

GROWTH OF INTERFACE CRACKS ON CONSECUTIVE FIBERS: ON THE SAME OR ON THE OPPOSITE SIDES?

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Education and Culture

Erasmus Mundus

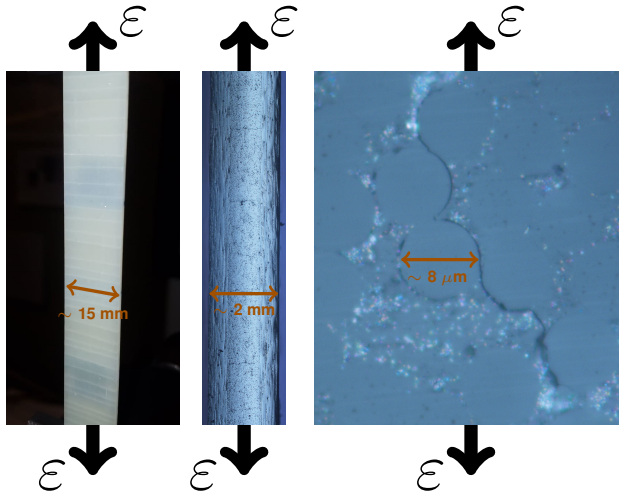


Outline

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

INITIATION OF TRANSVERSE CRACKS IN FRPCs

Microscopic Observations



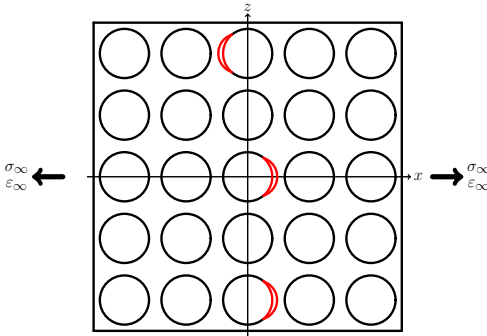
Left:
front view of $[0, 90_2]_S$,
visual inspection.

