

# INFLUENCE OF MICROSTRUCTURE ON DEBONDING AT THE FIBER/MATRIX INTERFACE IN FIBER-REINFORCED POLYMERS UNDER TENSILE LOADING

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Luleå (SE) - December 13, 2019



## Outline

- ➔ Introduction
- ➔ Modeling
- ➔ Convergence
- ➔ Debond Initiation
- ➔ Debond Propagation
- ➔ Moving Forward

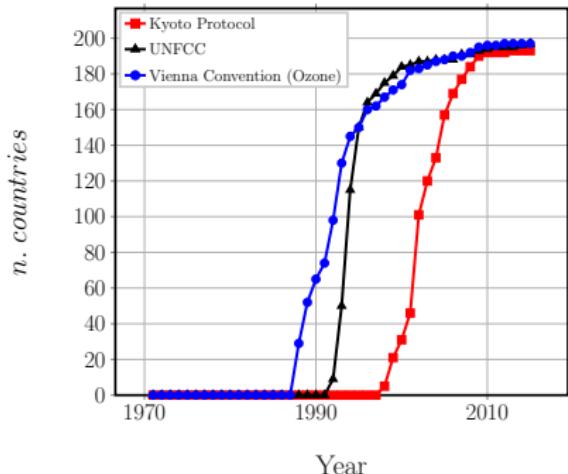
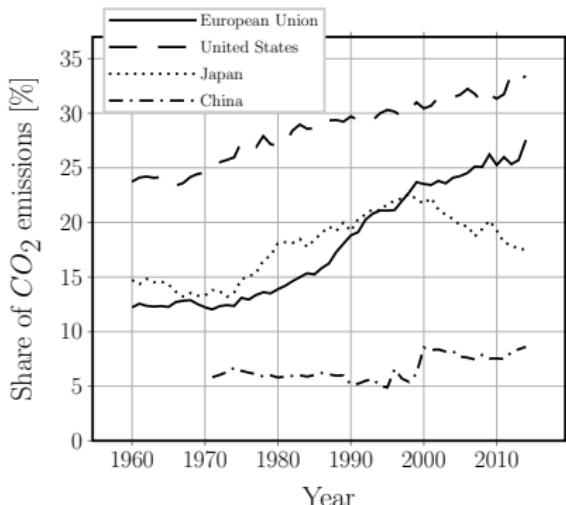
Introduction Modeling Convergence Debond Initiation Debond Propagation Moving Forward

Challenges of the transport sector The Thin-ply "Advantage" Micromechanics of Initiation

# INTRODUCTION

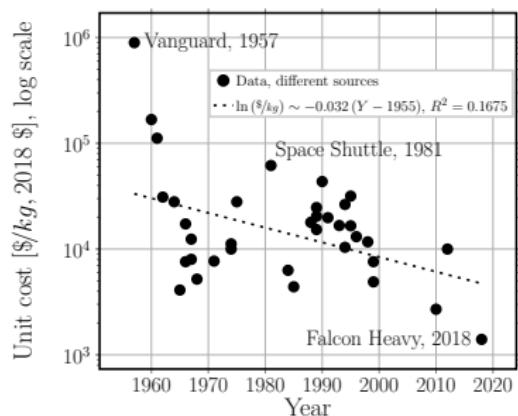
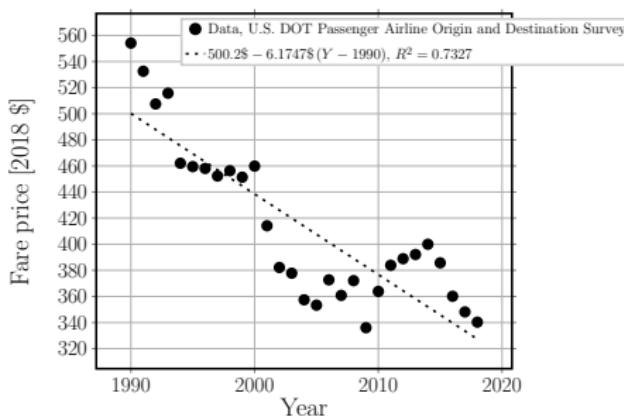
## Challenges of the transport sector

- Institutional and popular pressure to reduce  $CO_2$  emissions



# Challenges of the transport sector

- Downward pressure on prices

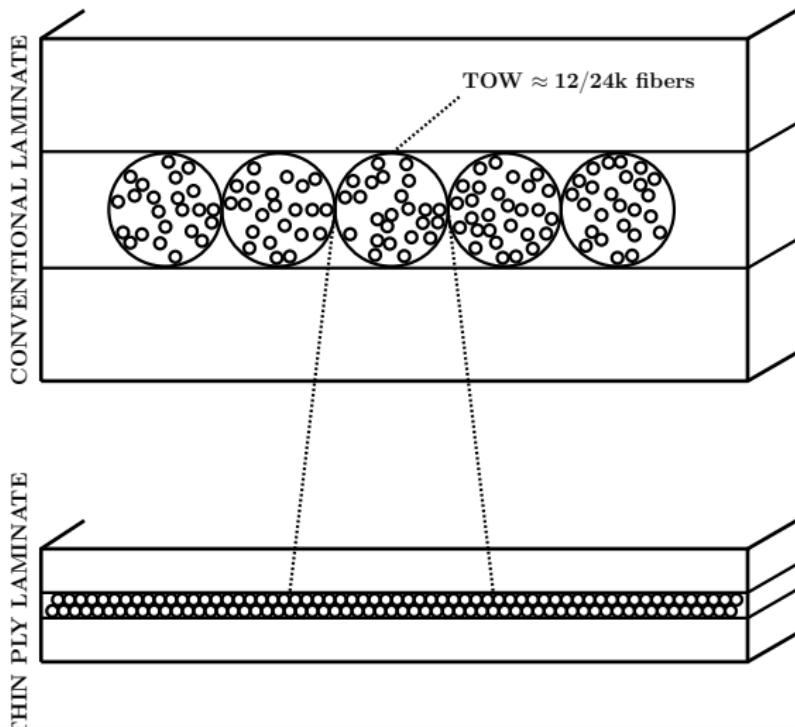


## Challenges of the transport sector

- Strict requirements of safety and crashworthiness

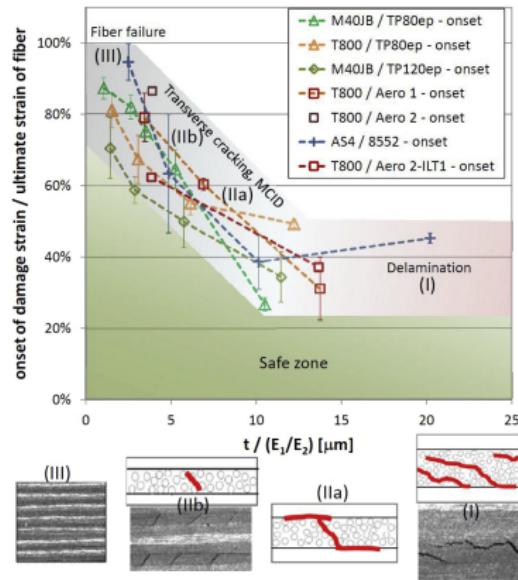


## The Thin-ply "Advantage": new material



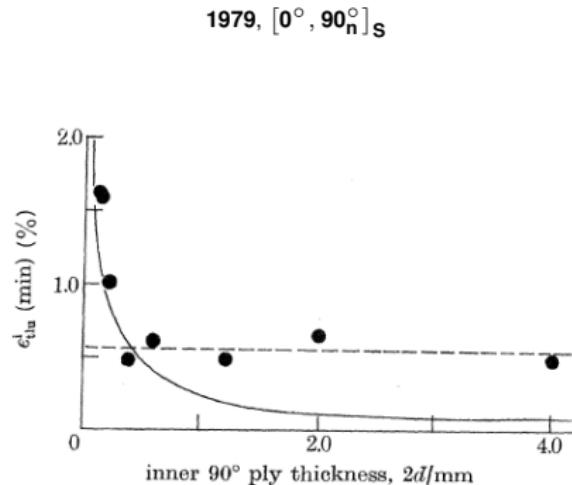
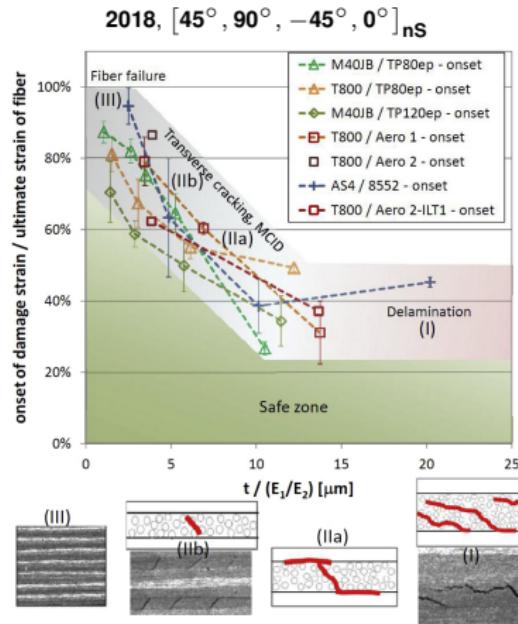
## The Thin-ply "Advantage": new material

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

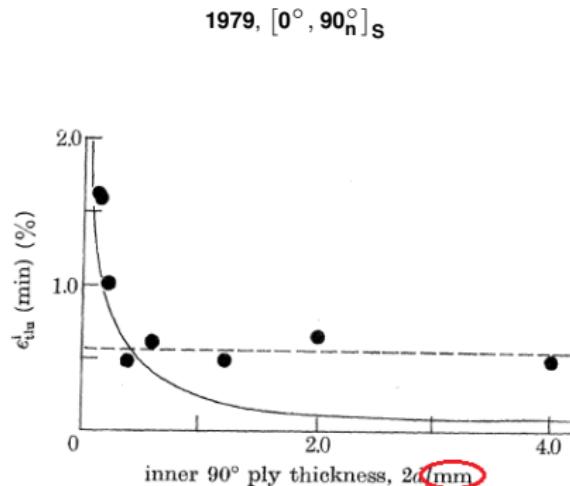
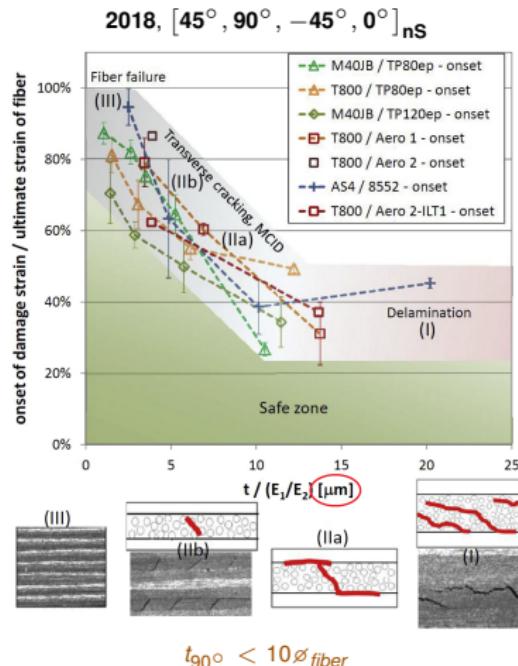


Cugnoni et al., Compos. Sci. Technol. **168**, 2018.

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



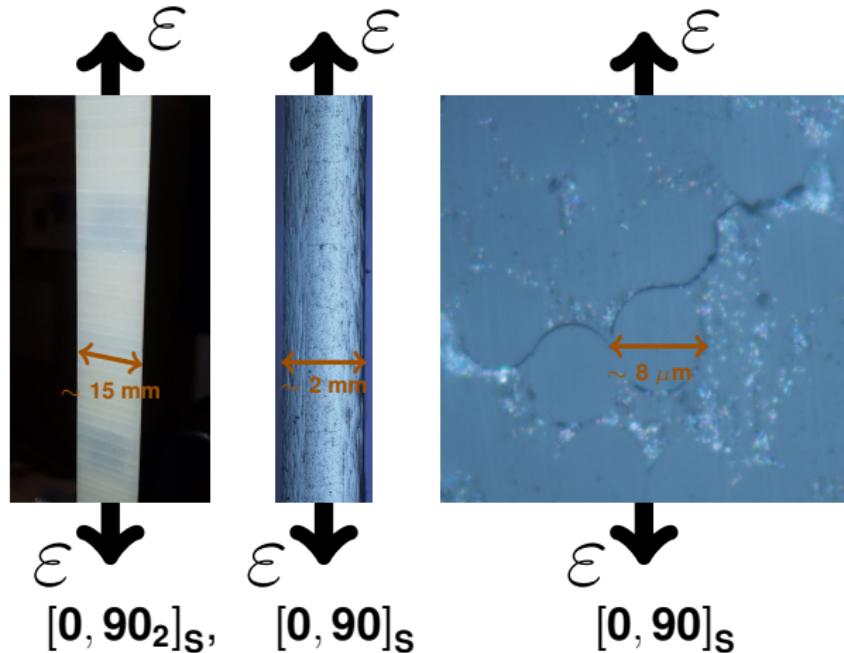
## The Thin-ply "Advantage": new material, old result?



