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L. Di Stasio[1,2], Z. Ayadi[1], J. Varna[2]

[1] EEIGM, Université de Lorraine, Nancy, France

[2] Division of Materials Science, Luleå University of Technology, Luleå, Sweden

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Outline

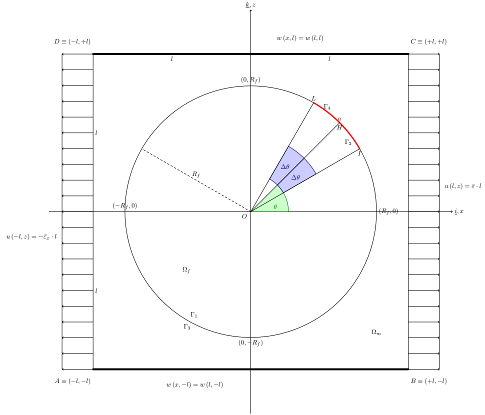
- Symbols, Models & Reference Data
- Review of work's progress
- Discussion of results

Symbols, Models & Reference Data

Symbols

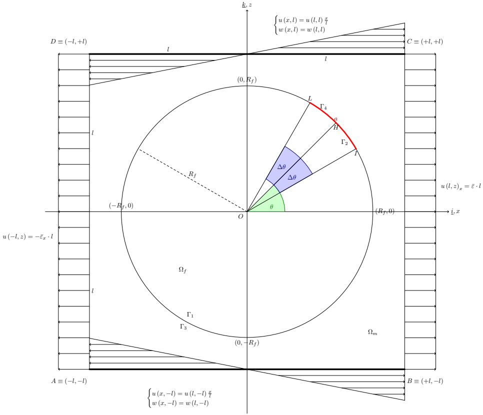
Symbol	Unit	Description
θ	$[^\circ]$	Debond position, with respect to the center of the arc defined by the debond
$\Delta\theta$	$[^\circ]$	Semi-angular aperture of the debond
δ	$[^\circ]$	Angle subtended by a single element at fiber/matrix interface
VF_f	$[-]$	Fiber volume fraction
l	$[\mu m]$	Half-thickness of the ply, equal to half side-length (square element)
u	$[\mu m]$	Displacement along x-direction
w	$[\mu m]$	Displacement along z-direction

Reference Models



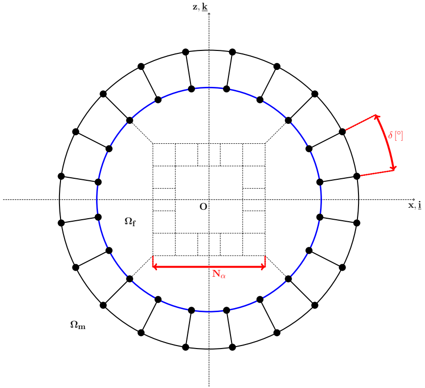
Isolated RVE with zero vertical displacement BC.

Reference Models



Isolated RVE with homogeneous displacement BC.

Angular discretization



Angular discretization at fiber/matrix interface: $\delta = \frac{360^\circ}{4N_\alpha}$.

Materials' properties

Material	$E\,[GPa]$	$G\,[GPa]$	$\nu\,[-]$
Glass Fiber	70,0	29,2	0,2
Epoxy	3,5	1,25	0,4

↘ REVIEW OF WORK'S PROGRESS

Where we were

➔ Run simulations with following characteristics:

	RUN 1	RUN 2
BC	$v(x, \pm l) = 0$	$v(x, \pm l) = 0, \quad u(x, \pm l) = \frac{u(l, \pm l)}{l} x$
$VF_f\ [-]$	0.001	0.001
δ	1°	1°
θ	0°	0°
$\Delta\theta$	$[10^{\circ}, 80^{\circ}]$ by 10° *steps*	$[10^{\circ}, 80^{\circ}]$ by 10° *steps*
Loading	Applied displacement	Applied displacement
Load	$u(\pm l, z) = \pm\varepsilon_{xx} l$	$u(\pm l, z) = \pm\varepsilon_{xx} l$
	$\varepsilon_{xx} = 0.01$	$\varepsilon_{xx} = 0.01$
Material system	Glass fiber/epoxy	Glass fiber/epoxy
ENRRT calculation	VCCT	VCCT

