PLY-THICKNESS EFFECT ON FIBER-MATRIX INTERFACE CRACK GROWTH

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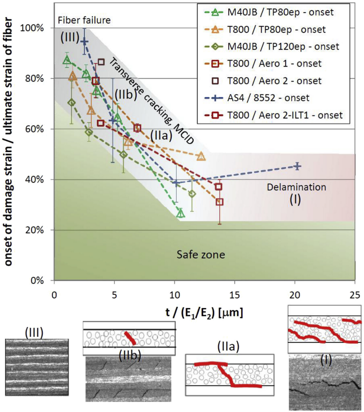
Outline

- Initiation of Transverse Cracks in Thin-plies
- Modeling the Fiber-Matrix Interface Crack
- Debond Energy Release Rate
- Conclusions

INITIATION OF TRANSVERSE CRACKS IN THIN-PLIES

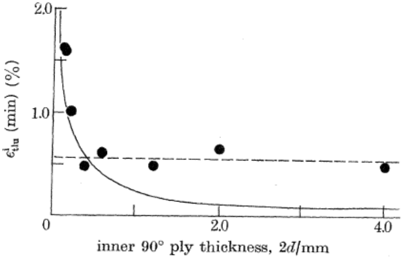
The Thin-ply "Advantage"

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



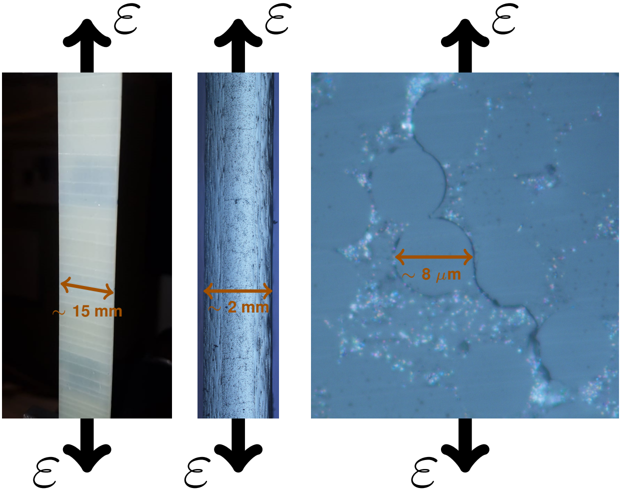
Cugnoni et al., Compos. Sci. Technol. **168**, 2018, p. 467–477.

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



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

Microscopic Observations



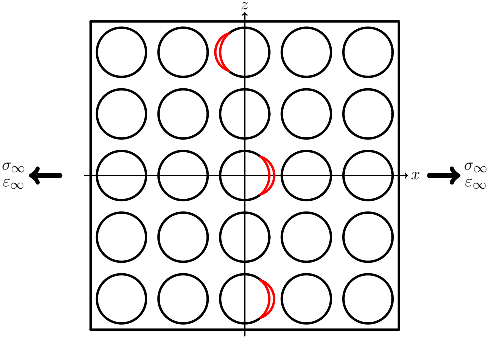
Left:
front view of $[0, 90_2]_S$, visual inspection.

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

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

Micromechanics of Initiation

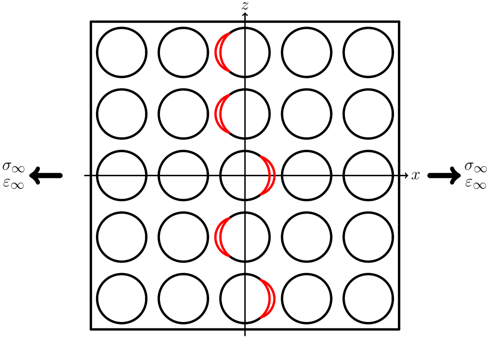
Stage 1: isolated debonds



Zhang, H., Ericson, M. L., Varna, J., Berglund, L.A.; 1997. *Transverse single-fibre test for interfacial debonding in composites: 1. Experimental observations*. *Compos. Part A-Appl. S.* **28** (4) pp. 309–315.

