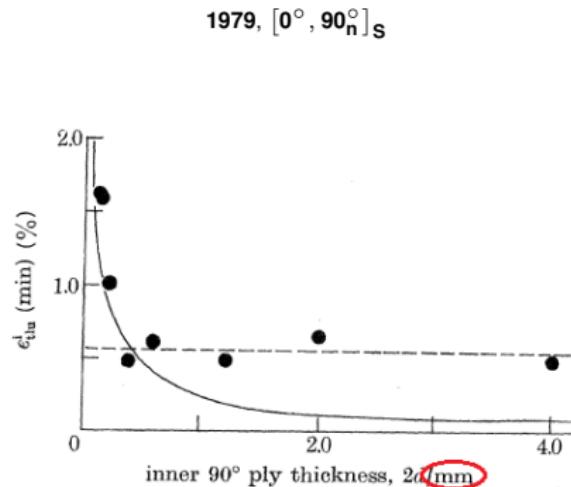
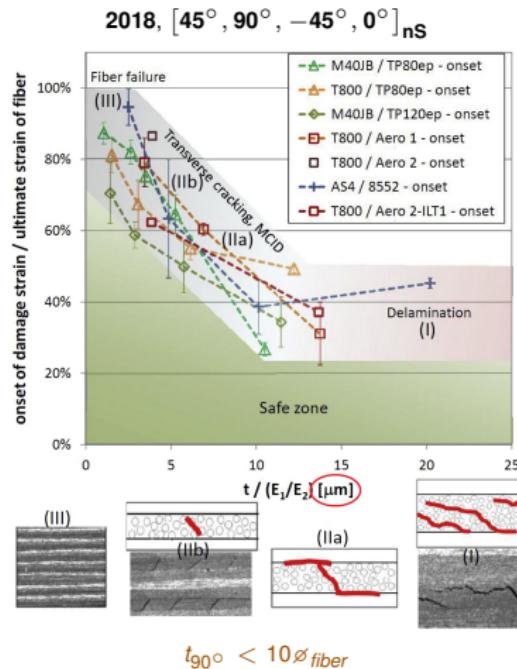
- material from NTPT (CH) (on the left)
- recent tests (master theses @ LTU) have shown the same behavior with material from Oxeon (SE)
- ✓ extended range of elastic behavior with no damage-induced stiffness reduction
- ✗ brittle failure of the whole laminate!
- ✗ very risky for application in safety-critical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

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

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

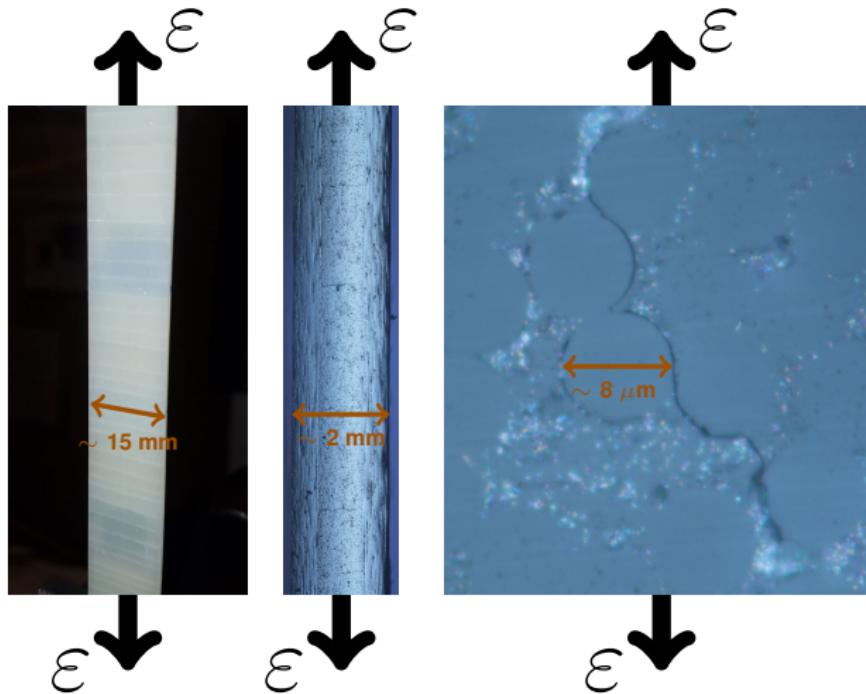


## The Thin-ply "Advantage": new material, old result?



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

## Micromechanics of Initiation



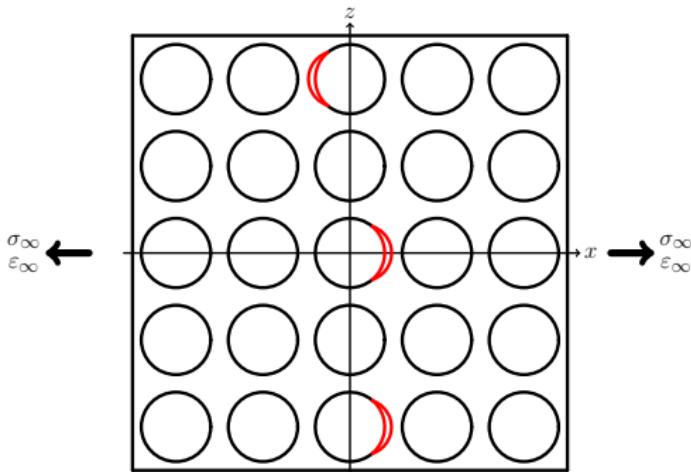
**Left:**  
front view of  $[0, 90]_S$ ,  
visual inspection.

**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



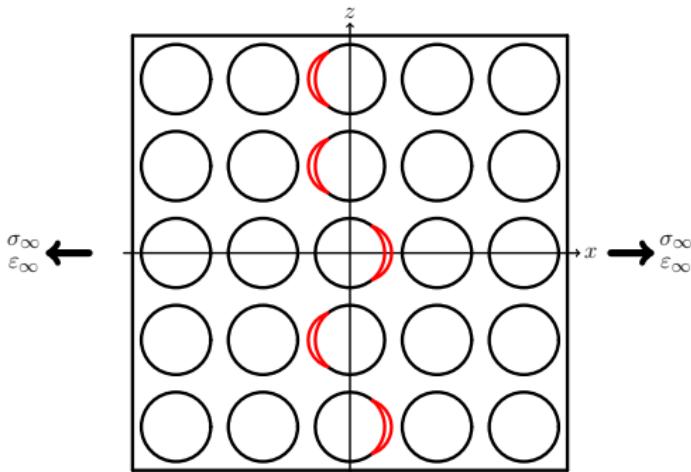
Bailey et al., P. Roy. Soc. A-Math. Phy. **366** (1727), 1979.

