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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Stockholm (SE) - October 16, 2019

Education and Culture
Erasmus Mundus

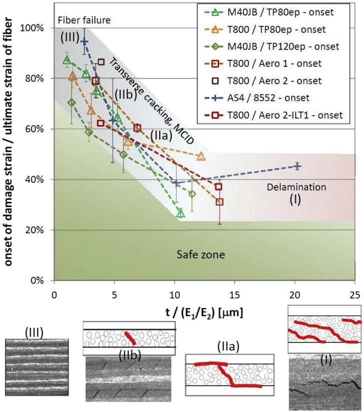
Outline

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

↘ TRANSVERSE CRACKING IN THIN-PLIES

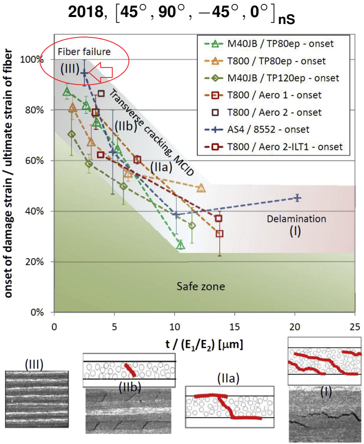
The Thin-ply “Advantage”: new material

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...

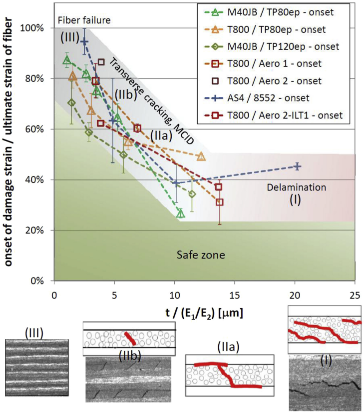


Cugnoni et al., Compos. Sci. Technol. **168**, 2018.

- ➔ 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!

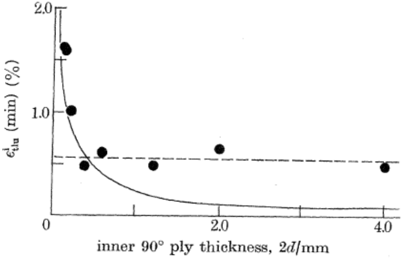
The Thin-ply "Advantage": new material, old result

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



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

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



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

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

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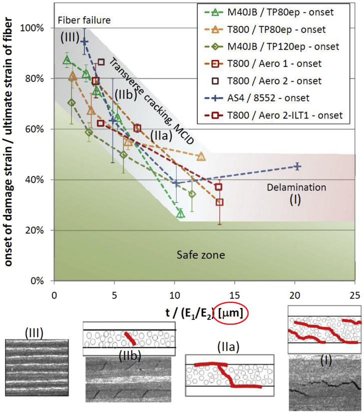
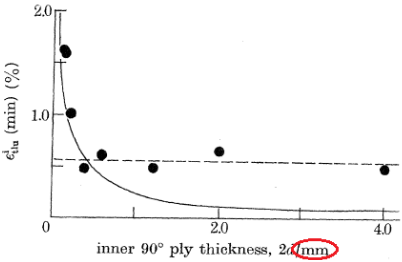


$t_{90^\circ} < 10\varnothing_{fiber}$

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

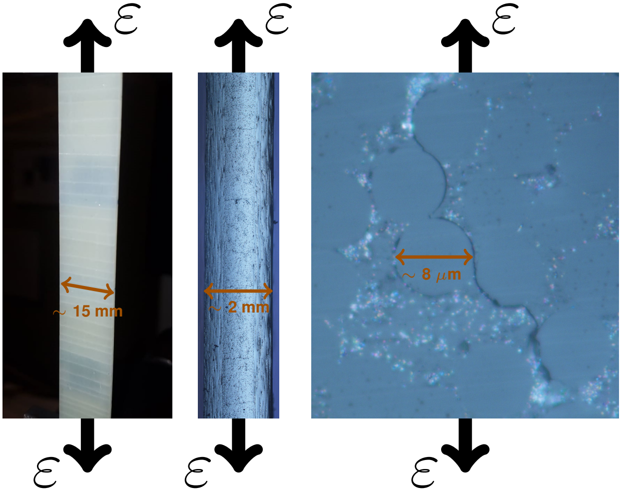
1979, $[0^\circ, 90^\circ_n]_S$



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

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

Micromechanics of Initiation



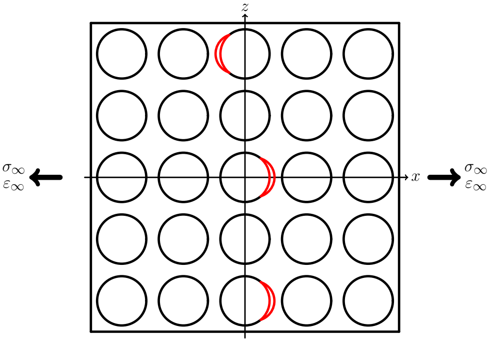
Left:
front view of $[0, 90_2]_S$, visual inspection.

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

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

Micromechanics of Initiation

Stage 1: isolated debonds



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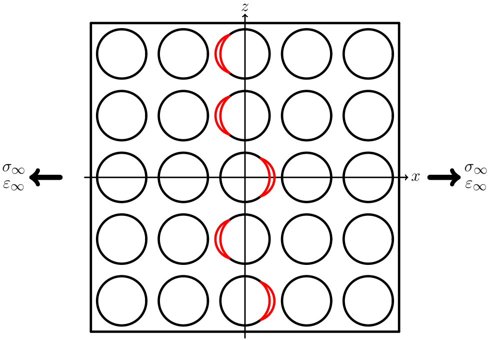
Bailey et al., J. Mater. Sci. **16** (3), 1981.