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

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

Micromechanics of Initiation

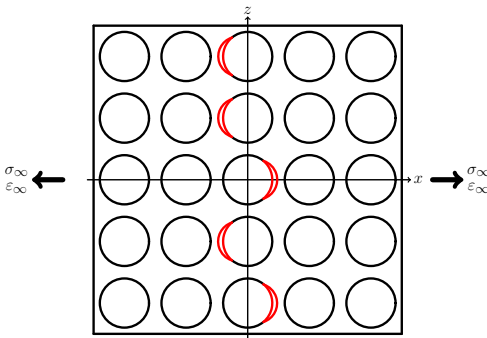
Stage 1: isolated debonds



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

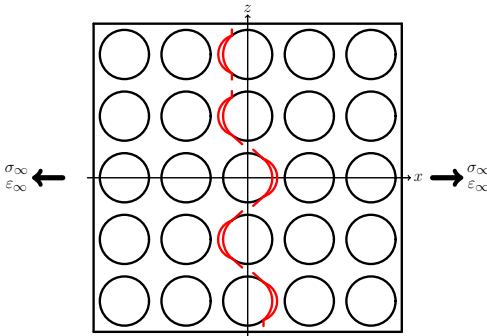
Stage 2: consecutive debonds



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

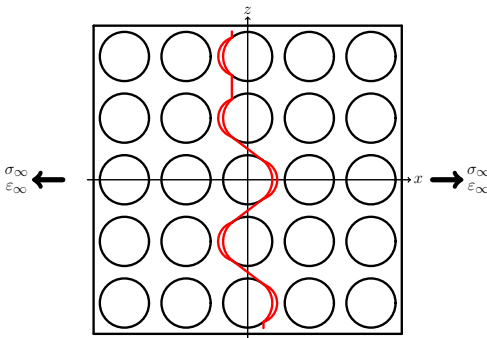
Stage 3: kinking



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

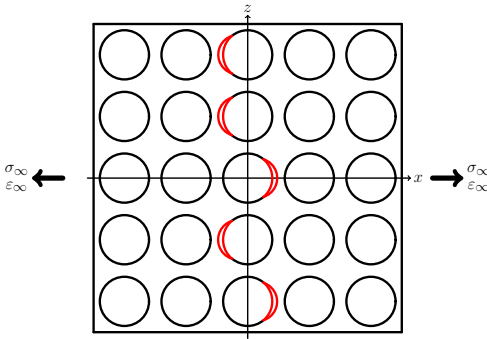
Stage 4: coalescence



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

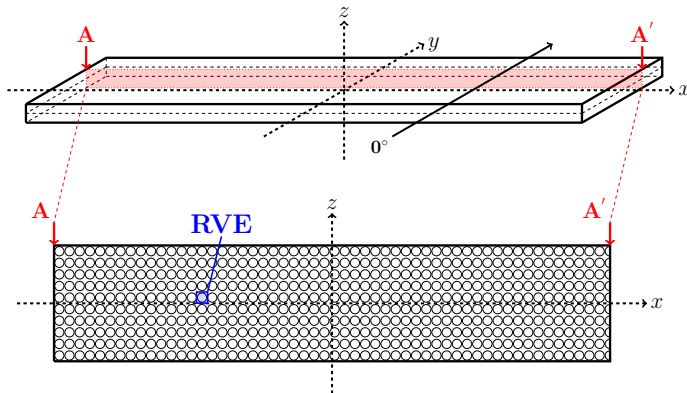
Stage 2: consecutive debonds



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

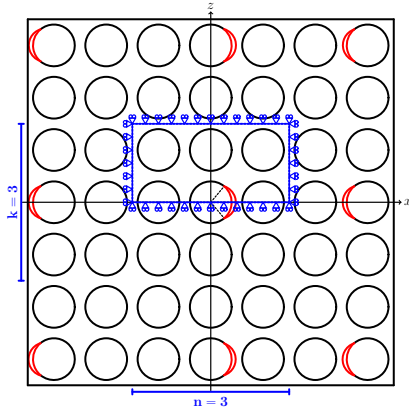
MODELING THE FIBER-MATRIX INTERFACE CRACK

Geometry

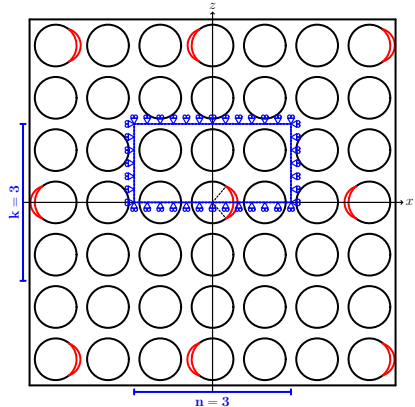


- $L, W \gg t$
- $L, W \rightarrow \infty$
- Square packing
- $L_d \gg \Delta\theta_d$
- 2D RVE

