UPDATE 2017-07-17

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Outline

- Symbols, Models, Equations & Reference Data
- Results

Symbols, Models, Equations & Reference Data

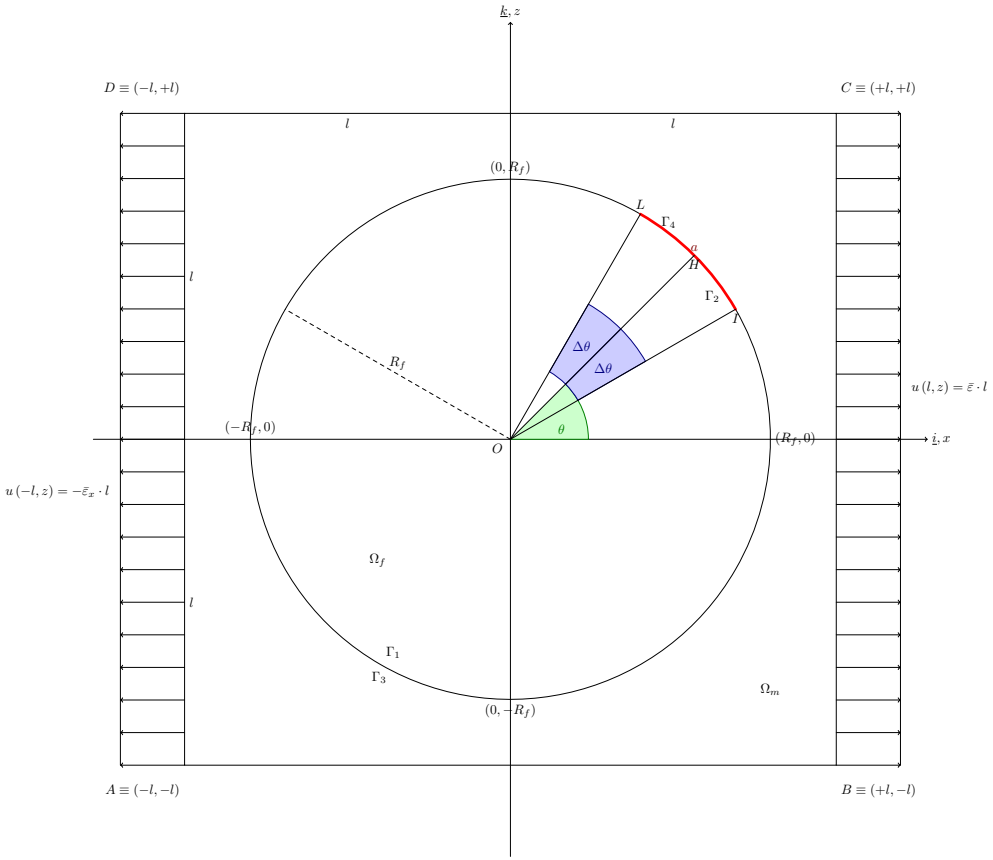
Symbols

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

Symbols

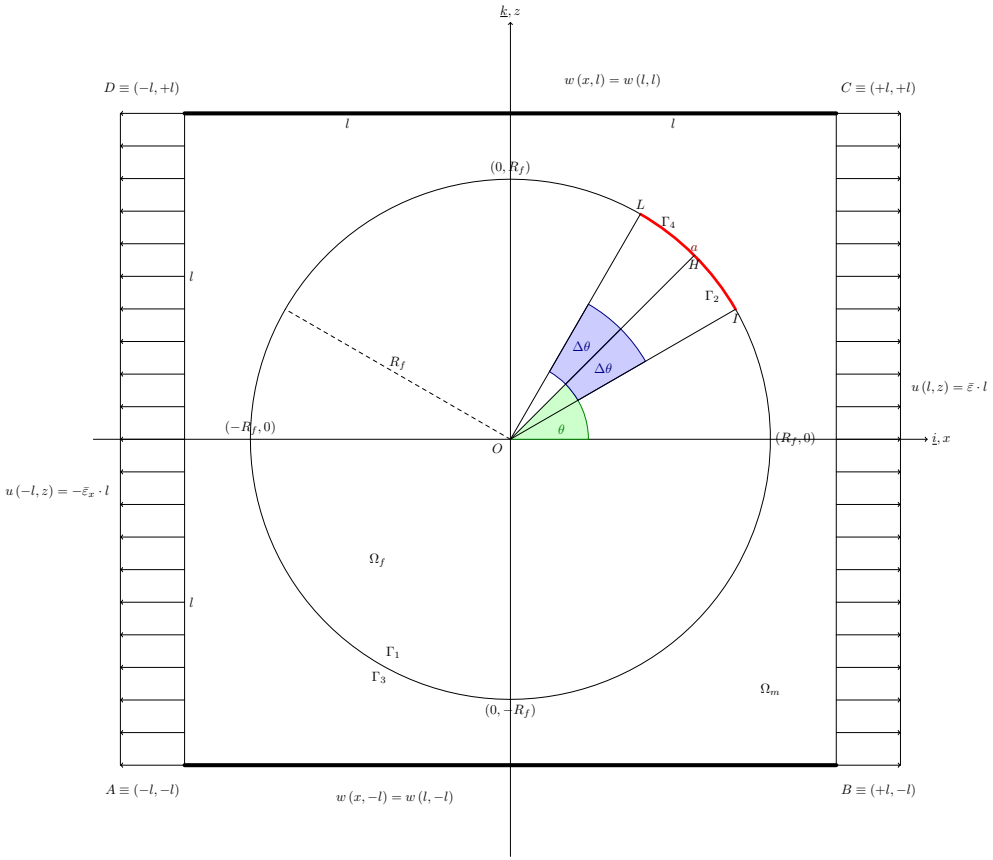
Symbol	Unit	Description
Γ_1	$[-]$	Bonded part of fiber surface
Γ_2	$[-]$	Free (debonded) part of fiber surface
Γ_3	$[-]$	Bonded part of matrix surface
Γ_4	$[-]$	Free (debonded) part of matrix surface