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

Micromechanics of Initiation

Stage 2: consecutive debonds



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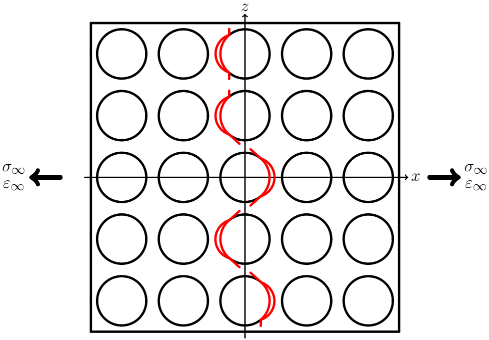
Zhang et al., Compos. Part A-Appl. S. **28** (4), 1997.

Micromechanics of Initiation

Stage 3: kinking



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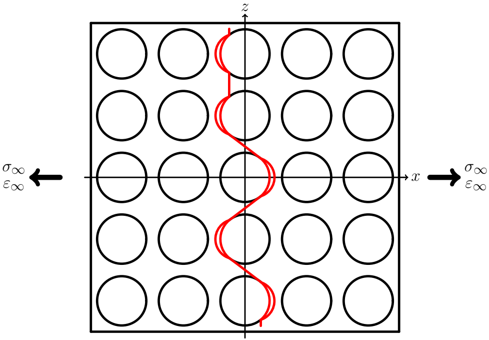
Micromechanics of Initiation

Stage 4: coalescence



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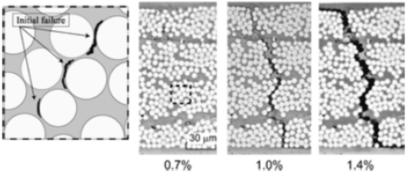
A Counter-intuitive Observation

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



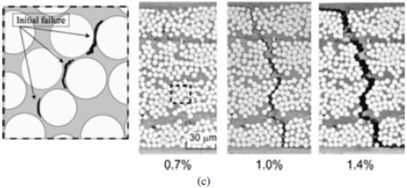
(c)

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

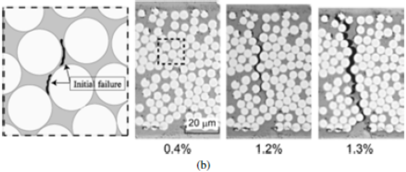
Saito et al., Adv. Compos. Mater. **21** (1), 2012.

A Counter-intuitive Observation

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



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

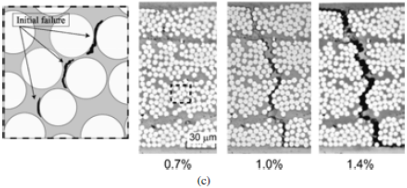


$n = 2$, $t_{90^\circ} = 80\mu m$

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

A Counter-intuitive Observation

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



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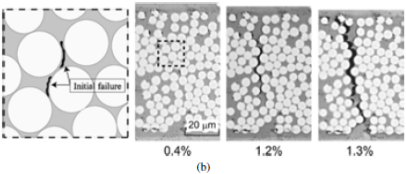

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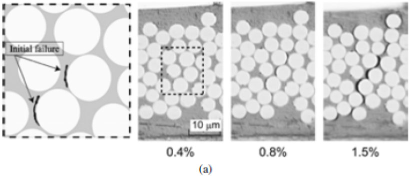
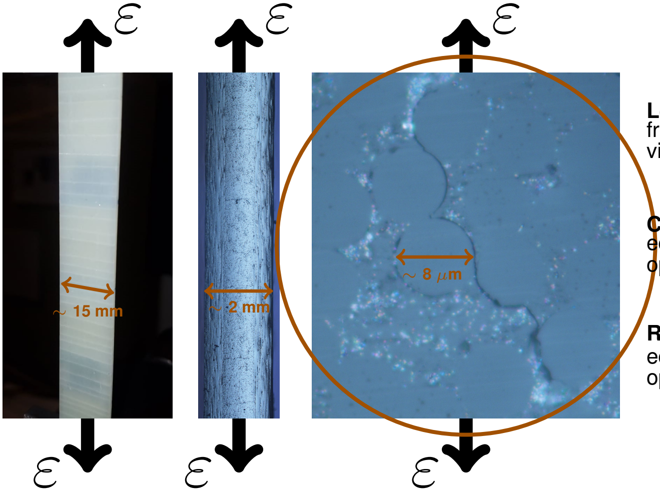


$n = 1$, $t_{90^\circ} = 40\mu m$

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

↘ Modeling Fiber/Matrix Debonding

Micromechanics of Initiation



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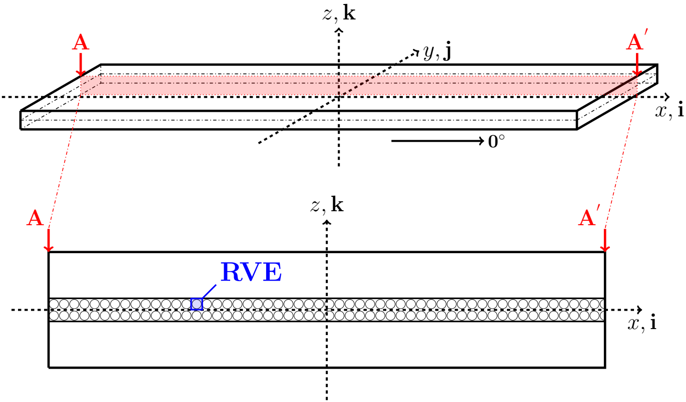
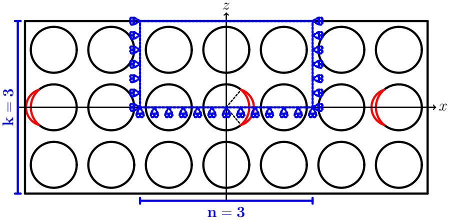
Geometry