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

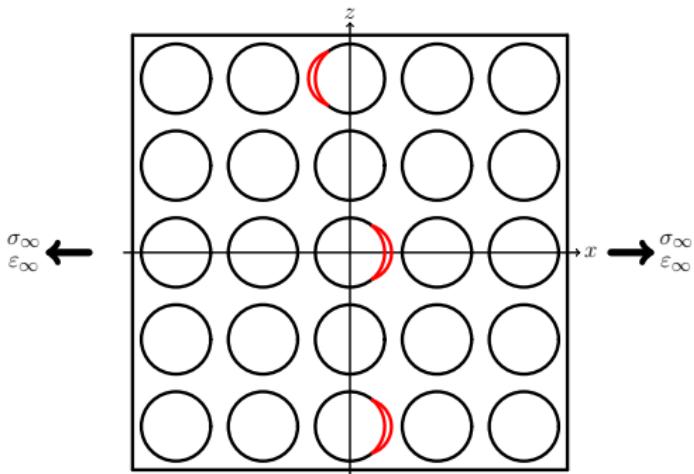
Bailey et al., P. Roy. Soc. A-Math. Phys. **366** (1727), 1979.

## Micromechanics of Initiation



## Micromechanics of Initiation

### Stage 1: isolated debonds



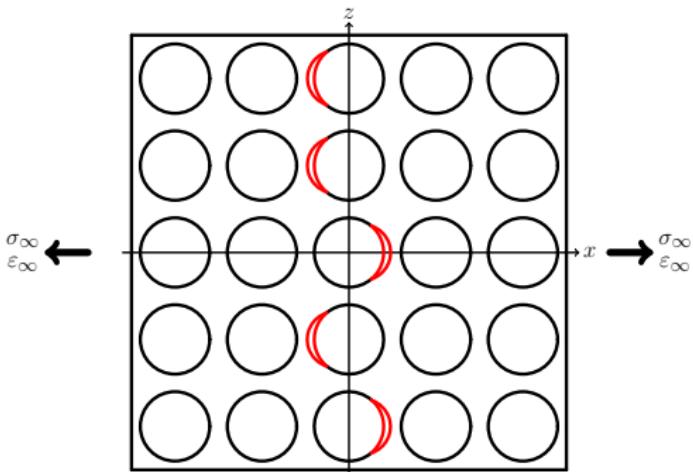
Bailey et al., P. Roy. Soc. A-Math. Phy. **366** (1727), 1979.

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



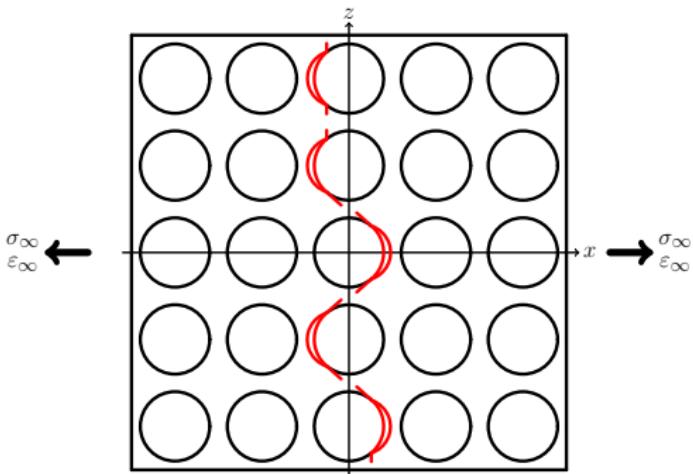
Bailey et al., P. Roy. Soc. A-Math. Phy. **366** (1727), 1979.

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

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

## Micromechanics of Initiation

### Stage 3: kinking



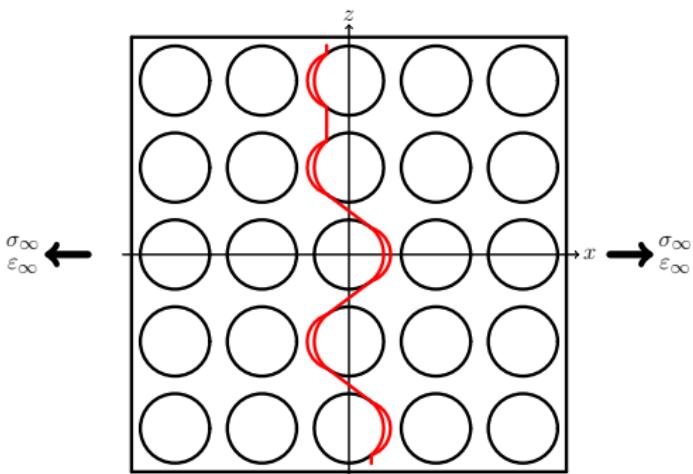
Bailey et al., P. Roy. Soc. A-Math. Phy. **366** (1727), 1979.

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

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

## Micromechanics of Initiation

### Stage 4: coalescence



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

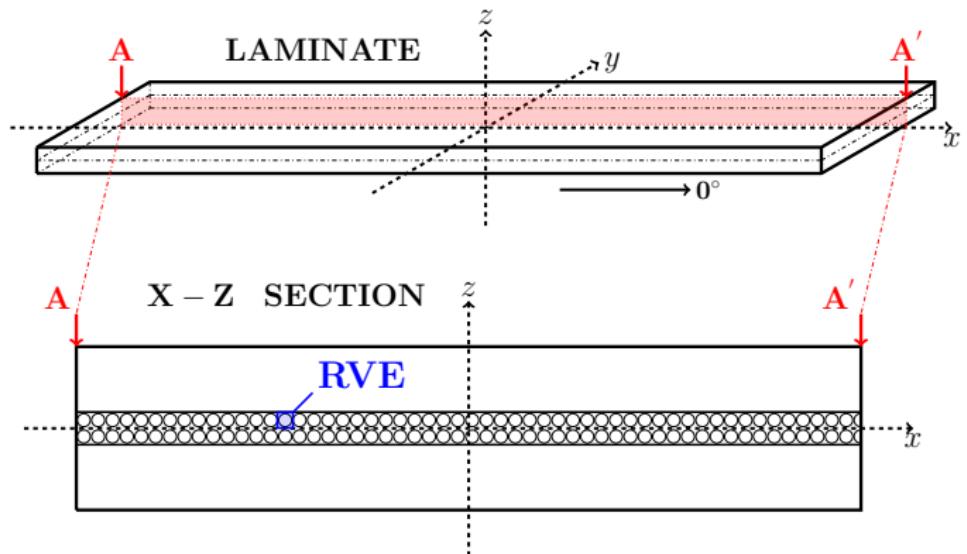
Bailey et al., J. Mater. Sci. **16** (3), 1981.

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

Introduction Modeling Convergence Debond Initiation Debond Propagation Moving Forward  
Geometry Representative Volume Elements Equivalent boundary conditions Assumptions Solution

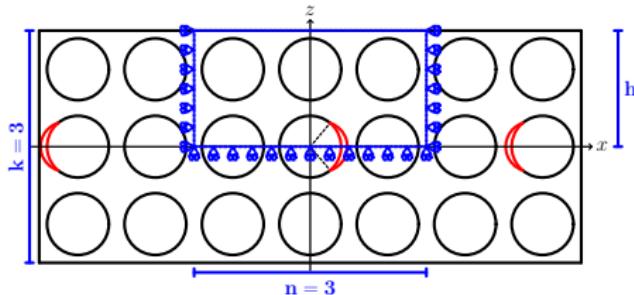
## MODELING

## Geometry



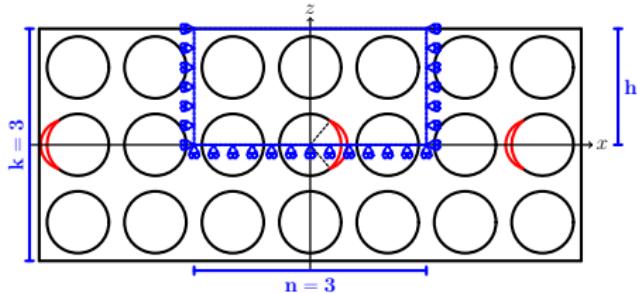
- $L, W \gg t$
- $L, W \rightarrow \infty$
- Square packing
- $L_d \gg \Delta\theta_d$
- 2D RVE