Reference Models



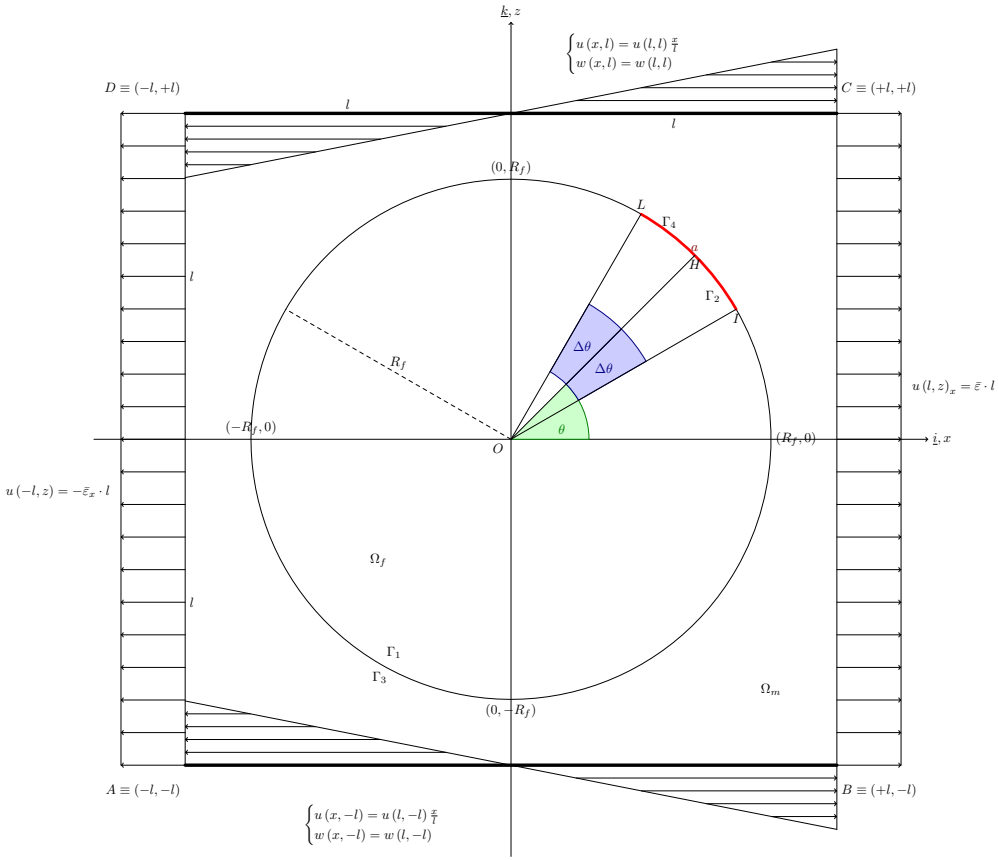
Simple RVE, BC: free.

Reference Models



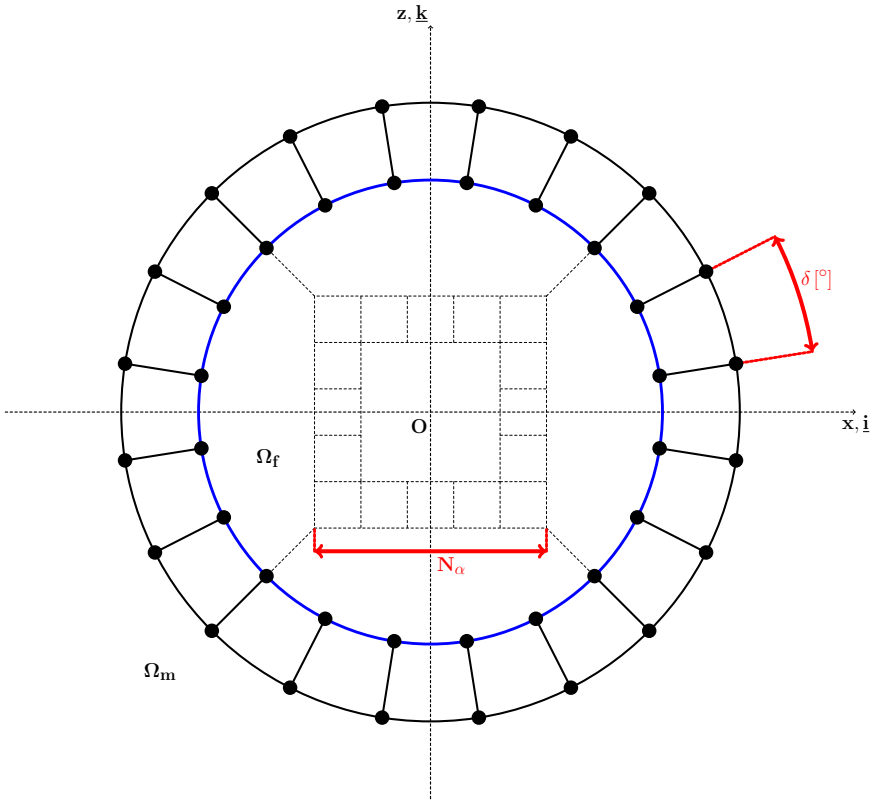
Simple RVE, BC: fixed vertical displacement.

Reference Models



Simple RVE, BC: fixed vertical and homogeneous horizontal displacement.

Angular discretization



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

Material properties

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

Evaluation of G_0

$$G_0 = \pi R_f \sigma_0^2 \frac{1 + k_m}{8 G_m} \tag{1}$$

$$k_m = 3 - 4\nu_m \tag{2}$$

$$\sigma_0^{undamaged} = \frac{E_m}{1 - \nu_m^2} \varepsilon_{xx} \tag{3}$$

VCCT in Forces

$$\Delta u = \left| \Delta u^{matrix}_{\text{1 element before crack tip}} - \Delta u^{fiber}_{\text{1 element before crack tip}} \right| \tag{4}$$

$$\Delta w = \left| \Delta w^{matrix}_{\text{1 element before crack tip}} - \Delta w^{fiber}_{\text{1 element before crack tip}} \right| \tag{5}$$

$$\beta = \arctan\left(\frac{z^{matrix,undef}_{\text{crack tip}}}{x^{matrix,undef}_{\text{crack tip}}} \right) \tag{6}$$

$$\Delta_r = \cos(\beta)\Delta u + \sin(\beta)\Delta w \qquad \Delta_\theta = -\sin(\beta)\Delta u + \cos(\beta)\Delta w \tag{7}$$

$$F_r = \cos(\beta)F_x^{reaction} + \sin(\beta)F_z^{reaction} \qquad F_\theta = -\sin(\beta)F_x^{reaction} + \cos(\beta)F_z^{reaction} \tag{8}$$