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



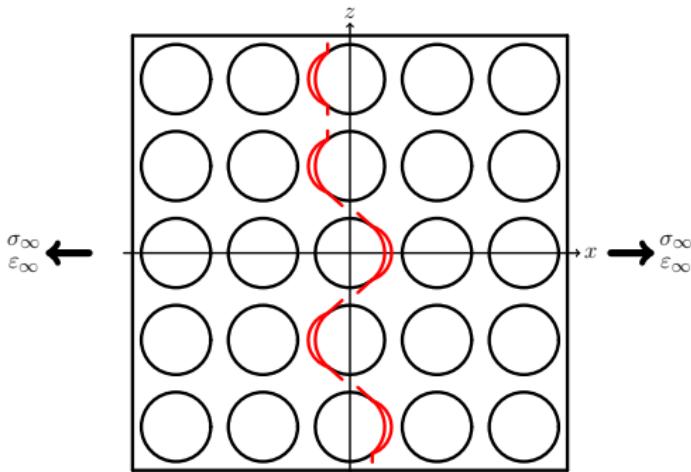
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Bailey et al., J. Mater. Sci. **16** (3), 1981.

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

## Micromechanics of Initiation

### Stage 3: kinking



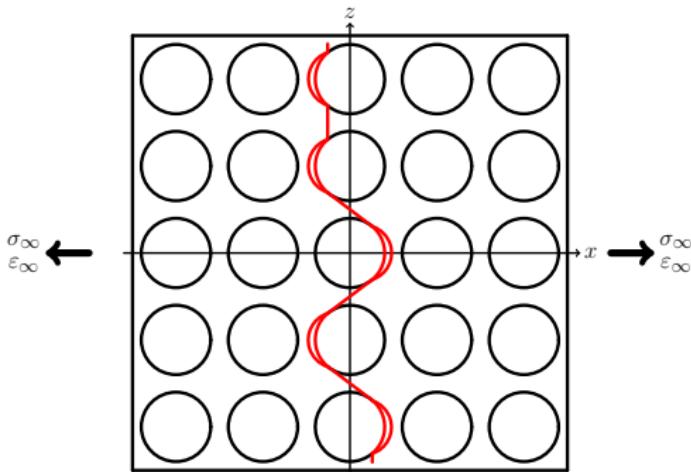
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Bailey et al., J. Mater. Sci. **16** (3), 1981.

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

## Micromechanics of Initiation

### Stage 4: coalescence



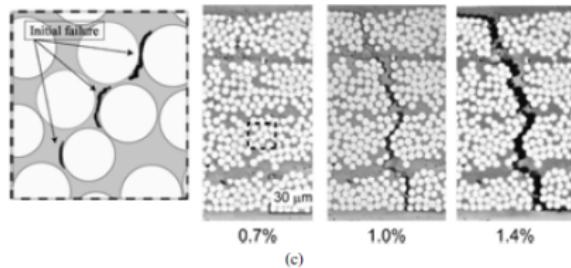
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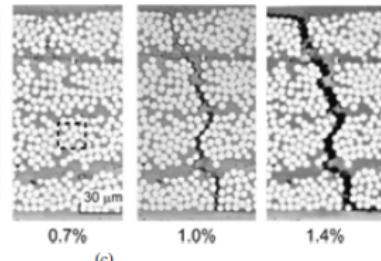
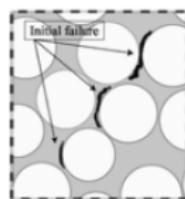
## A Counter-intuitive Observation