Where we were

➔ Conclusions from simulations:

- ✓ Correct global elastic response
- ✓ Symmetric model gives symmetric results
- ✓ For $VF_f \rightarrow 0$ boundary conditions are not relevant, same result is obtained
- ✓ Correct order of magnitude of normalized energy release rates
- ✓ Physically sound mode ratio: $G_I \uparrow \Delta\theta \downarrow$, $G_{II} \uparrow \Delta\theta \uparrow$

- ✗ No agreement with BEM results
- ✗ ENRRTs overestimated

What was to be done

- ☐ Add J-integral calculations to LEFM models
- ☐ Add correct treatment of 0° case
- ☐ Add extraction of stresses and displacements at interface (post-processing)
- ☐ Add extraction of stresses and strains at sections inside the domain (post-processing)
- ☐ Run simulations with refined mesh and J-integral evaluation
- ☐ Analyse simulations' results

Where we are

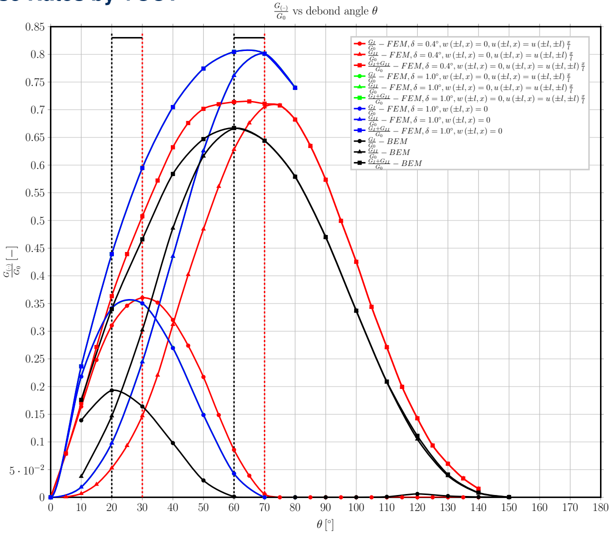
- ☑ Added J-integral calculations to LEFM models
- ☑ Added correct treatment of 0° case
- ☑ Added extraction of stresses and displacements at interface (post-processing)
- ☑ Added extraction of stresses and strains along user-defined radial and circumferential sections inside the domain (post-processing)
- ☑ Run simulations with refined mesh and J-integral evaluation
- ☑ Analysed simulations' results

Where we are

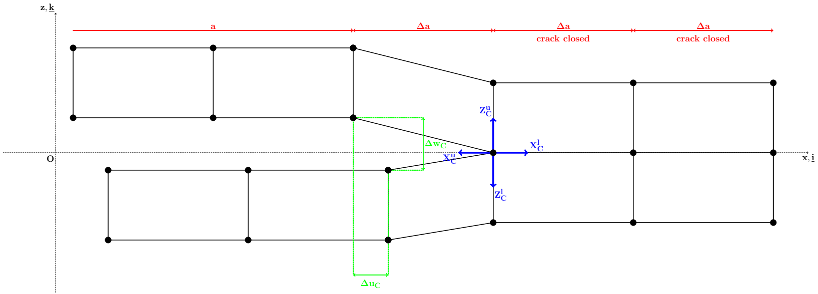
	RUN 1	RUN 2	RUN 3
BC	$v(x, \pm l) = 0$	$v(x, \pm l) = 0$	$v(x, \pm l) = 0$
BC		$u(x, \pm l) = \frac{u(l, \pm l)}{l} x$	$u(x, \pm l) = \frac{u(l, \pm l)}{l} x$
$VF_f\ [-]$	0.001	0.001	0.001
δ	1°	1°	0.4°
θ	0°	0°	0°
$\Delta\theta$	$[10^\circ, 80^\circ]$ by 10° *steps*	$[10^\circ, 80^\circ]$ by 10° *steps*	$[0^\circ, 140^\circ]$ by 5° *steps*
Loading	Applied displacement	Applied displacement	Applied displacement
Load	$u(\pm l, z) = \pm\varepsilon_{xx} l$	$u(\pm l, z) = \pm\varepsilon_{xx} l$	$u(\pm l, z) = \pm\varepsilon_{xx} l$
	$\varepsilon_{xx} = 0.01$	$\varepsilon_{xx} = 0.01$	$\varepsilon_{xx} = 0.01$
Material system	Glass fiber/epoxy	Glass fiber/epoxy	Glass fiber/epoxy
ENRRT calculation	VCCT	VCCT	VCCT & J-Integral