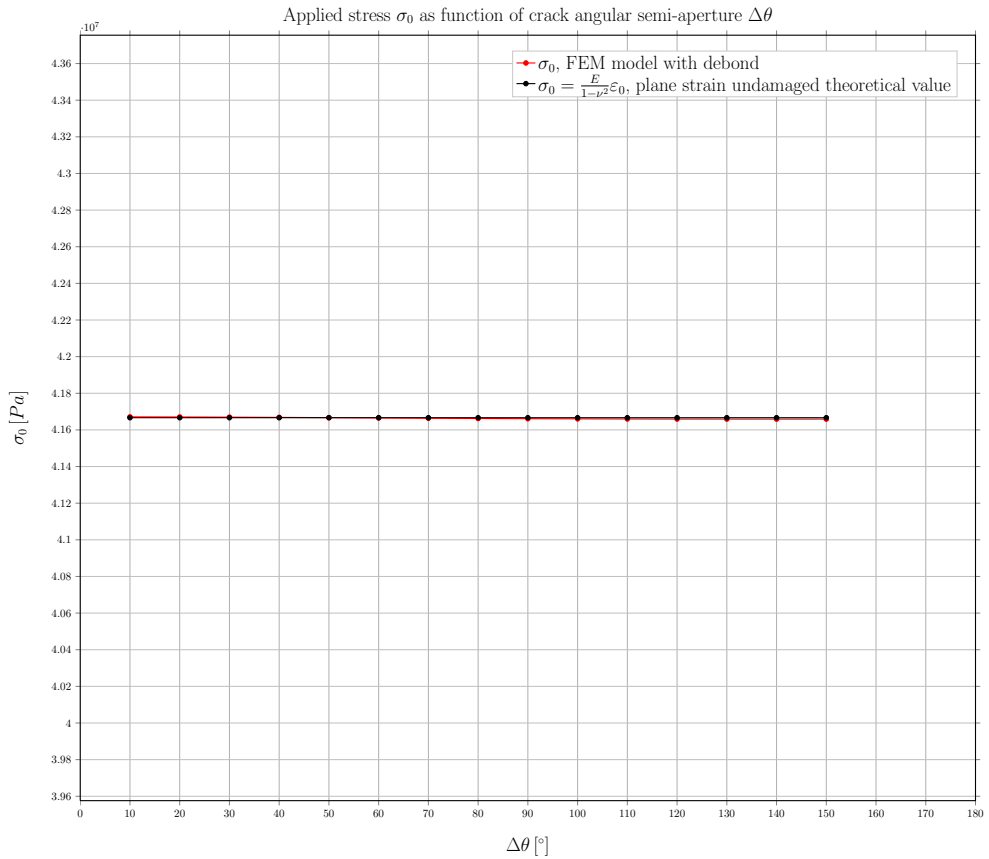
$$G_I = \frac{1}{2}\frac{F_r \Delta_r}{R_f \delta} \qquad G_{II} = \frac{1}{2}\frac{F_\theta \Delta_\theta}{R_f \delta} \qquad b = 1.0 \leftrightarrow \Delta A = b R_f \delta \tag{9}$$

VCCT in Stresses

↘ RESULTS

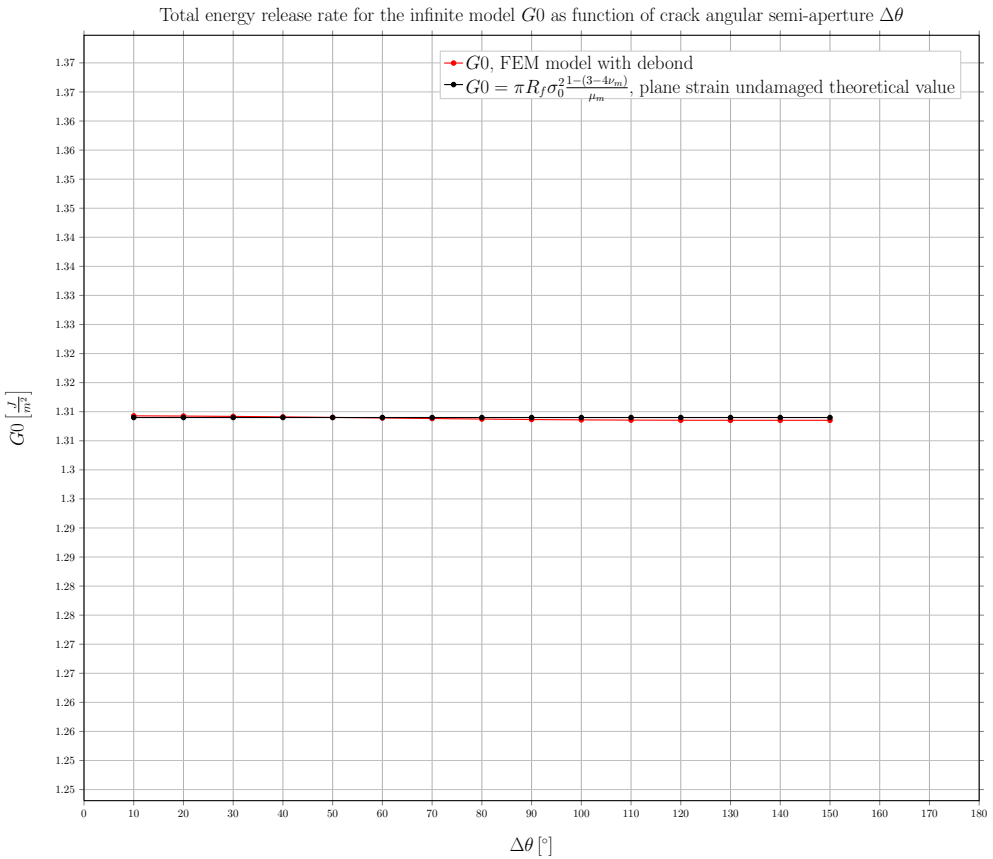
Model Data

σ_0, $\delta = 1.0°$



In red small strain FEM, in black analytical plain strain value.