Micromechanics of Initiation

Stage 2: consecutive debonds



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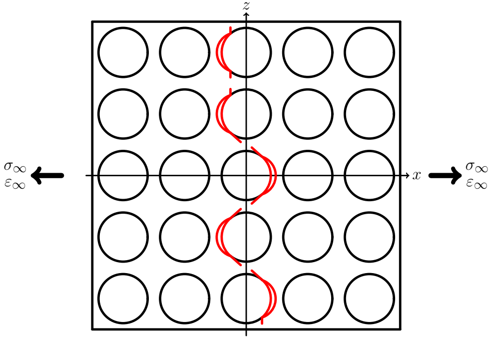
Micromechanics of Initiation

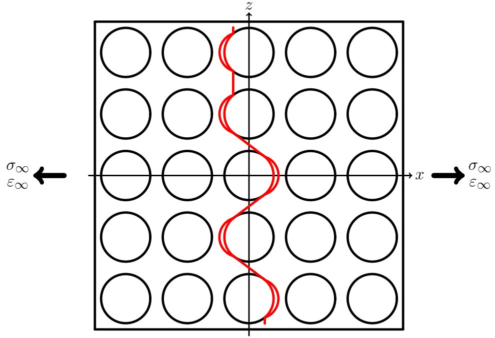
Stage 3: kinking



Zhang, H., Ericson, M. L., Varna, J., Berglund, L.A.; 1997. *Transverse single-fibre test for interfacial debonding in composites: 1. Experimental observations. Compos. Part A-Appl. S.* **28** (4) pp. 309–315.

Micromechanics of Initiation

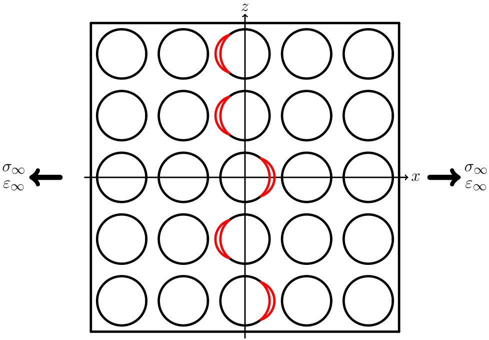
Stage 4: coalescence



Zhang, H., Ericson, M. L., Varna, J., Berglund, L.A.; 1997. *Transverse single-fibre test for interfacial debonding in composites: 1. Experimental observations. Compos. Part A-Appl. S.* **28** (4) pp. 309–315.

Objective of the Study

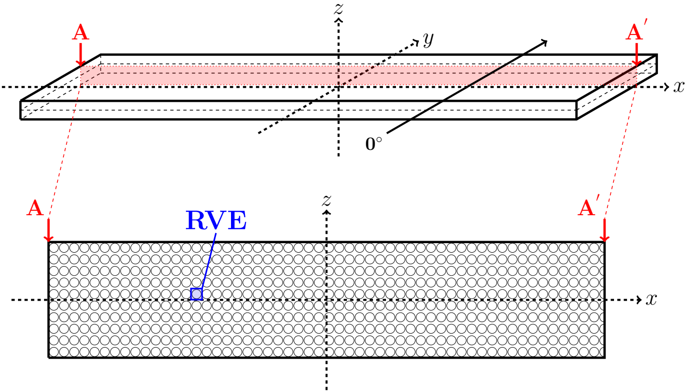
Stage 2: consecutive debonds



- ➔ Effect of debond-fiber interaction?
- ➔ Effect of debond-debond interaction?
- ➔ Effect of relative debond position on consecutive fibers: same or opposite sides?