## Representative Volume Elements



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

## Representative Volume Elements

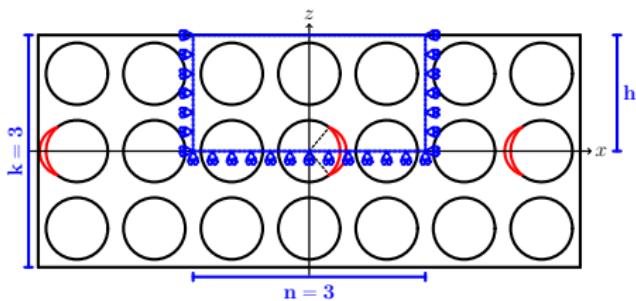


$n \times k - \text{free}$

$n \times k - H$

$$H : u_x(x, h) = \bar{\varepsilon}_x x$$

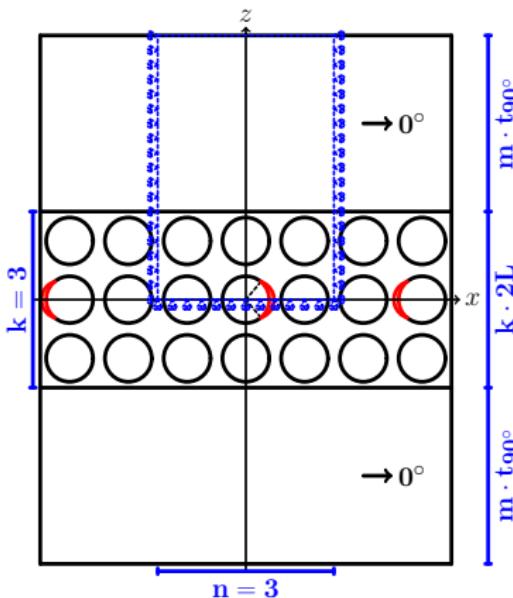
## Representative Volume Elements



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

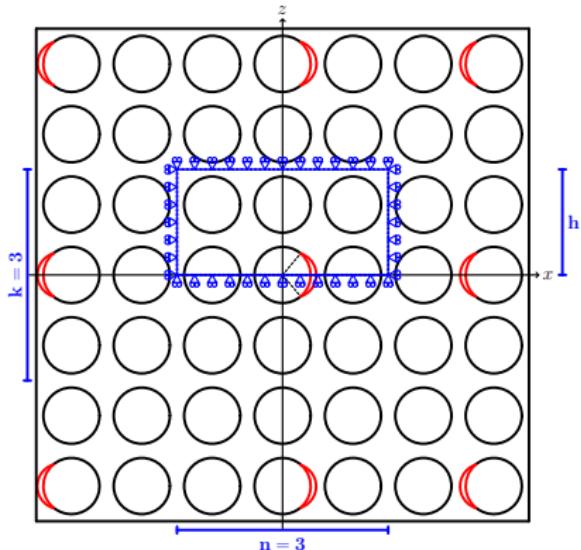
$n \times k - H$

$$H: u_x(x, h) = \bar{\varepsilon}_x x$$



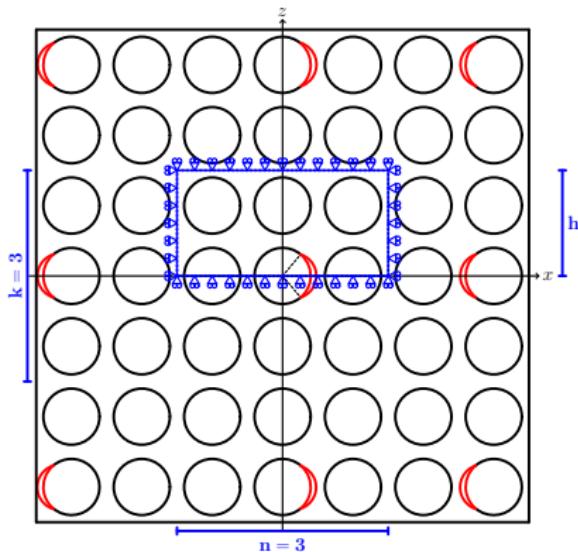
$$n \times k - m \cdot t_{90^\circ}$$

## Representative Volume Elements



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

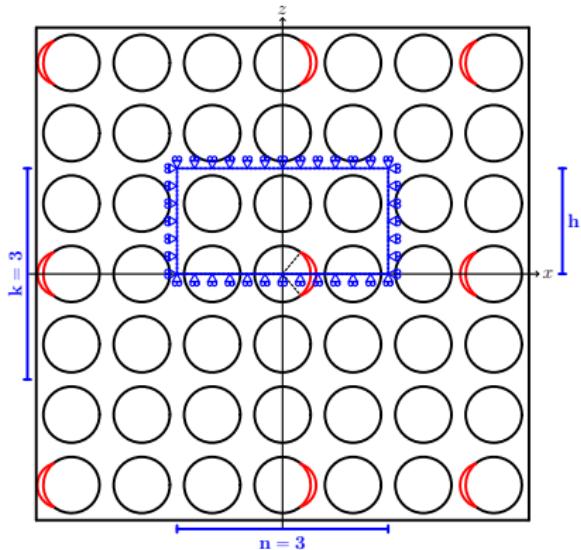
## Representative Volume Elements



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

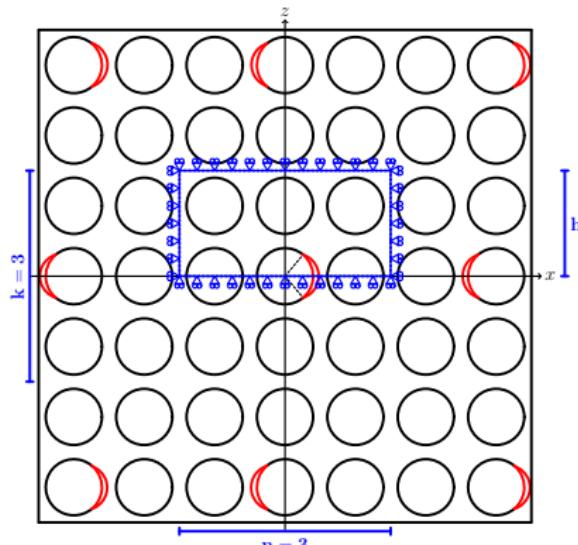
$n \times k - \text{coupling} + H$

## Representative Volume Elements



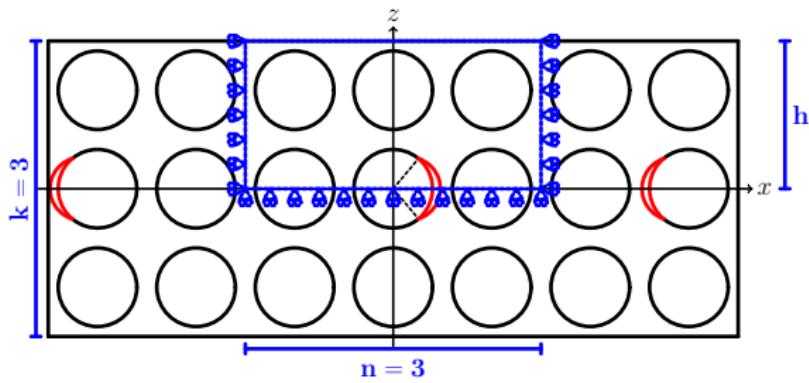
$n \times k - \text{symm (coupling)}$

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



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

## Equivalent boundary conditions: linear horizontal displacement ( $H$ )

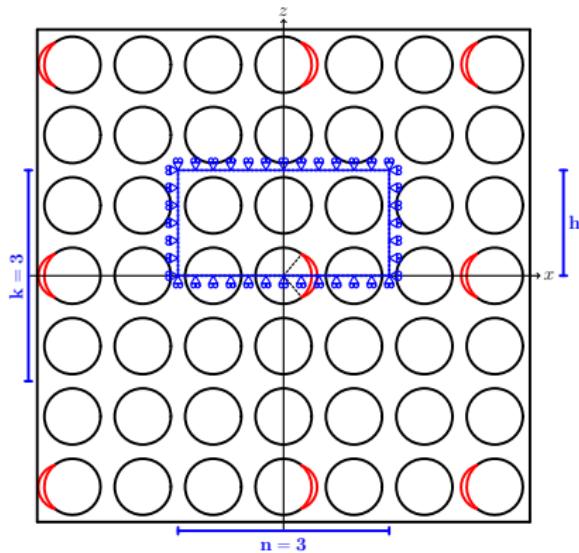


$$n \times k - H$$

$$\bar{\varepsilon}_x = \text{const}$$

$$u_x(x, h) = \bar{\varepsilon}_x x$$

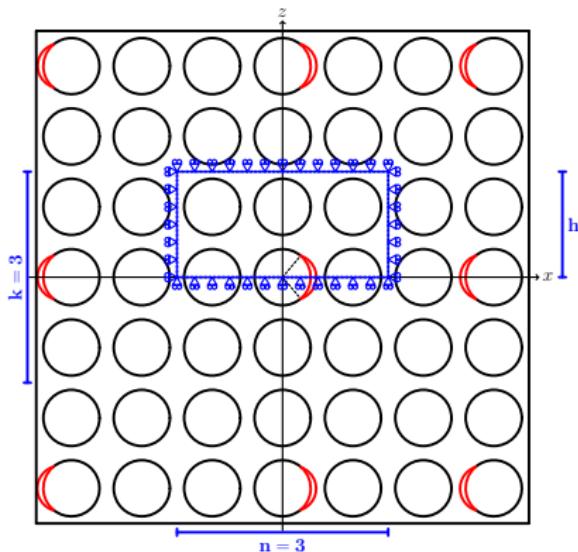
## Equivalent boundary conditions: symmetric coupling



$$u_z(x, h) = \text{const}$$

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

## Equivalent boundary conditions: coupling + H



$$u_z(x, h) = \text{const}$$

$$\bar{\varepsilon}_x = \text{const}$$

$$u_x(x, h) = \bar{\varepsilon}_x x$$

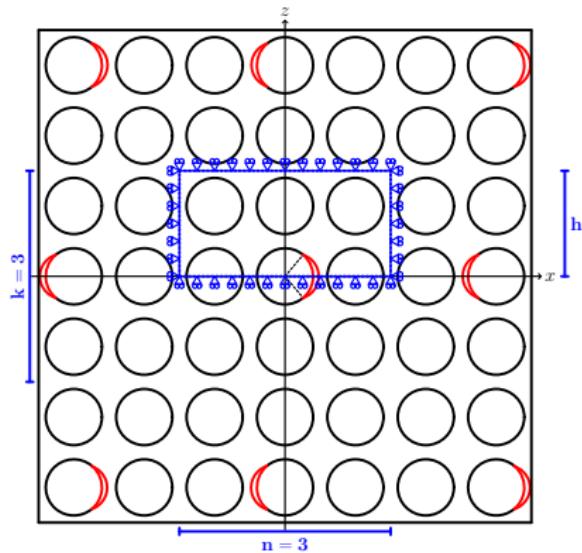
$$n \times k - \text{coupling} + H$$

## Equivalent boundary conditions: anti-symmetric coupling

New set of BC!

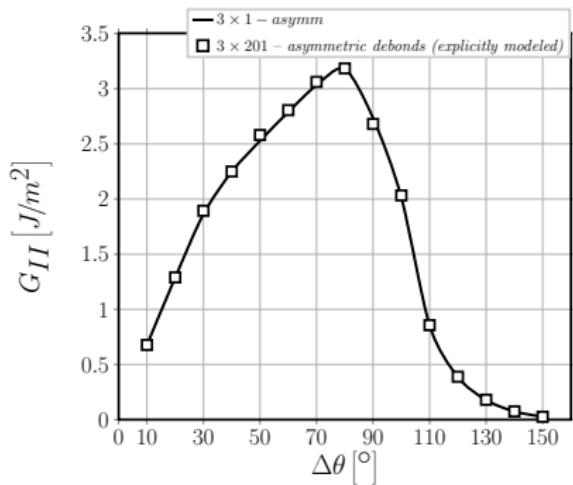
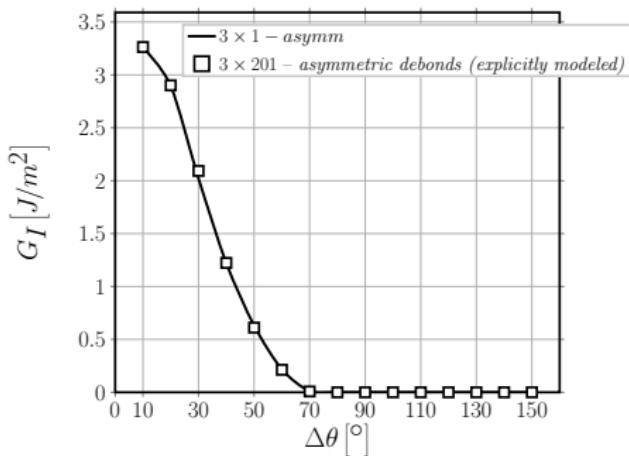
To represent debonds appearing on alternating sides along the vertical direction.

$$\begin{aligned} u_z(x, h) - u_z(0, h) &= \\ &- (u_z(-x, h) - u_z(0, h)) \\ u_x(x, h) &= -u_x(-x, h) \end{aligned}$$

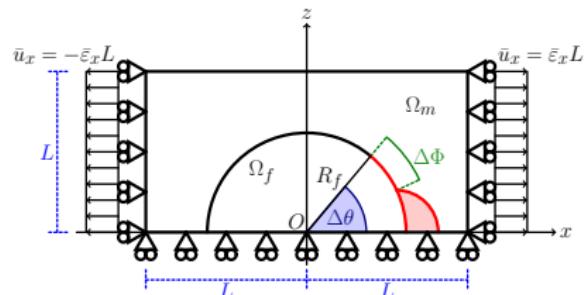


$n \times k - \text{asym}$

## Equivalent boundary conditions: anti-symmetric coupling, validation



## Assumptions

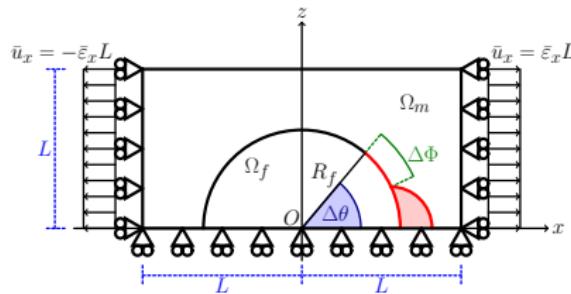


$$R_f = 1 \text{ } [\mu\text{m}] \quad L = \frac{R_f}{2} \sqrt{\frac{\pi}{V_f}}$$

- 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  $\bar{\epsilon}_x = 1\%$
- $V_f = 60\%$

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



- Compatibility conditions
- Equilibrium equations
- Non-interpenetration of crack faces
- Frictionless sliding of crack faces
- $0^\circ \leq \Delta\theta \leq 150^\circ$
- $\Delta\theta = 0^\circ \leftrightarrow$  no debond!

$\forall \Delta\theta \neq 0^\circ$

- oscillating singularity
- Mode I and Mode II SIF and ERR not defined for *open crack*
- ERR over finite distance
- FEM + LEFM (VCCT)

→ receding contact

$$\frac{G(R_{f,2})}{G(R_{f,1})} = \frac{R_{f,2}}{R_{f,1}}, \frac{G(\bar{\varepsilon}_{x,2})}{G(\bar{\varepsilon}_{x,1})} = \frac{\bar{\varepsilon}_{x,2}^2}{\bar{\varepsilon}_{x,1}^2}$$

→ regular mesh of quadrilaterals at the crack tip:

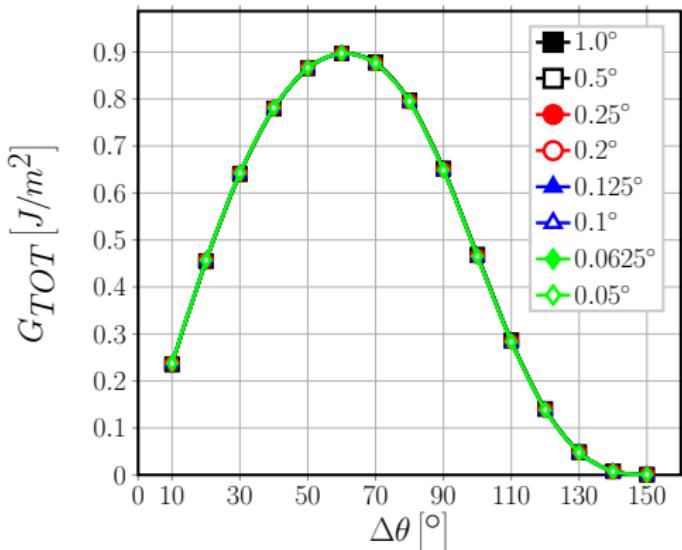
$$- AR \sim 1, \quad \delta = 0.05^\circ$$

$\forall \Delta\theta$

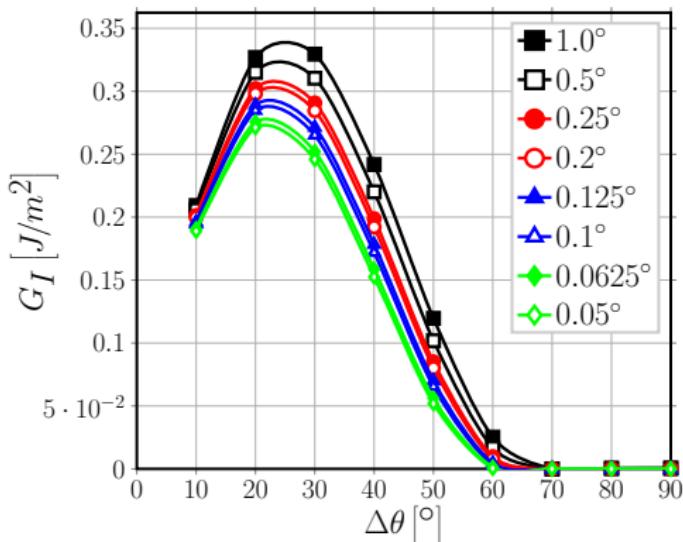
→ 2<sup>nd</sup> order shape functions

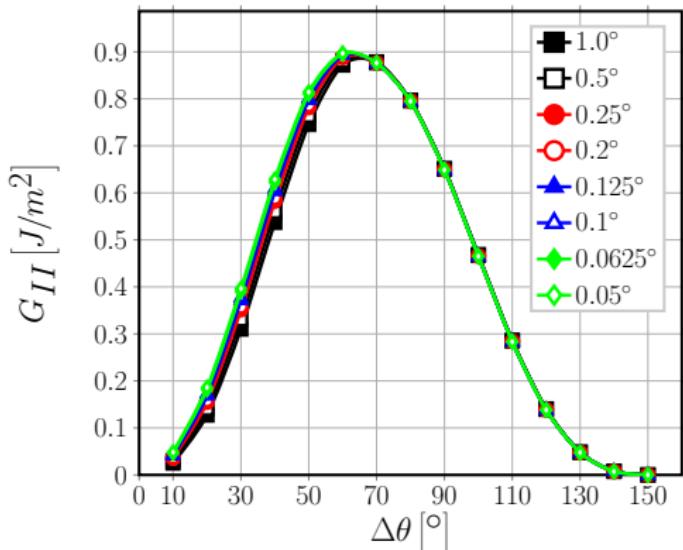
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 $G_{TOT}$   $G_I$   $G_{II}$  Vectorial formulation of VCCT Asymptotic behavior Numerical convergence Observations  $\delta$  selection