Representative Volume Elements

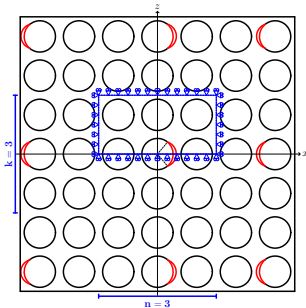


$n \times k - \text{coupling}$



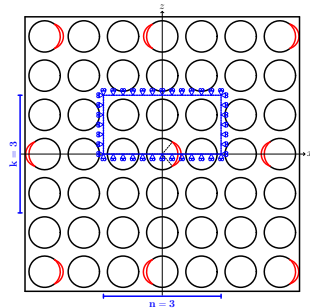
$n \times k - \text{asymm}$

Equivalent Boundary Conditions



Symmetric Coupling

$$u_z(x, h) = u_z^\nu$$

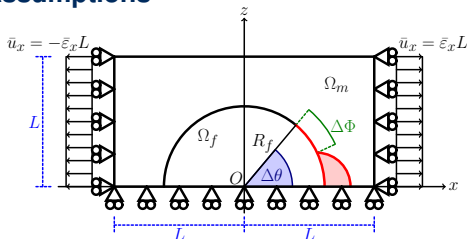


Anti-symmetric Coupling

$$u_z(x, h) - u_z(0, h) = -(u_z(-x, h) - u_z(0, h))$$

$$u_x(x, h) = -u_x(-x, h)$$

Assumptions

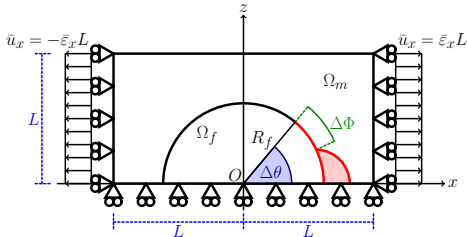


$$R_f = 1 \text{ } [\mu\text{m}] \quad L = \frac{R_f}{2} \sqrt{\frac{\pi}{V_f}}$$

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

Solution



in Ω_f, Ω_m :

$$\frac{\partial^2 \varepsilon_{xx}}{\partial z^2} + \frac{\partial^2 \varepsilon_{zz}}{\partial x^2} = \frac{\partial^2 \gamma_{zx}}{\partial x \partial z} \quad \text{for } 0^\circ \leq \alpha \leq \Delta\theta :$$

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

$$\varepsilon_y = \gamma_{xy} = \gamma_{yz} = 0 \quad \text{for } \Delta\theta \leq \alpha \leq 180^\circ :$$

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

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

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

→ Oscillating singularity

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

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

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

→ Finite Element Method (FEM) in AbaqusTM

→ 2nd order shape functions

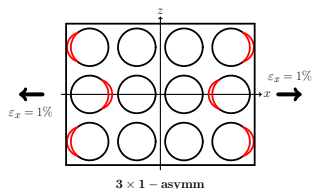
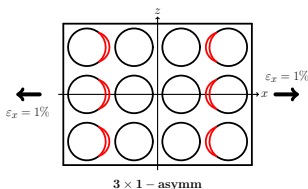
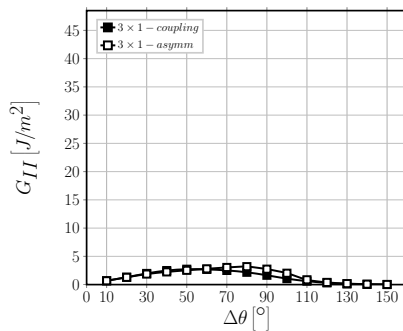
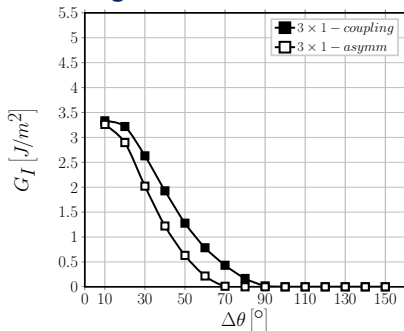
→ 6-nodes triangles & 8-nodes quadrilaterals

→ regular mesh of quadrilaterals at the crack tip:

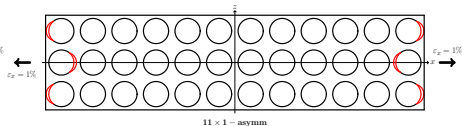
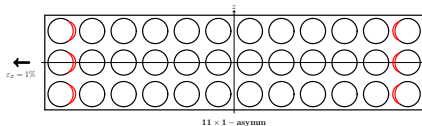
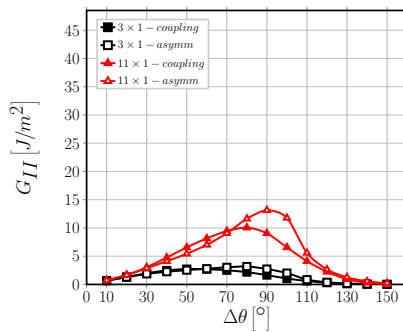
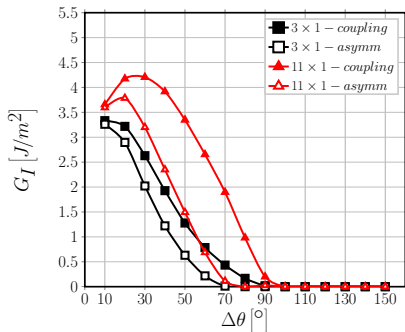
- $AR \sim 1$
- $\delta = 0.05^\circ$

