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

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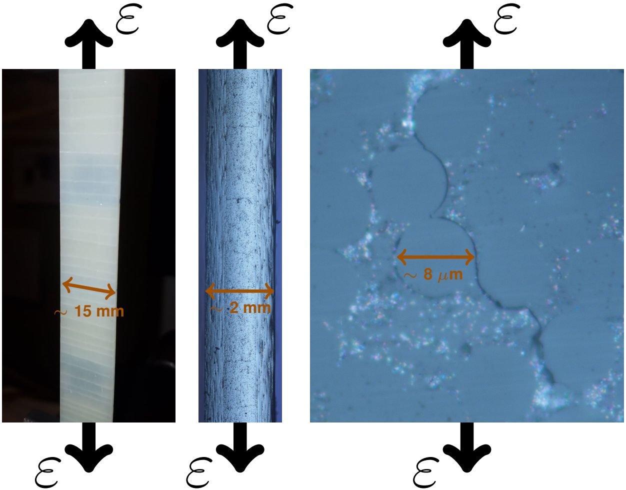
Outline

- Micromechanical Modeling of Initiation of Transverse Cracks
- Modeling the Fiber-Matrix Interface Crack
- Energy Release Rate of the Fiber-Matrix Interface Cracks
- Conclusions

↘ Initiation of Transverse Cracks

Initiation of Transverse Cracking in FRPCs: Microscopic Observations



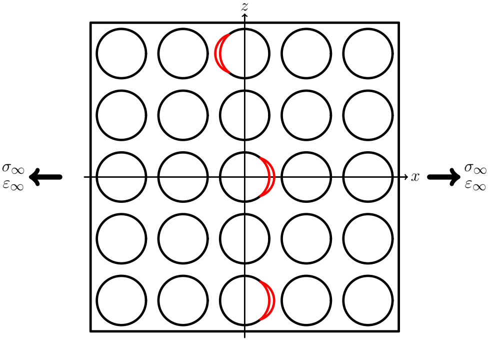
Left:
front view of $[0, 90_2]_S$, visual inspection.

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

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

Initiation of Transverse Cracking in FRPCs: Micromechanics

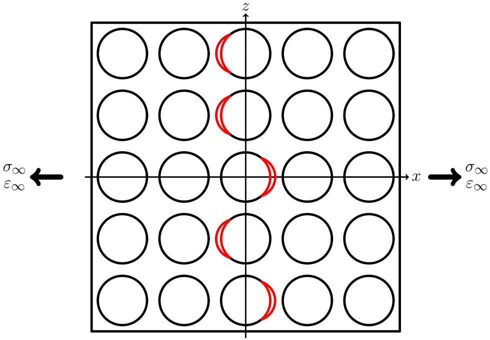
Stage 1: isolated debonds



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.

Initiation of Transverse Cracking in FRPCs: Micromechanics

Stage 2: consecutive debonds



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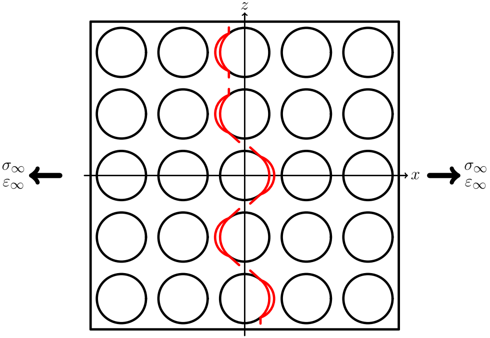
Initiation of Transverse Cracking in FRPCs: Micromechanics

Stage 3: kinking



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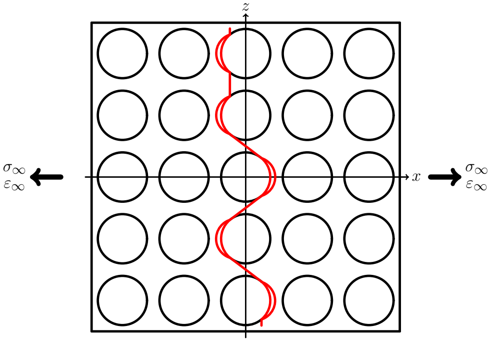
Initiation of Transverse Cracking in FRPCs: Micromechanics