# CONVERGENCE

$G_{TOT}$ 

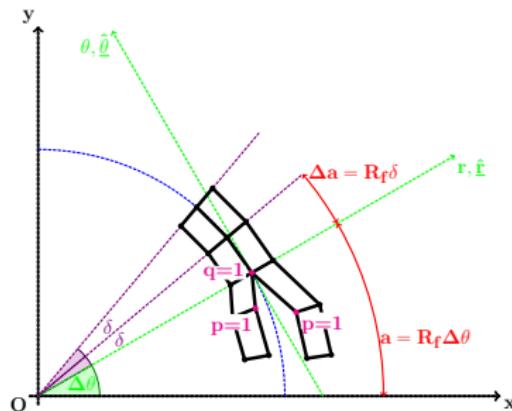
$\rightarrow 1 \times 1 - free, V_f = 0.1\%, 2^{nd} order elements$

$G_I$  $\rightarrow 1 \times 1 - free, V_f = 0.1\%, 2^{nd} \text{ order elements}$

$G_{II}$ 

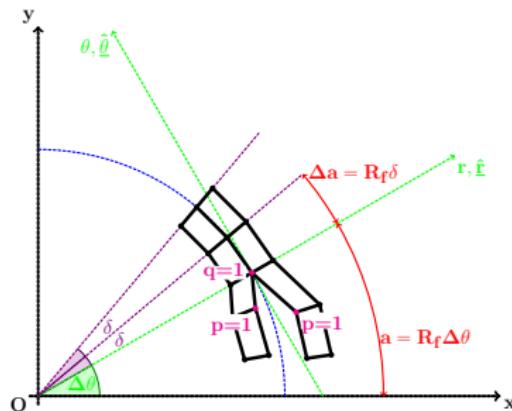
$\rightarrow 1 \times 1 - free, V_f = 0.1\%, 2^{nd} order elements$

## Vectorial formulation of VCCT



$$\begin{aligned}
 G_{TOT} = & \frac{1}{2R_f \delta} \sum_{p=1}^{m+1} \sum_{q=1}^{m+1} \text{Tr} \left( Q \underline{\underline{R}}_{\underline{\underline{\delta}}=\Delta\theta} \underline{\underline{K}}_{xy,q} \underline{u}_{xy,q}^T \underline{\underline{u}}_{xy,p} \underline{\underline{R}}_{\underline{\underline{\delta}}=\Delta\theta}^T \underline{\underline{P}}_{pq}^T \underline{\underline{T}}_{pq}^T \right) + \\
 & + \frac{1}{2R_f \delta} \sum_{p=1}^{m+1} \sum_{q=1}^{m+1} \text{Tr} \left( Q \underline{\underline{R}}_{\underline{\underline{\delta}}=\Delta\theta} \widetilde{\underline{\underline{F}}}_{xy,q} \underline{u}_{xy,p}^T \underline{\underline{R}}_{\underline{\underline{\delta}}=\Delta\theta}^T \underline{\underline{P}}_{pq}^T \underline{\underline{T}}_{pq}^T \right)
 \end{aligned}$$

## Vectorial formulation of VCCT



$$\begin{aligned} \underline{G} = \begin{bmatrix} G_I \\ G_{II} \end{bmatrix} &= \frac{1}{2R_f\delta} \sum_{p=1}^{m+1} \sum_{q=1}^{m+1} \text{Diag} \left( Q_{\underline{\delta}=\Delta\theta} R_{\underline{\Delta\theta}=\underline{\delta}} K_{\underline{x}_{xy},q} u_{xy,q}^T R_{\underline{\Delta\theta}=\underline{\delta}}^T P_{\underline{\delta}=pq}^T T^T \right) + \\ &+ \frac{1}{2R_f\delta} \sum_{p=1}^{m+1} \sum_{q=1}^{m+1} \text{Diag} \left( Q_{\underline{\delta}=\Delta\theta} R_{\underline{\Delta\theta}=\underline{\delta}} \tilde{K}_{N,q} u_N^T u_{xy,p}^T R_{\underline{\Delta\theta}=\underline{\delta}}^T P_{\underline{\delta}=pq}^T T^T \right) \end{aligned}$$

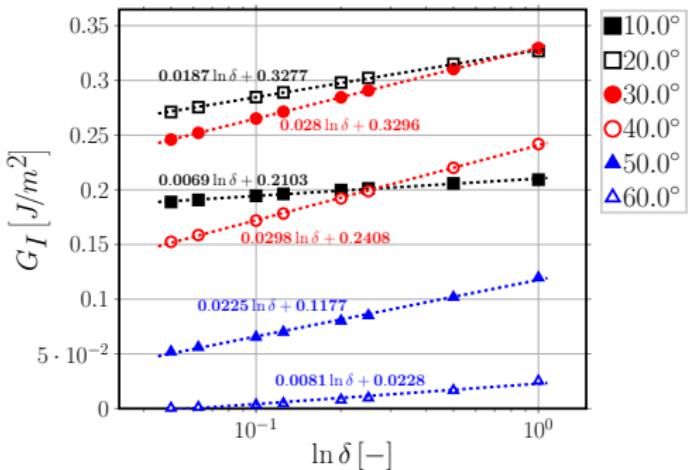
## Asymptotic behavior

$$\frac{\partial \underline{G}}{\partial \delta} = \frac{1}{\delta} \underline{G} + \frac{1}{2R_f \delta} (\dots)$$

$$u(\delta) \sim \sqrt{\delta} (\sin, \cos)(\epsilon \log \delta) \quad \text{with} \quad \epsilon = \frac{1}{2\pi} \log \left( \frac{1-\beta}{1+\beta} \right)$$

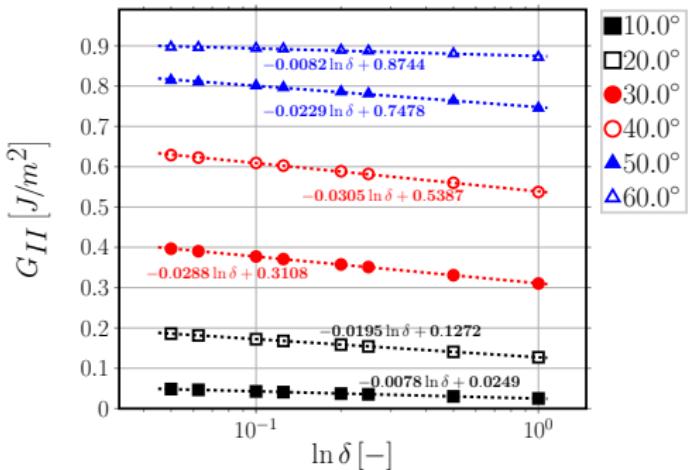
$$\lim_{\delta \rightarrow 0} \frac{\partial \underline{G}}{\partial \delta} \sim \frac{1}{\delta} \xrightarrow{\int d\delta} \lim_{\delta \rightarrow 0} \underline{G} \sim \underline{A} \log(\delta) + \underline{B}.$$

## Numerical convergence: $G_I$



$\rightarrow 1 \times 1 - free, V_f = 0.1\%, 2^{nd} order elements$

## Numerical convergence: $G_{II}$



$\rightarrow 1 \times 1 - \text{free}, V_f = 0.1\%, 2^{\text{nd}} \text{ order elements}$

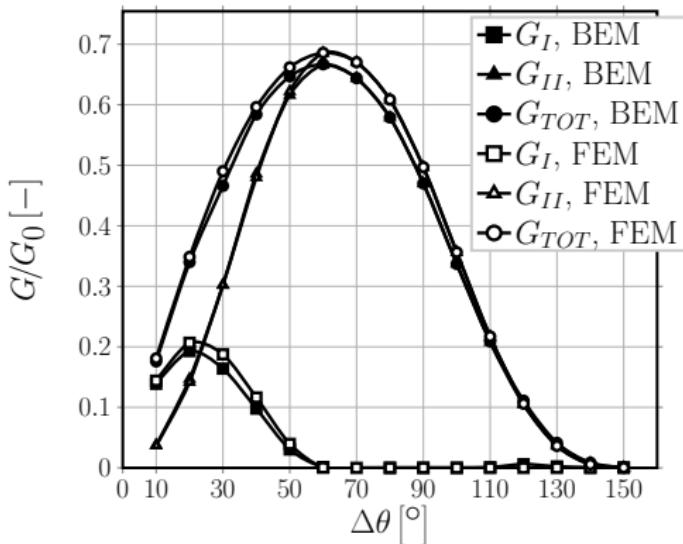
## Observations

- Total ERR does not depend on element size at the crack tip in any configuration of the crack.
- For the *close crack*, Mode II ERR does not depend on element size, as it is equal to the total ERR.
- For the *open crack*, Mode I and Mode II ERR depend logarithmically on element size.
- For the *open crack*, Mode I and Mode II ERR are not bounded.

**It seems reasonable to conclude that...**

...a criterion based on the reduction of the error between successive iterations is inadequate to identify the optimal element size. The FEM model has to be validated with respect to external data (experimental, analytical or numerical from a different method).

## $\delta$ selection

París et al., J. Appl. Mech. **74** (4), 2007.Sandino et al., Eng. Fract. Mech. **168**, 2016. $\rightarrow 1 \times 1 - free, V_f = 0.01\%, 2^{nd} \text{ order elements}, \delta = 0.05^\circ$

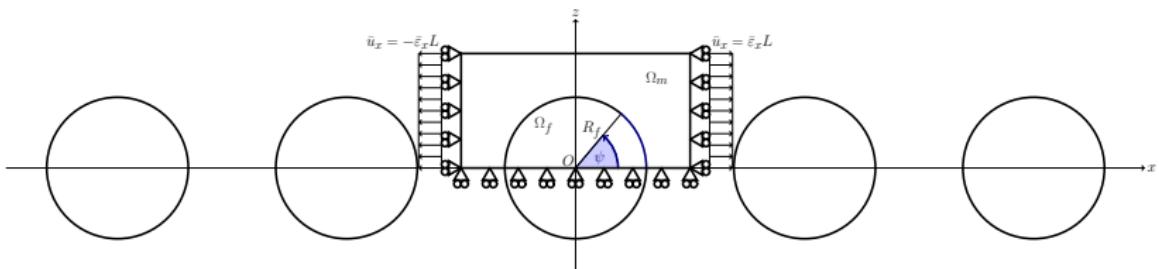
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Analysis of initiation: main features Stress profiles in the matrix at the interface Observations

## DEBOND INITIATION

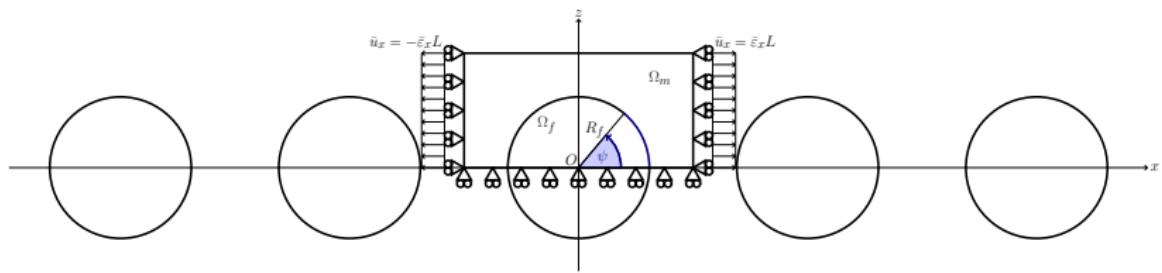
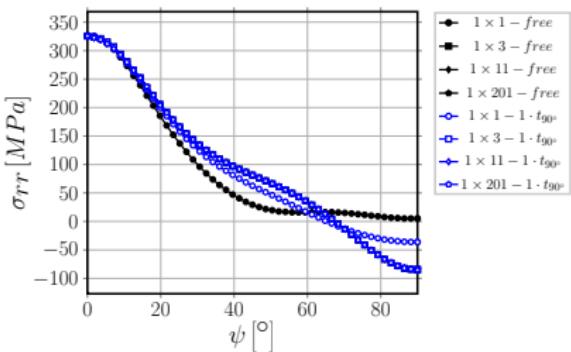
## Analysis of initiation: main features

NO DEBOND!