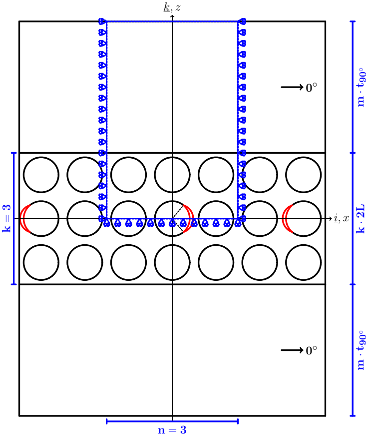
- ➔ $L, W >> t$
- ➔ $L, W \rightarrow \infty$
- ➔ Square packing
- ➔ $L_d >> \Delta\theta_d$
- ➔ 2D RVE

Representative Volume Elements



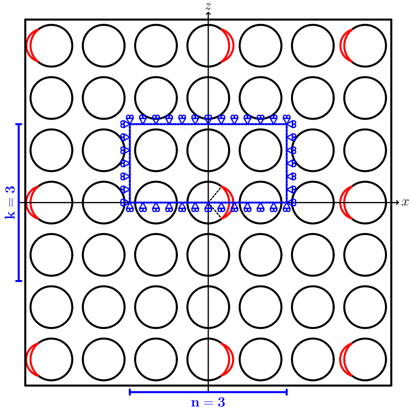
$$n \times k - free$$

$$n \times k - H$$



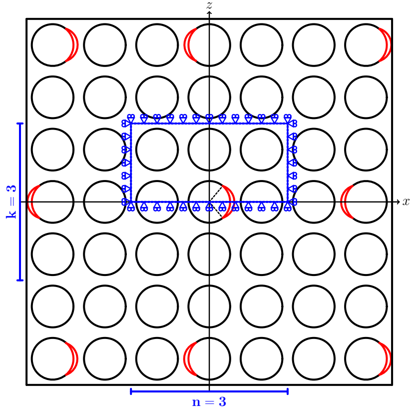
$$n \times k - m \cdot t_{90^\circ}$$

Representative Volume Elements



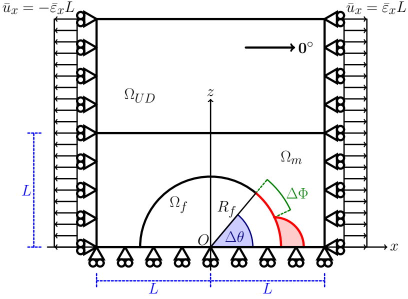
$n \times k - symm\ (coupling)$

$n \times k - coupling + H$



$n \times k - asymm$

Assumptions

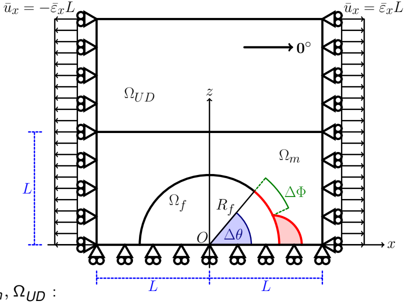


$R_f = 1$ $[\mu m]$ $\quad L = \frac{R_f}{2}\sqrt{\frac{\pi}{V_f}}$

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

Material	V_f [%]	E_L $[GPa]$	E_T $[GPa]$	μ_{LT} $[GPa]$	ν_{LT} $[-]$	ν_{TT} $[-]$
Glass fiber	-	70.0	70.0	29.2	0.2	0.2
Epoxy	-	3.5	3.5	1.25	0.4	0.4
UD	60.0	43.442	13.714	4.315	0.273	0.465

Solution



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

$$\frac{\partial^2 \varepsilon_{xx}}{\partial z^2} + \frac{\partial^2 \varepsilon_{zz}}{\partial x^2} = \frac{\partial^2 \gamma_{zx}}{\partial x \partial z}$$

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

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

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

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

for $0^\circ \leq \alpha \leq \Delta\theta$:

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

for $\Delta\theta \leq \alpha \leq 180^\circ$:

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

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

$$+ BC$$

- ➔ Oscillating singularity

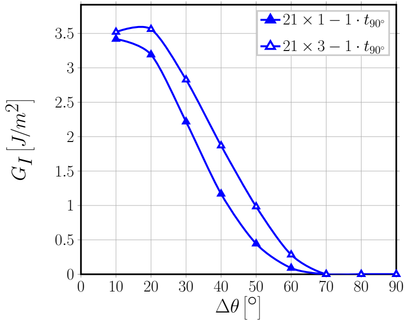
$$\sigma \sim r^{-\frac{1}{2}} \sin\left(\varepsilon \log r\right), \quad V_f \to 0$$