DEBOND ENERGY RELEASE RATE

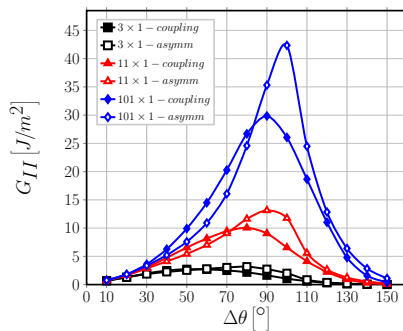
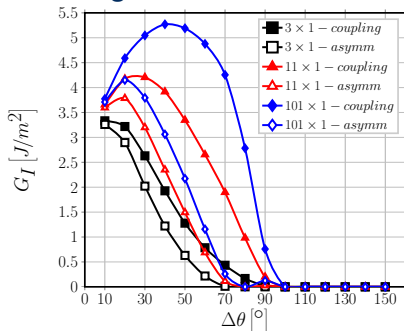
Strain Magnification



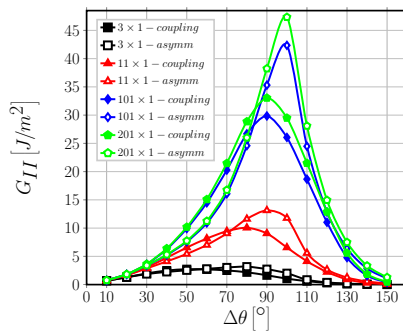
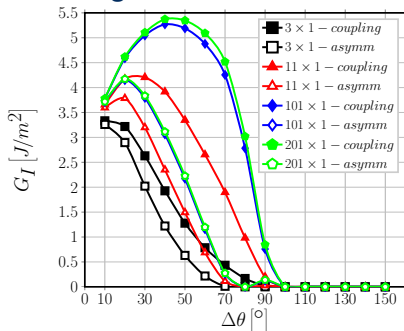
Strain Magnification



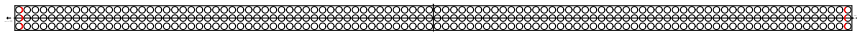
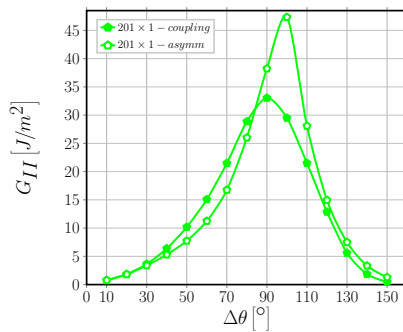
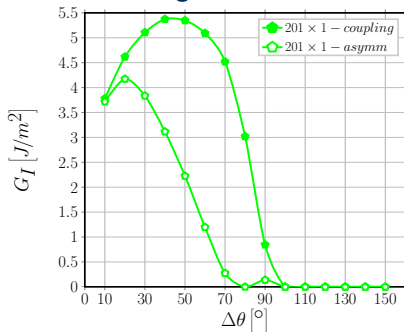
Strain Magnification



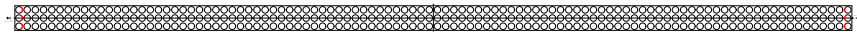
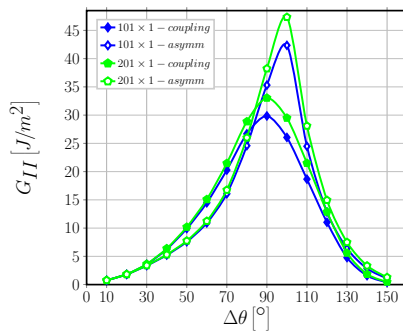
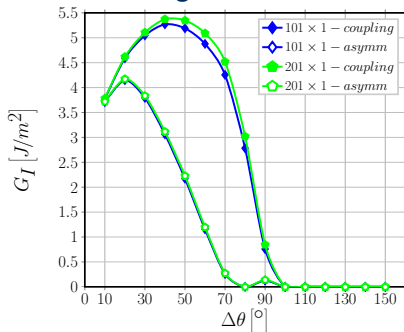
Strain Magnification