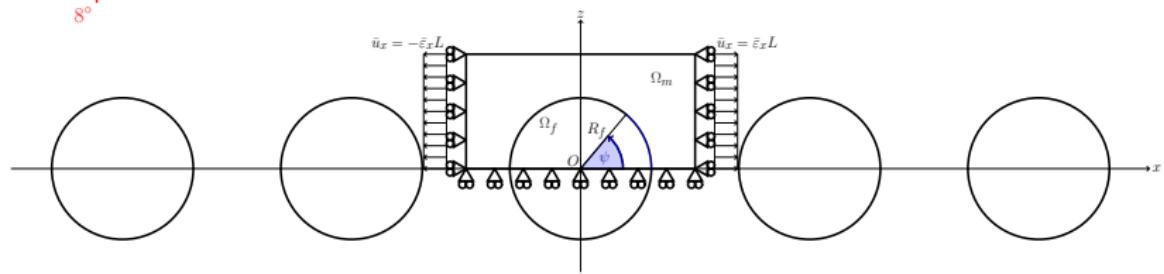
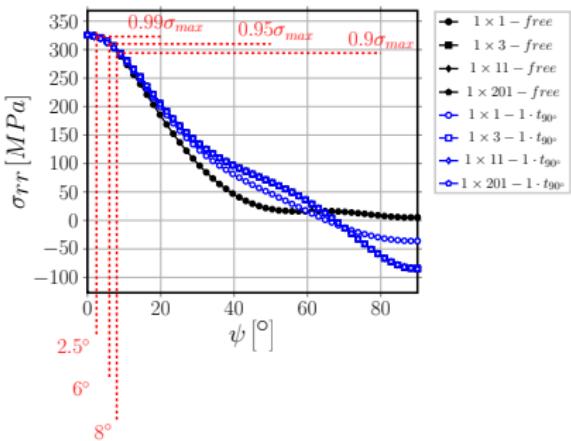


- No stress-based initiation criterion is assumed
- Profiles of stresses in the matrix at the interface are analyzed
- Where does the maximum occur? How fast does the stress decrease from the peak value?
- Effect of thickness of UD/90° ply? Effect of the presence of 0° ply?

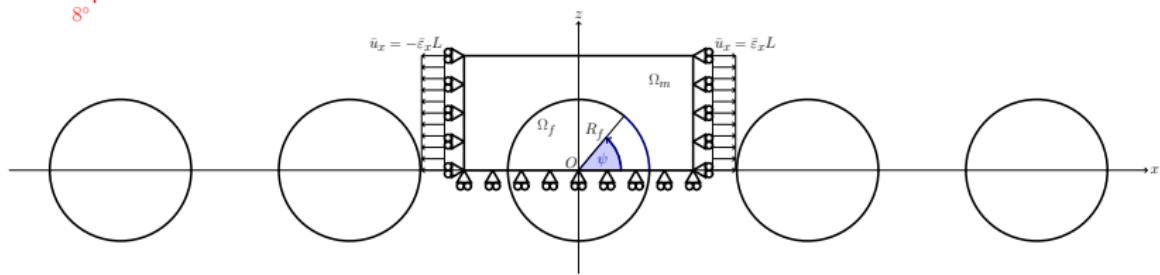
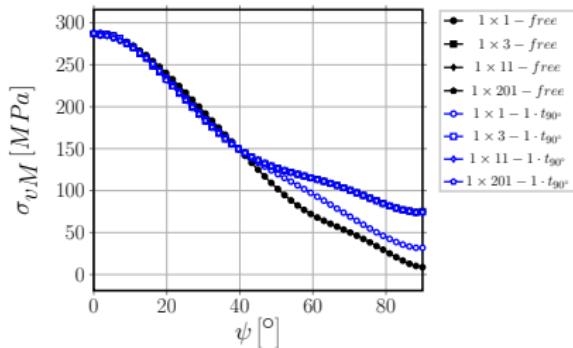
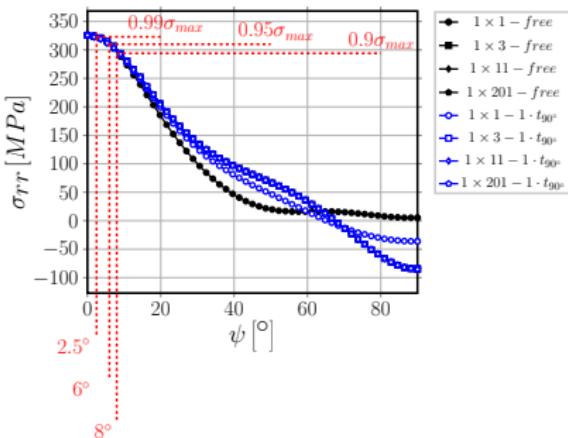
## Stress profiles in the matrix at the interface



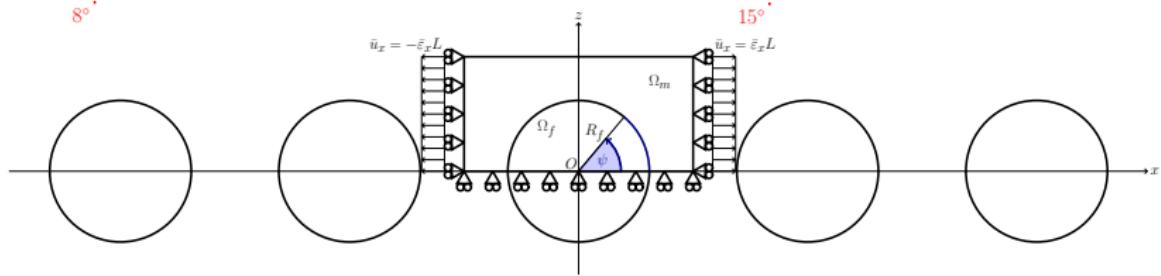
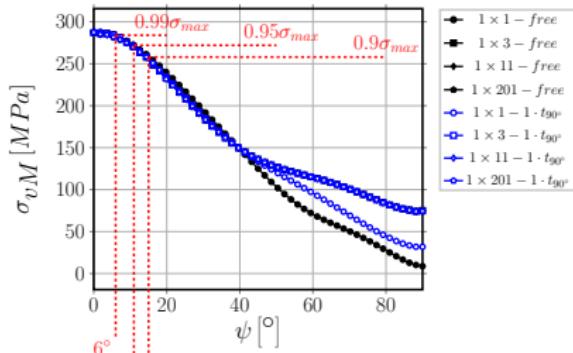
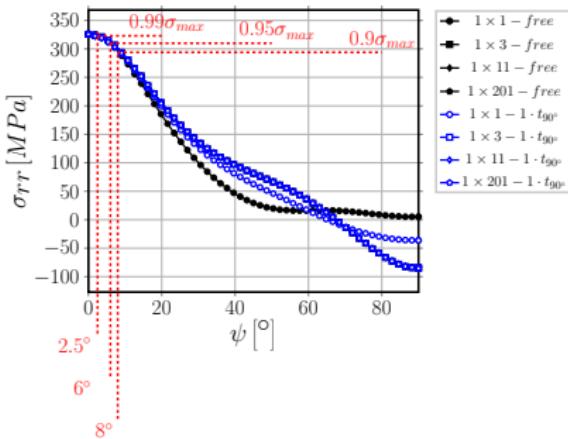
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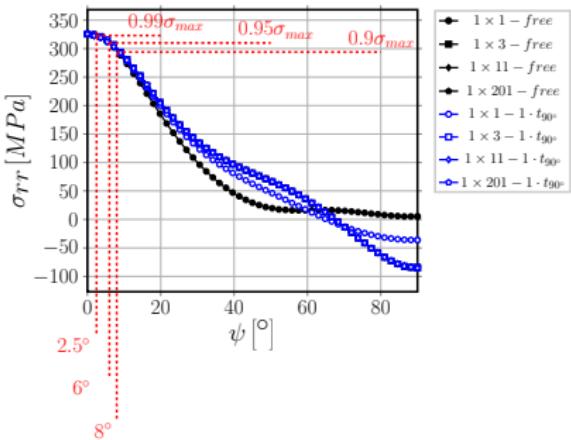
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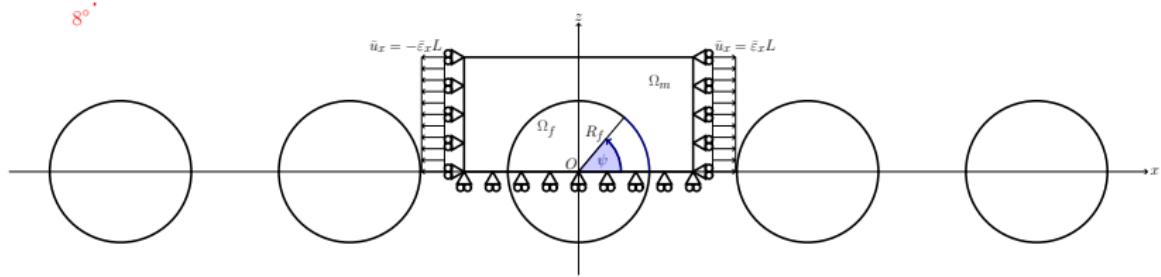
## Stress profiles in the matrix at the interface



Similar results for:

$$\sigma_{LHS,2D} - \sigma_{LHS,3D}$$

$$\sigma_{LMPS,2D} - \sigma_{LMPS,3D}$$



## Observations

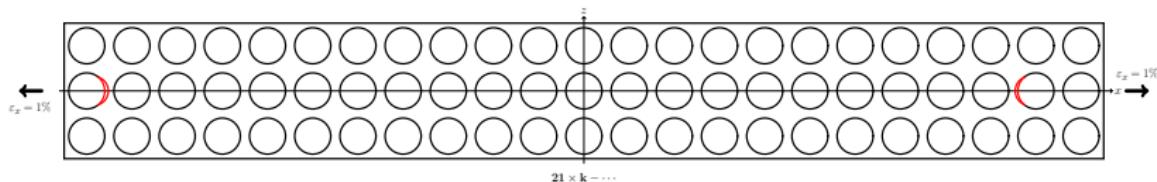
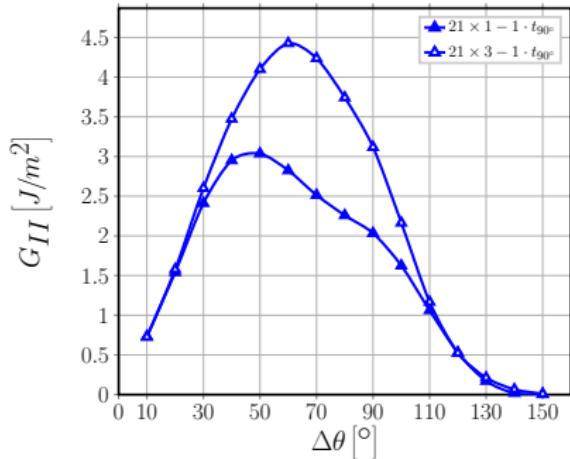
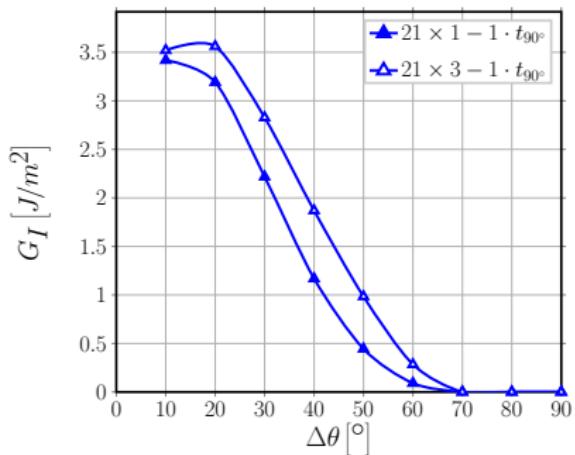
- For all stresses analyzed, no significant difference is present between the different RUCs for  $\psi \leq 10^\circ$ ;
- for all stresses analyzed, no difference can be observed by increasing  $k$  when  $k \geq 3$ ;
- for all stresses analyzed, no difference can be observed between  $1 \times k - \text{free}$  and  $1 \times k - 1 \cdot t_{90^\circ}$  for  $k \geq 3$ ;
- $\sigma_{rr}$ ,  $\sigma_{LHS,2D}$ ,  $\sigma_{LHS,3D}$ ,  $\sigma_{vM,2D}$ ,  $\sigma_{LMPS,2D}$  and  $\sigma_{LMPS,3D}$  all reach their peak value at  $0^\circ$  and  $180^\circ$  and decrease to 99% the peak value between  $2^\circ$  and  $8^\circ$ , to 95% the peak value between  $6^\circ$  and  $12^\circ$  and to 90% the peak value between  $8^\circ$  and  $15^\circ$  from the occurrence of the maximum.