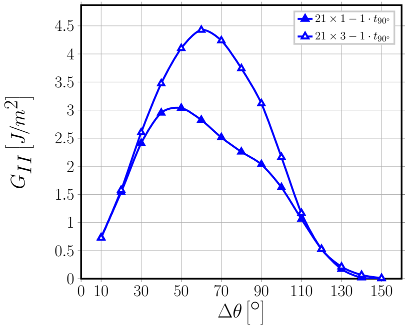
$$\varepsilon = \frac{1}{2\pi} \log\left(\frac{1-\beta}{1+\beta}\right)$$

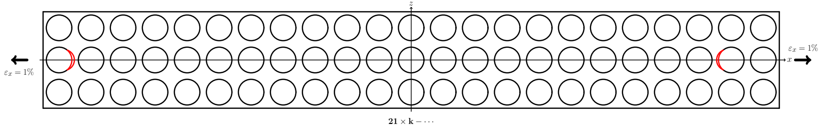
$$\beta = \frac{\mu_2\left(\kappa_1 - 1\right) - \mu_1\left(\kappa_2 - 1\right)}{\mu_2\left(\kappa_1 + 1\right) + \mu_1\left(\kappa_2 + 1\right)}$$

- ➔ receding contact problem
- ➔ Finite Element Method (FEM) in Abaqus^{TM}+ VCCT
- ➔ 2^{nd} order shape functions
- ➔ 6-nodes triangles & 8-nodes quadrilaterals
- ➔ regular mesh of quadrilaterals at the crack tip:
  - $AR \sim 1$
  - $\delta = 0.05^\circ$

Interaction of Debonds: Crack Shielding







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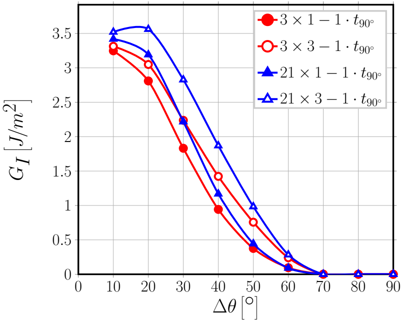

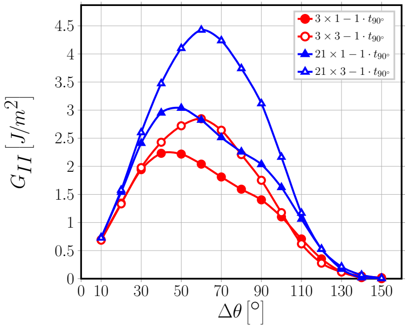

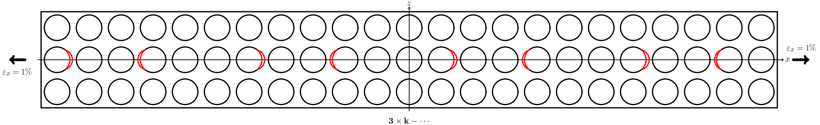

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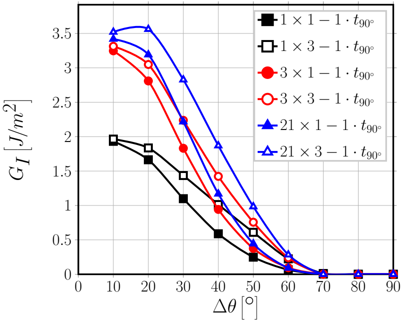
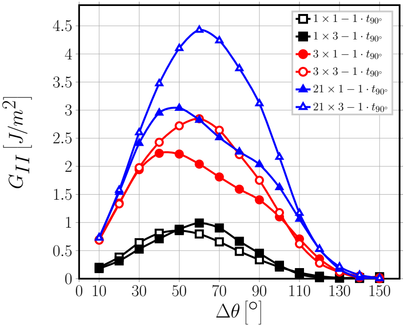
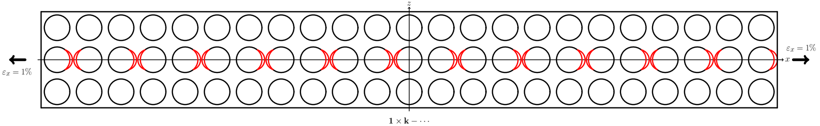
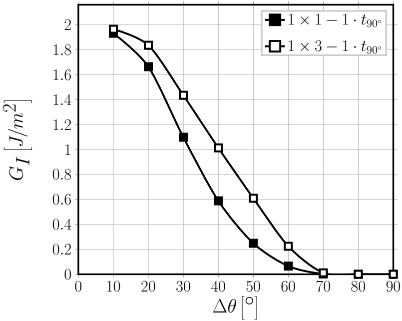
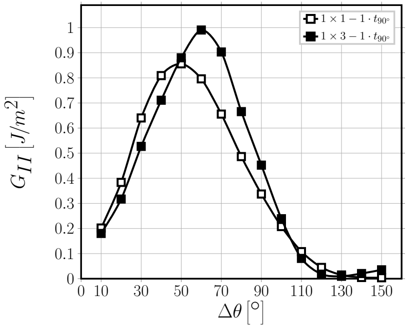


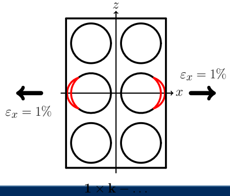




Interaction of Debonds: Strain Magnification







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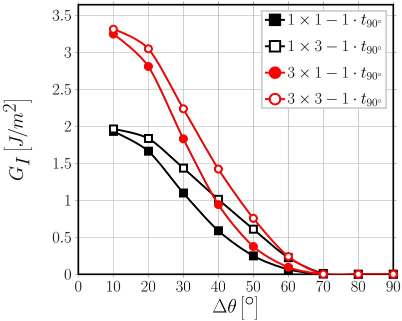