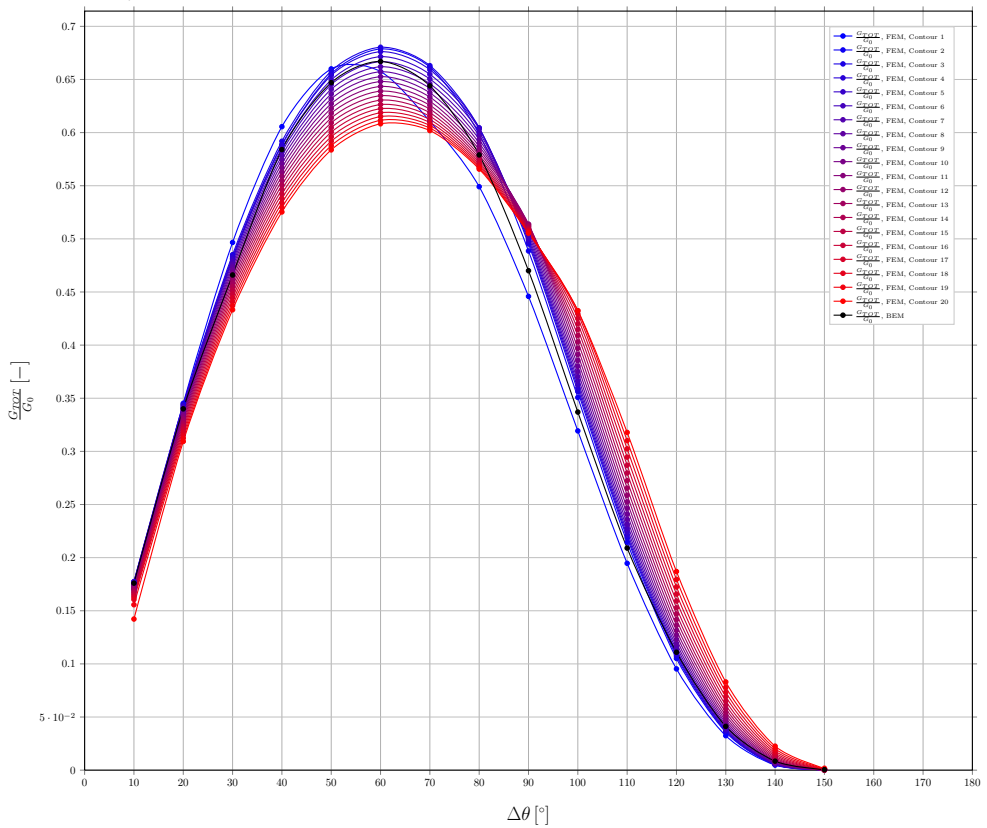
G_0, $\delta = 1.0°$



In red small strain FEM, in black analytical plain strain value.

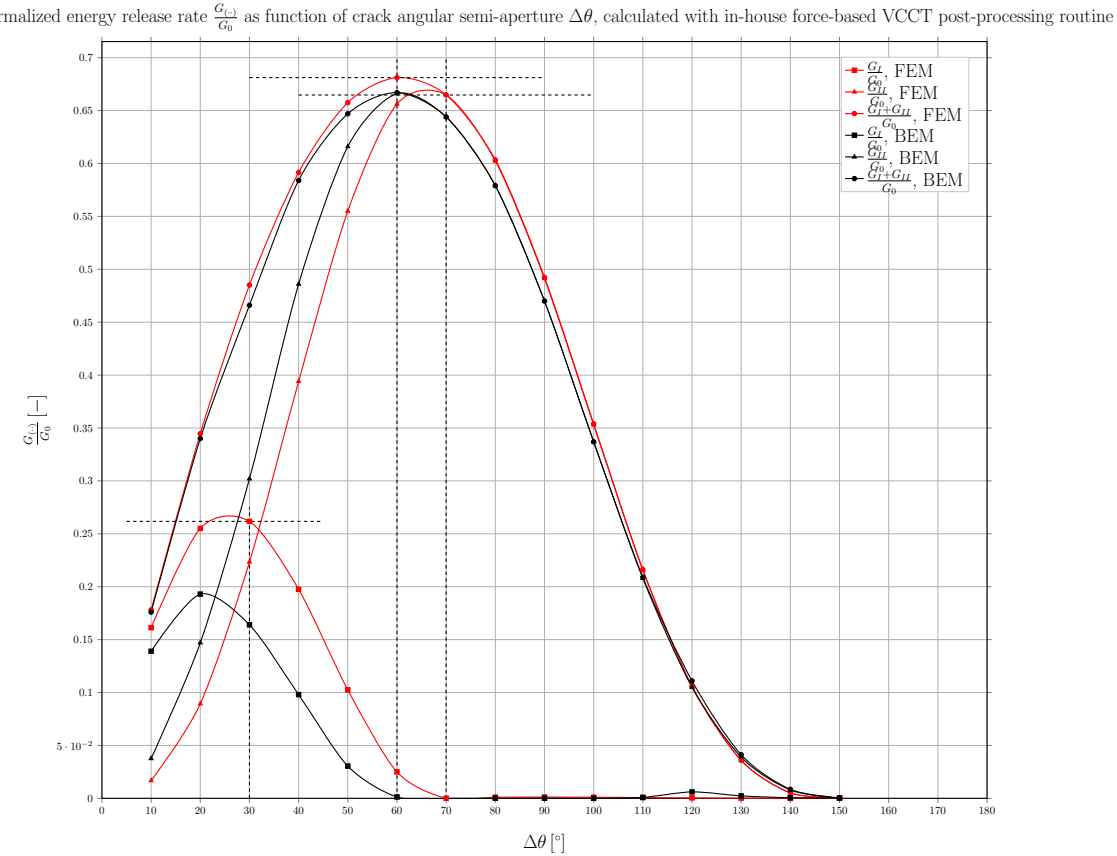
J-Integral (Abaqus built-in routine), $\delta = 1.0°$

Normalized total energy release rate $\frac{G_{TOT}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with Abaqus built-in J-Integral post-processing routine (*CONTOUR INTEGRAL)



Fading from blue to red for contours further from the crack tip, FEM results; in black BEM results.