**It seems reasonable to conclude that...**

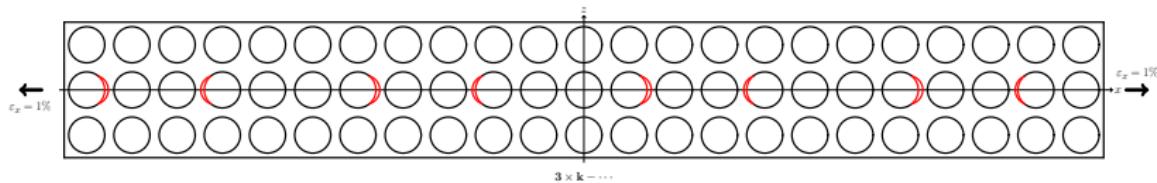
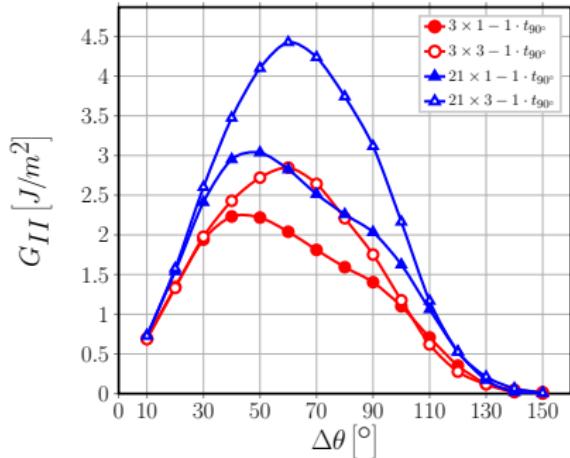
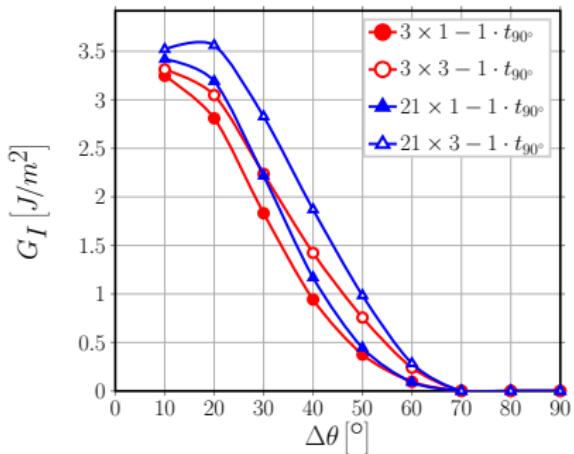
...a stress-based criterion would predict, irrespectively of the specific criterion chosen, the onset of an interface crack at  $0^\circ$  or  $180^\circ$  with an initial size at least comprised in the range  $2^\circ - 8^\circ$  (1% margin) and likely in the range  $6^\circ - 12^\circ$  (5% margin). Thus, no evident effect of  $90^\circ$  or  $0^\circ$  layer thickness can be observed.

# DEBOND PROPAGATION

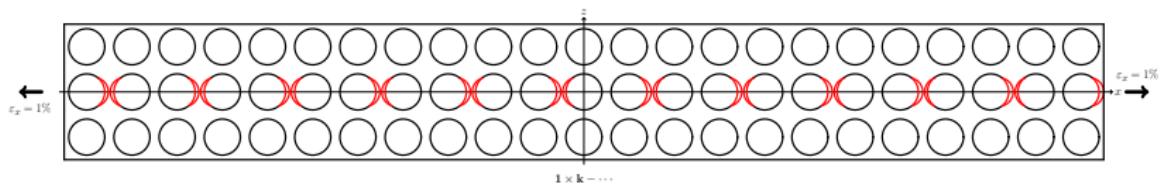
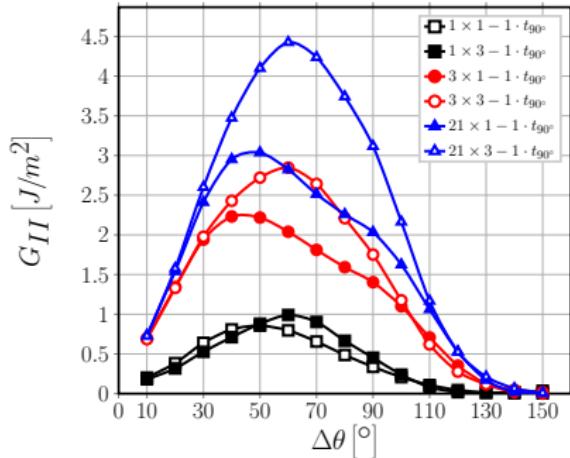
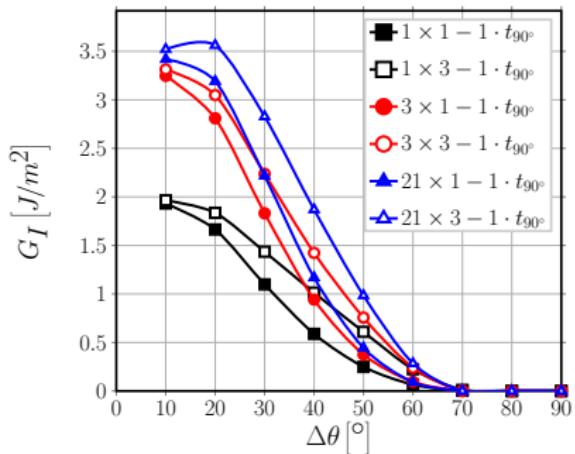
## Debond interaction: horizontal (loading) direction



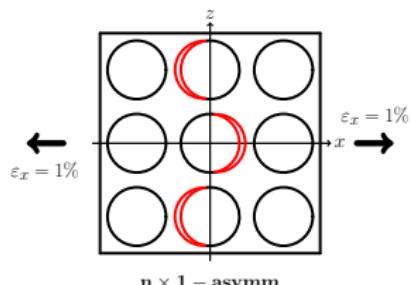
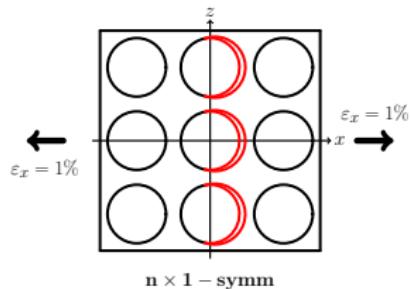
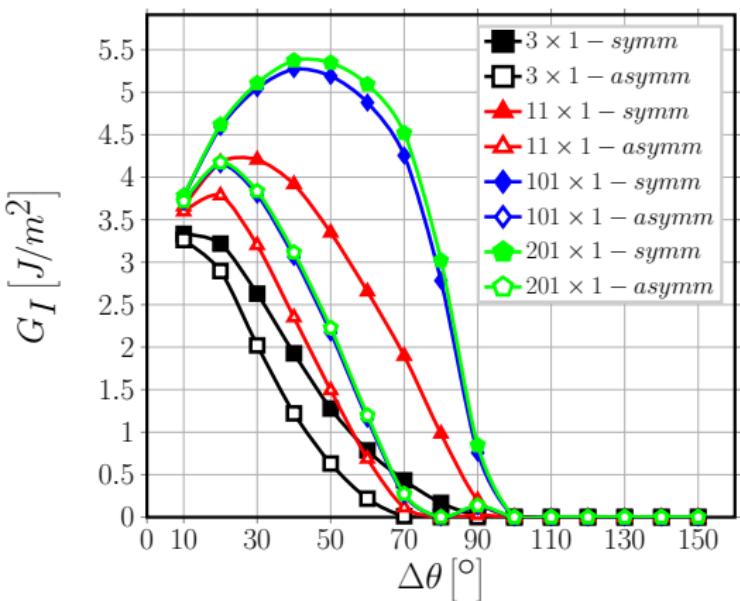
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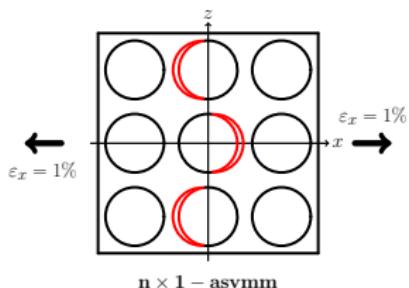
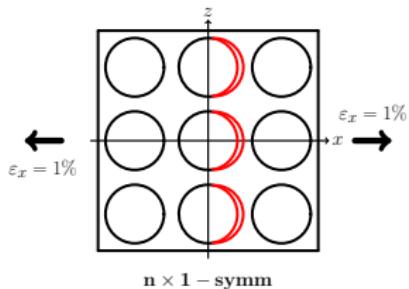
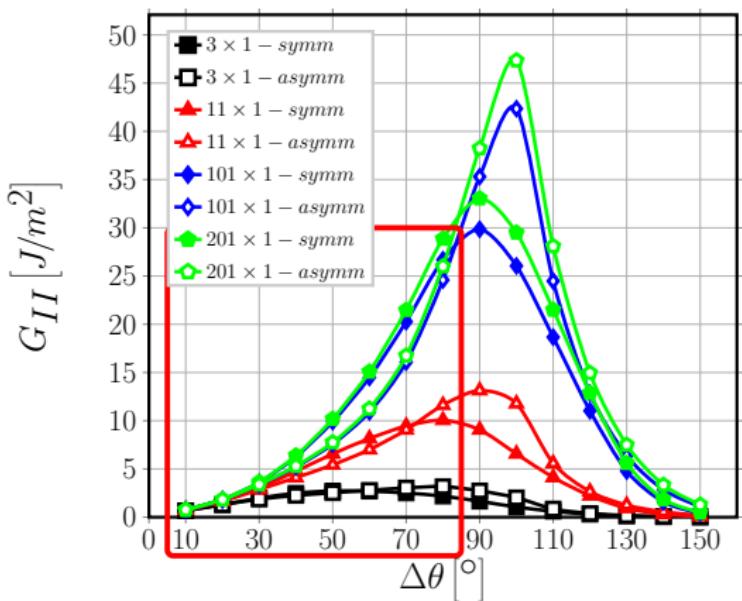
## Debond interaction: horizontal (loading) direction



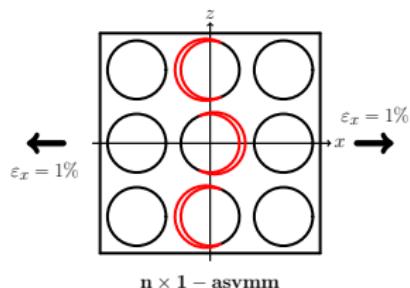
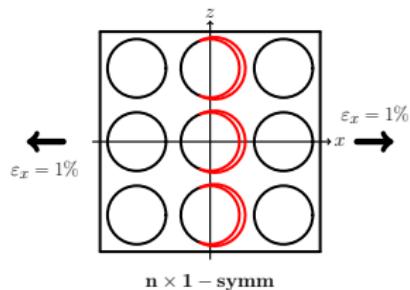
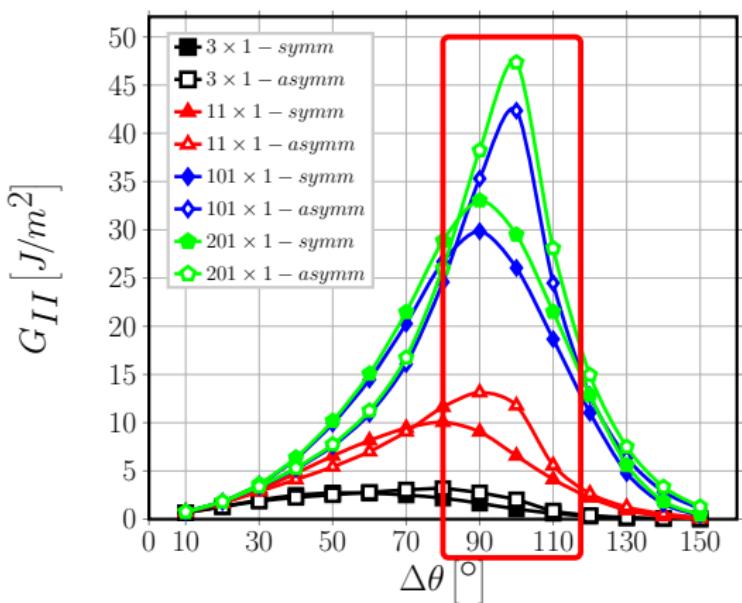
## Consecutive Debonds: Mode I



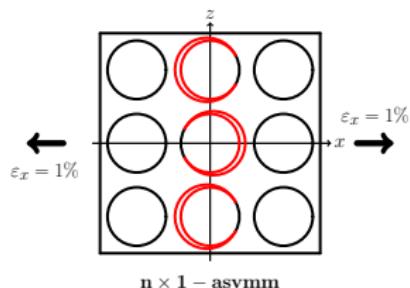
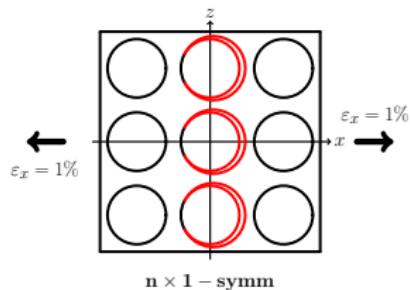
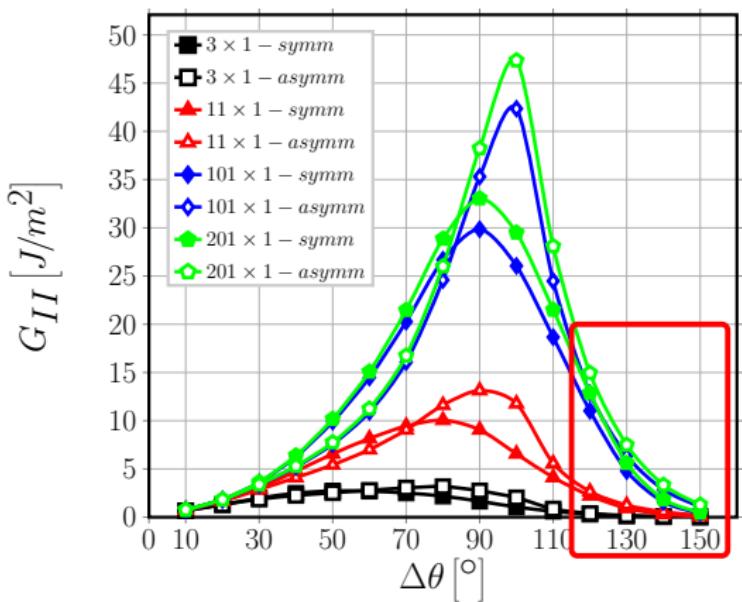
## Consecutive Debonds: Mode II