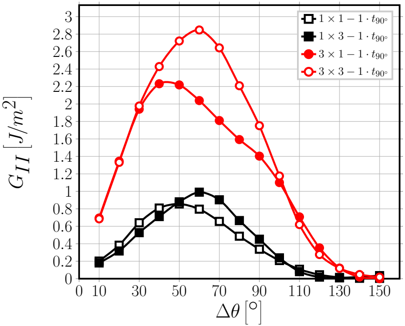

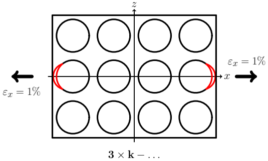

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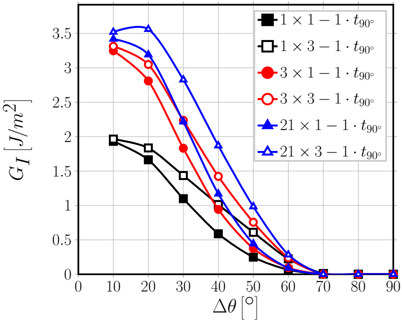
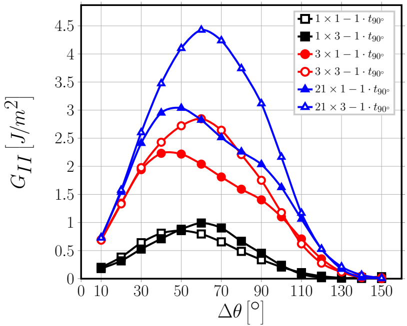
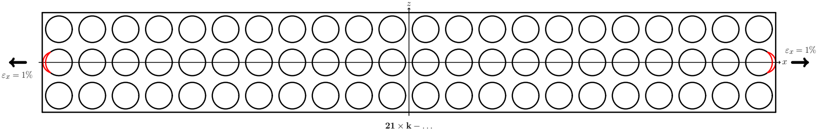
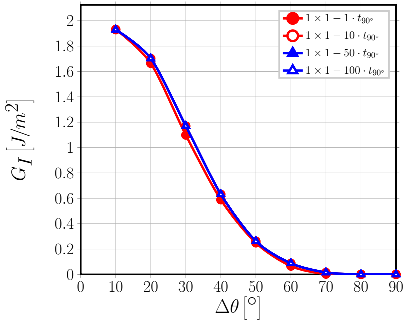
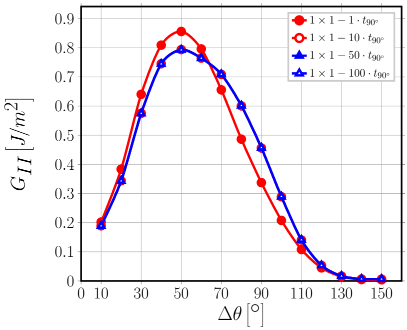


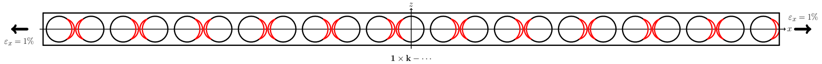




Effect of 0° ply thickness







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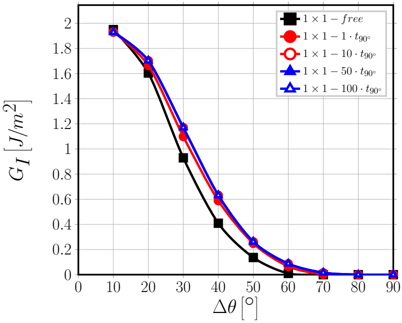

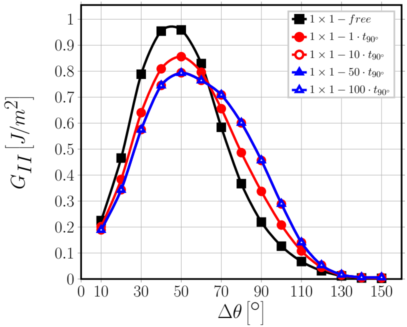

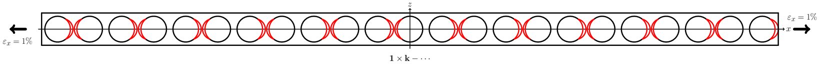

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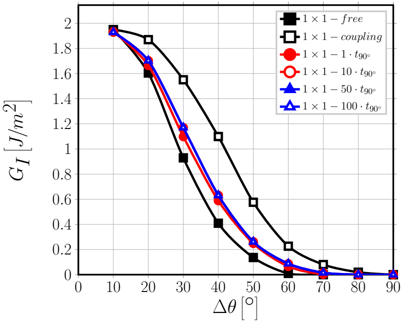
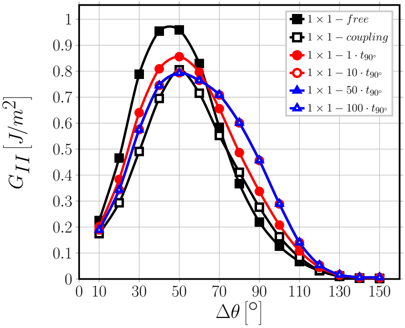
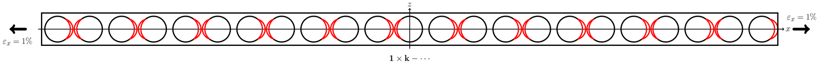
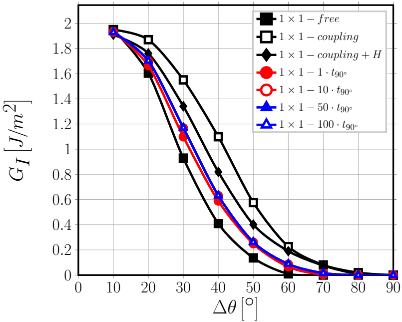
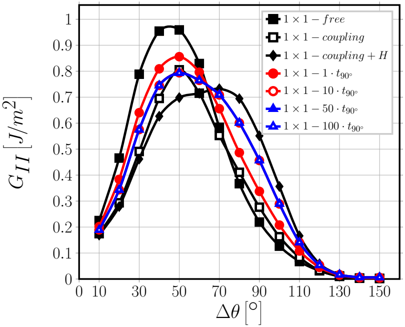