DISCUSSION OF RESULTS

Energy Release Rates by VCCT



G_c Numerical Evaluation by VCCT



$$G_I = \frac{Z_C \Delta w_C}{2B\Delta a} = \frac{Z_C(\Delta w_C)\Delta w_C}{2B\Delta a} \sim G_I\left(\Delta w_C^2\right) \qquad G_{II} = \frac{X_C \Delta u_C}{2B\Delta a} = \frac{X_C(\Delta u_C)\Delta u_C}{2B\Delta a} \sim G_{II}\left(\Delta u_C^2\right)$$

Comments

➔ Finer mesh gives results closer to correct ones:

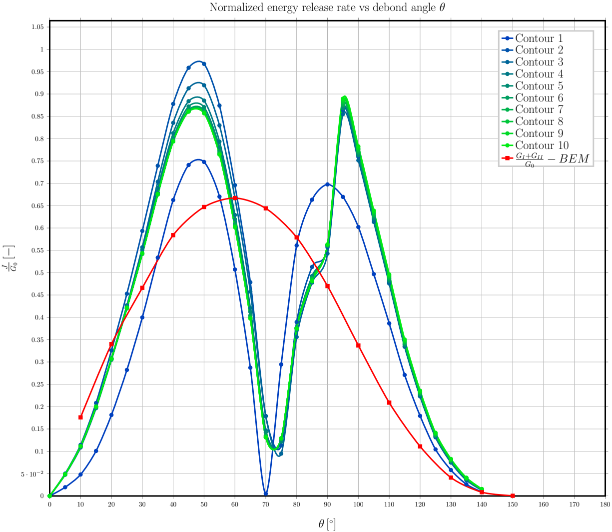
- approximation from above in terms of energy
- in FEM, the coarser the mesh, the more rigid the system; thus higher energy release
- for the same number of elements opened at the interface (crack is an ensemble of elements), a larger crack surface is created