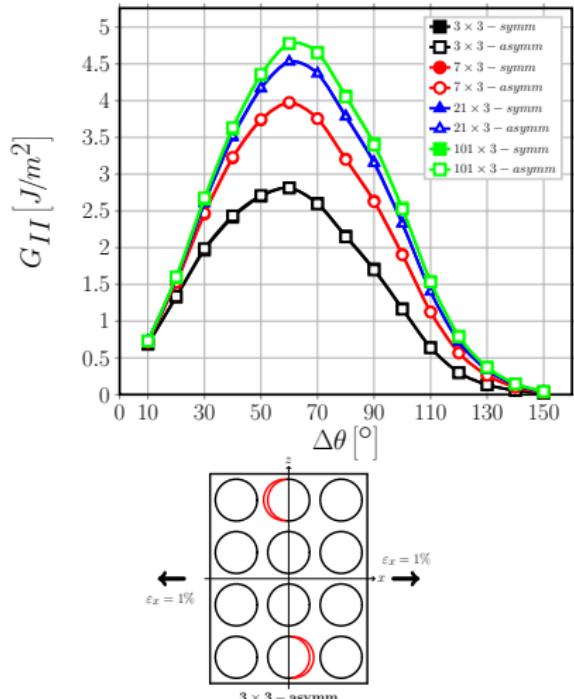
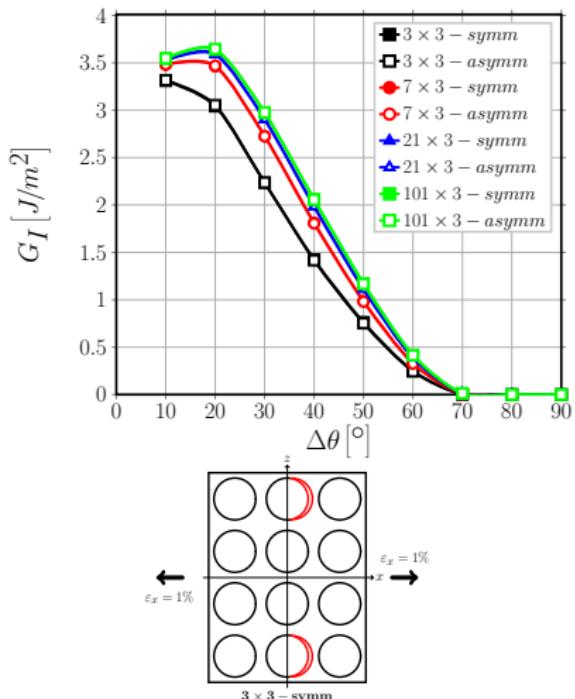
## Consecutive Debonds: Mode II



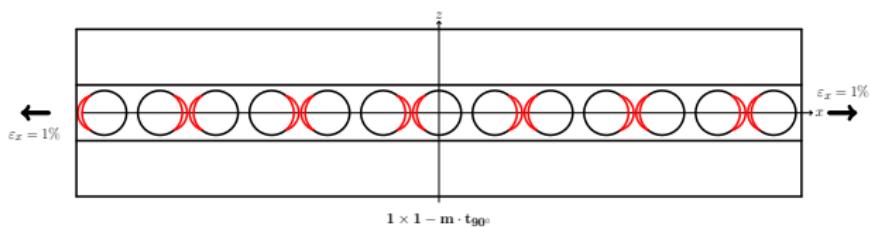
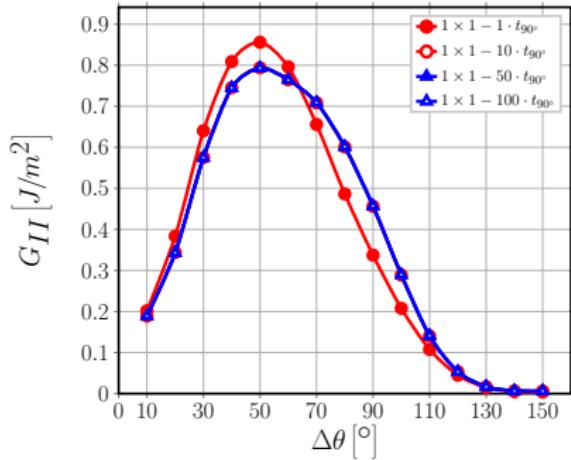
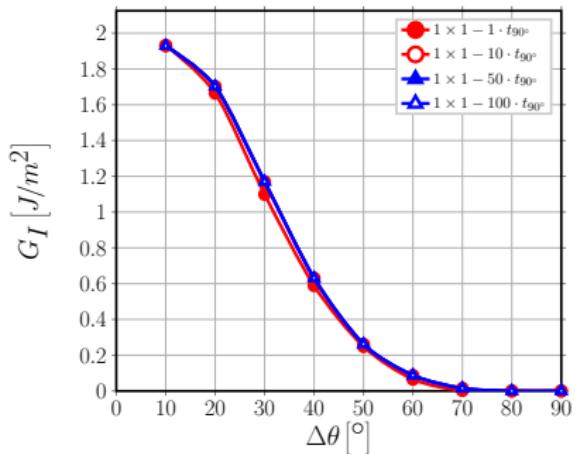
## Consecutive Debonds: Mode II



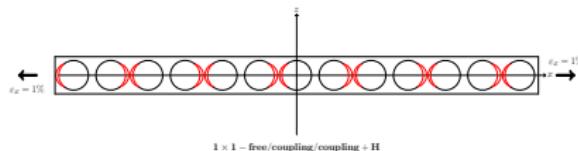
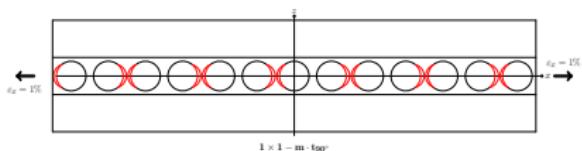
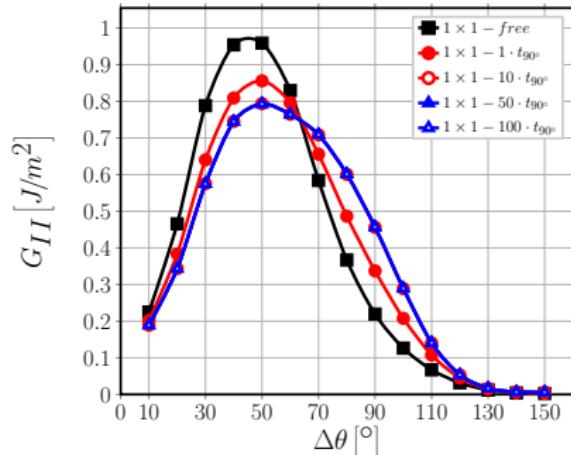
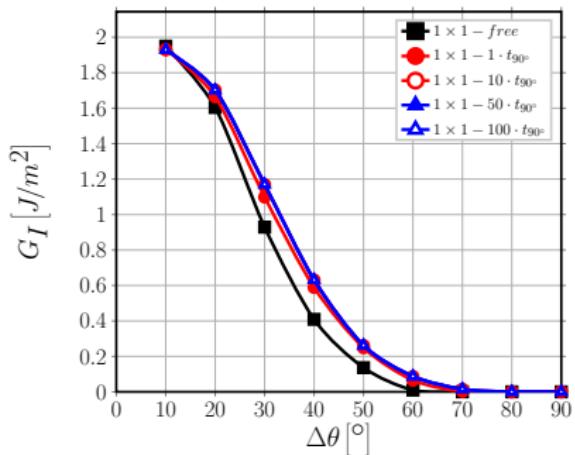
## Non-Consecutive Debonds



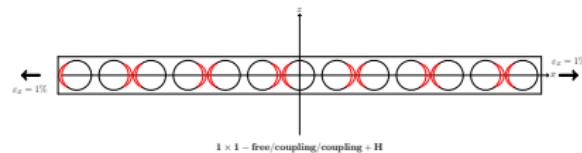
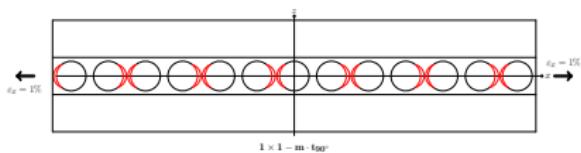
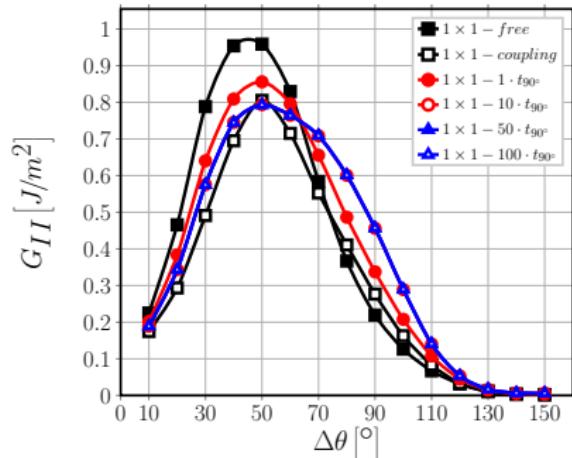
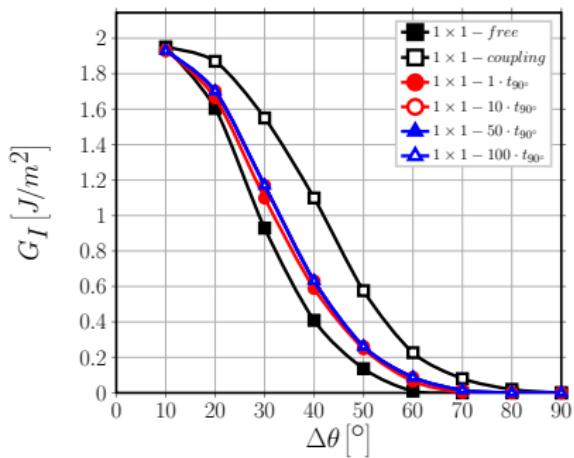
## Effect of $0^\circ$ ply thickness



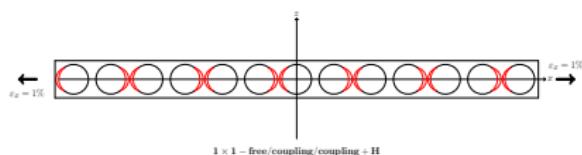
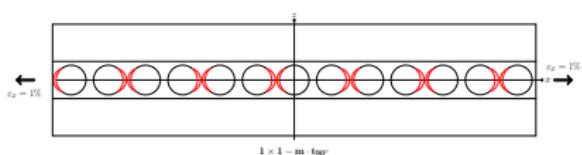
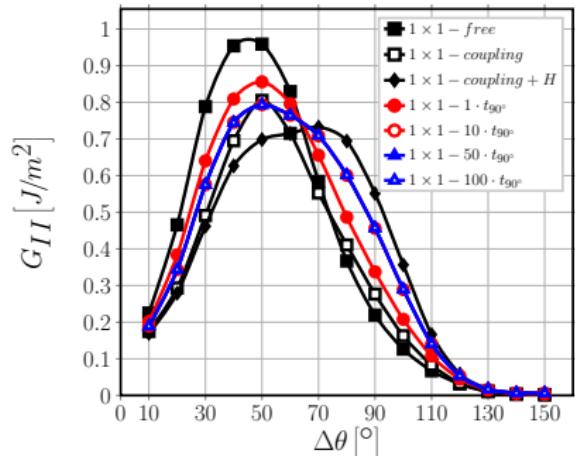
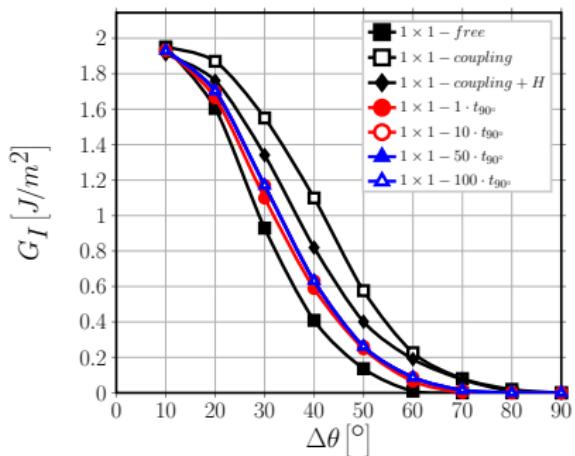
## Effect of the presence of $0^\circ$ ply: comparison with equivalent BC