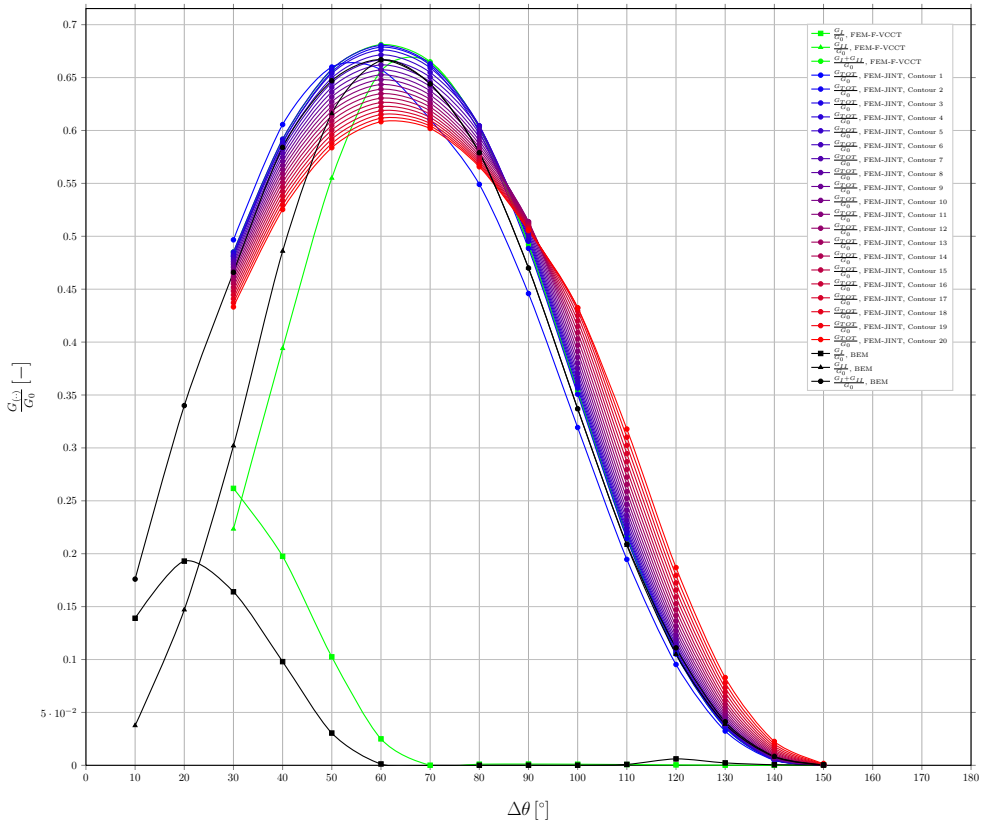
VCCT in forces (in-house Python routine), $\delta = 1.0°$



In green VCCT from FEM results, in black BEM results; positions of maxima highlighted by dashed lines.

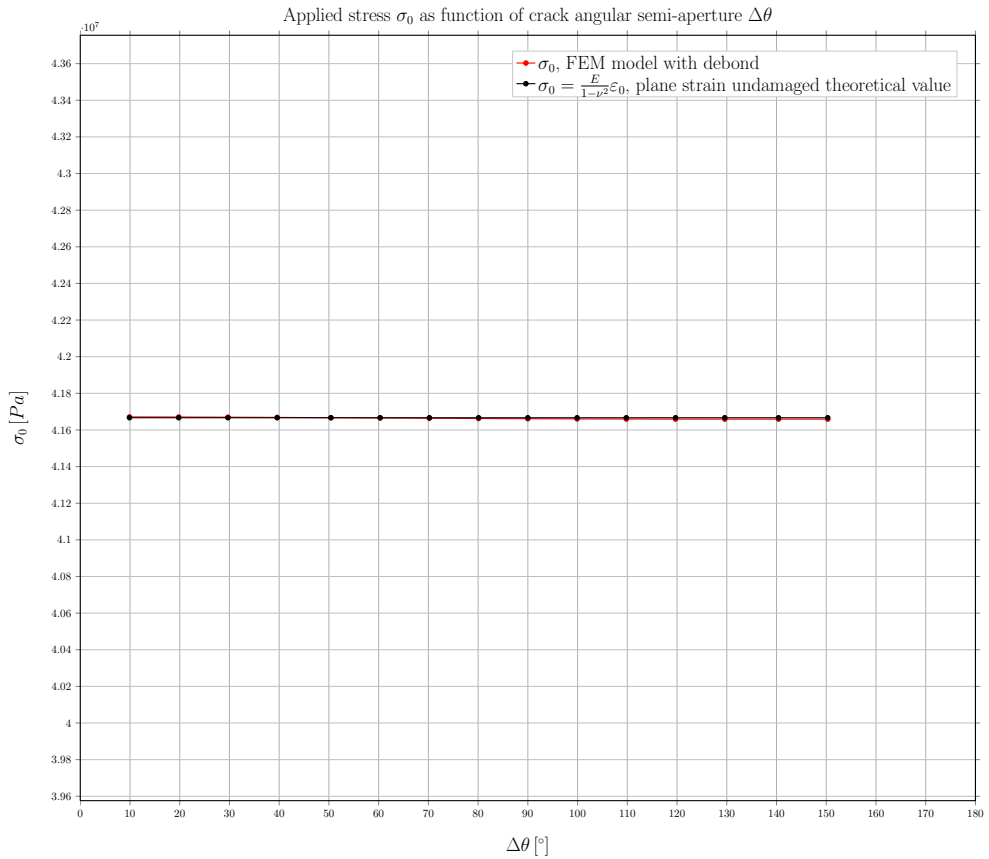
J-Integral and VCCT in forces, $\delta = 1.0°$

Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT and Abaqus built-in J-Integral (*CONTOUR INTEGRAL) post-processing routines