[0°, 90°]<sub>n</sub> s

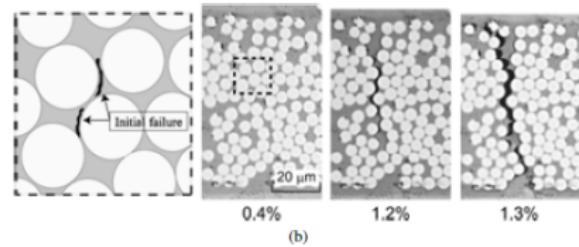


## A Counter-intuitive Observation

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



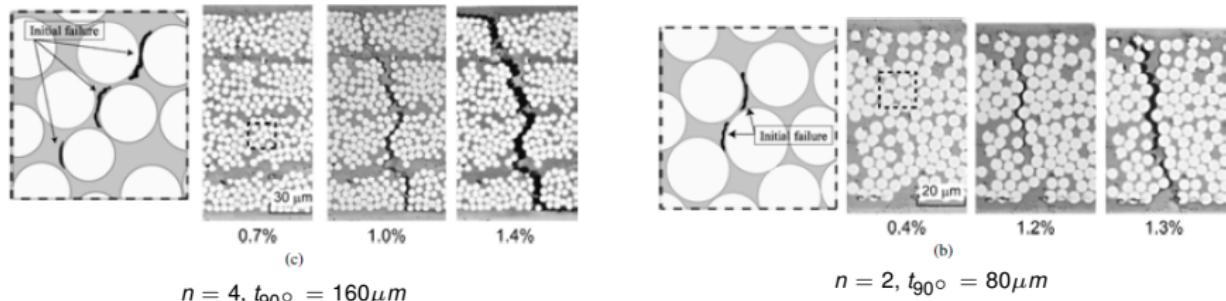
$$n = 4, t_{90^\circ} = 160 \mu m$$



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

## A Counter-intuitive Observation

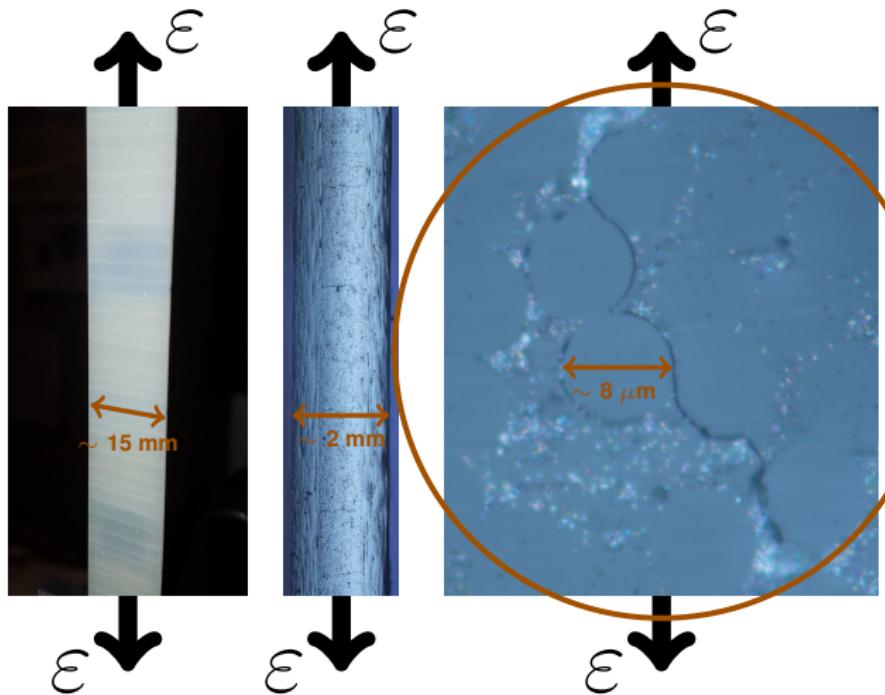
$[0^\circ, 90^\circ]_S$



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

# MODELING FIBER/MATRIX DEBONDING

## Micromechanics of Initiation

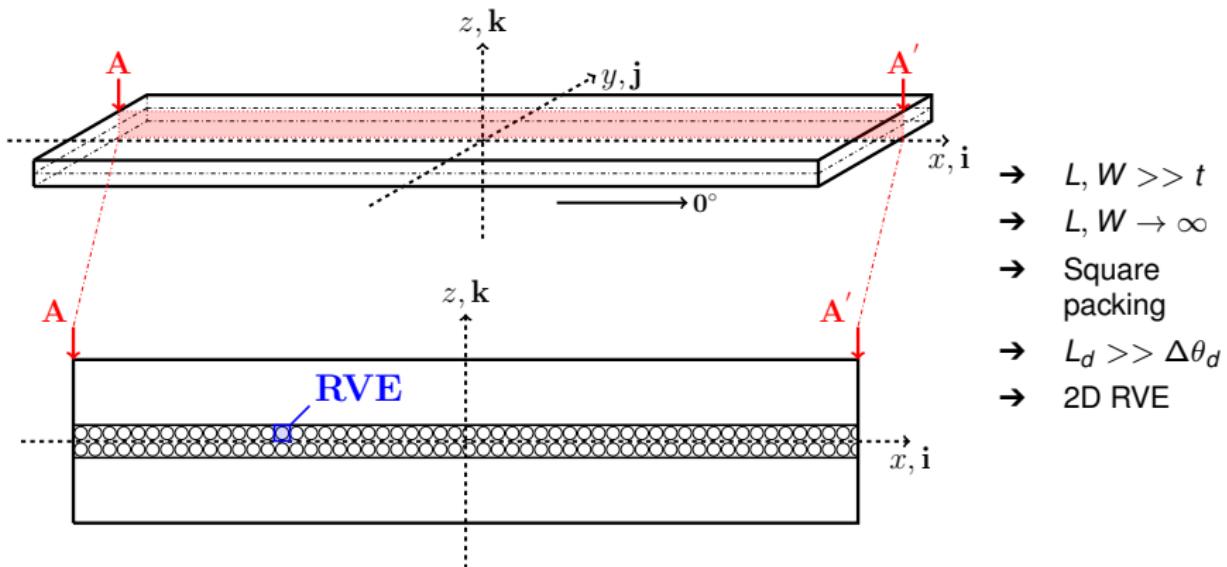


**Left:**  
front view of  $[0, 90]_S$ ,  
visual inspection.

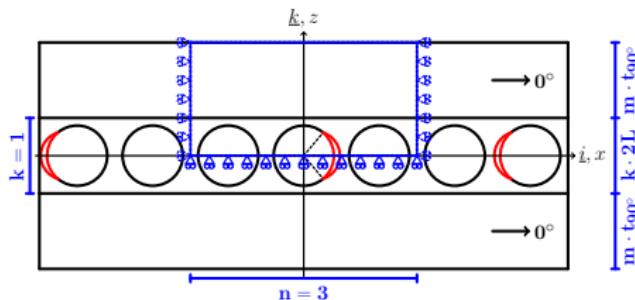
**Center:**  
edge view of  $[0, 90]_S$ ,  
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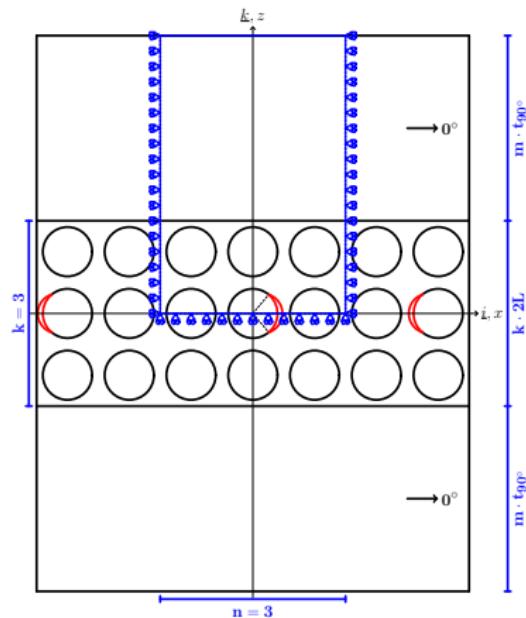
## Geometry



## Representative Volume Elements (RVEs)

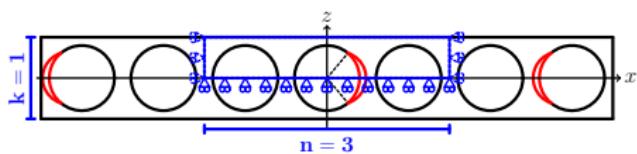


$$n \times 1 - m \cdot t_{90^\circ}$$



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

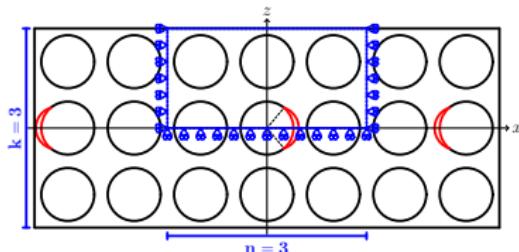
## Representative Volume Elements



– free

$n \times 1$  – coupling

– coupling +  $H$

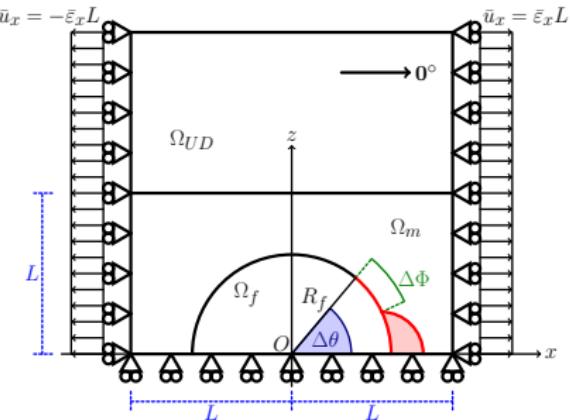


– free

$n \times k$  – coupling

– coupling +  $H$

## Assumptions

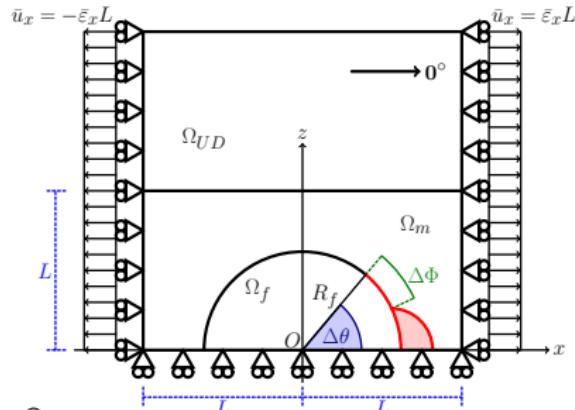


$$R_f = 1 \text{ } [\mu\text{m}] \quad L = \frac{R_f}{2} \sqrt{\frac{\pi}{V_f}}$$

- 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]	$\mu_{LT}$ [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  $\Omega_f$ ,  $\Omega_m$ ,  $\Omega_{UD}$ :

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

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

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{zx}}{\partial z} = 0$$

$$\frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \sigma_{zz}}{\partial z} = 0$$