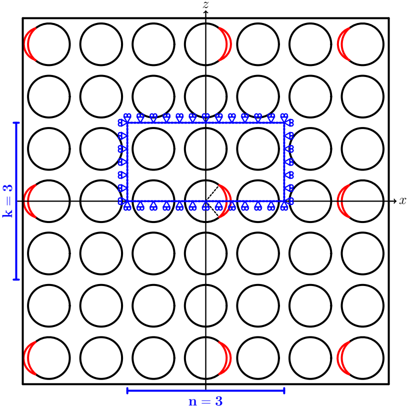
↘ MODELING THE FIBER-MATRIX INTERFACE CRACK

Geometry

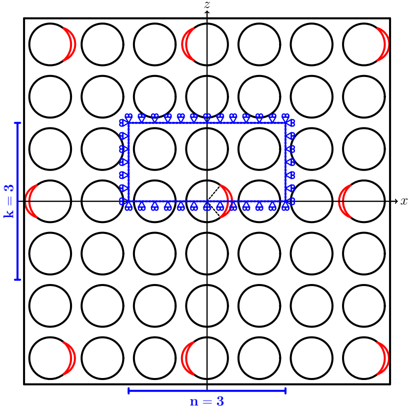


- ➔ $L, W >> t$
- ➔ $L, W \to \infty$
- ➔ Square packing
- ➔ $L_d >> \Delta\theta_d$
- ➔ 2D RVE

Representative Volume Elements

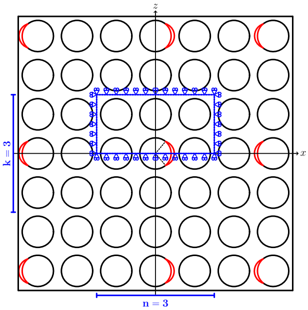


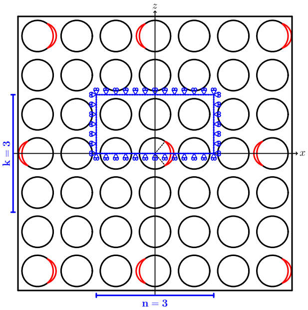
$n \times k - coupling$



$n \times k - asymm$

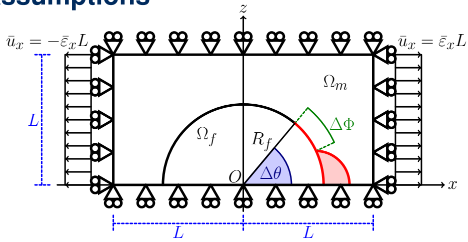
Equivalent Boundary Conditions





Symmetric Coupling	Anti-symmetric Coupling
$u_z(x,h) = u_z^{\nu}$	$u_z(x,h) - u_z(0,h) = -(u_z(-x,h) - u_z(0,h))$ $u_x(x,h) = -u_x(-x,h)$

Assumptions

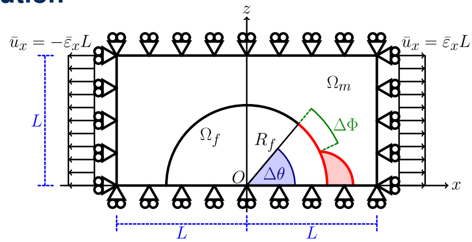


$R_f = 1 \ [\mu m] \quad L = \frac{R_f}{2}\sqrt{\frac{\pi}{V_f}}$

Material	E	ν
glass fiber	70.0	0.2
epoxy	3.5	0.4

- ➔ Linear elastic, homogeneous and isotropic materials
- ➔ 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 $\bar{\varepsilon}_x = 1\%$
- ➔ $V_f = 60\%$

Solution



in Ω_f, Ω_m :

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

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

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

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

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

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

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

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

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

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

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

➔ Finite Element Method (FEM) in Abaqus^{TM}

➔ 2^{nd} order shape functions

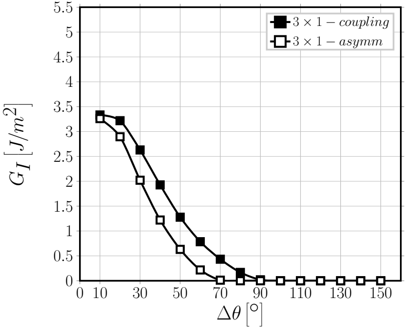
➔ 6-nodes triangles & 8-nodes quadrilaterals

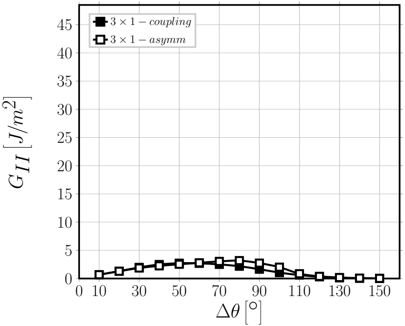
➔ regular mesh of quadrilaterals at the crack tip:

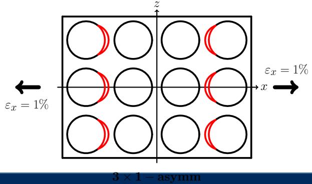
- $AR \sim 1$
- $\delta = 0.05^\circ$

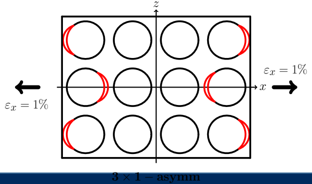
↘ DEBOND ENERGY RELEASE RATE

Strain Magnification









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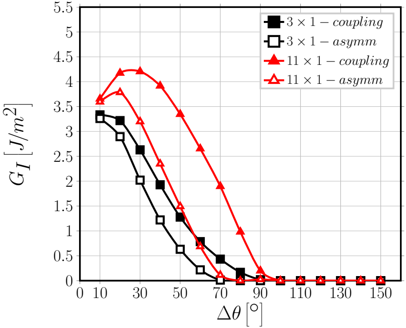
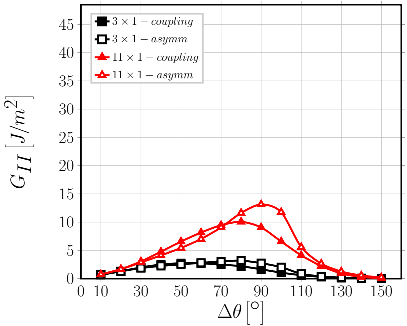
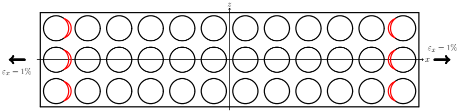
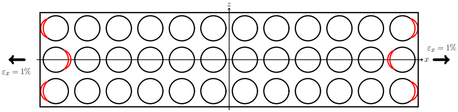






$11 \times 1 - \mathbf{asymm}$



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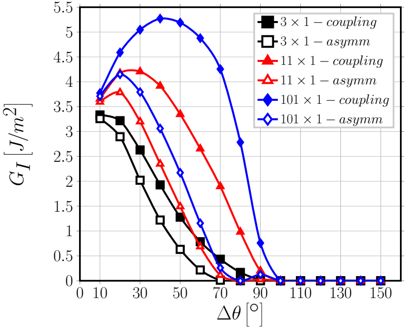