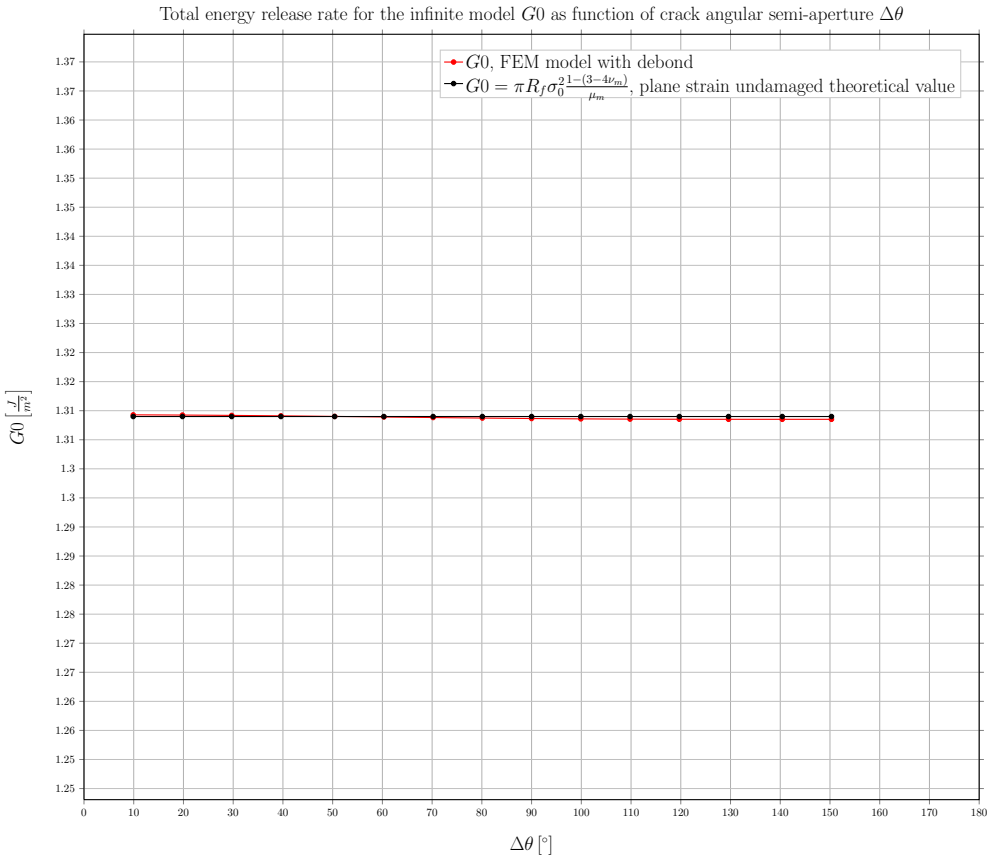
Fading from blue to red for contours further from the crack tip, J-Integral from FEM results; in green VCCT from FEM results; in black BEM results.

σ_0, $\delta = 0.9°$



In red small strain FEM, in black analytical plain strain value.

G_0, $\delta = 0.9°$



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J-Integral (Abaqus built-in routine), $\delta = 0.9°$

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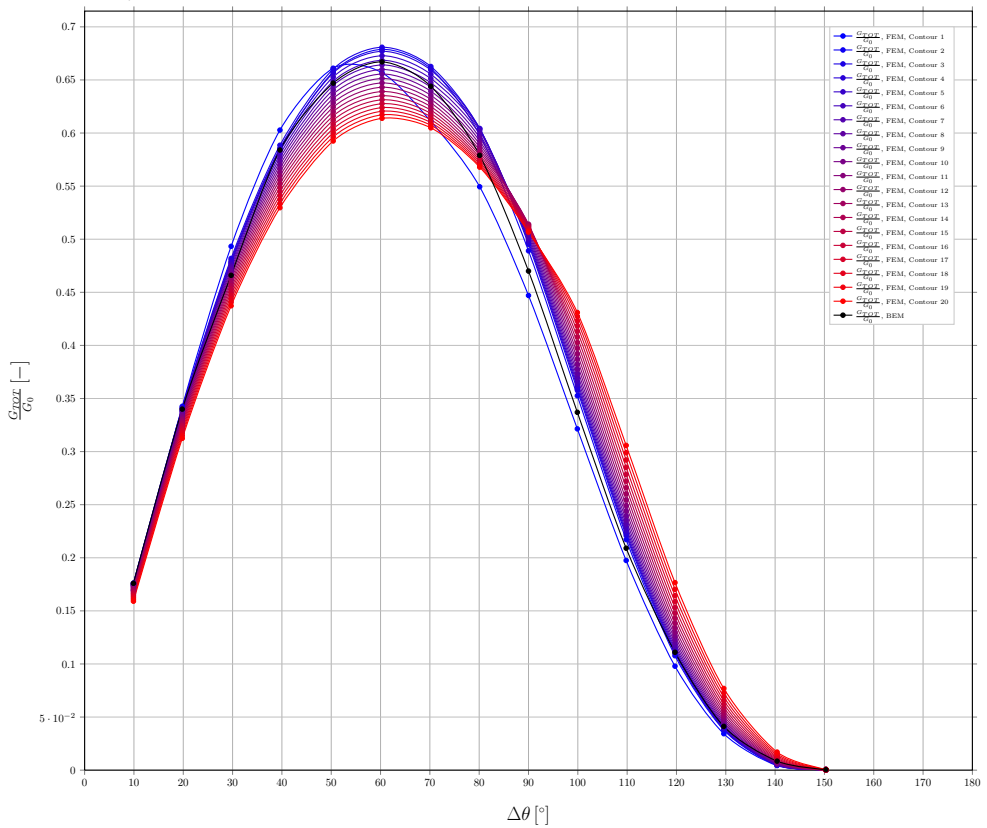

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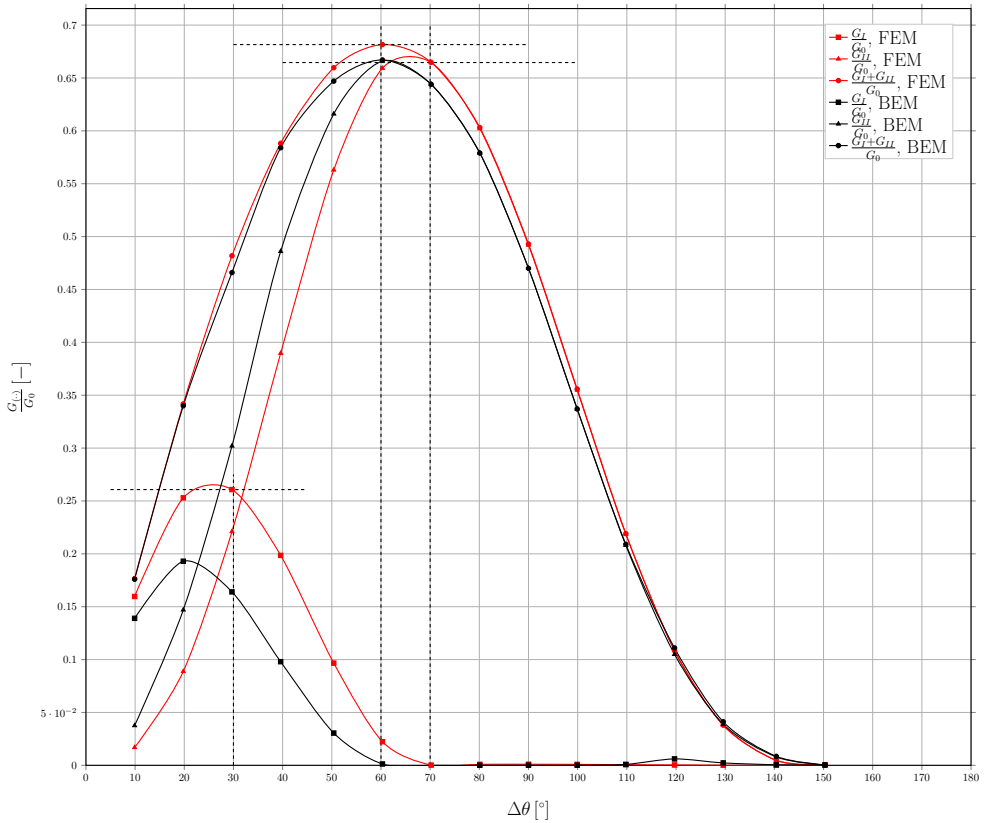
VCCT in forces (in-house Python routine), $\delta = 0.9°$