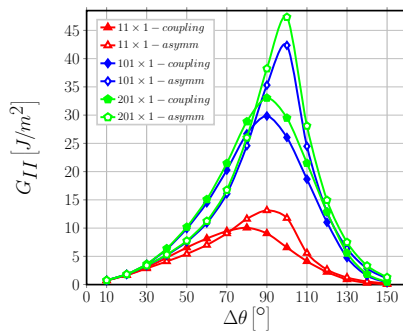
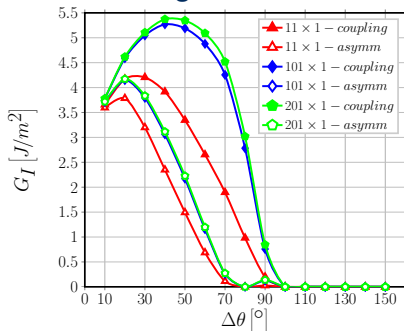
Crack Shielding



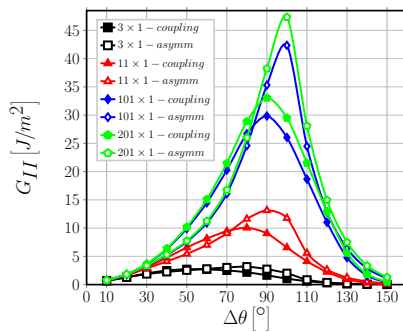
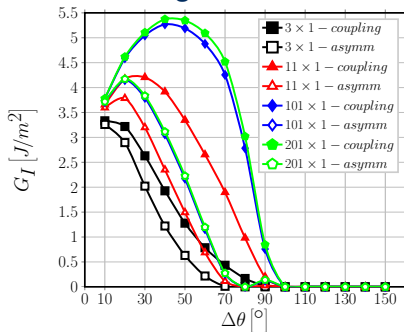
Crack Shielding



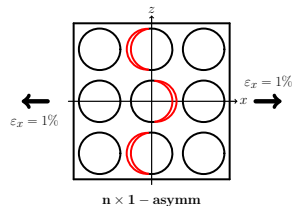
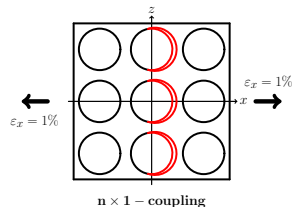
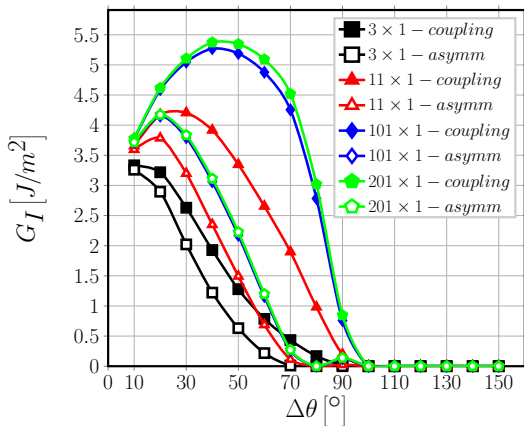
Crack Shielding



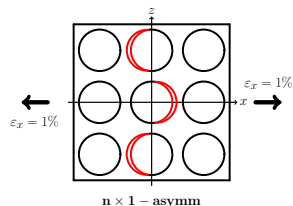
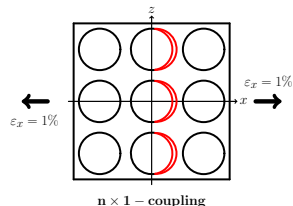
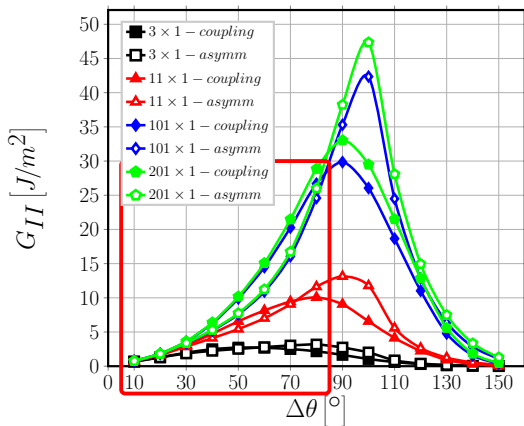
Crack Shielding