Stage 4: coalescence



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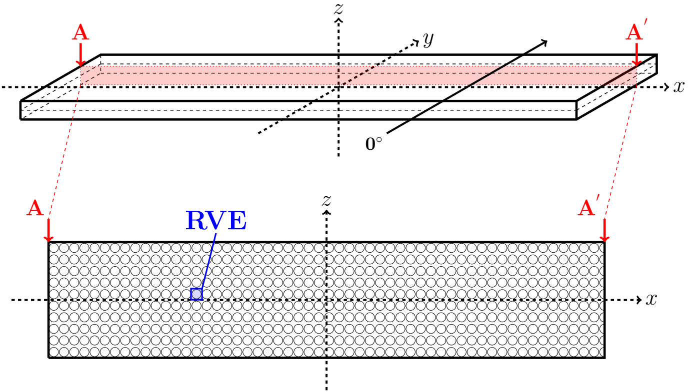
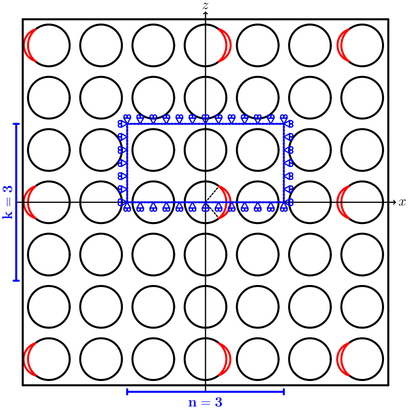
↘ DEBOND MODELING

Geometry

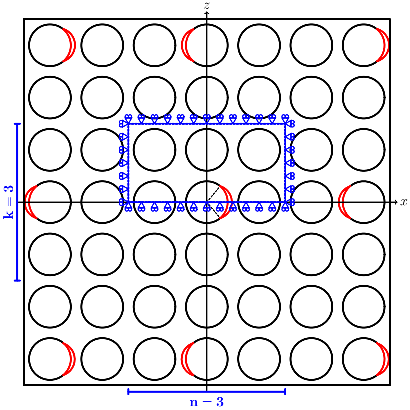


- ➔ $L, W >> t$
- ➔ $L, W \to \infty$
- ➔ Square packing
- ➔ $L_d >> \Delta\theta_d$
- ➔ 2D RVE

Representative Volume Elements

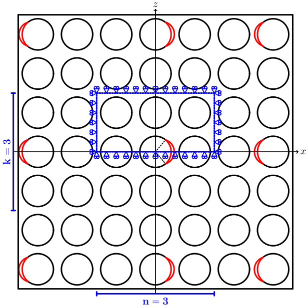


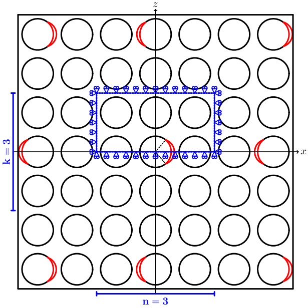
$n \times k - coupling$



$n \times k - asymm$

Equivalent Boundary Conditions





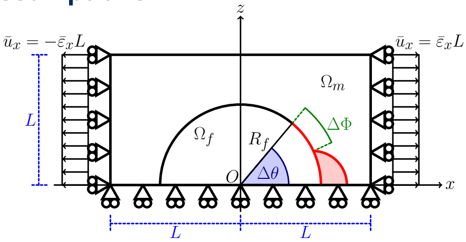
Symmetric Coupling

$$u_z\left(x,h\right)=u_z^{\nu}$$

Anti-symmetric Coupling

$$u_z\left(x,h\right)-u_z\left(0,h\right)=-\left(u_z\left(-x,h\right)-u_z\left(0,h\right)\right)$$
$$u_x\left(x,h\right)=-u_x\left(-x,h\right)$$

Assumptions

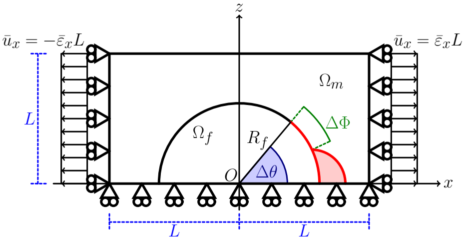


$$R_f = 1 \ [\mu m] \qquad L = \frac{R_f}{2}\sqrt{\frac{\pi}{V_f}}$$

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 $\bar{\varepsilon}_x = 1\%$