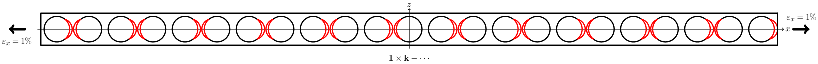




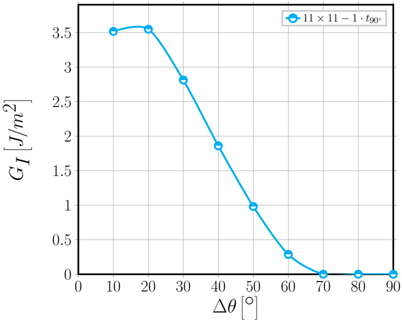
Effect of 0° ply thickness

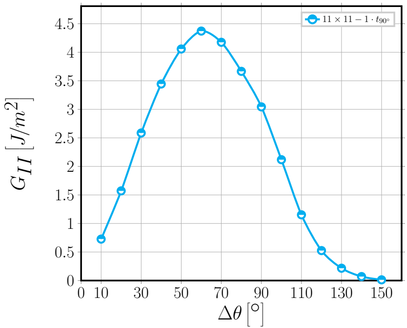


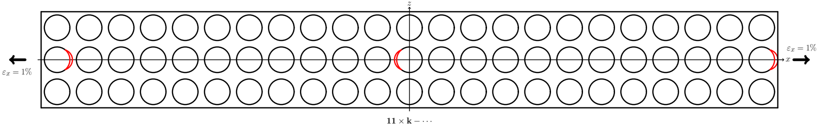




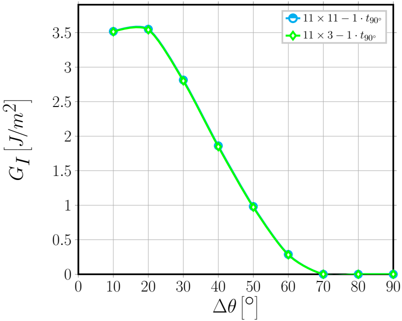
Effect of 90° ply thickness

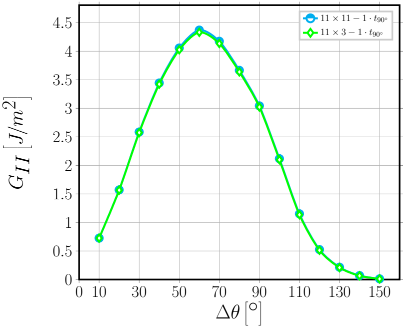


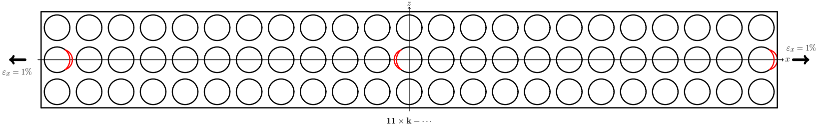




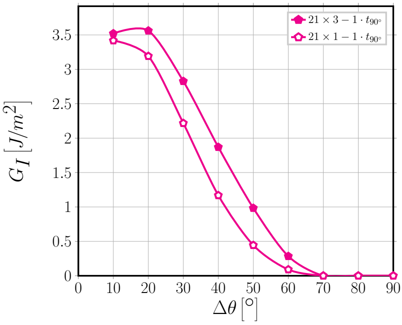
Effect of 90° ply thickness

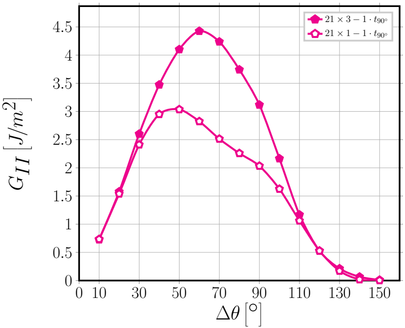


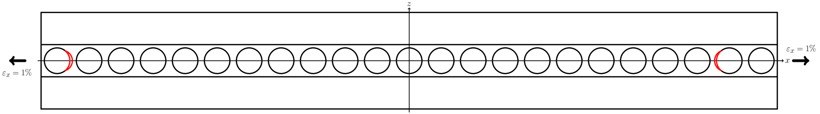




Effect of 90° ply thickness







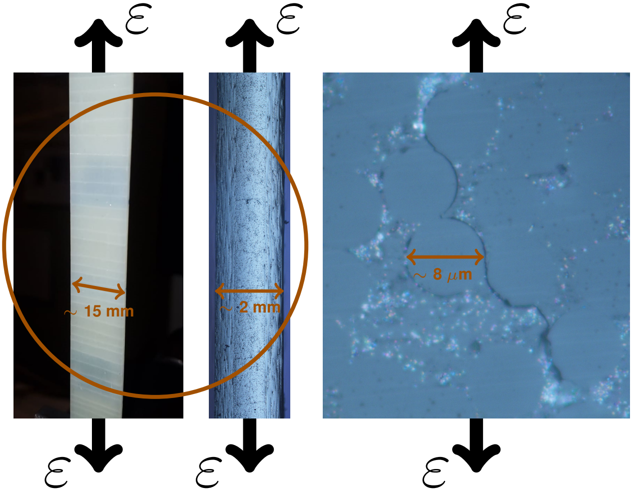
$\mathbf{21 \times 1 - 1 \cdot t_{90°}}$