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

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

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

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

$$+ BC$$

→ Oscillating singularity

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

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

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

→ receding contact problem

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

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

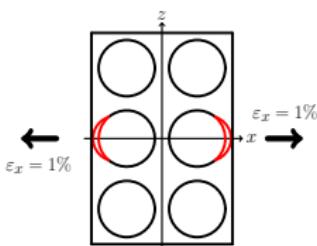
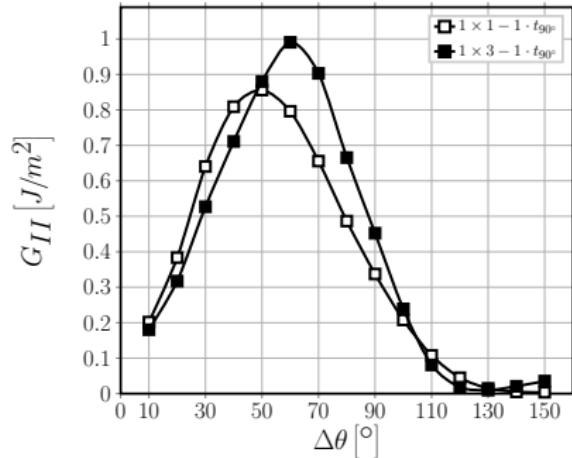
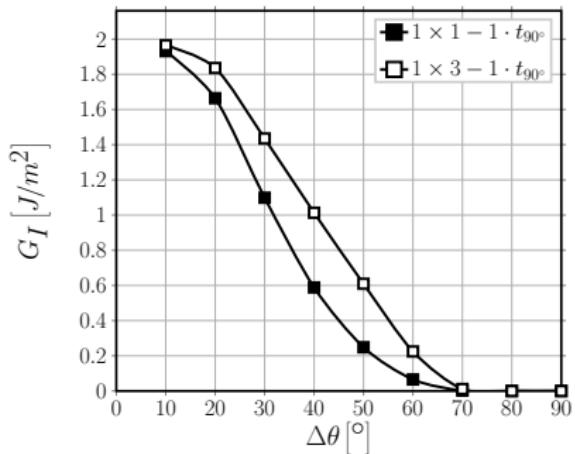
→ 6-nodes triangles & 8-nodes quadrilaterals

→ regular mesh of quadrilaterals  
at the crack tip:

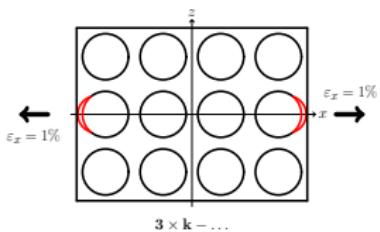
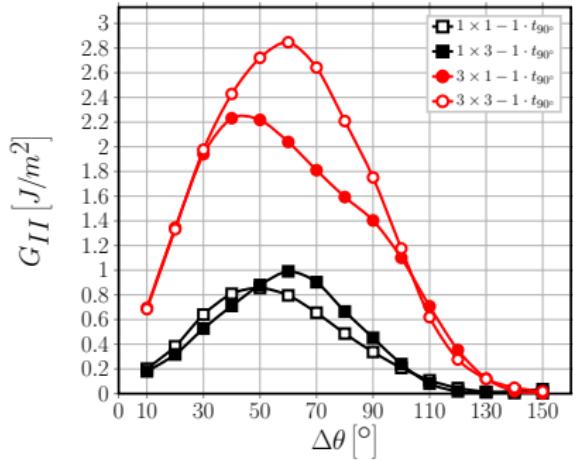
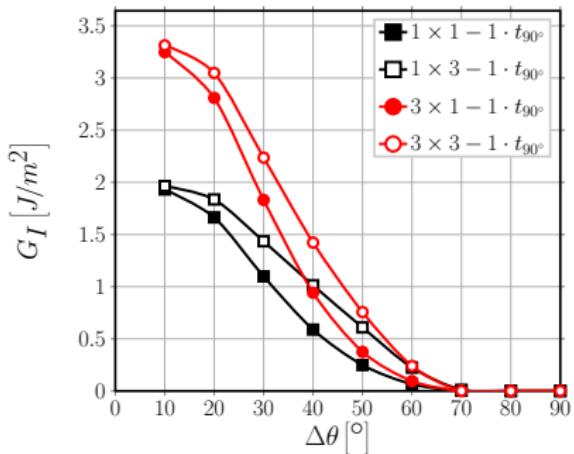
- $AR \sim 1$

- $\delta = 0.05^\circ$

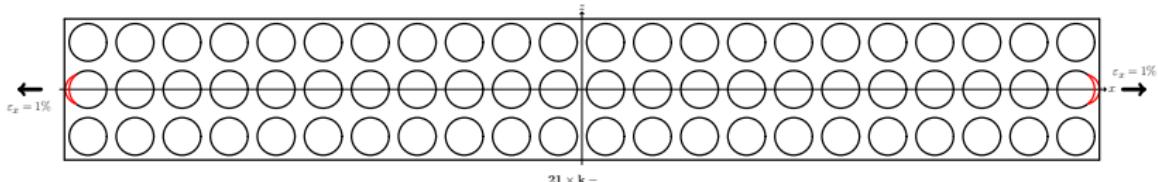
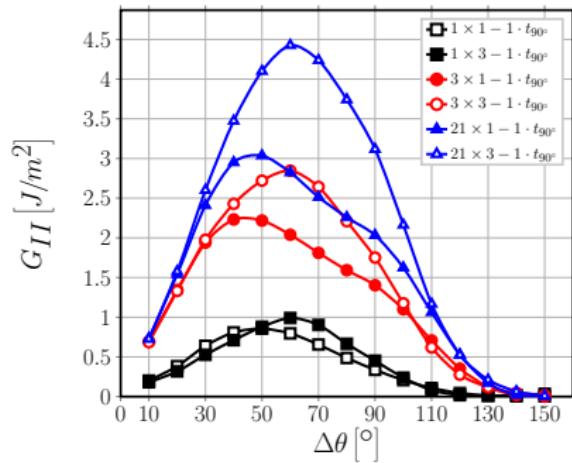
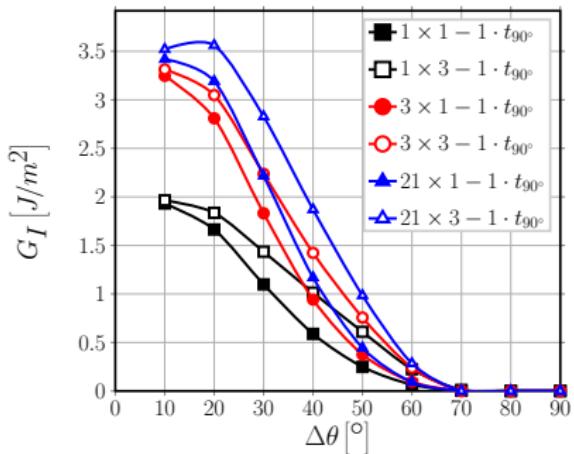
## Interaction of Debonds: Strain Magnification