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

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

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

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

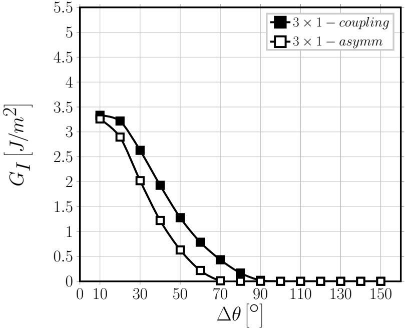
$$\varepsilon = \frac{1}{2\pi} \log\left(\frac{1-\beta}{1+\beta}\right)$$

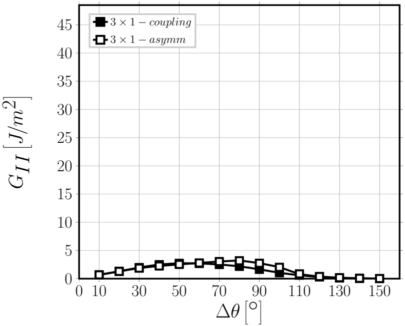
$$\beta = \frac{\mu_2\left(\kappa_1 - 1\right) - \mu_1\left(\kappa_2 - 1\right)}{\mu_2\left(\kappa_1 + 1\right) + \mu_1\left(\kappa_2 + 1\right)}$$

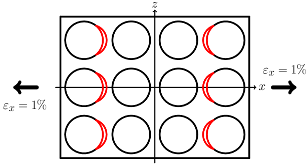
- ➔ Finite Element Method (FEM) in Abaqus™
- ➔ 2^{nd} order shape functions
- ➔ 6-nodes triangles & 8-nodes quadrilaterals
- ➔ regular mesh of quadrilaterals at the crack tip:
  - $AR \sim 1$
  - $\delta = 0.05^\circ$

Debond ERR

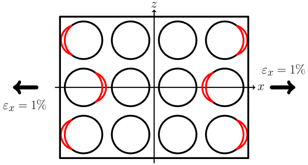
Strain Magnification





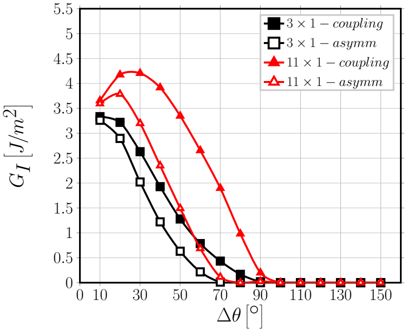


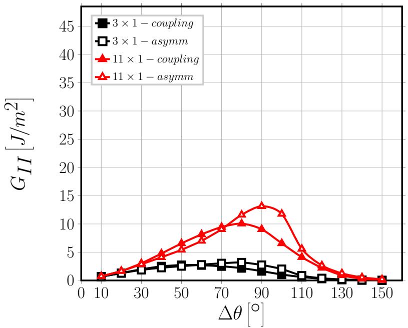
3×1 – asymm

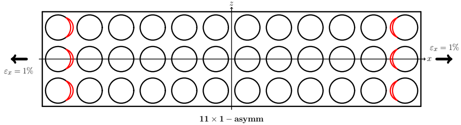


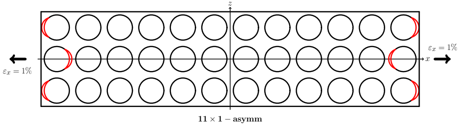
3×1 – asymm

Strain Magnification









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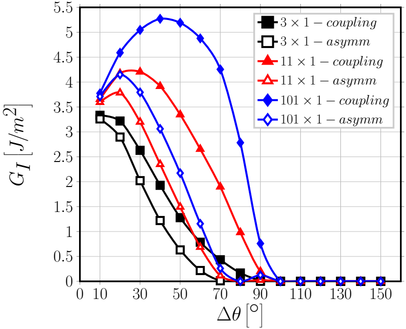