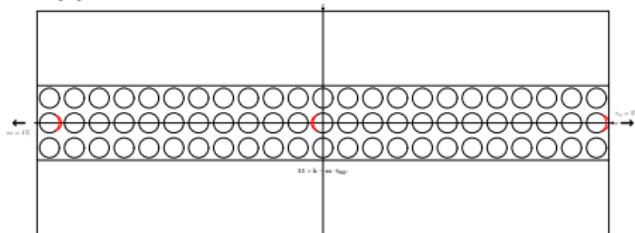
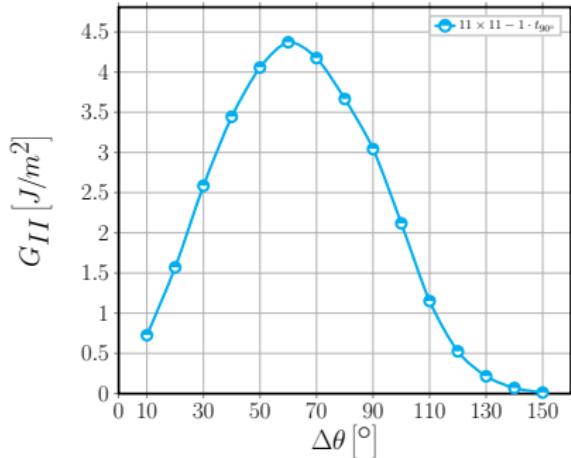
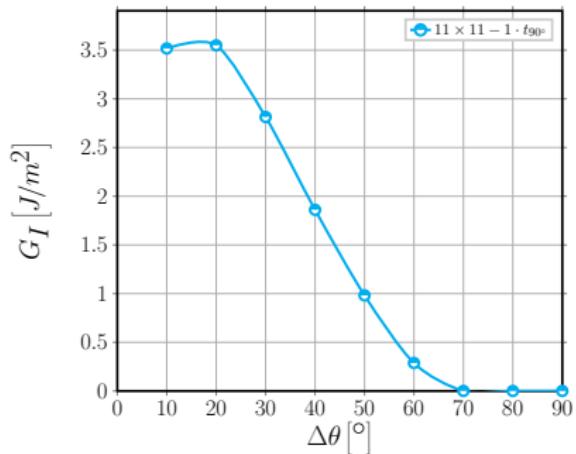
## Effect of the presence of $0^\circ$ ply: comparison with equivalent BC



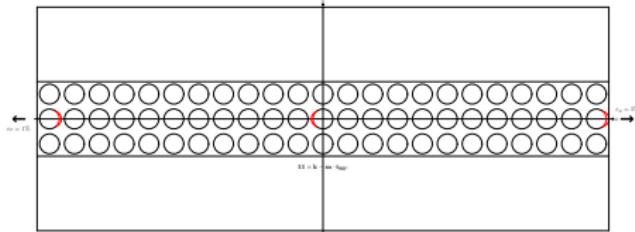
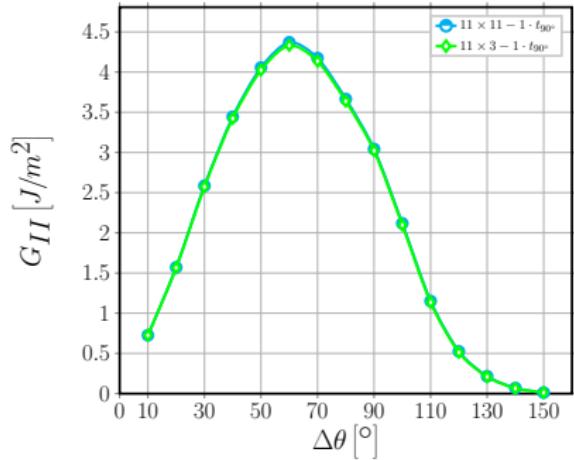
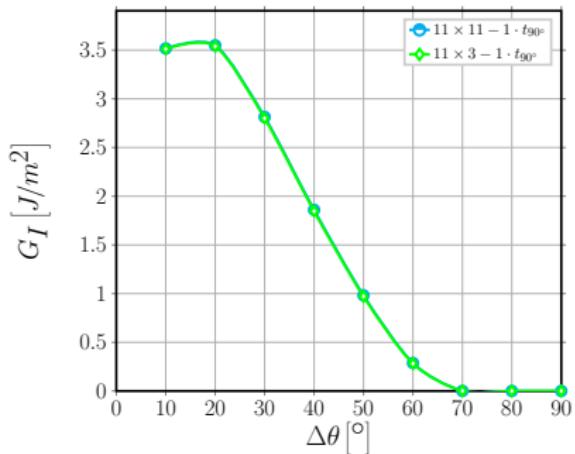
## Effect of the presence of $0^\circ$ ply: comparison with equivalent BC



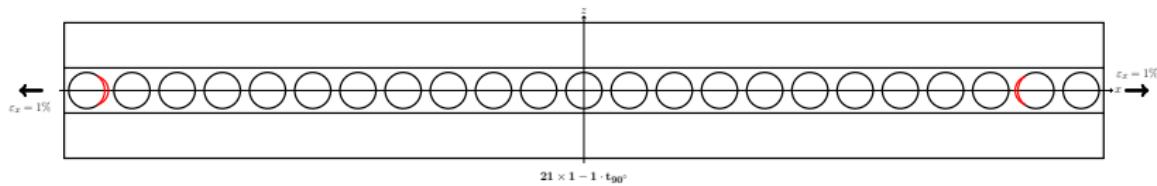
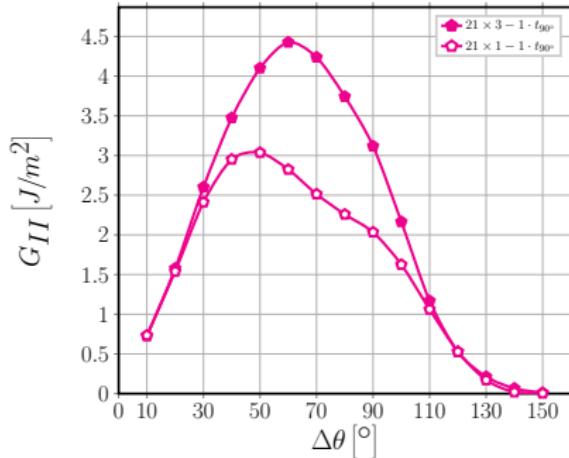
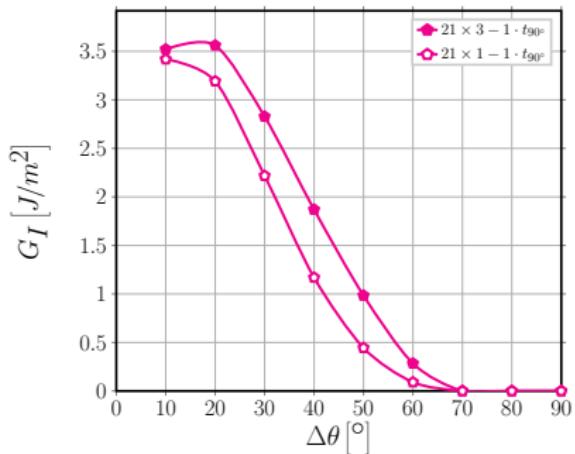
## Effect of the presence of 0° ply: comparison with equivalent BC



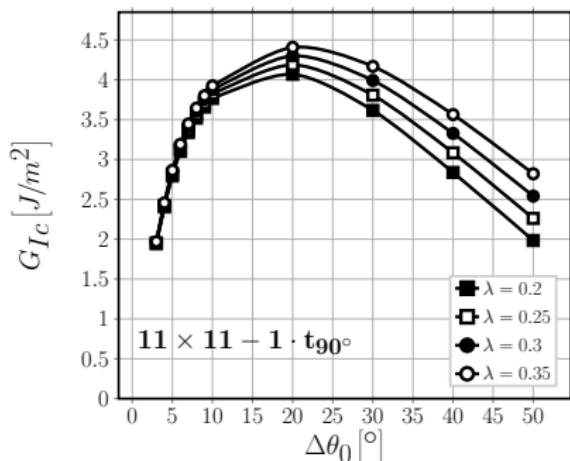
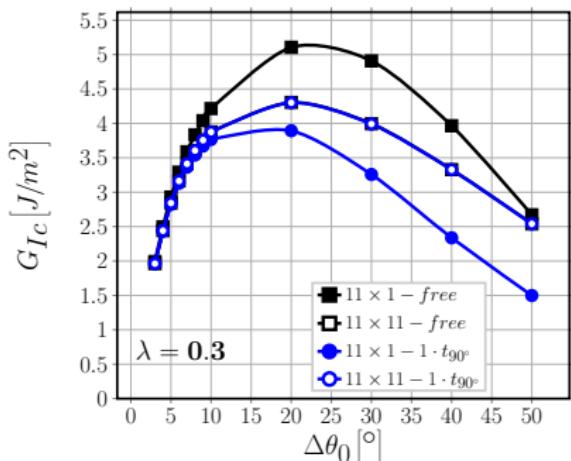
## Effect of the presence of 0° ply: comparison with equivalent BC



## Effect of the presence of 0° ply: comparison with equivalent BC



## Estimation of $G_{Ic}$



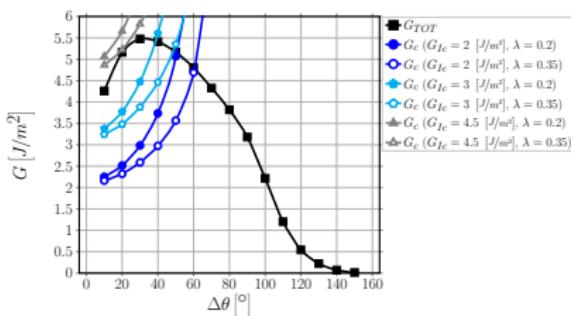
$$G_{Ic} = \frac{G_c}{1 + \tan^2((1 - \lambda) \Psi_G)} \Big|_{G_c=G_{TOT}(\Delta\theta_0)}, \quad \Psi_G = \tan^{-1} \left( \sqrt{\frac{G_{II}}{G_I}} \right) \Big|_{\Delta\theta_0}$$

With input  $R_f = 1 \mu m, \bar{\varepsilon}_x = 1\% \rightarrow G_{Ic} \in [2, 4.5] J/m^2$

Experimentally  $R_f \sim 10 \mu m, \bar{\varepsilon}_x \sim 0.4\% \xrightarrow{\text{rescaling}} G_{Ic} \in [3.2, 7.2] J/m^2$

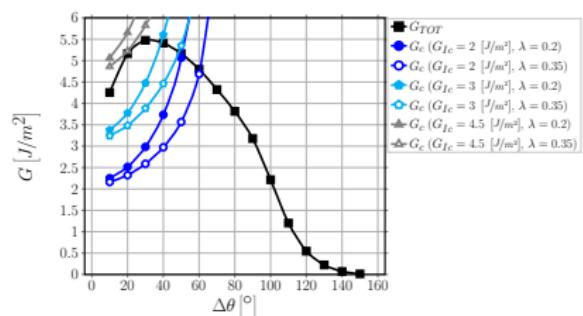
## Estimation of $\Delta\theta_{max}$

$21 \times 21 - free$



$$\Delta\theta_{max} \in (40^\circ - 60^\circ)$$

$21 \times 21 - 1 \cdot t_{90^\circ}$



$$\Delta\theta_{max} \in (40^\circ - 60^\circ)$$

$$G_{TOT}(\Delta\theta) > G_c = G_{lc} \left( 1 + \tan^2((1-\lambda)\Psi_G) \right), \quad \Psi_G = \tan^{-1} \left( \sqrt{\frac{G_{II}}{G_I}} \right) \Big|_{\Delta\theta}$$

## Estimation of $\Delta\theta_{max}$

Estimated debond size range in cross-ply ( $n \times k - 1 \cdot t_{90^\circ}$ )

40° – 60°

Measured debond size range in cross-ply ( Correa et al., Compos. Sci. Technol. 155 (213-220), 2018 )

21.4° – 89.2°, average 49.3°, standard deviation of 11.7°

63% of measurements in 40° – 60° range

## Observations

- The presence of the 0° layer results in a sizeable effect on debond ERR only in the case of a 1-fiber-row 90° layer, i.e. 0° layer extremely close to the debond.
- If there is just one row of fully bonded fibers between the debond and the 0° layer, the effect of the latter becomes almost negligible.
- Debond-debond interaction along the vertical direction has significant influence on ERR, but the presence of just 2 fully bonded fibers in between drastically reduces its importance.
- No significant effect of the 90° layer thickness has been observed.
- No significant effect of the 0° layer thickness has been observed.

It seems reasonable to conclude that...

...debond ERR, and thus debond propagation, is affected by changes in the microstructure only in a very small neighborhood,  $\sim 1 - 2 \phi_{fiber}$  around the debond itself.

 **MOVING FORWARD**

## Moving Forward: Ideas

- ▶ Microscopic characterization of transverse cracks, debonds and microstructure: optical microscope and image analysis, edge view (both sides), increasing load levels on same specimen, different lay-ups and materials
  - SEM? TEM?  $\mu$ -CT?
- ▶ Microstructure-controlled debonding as toughening mechanisms for thin-ply laminates
  - 3D-printing? Improved spread-tow technique?

**Thank you for listening today!**



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Erasmus Mundus