➔ Values still too big

➔ Too much mode I

➔ Shift of peaks by $\sim 10^\circ$

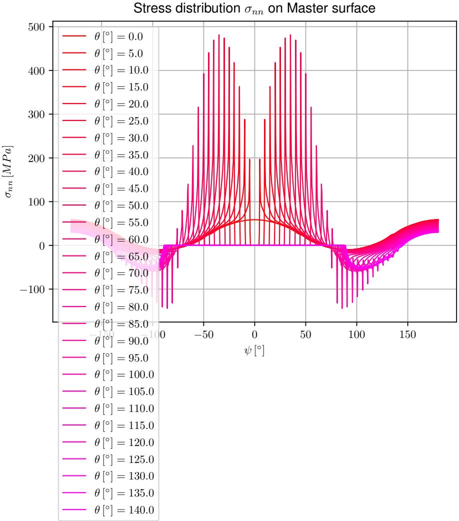
Total Energy Release Rate by J-integral



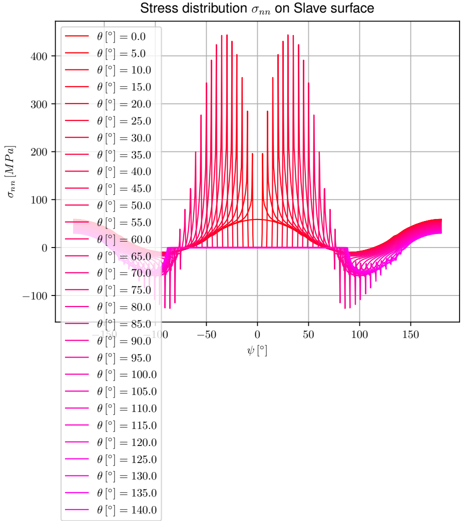
Comments

- ➔ Convergence across contour
- ➔ Very far from BEM result
- ➔ Minimum at $\sim 70^\circ$, which corresponds to the mode II maximum

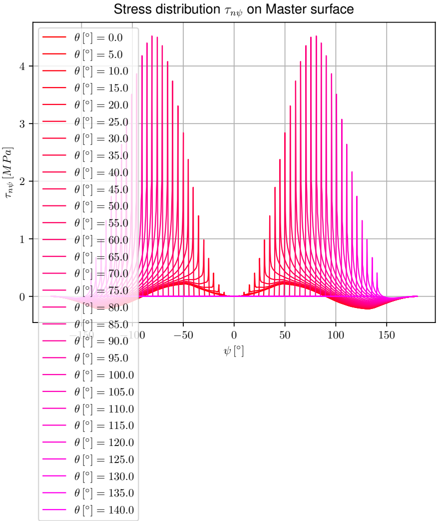
Interface


Stress distribution σ_{nn} on Master surface
σ_{nn} [MPa]
500
400
300
200
100
0
−100
−150
−100
−50
0
50
100
150
ψ [°]
θ [°] = 0.0
θ [°] = 5.0
θ [°] = 10.0
θ [°] = 15.0
θ [°] = 20.0
θ [°] = 25.0
θ [°] = 30.0
θ [°] = 35.0
θ [°] = 40.0
θ [°] = 45.0
θ [°] = 50.0
θ [°] = 55.0
θ [°] = 60.0
θ [°] = 65.0
θ [°] = 70.0
θ [°] = 75.0
θ [°] = 80.0
θ [°] = 85.0
θ [°] = 90.0
θ [°] = 95.0
θ [°] = 100.0
θ [°] = 105.0
θ [°] = 110.0
θ [°] = 115.0
θ [°] = 120.0
θ [°] = 125.0
θ [°] = 130.0
θ [°] = 135.0
θ [°] = 140.0