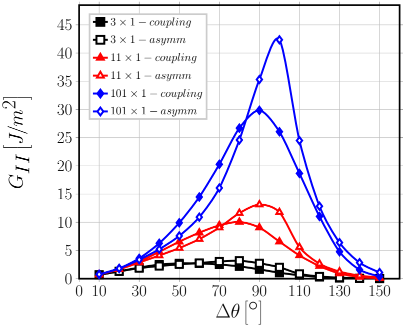

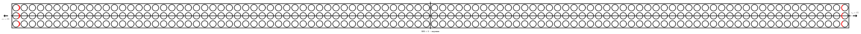

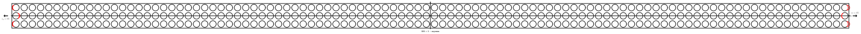

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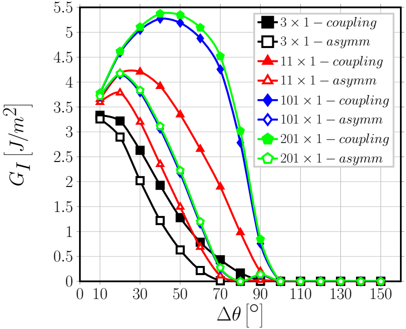
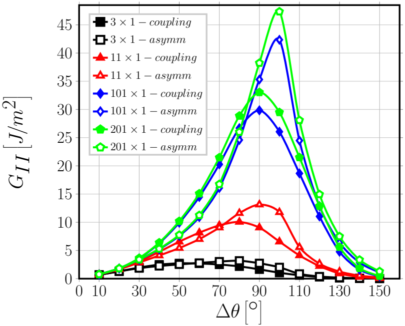
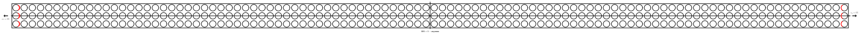
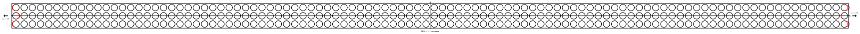
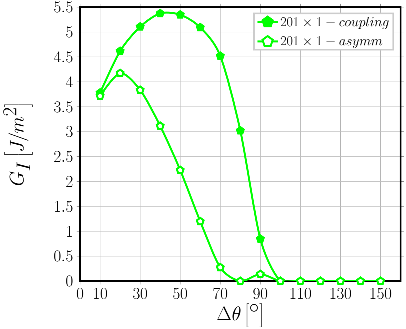


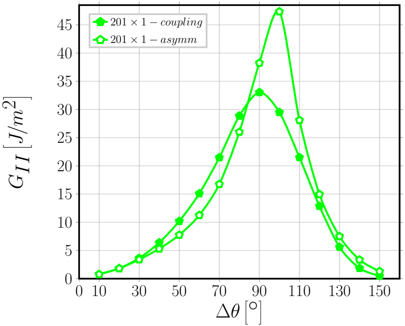


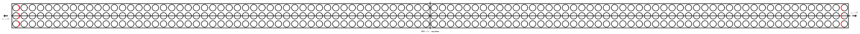


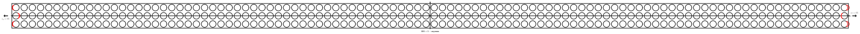


Crack Shielding









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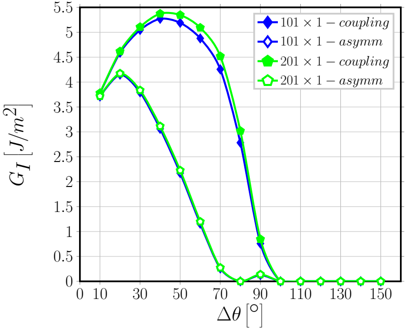

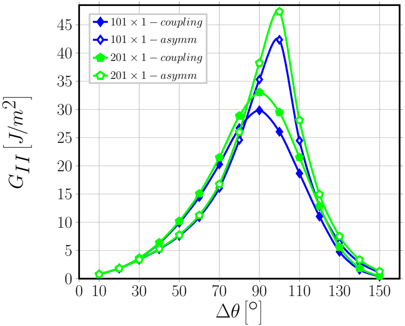

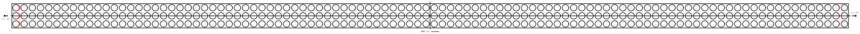

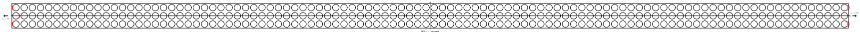

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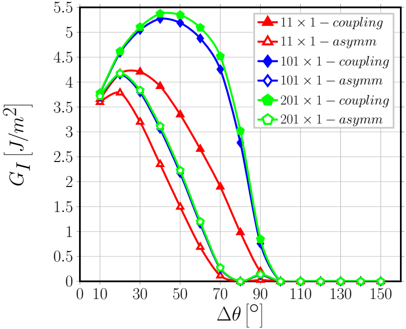