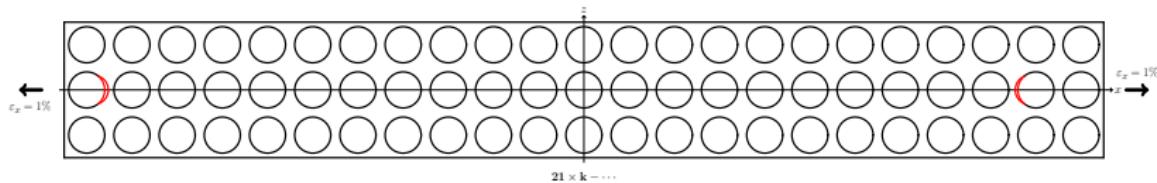
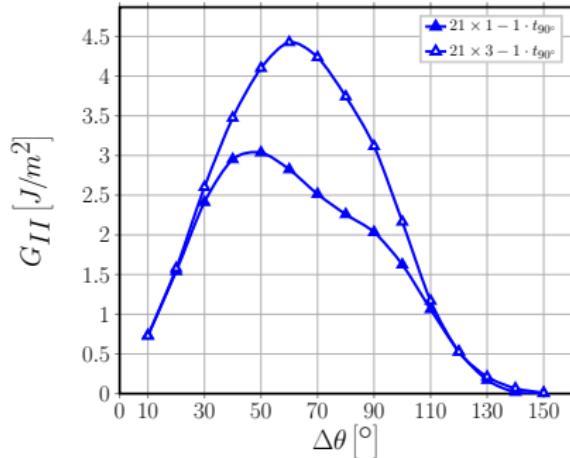
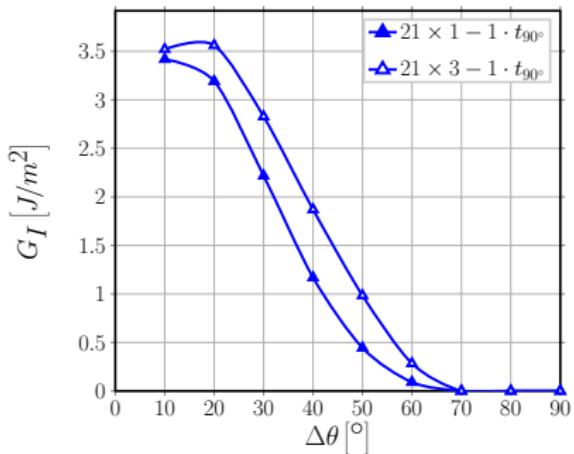
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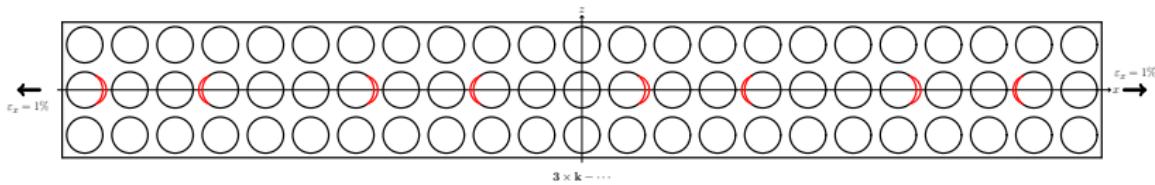
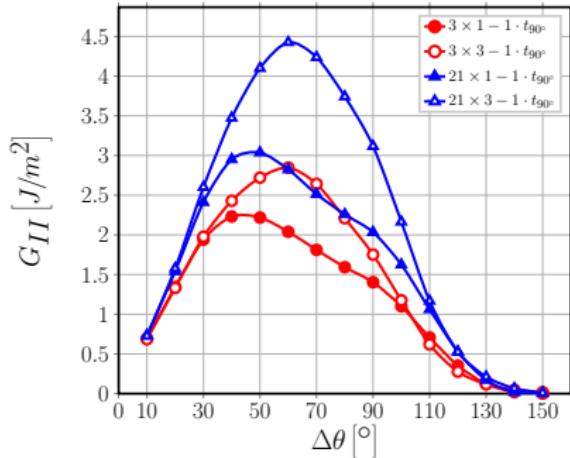
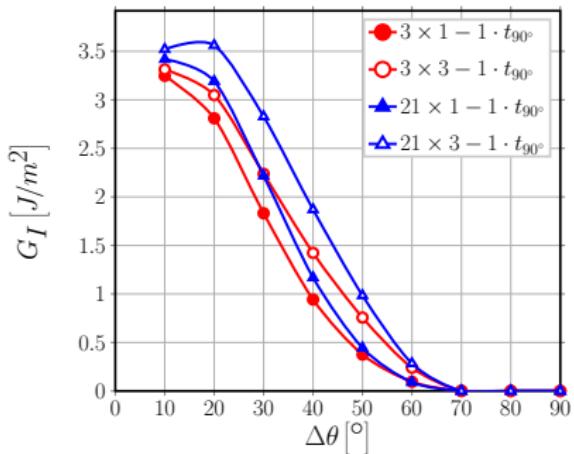
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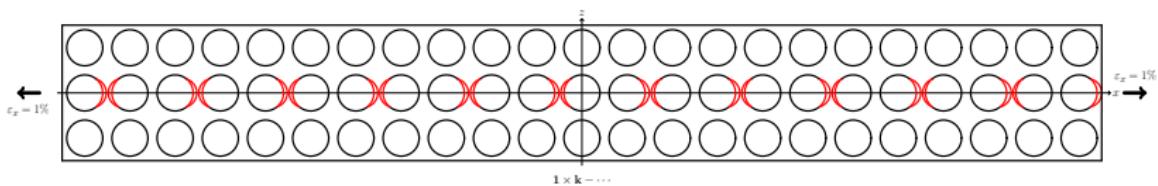
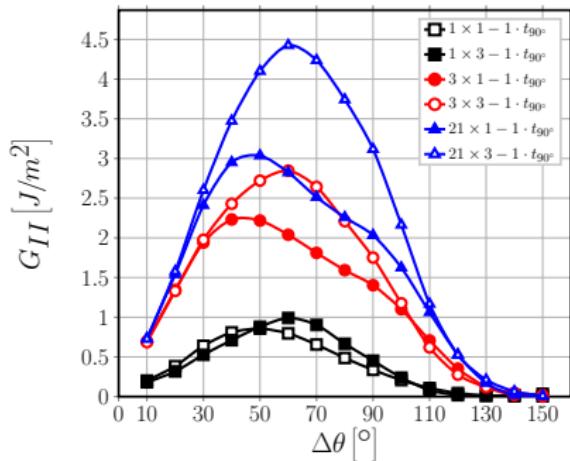
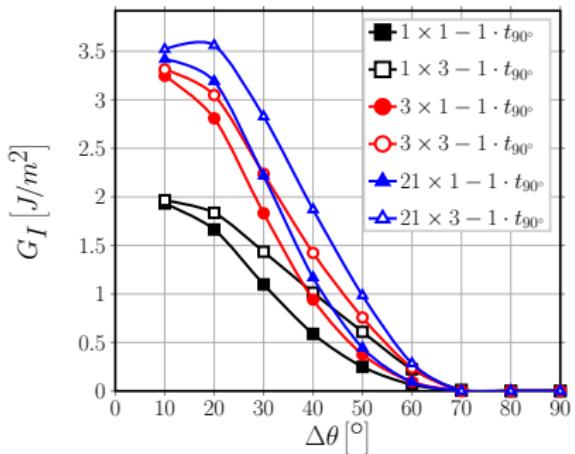
## Interaction of Debonds: Crack Shielding