Summary

- No effect of 90° ply thickness can be observed when t_{90° is at least $\sim 3\varnothing_{fiber}$
- Only if t_{90° is reduced to $1\varnothing_{fiber}$, ERR is reduced for a given level of applied strain, i.e. debond growth is delayed to higher levels of applied strain ($G \sim \varepsilon^2_{applied}$)
- No effect of 0° ply thickness can be observed when $t_{0^\circ}/t_{90^\circ} > 1$
- A small difference can be observed when $t_{0^\circ} = t_{90^\circ}$, due to the smaller bending stiffness of a thinner 0° layer

Measuring Transverse Cracks Propagation

Micromechanics of Initiation

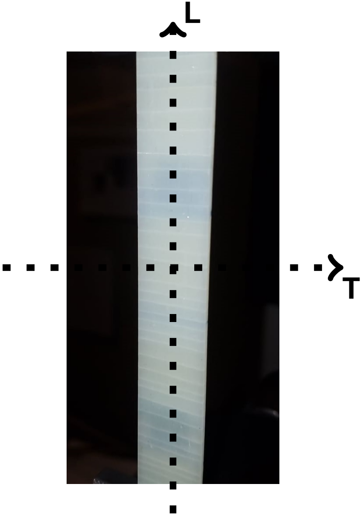


Left:
front view of $[0, 90_2]_S$, visual inspection.

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

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

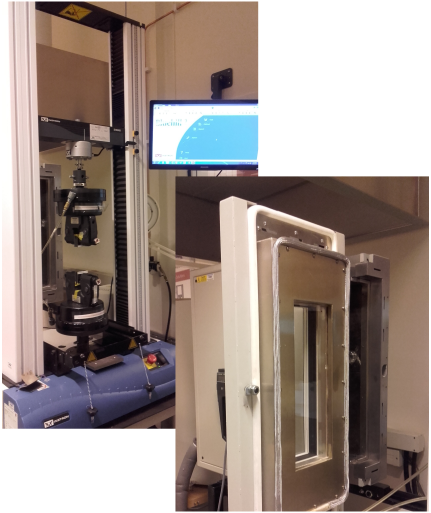
Materials



- Glass fiber/epoxy prepreg
- $V_f \sim 50 - 55\%$
- Lay-up $\left[0^\circ, 90^\circ_2\right]$
- Manufacturing: manual lay-up + vacuum bag + hot press
- Cutting and polishing of specimens
- Specimen size (nominal): $200\ mm \times 15\ mm \times 1.85\ mm$

UD properties (measured)	
E_L $[GPa]$	38.5
E_T $[GPa]$	15.3
ν_{LT} $[-]$	0.3
G_{LT} $[GPa]$	3.5
ε_T^{lim} $[\%]$	0.43
σ_T^{lim} $[MPa]$	60
$T_{stress\ free}$ $[^\circ C]$	116.3

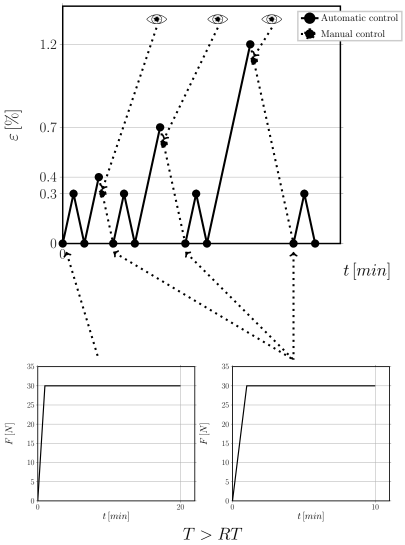
Equipment



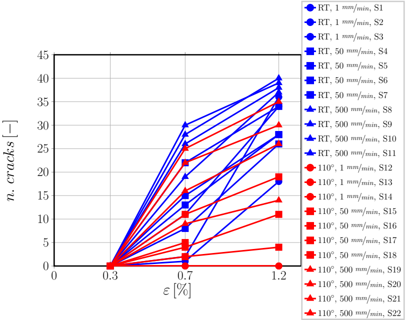
- ➔ Universal electro-mechanical testing machine (Instron 3366)
- ➔ Environmental chamber (Instron), temperature range: -100° to $+350^\circ C$
- ➔ Extensometer (Instron), gauge length: 50 *mm*

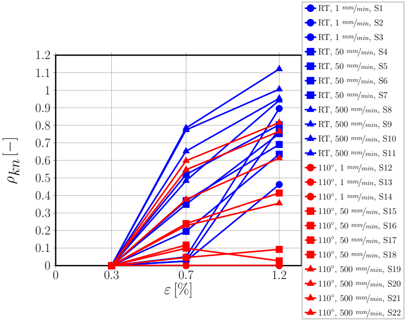
Testing procedure

	RT	$110^{\circ}C$
$1\ ^{mm}/_{min}$	3 sp.	3 sp.
$50\ ^{mm}/_{min}$	4 sp.	4 sp.
$500\ ^{mm}/_{min}$	4 sp.	4 sp.