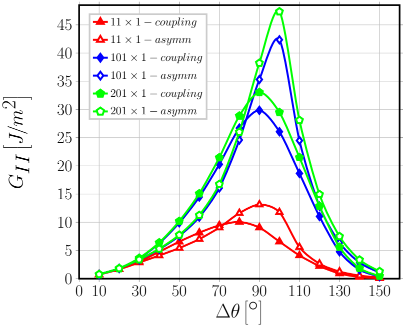

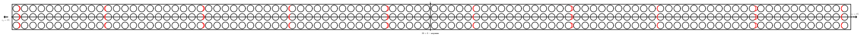

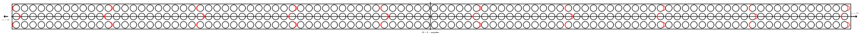

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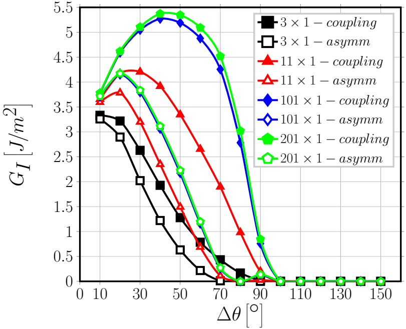
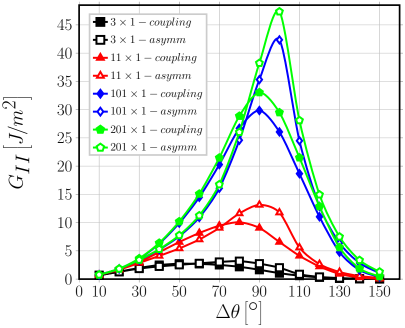
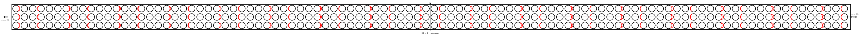
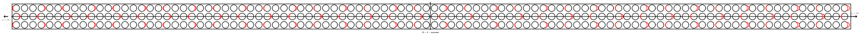
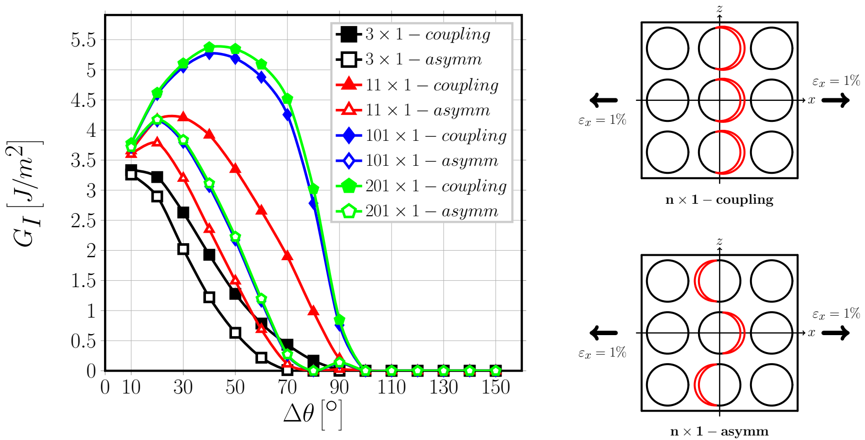