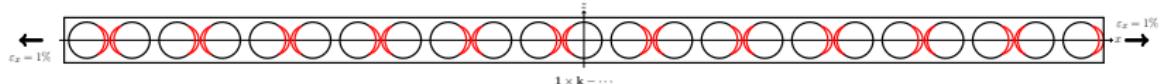
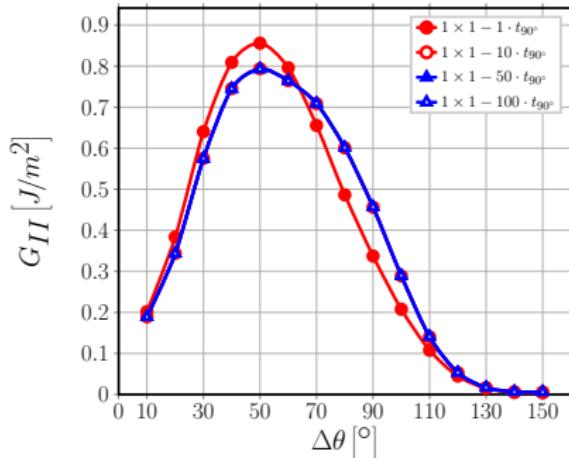
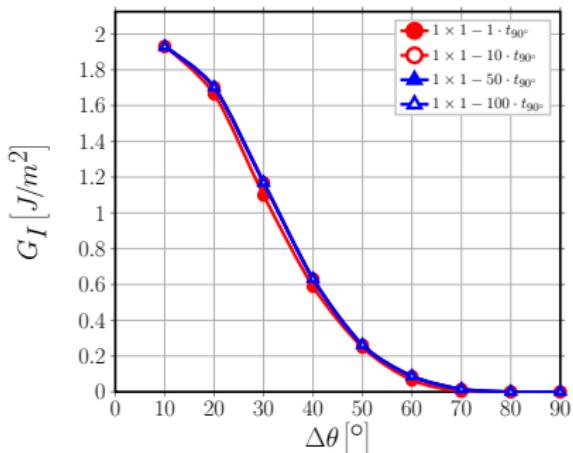
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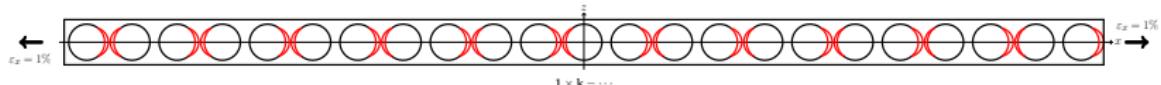
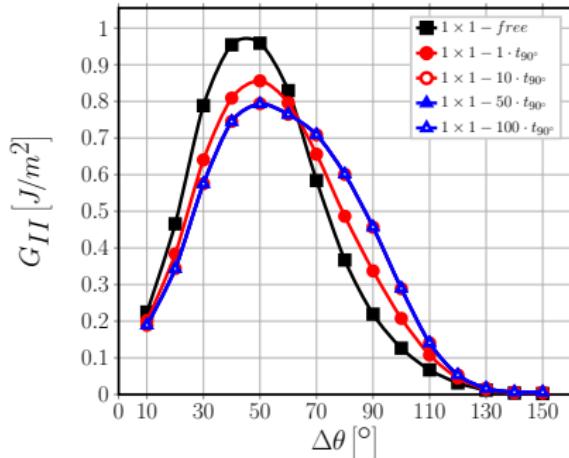
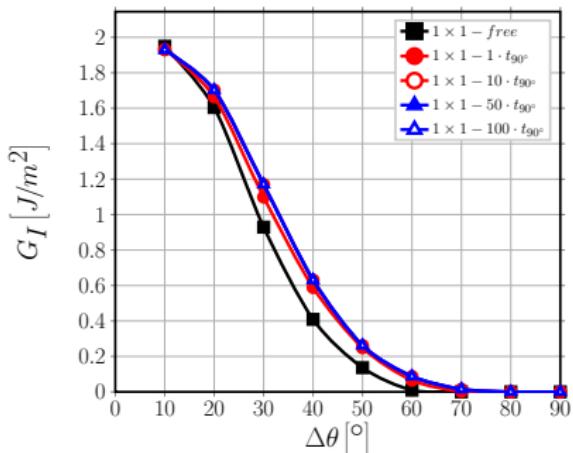
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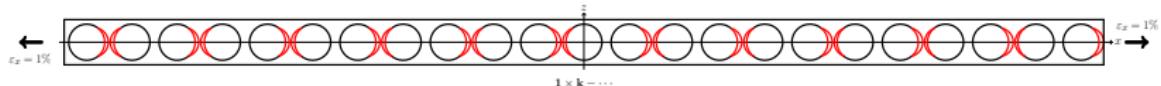
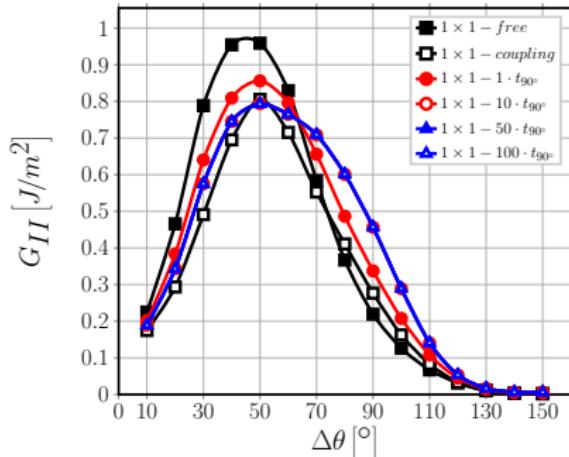
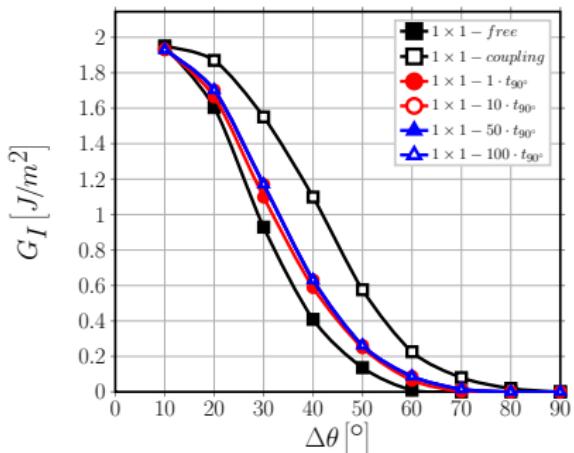
## Effect of 0° ply thickness