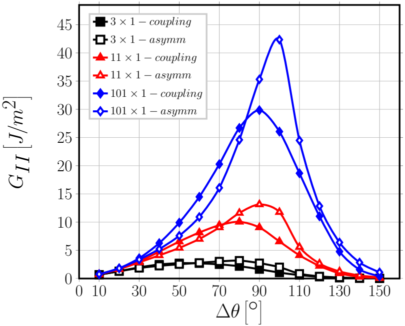

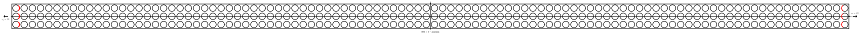

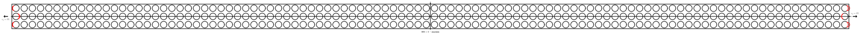

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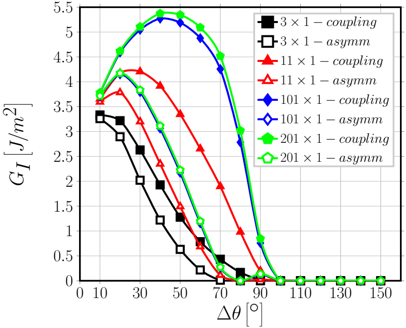
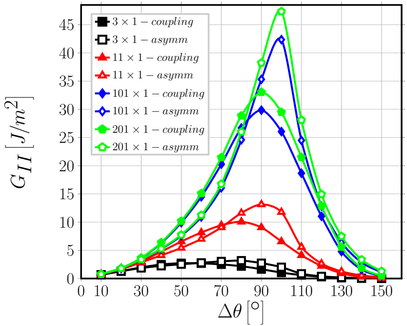
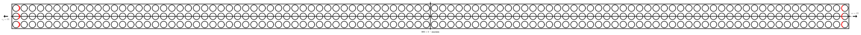
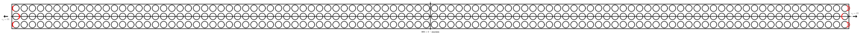
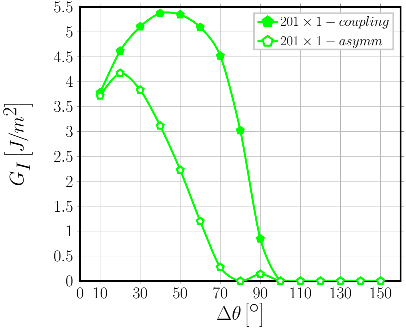


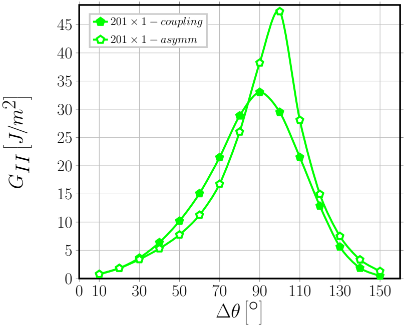


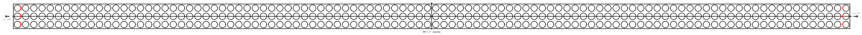


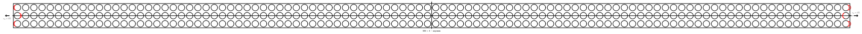


Crack Shielding









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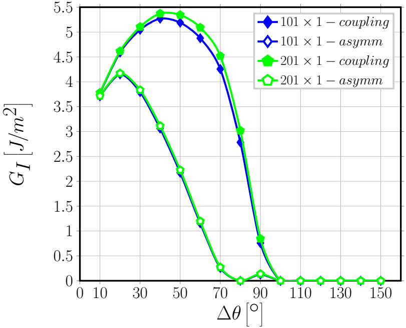

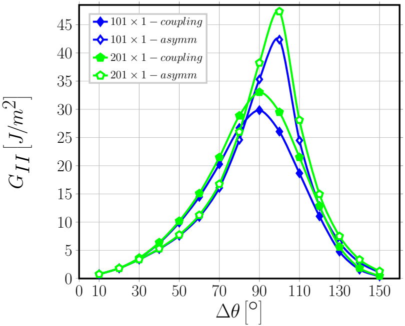

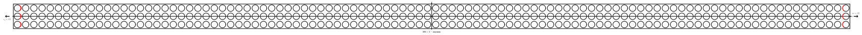

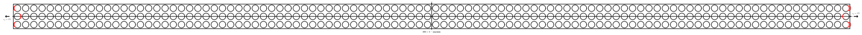

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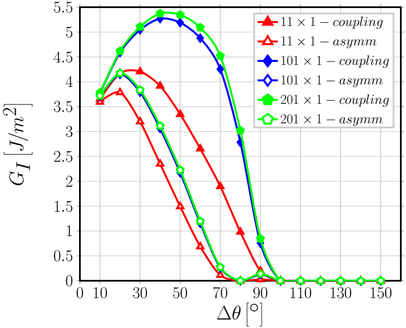