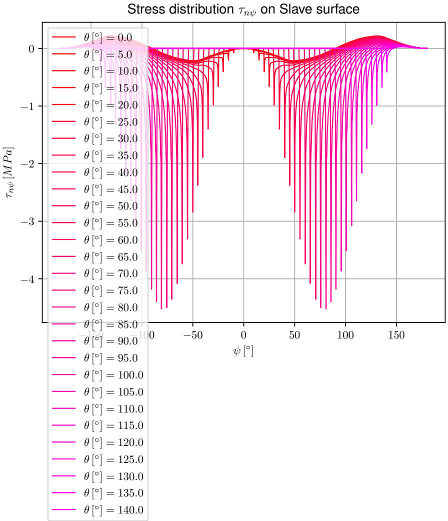
Interface


Stress distribution σ_{nn} on Slave surface
σ_{nn} $[MPa]$
ψ [°]
400
300
200
100
0
−100
−150
−100
−50
0
50
100
150
θ [°] = 0.0
θ [°] = 5.0
θ [°] = 10.0
θ [°] = 15.0
θ [°] = 20.0
θ [°] = 25.0
θ [°] = 30.0
θ [°] = 35.0
θ [°] = 40.0
θ [°] = 45.0
θ [°] = 50.0
θ [°] = 55.0
θ [°] = 60.0
θ [°] = 65.0
θ [°] = 70.0
θ [°] = 75.0
θ [°] = 80.0
θ [°] = 85.0
θ [°] = 90.0
θ [°] = 95.0
θ [°] = 100.0
θ [°] = 105.0
θ [°] = 110.0
θ [°] = 115.0
θ [°] = 120.0
θ [°] = 125.0
θ [°] = 130.0
θ [°] = 135.0
θ [°] = 140.0

Interface


Stress distribution $\tau_{n\psi}$ on Master surface
$\tau_{n\psi}$ [MPa]
ψ [°]
0
1
2
3
4
−150
−100
−50
0
50
100
150
θ [°] = 0.0
θ [°] = 5.0
θ [°] = 10.0
θ [°] = 15.0
θ [°] = 20.0
θ [°] = 25.0
θ [°] = 30.0
θ [°] = 35.0
θ [°] = 40.0
θ [°] = 45.0
θ [°] = 50.0
θ [°] = 55.0
θ [°] = 60.0
θ [°] = 65.0
θ [°] = 70.0
θ [°] = 75.0
θ [°] = 80.0
θ [°] = 85.0
θ [°] = 90.0
θ [°] = 95.0
θ [°] = 100.0
θ [°] = 105.0
θ [°] = 110.0
θ [°] = 115.0
θ [°] = 120.0
θ [°] = 125.0
θ [°] = 130.0
θ [°] = 135.0
θ [°] = 140.0

Interface


Stress distribution $\tau_{n\psi}$ on Slave surface
$\tau_{n\psi}$ [MPa]
ψ [°]
0
−1
−2
−3
−4
−50
0
50
100
150
θ [°] = 0.0
θ [°] = 5.0
θ [°] = 10.0
θ [°] = 15.0
θ [°] = 20.0
θ [°] = 25.0
θ [°] = 30.0
θ [°] = 35.0
θ [°] = 40.0
θ [°] = 45.0
θ [°] = 50.0
θ [°] = 55.0
θ [°] = 60.0
θ [°] = 65.0
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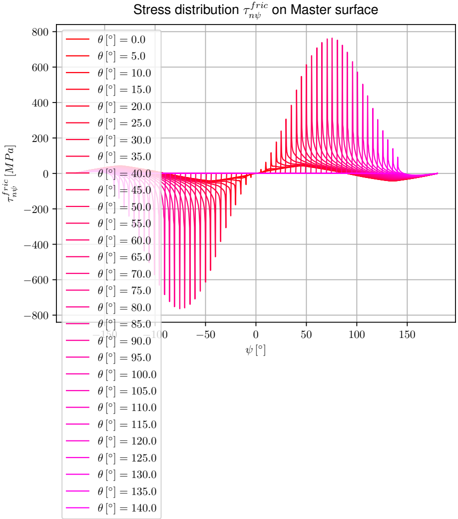
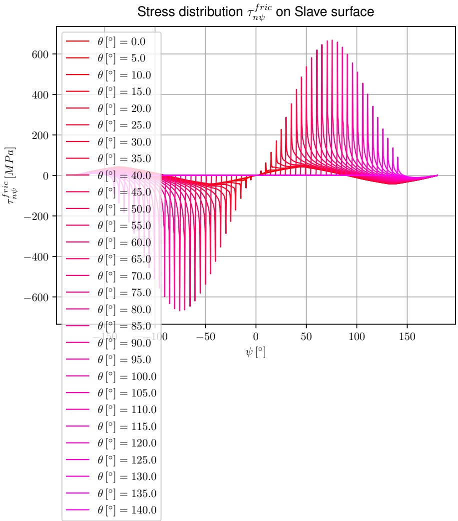
θ [°] = 80.0
θ [°] = 85.0
θ [°] = 90.0
θ [°] = 95.0
θ [°] = 100.0
θ [°] = 105.0
θ [°] = 110.0
θ [°] = 115.0
θ [°] = 120.0
θ [°] = 125.0
θ [°] = 130.0
θ [°] = 135.0
θ [°] = 140.0