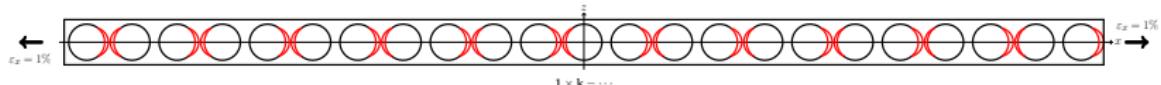
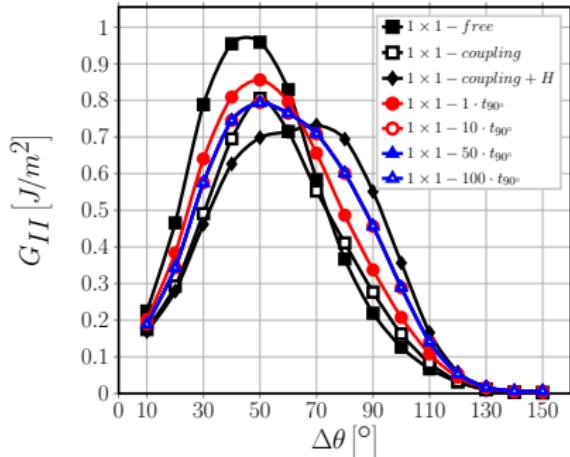
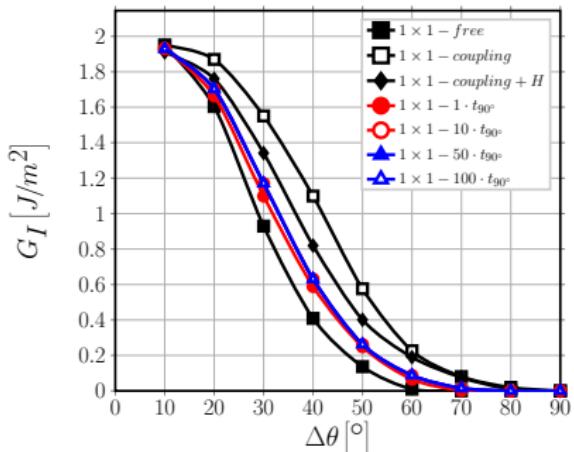
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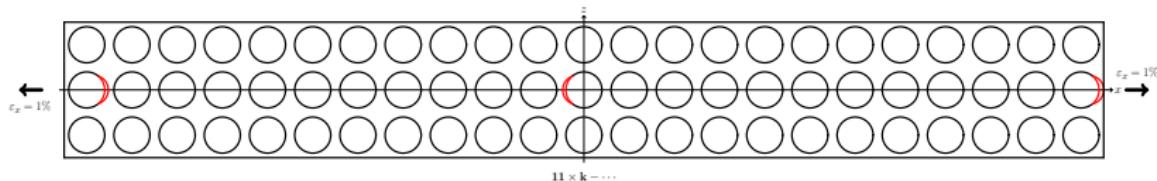
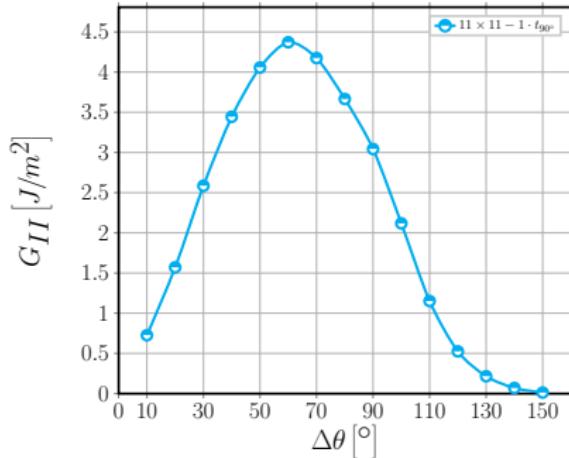
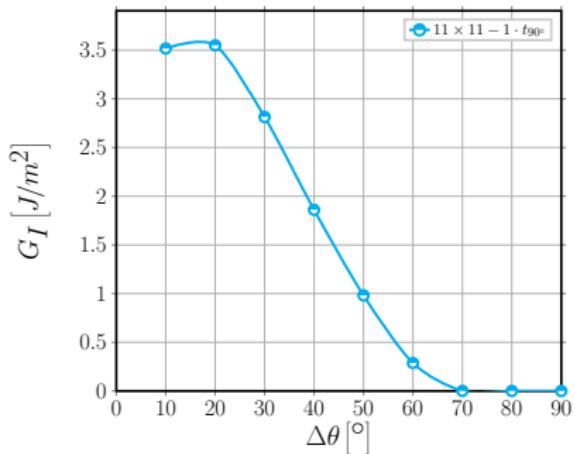
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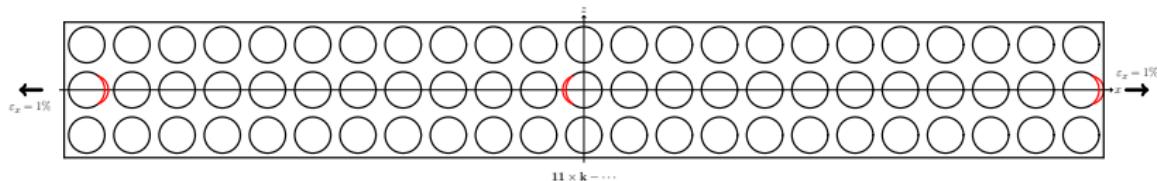
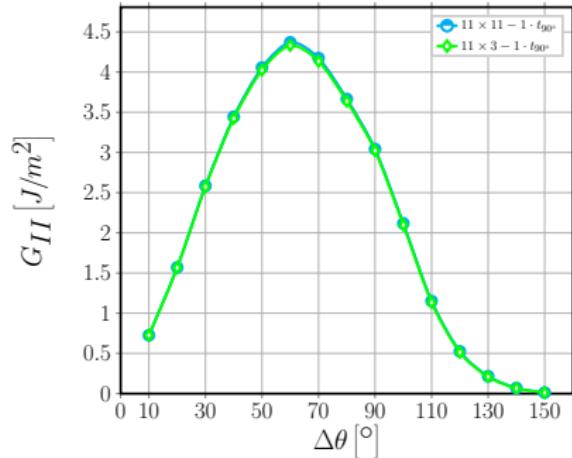
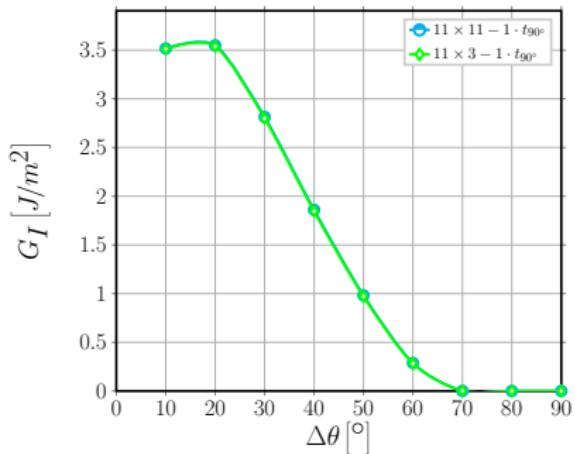
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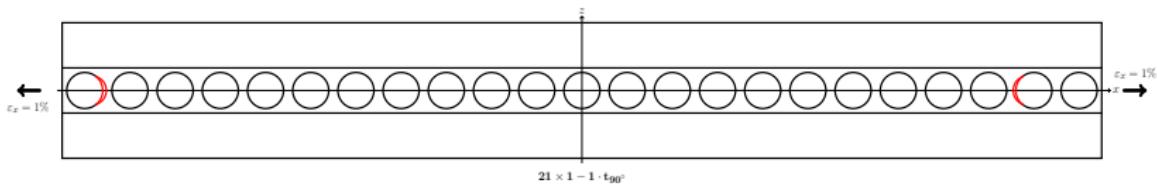
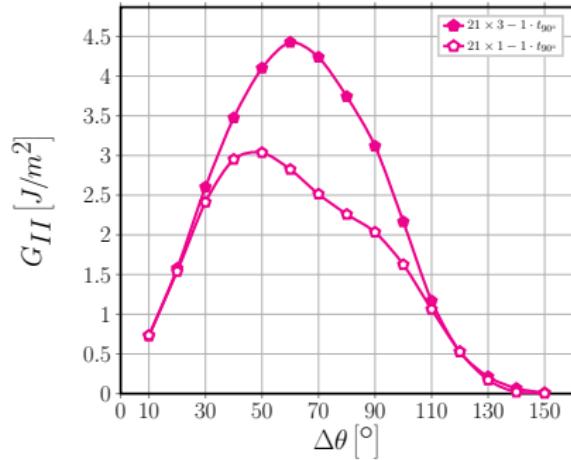
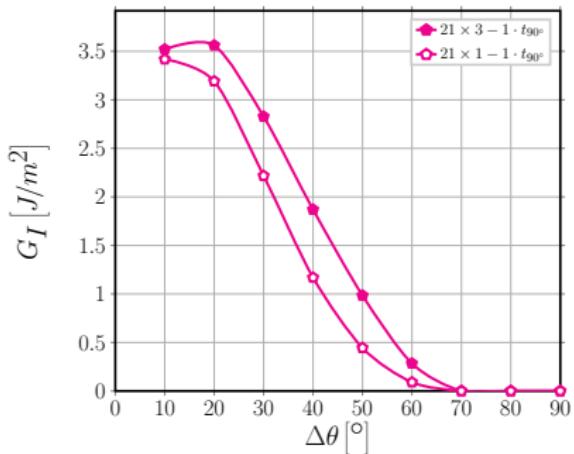
## Effect of 90° ply thickness