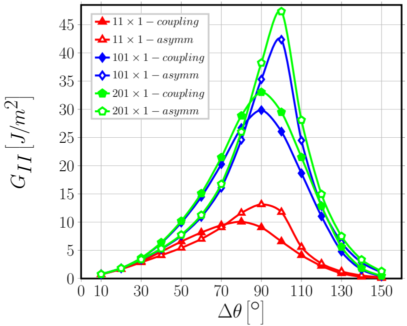

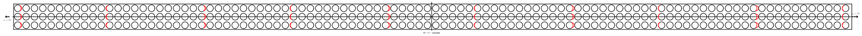

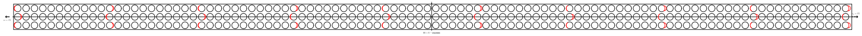

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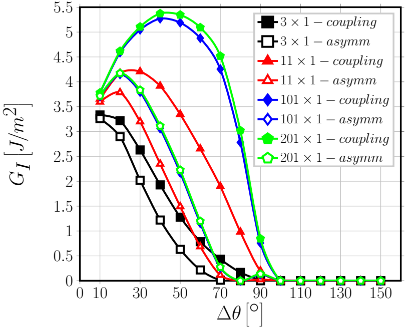
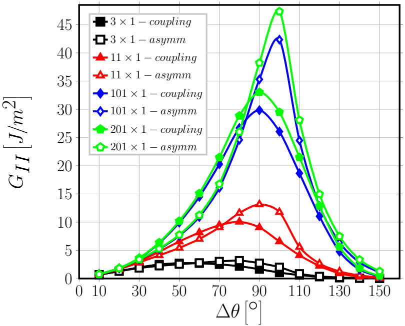
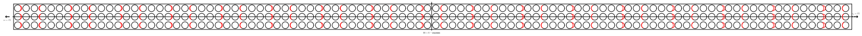
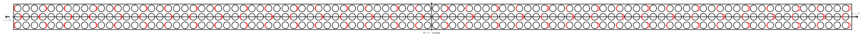
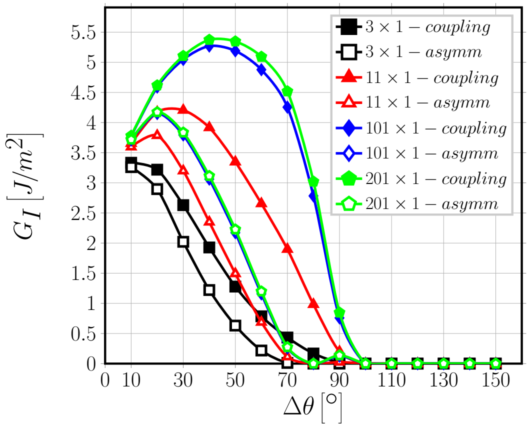