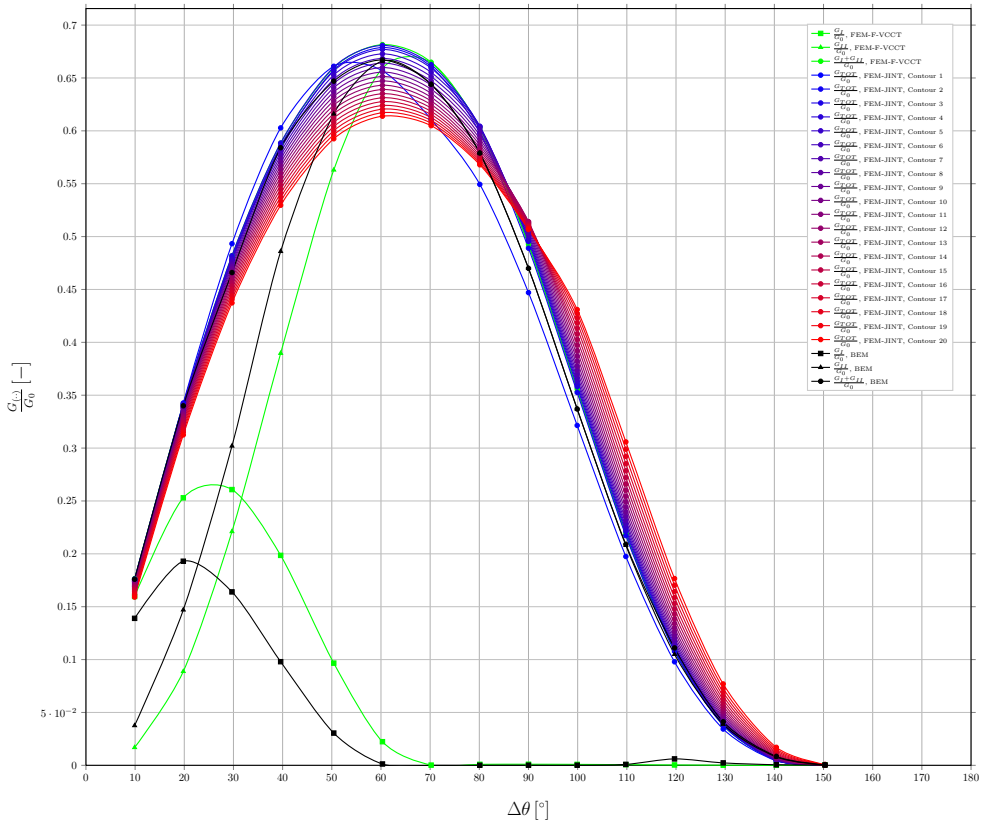
Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT post-processing routine



In green VCCT from FEM results, in black BEM results; positions of maxima highlighted by dashed lines.

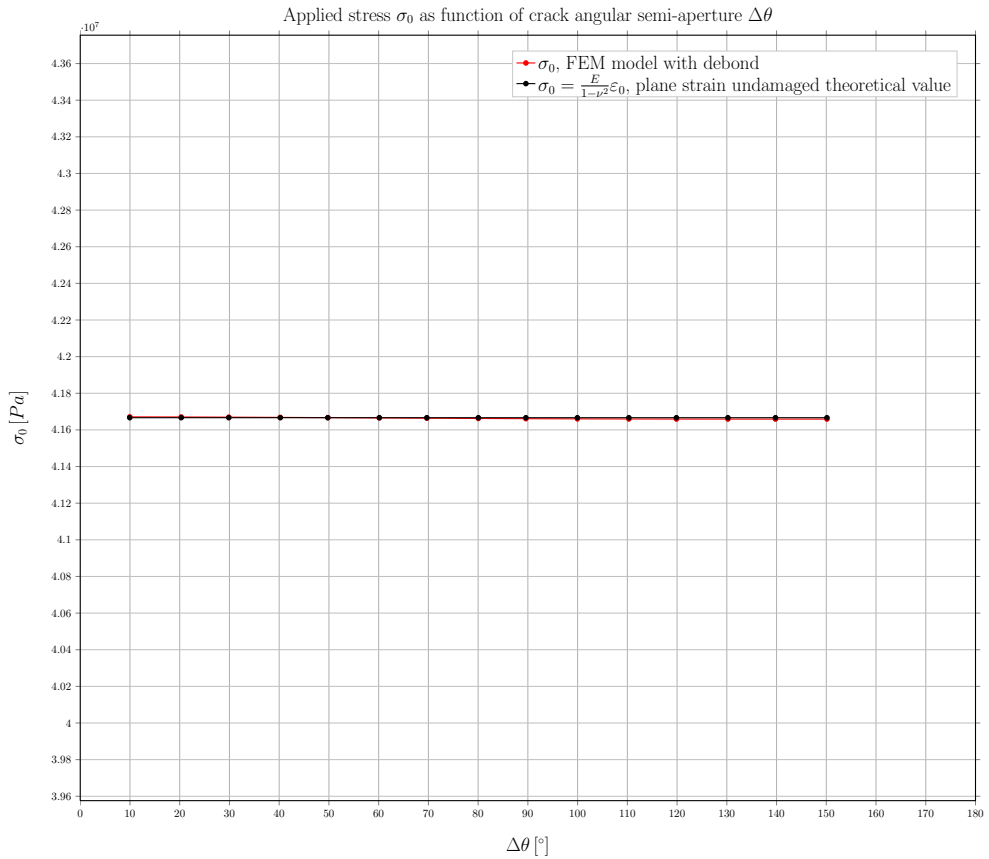
J-Integral and VCCT in forces, $\delta = 0.9°$

Normalized energy release rate $\frac{G_{(-)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT and Abaqus built-in J-Integral (*CONTOUR INTEGRAL) post-processing routines



Fading from blue to red for contours further from the crack tip, J-Integral from FEM results; in green VCCT from FEM results; in black BEM results.