## Effect of 90° ply thickness



## Effect of 90° ply thickness



## Summary

- No effect of 90° ply thickness can be observed when  $t_{90^\circ}$  is at least  $\sim 3\phi_{fiber}$
- Only if  $t_{90^\circ}$  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

Prelude

Materials

Equipment Testing procedure



## MEASURING TRANSVERSE CRACKS PROPAGATION

Transverse Cracking in Thin-ply

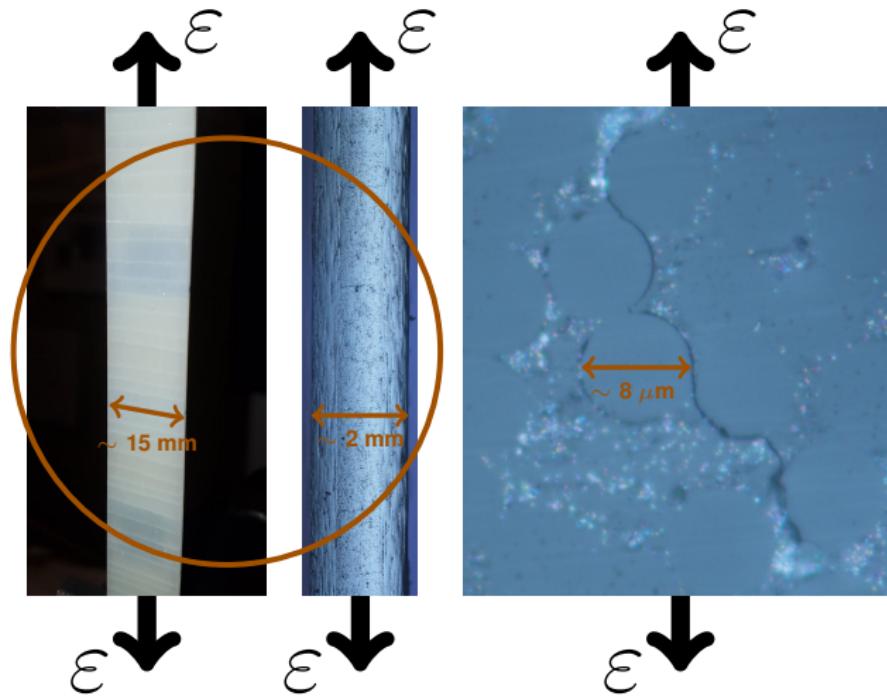
Modeling Fiber/Matrix Debonding

Measuring Transverse Cracks Propagation

Prelude Materials Equipment

Testing procedure

## Micromechanics of Initiation



**Left:**  
front view of [0, 90]<sub>S</sub>,  
visual inspection.

**Center:**  
edge view of [0, 90]<sub>S</sub>,  
optical microscope.

**Right:**  
edge view of [0, 90]<sub>S</sub>,  
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

Transverse Cracking in Thin-ply

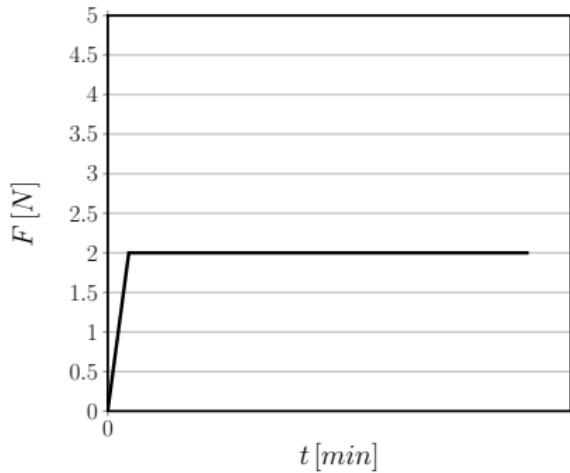
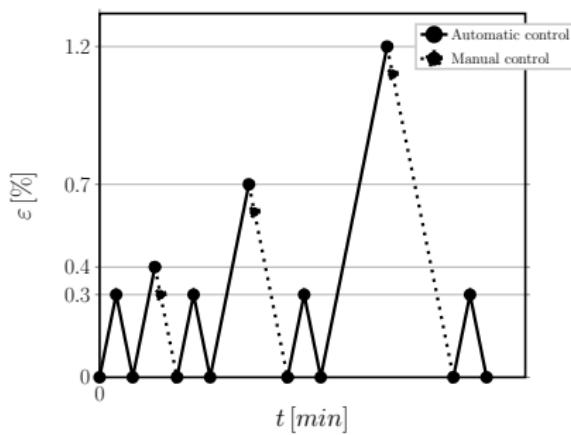
Modeling Fiber/Matrix Debonding

Measuring Transverse Cracks Propagation

Prelude Materials Equipment

Testing procedure

## 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.



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Education and Culture

Erasmus Mundus