Interface

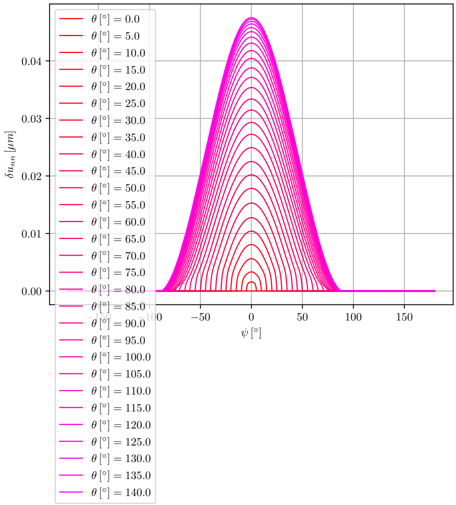

Stress distribution $\tau_{n\psi}^{fric}$ on Master surface
$\tau_{n\psi}^{fric}$ [MPa]
ψ [°]
800
600
400
200
0
−200
−400
−600
−800
−150
−100
−50
0
50
100
150
θ [°] = 0.0
θ [°] = 5.0
θ [°] = 10.0
θ [°] = 15.0
θ [°] = 20.0
θ [°] = 25.0
θ [°] = 30.0
θ [°] = 35.0
θ [°] = 40.0
θ [°] = 45.0
θ [°] = 50.0
θ [°] = 55.0
θ [°] = 60.0
θ [°] = 65.0
θ [°] = 70.0
θ [°] = 75.0
θ [°] = 80.0
θ [°] = 85.0
θ [°] = 90.0
θ [°] = 95.0
θ [°] = 100.0
θ [°] = 105.0
θ [°] = 110.0
θ [°] = 115.0
θ [°] = 120.0
θ [°] = 125.0
θ [°] = 130.0
θ [°] = 135.0
θ [°] = 140.0

Interface

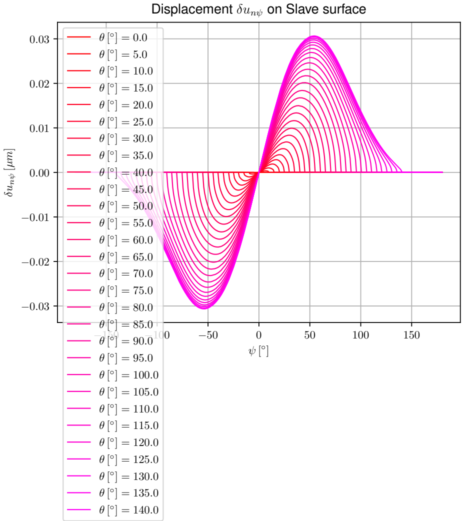

Stress distribution $\tau_{n\psi}^{fric}$ on Slave surface
$\theta\,[°] = 0.0$
$\theta\,[°] = 5.0$
$\theta\,[°] = 10.0$
$\theta\,[°] = 15.0$
$\theta\,[°] = 20.0$
$\theta\,[°] = 25.0$
$\theta\,[°] = 30.0$
$\theta\,[°] = 35.0$
$\theta\,[°] = 40.0$
$\theta\,[°] = 45.0$
$\theta\,[°] = 50.0$
$\theta\,[°] = 55.0$
$\theta\,[°] = 60.0$
$\theta\,[°] = 65.0$
$\theta\,[°] = 70.0$
$\theta\,[°] = 75.0$
$\theta\,[°] = 80.0$
$\theta\,[°] = 85.0$
$\theta\,[°] = 90.0$
$\theta\,[°] = 95.0$
$\theta\,[°] = 100.0$
$\theta\,[°] = 105.0$
$\theta\,[°] = 110.0$
$\theta\,[°] = 115.0$
$\theta\,[°] = 120.0$
$\theta\,[°] = 125.0$
$\theta\,[°] = 130.0$
$\theta\,[°] = 135.0$
$\theta\,[°] = 140.0$
$\tau_{n\psi}^{fric}\,[MPa]$
600
400
200
0
−200
−400
−600
−150
−100
−50
0
50
100
150
$\psi\,[°]$