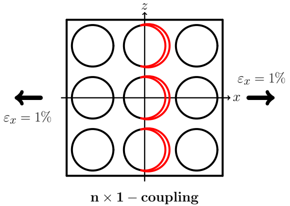


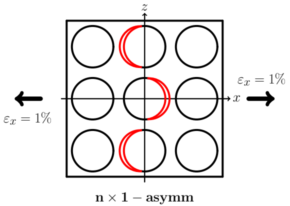




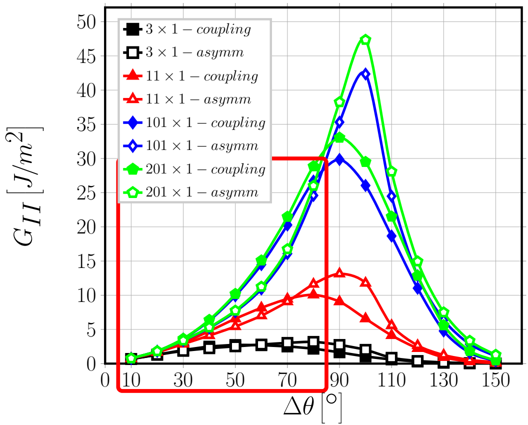
Consecutive Debonds: Mode I

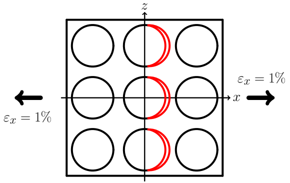




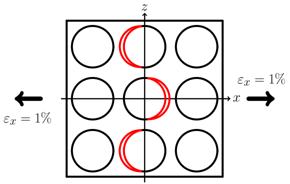


Consecutive Debonds: Mode II



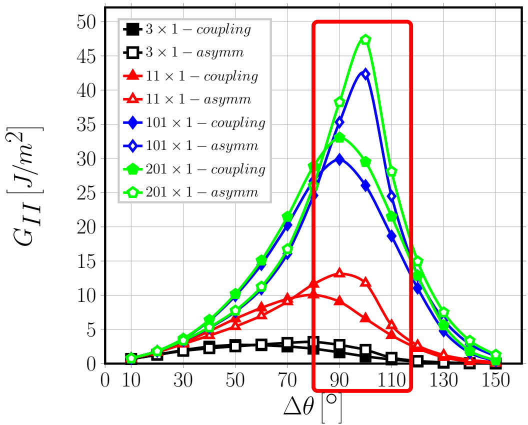


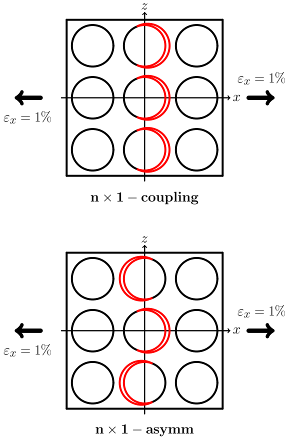
n × 1 − coupling



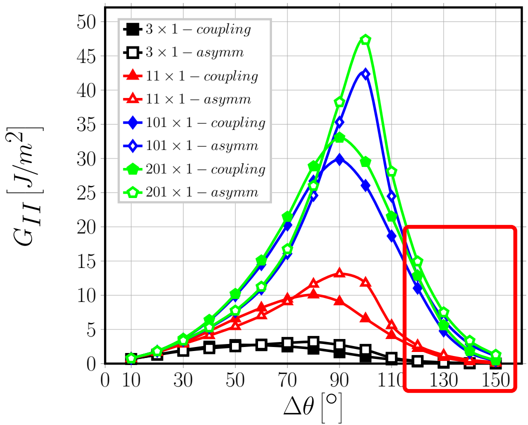
n × 1 − asymm

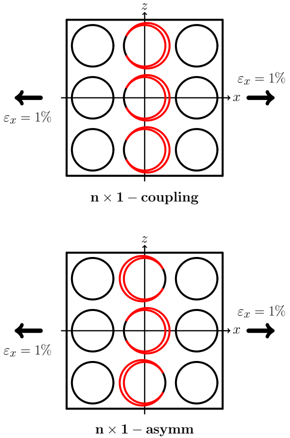
Consecutive Debonds: Mode II



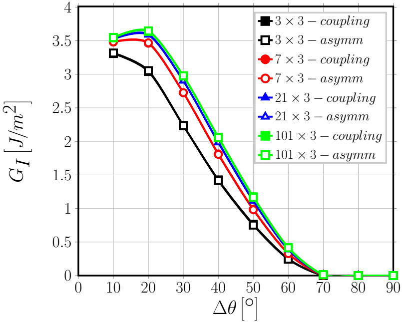


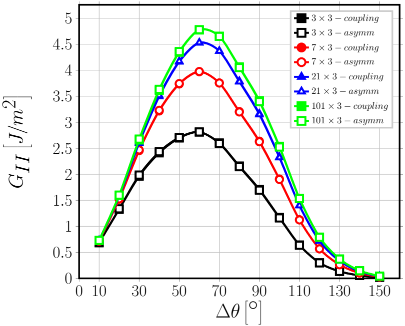
Consecutive Debonds: Mode II

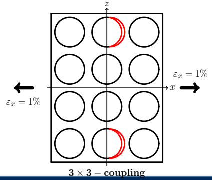


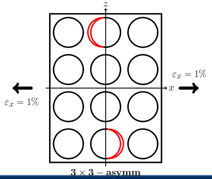


Non-Consecutive Debonds









↘ CONCLUSIONS

Conclusions

- ➔ Debond-debond interaction in the through-the-thickness direction is extremely localized: with only a couple of undamaged fibers in between, no effect can be seen!
- ➔ For debonds on consecutive vertically-aligned fibers, G_I is higher and contact zone onset delayed if debonds are on the same side of their respective fiber.
- ➔ No significant difference in G_{II} observed, except in the range $80^\circ - 100^\circ$.
- ➔ In the range $80^\circ - 100^\circ$, G_{II} is higher when debonds are located on opposite sides of consecutive vertically-aligned fibers.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