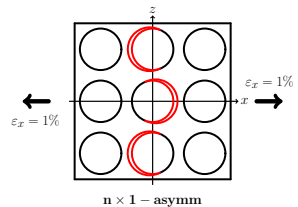
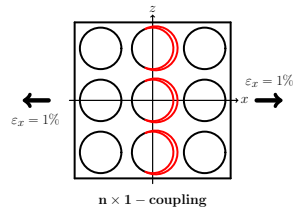
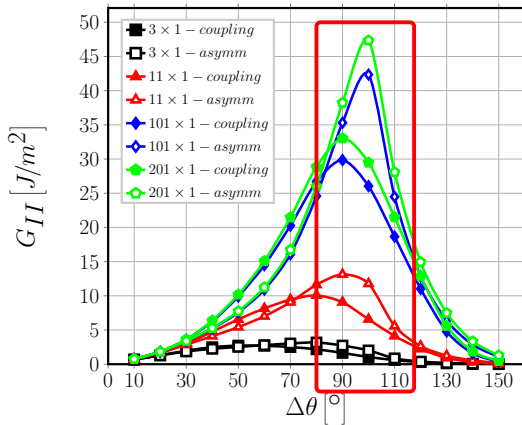
Consecutive Debonds: Mode I



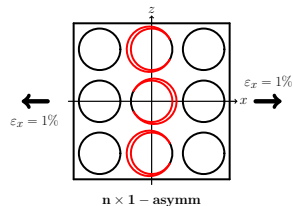
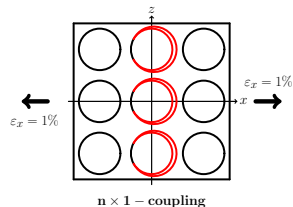
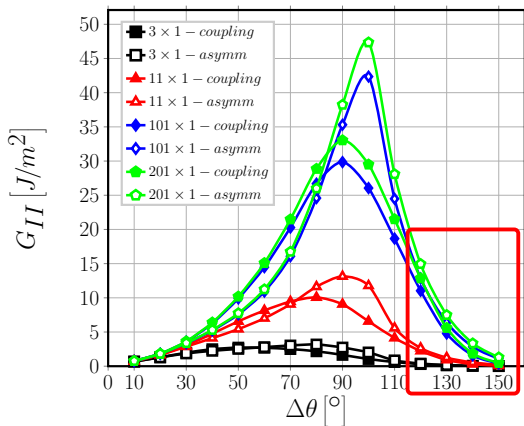
Consecutive Debonds: Mode II



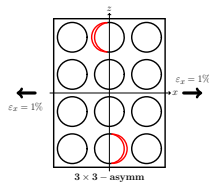
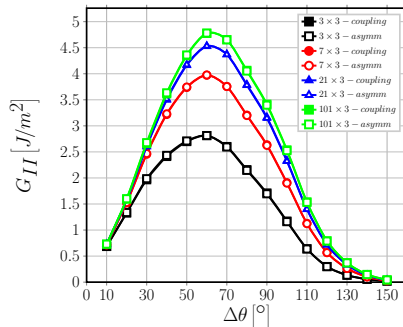
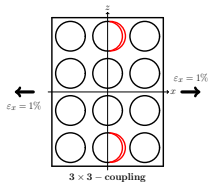
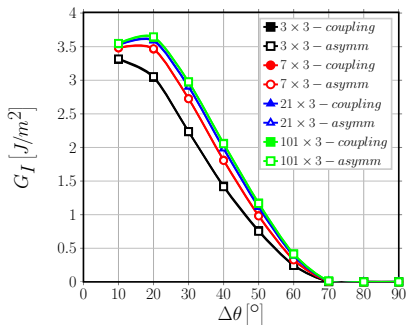
Consecutive Debonds: Mode II



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.