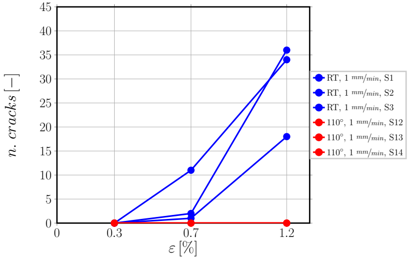
Crack density

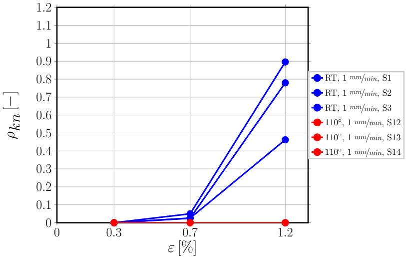




$$\rho_{kn} = \frac{n\ cracks}{L_{gauge}} t_{90^\circ}$$

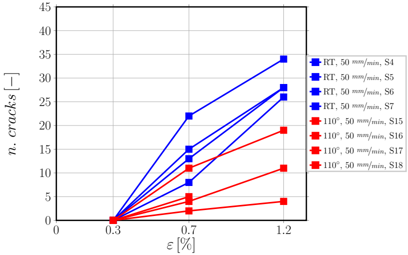
Crack density

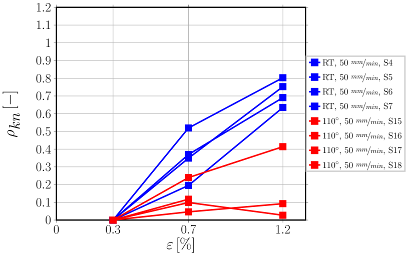




$$\rho_{kn} = \frac{n\ cracks}{L_{gauge}} t_{90^\circ}$$

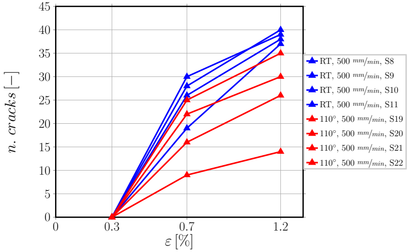
Crack density

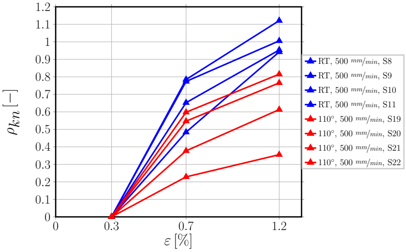




$$\rho_{kn} = \frac{n\ cracks}{L_{gauge}} t_{90^\circ}$$

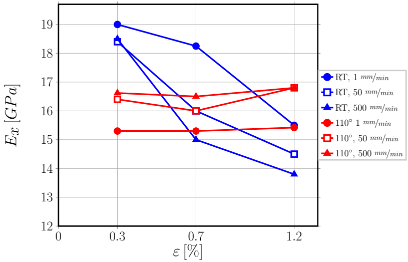
Crack density

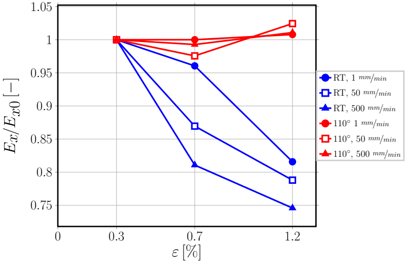




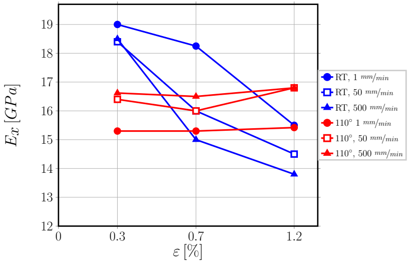
$$\rho_{kn} = \frac{n\ cracks}{L_{gauge}} t_{90^\circ}$$

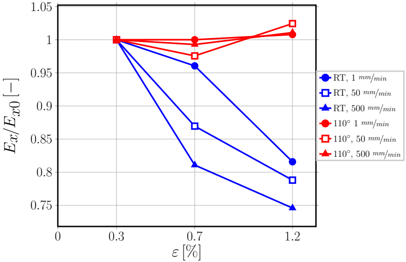
Young's modulus





Re-bonding?


19
18
17
16
15
14
13
12
0
0.3
0.7
1.2
$Ex\ [GPa]$
$\varepsilon\ [\%]$
RT, 1 mm/min
RT, 50 mm/min
RT, 500 mm/min
110° 1 mm/min
110°, 50 mm/min
110°, 500 mm/min


1.05
1
0.95
0.9
0.85
0.8
0.75
0
0.3
0.7
1.2
$Ex/Ex0\ [-]$
$\varepsilon\ [\%]$
RT, 1 mm/min
RT, 50 mm/min
RT, 500 mm/min
110° 1 mm/min
110°, 50 mm/min
110°, 500 mm/min

↘ Design Idea

Design Idea

- ✎ Use weak fiber/matrix interfaces $+$ microstructure $\rightarrow$ dissipate energy through diffuse debonding $+$ lower stiffness reduction
- ✎ Use microstructure (*ply-thickness effect*) $\rightarrow$ 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$\rightarrow$ re-bonding @$T \sim T_{stress\ free}$ in unloaded state $=$ stiffness recovery

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LULEÅ UNIVERSITY OF TECHNOLOGY

Education and Culture

Erasmus Mundus