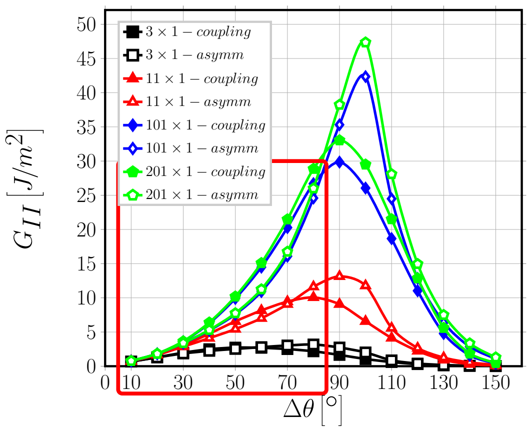


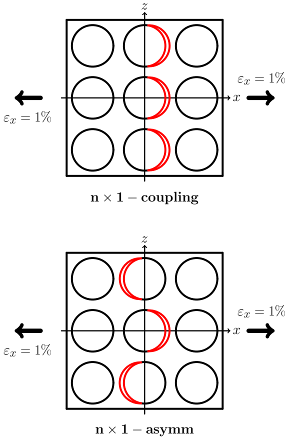


Consecutive Debonds: Mode I



Consecutive Debonds: Mode II





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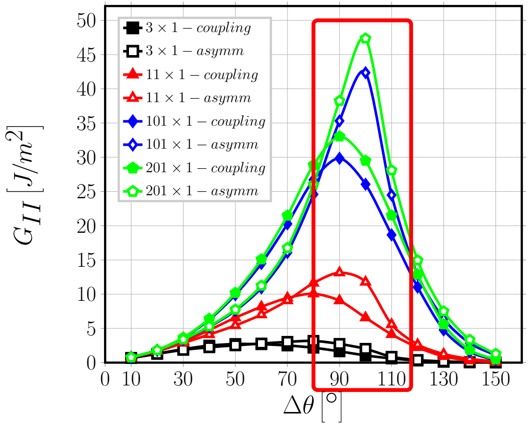
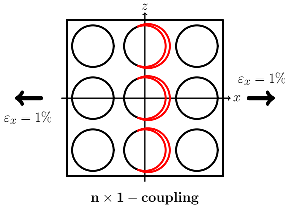
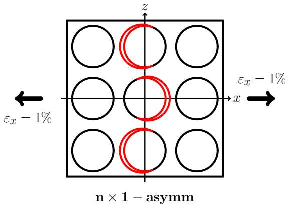
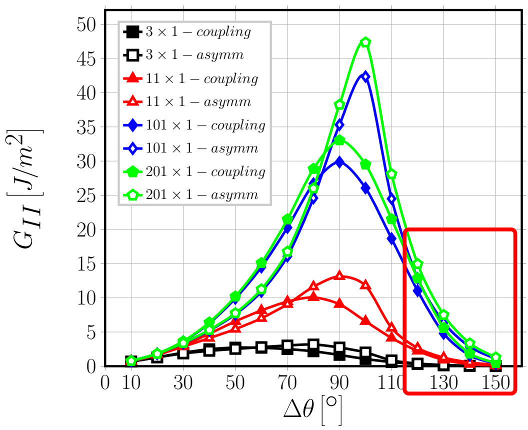
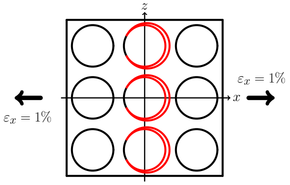




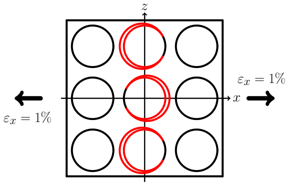


Consecutive Debonds: Mode II



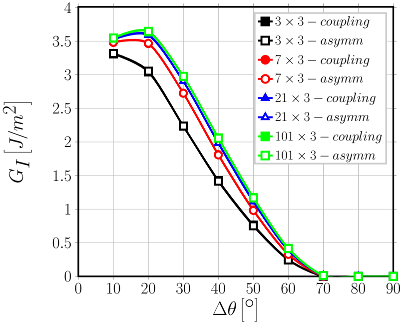


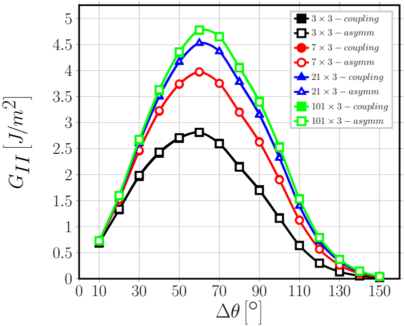
$\mathbf{n \times 1 - coupling}$

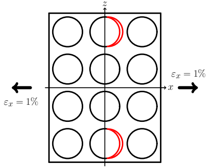


$\mathbf{n \times 1 - asymm}$

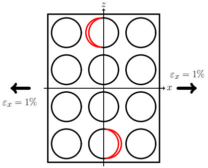
Non-Consecutive Debonds







3 × 3 − coupling



3 × 3 − asymm

Conclusions

Conclusions

➔ $f_{\text{straight crack}}\left(\Delta\theta\right)$: $\checkmark\, G_{I}$, $\times\, G_{II}$

$f_{\text{inclined crack}}\left(\Delta\theta\right)$: $\checkmark\, G_{I}$, $\checkmark\, G_{II}$, $\times \nexists\, f_{\text{inclined crack}}\left(\Delta\theta = \frac{\pi}{2}\right)$

$f_{\text{curved crack}}\left(\Delta\theta\right)$: $\checkmark\, G_{I}$, $\checkmark\, G_{II}$

➔ scaling breaks for $\Delta\theta \leq 20^{\circ} \rightarrow$ microstructure is important for small debonds!

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