Interface

Displacement δu_{nn} on Slave surface



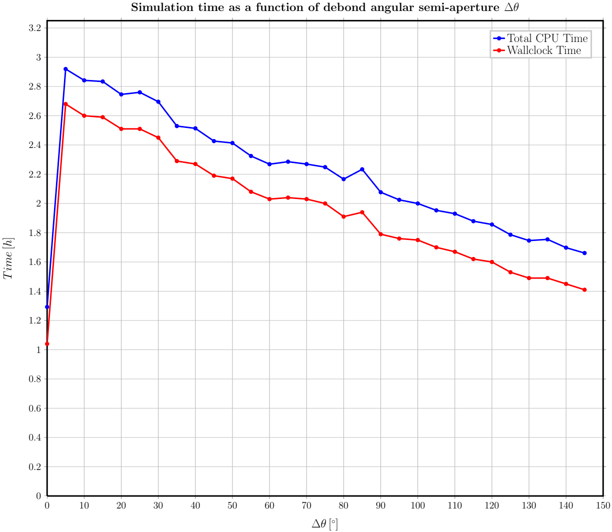
Interface


Displacement $\delta u_{n\psi}$ on Slave surface
0.03
0.02
0.01
0.00
−0.01
−0.02
−0.03
$\delta u_{n\psi}$ [μm]
−150
−100
−50
0
50
100
150
ψ [°]
θ [°] = 0.0
θ [°] = 5.0
θ [°] = 10.0
θ [°] = 15.0
θ [°] = 20.0
θ [°] = 25.0
θ [°] = 30.0
θ [°] = 35.0
θ [°] = 40.0
θ [°] = 45.0
θ [°] = 50.0
θ [°] = 55.0
θ [°] = 60.0
θ [°] = 65.0
θ [°] = 70.0
θ [°] = 75.0
θ [°] = 80.0
θ [°] = 85.0
θ [°] = 90.0
θ [°] = 95.0
θ [°] = 100.0
θ [°] = 105.0
θ [°] = 110.0
θ [°] = 115.0
θ [°] = 120.0
θ [°] = 125.0
θ [°] = 130.0
θ [°] = 135.0
θ [°] = 140.0

Comments

- ➔ Periodic distribution with peaks at crack tips
- ➔ Existence of contact zones where crack is open and surfaces slide on each other
- ➔ Shear due to friction

Numerical performances



Comments

- J-integral is highly time-consuming
- Use of parallelization is only partly effective ($\sim$ 20% boost) due to contact pair interaction and LEFM evaluations

Conclusion

- ➔ VCCT is optimal wrt J-integral for crack tip determination: Gs are zero everywhere except at crack tips
- ➔ J-integral is not reliable and time-consuming: it should be put aside in favour of VCCT
- ➔ It might be interesting to study J-integral behavior after validation is attained
- ➔ Material properties are the same as Linqi's: they shouldn't be a problem
- ➔ Applied displacement as in Linqi's model: however, value is different $\varepsilon_{xx} = 0.01$ (this model) vs $\varepsilon_{xx} = 0.05$ (Linqi)
- ➔ Shear due to friction at the interface: just an output? Does it enter the mechanics of the interface?
- ➔ Mesh: do we need a finer mesh? Probably, but it might not be the only variable at play.

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Education and Culture

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