σ_0, $\delta = 0.8°$



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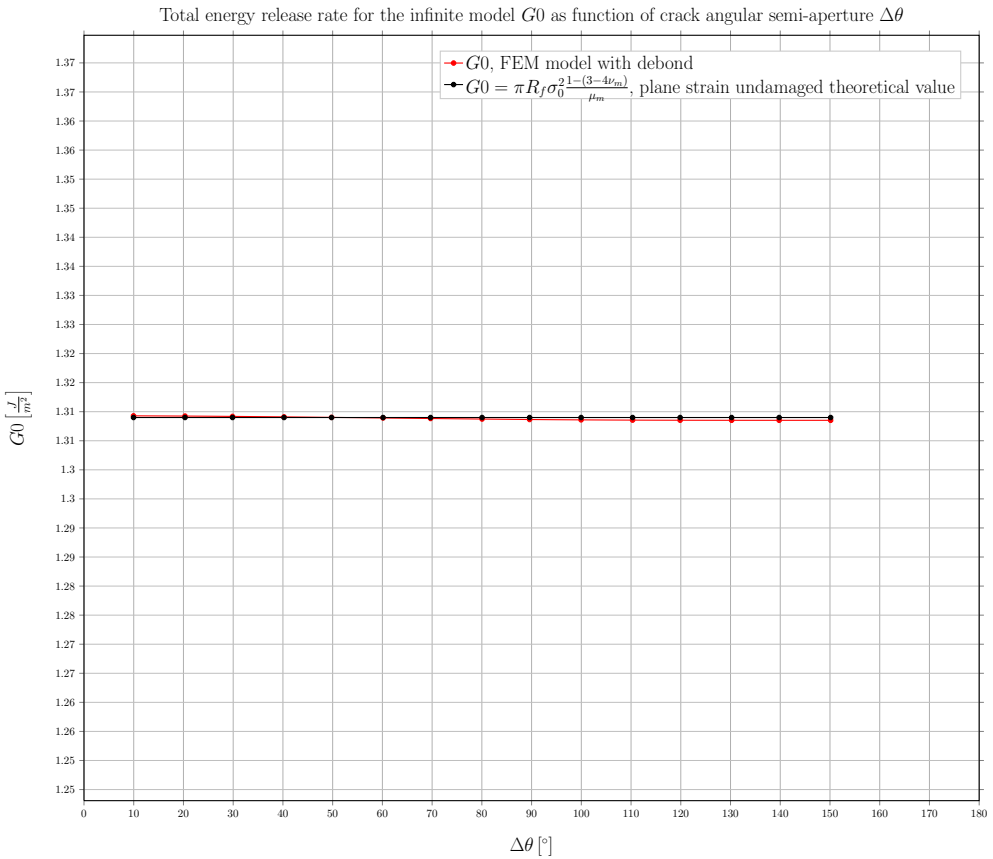
G_0, $\delta = 0.8°$



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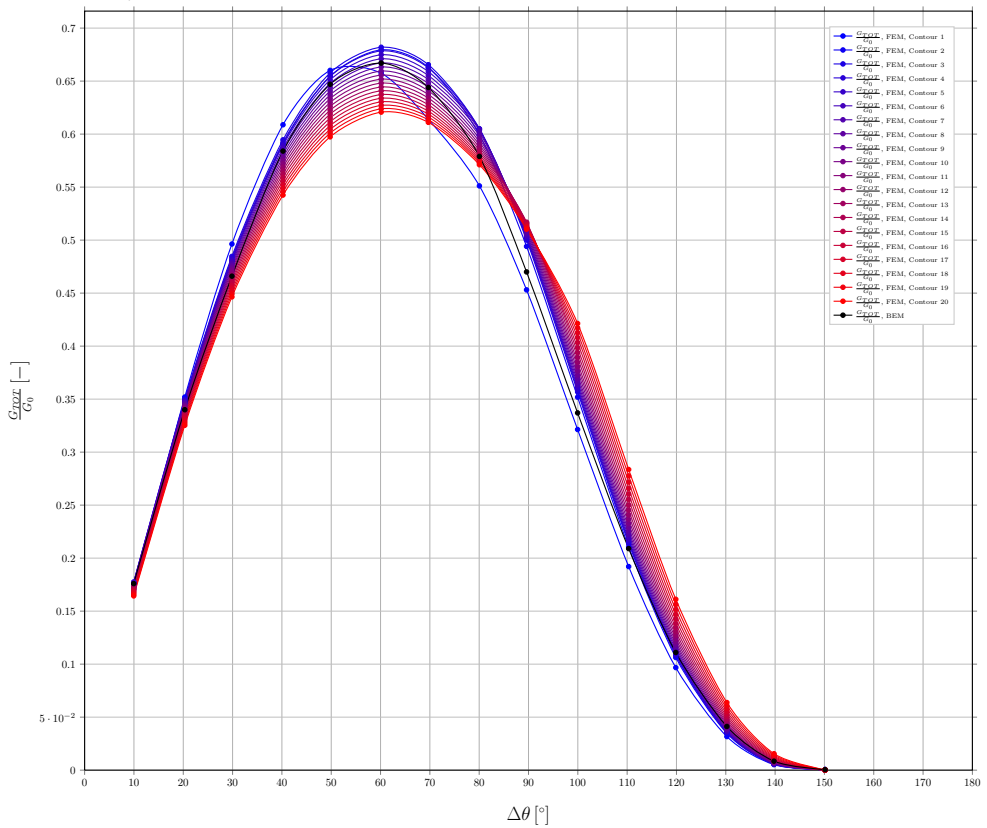
J-Integral (Abaqus built-in routine), $\delta = 0.8°$

Normalized total energy release rate $\frac{G_{TOT}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with Abaqus built-in J-Integral post-processing routine (*CONTOUR INTEGRAL)



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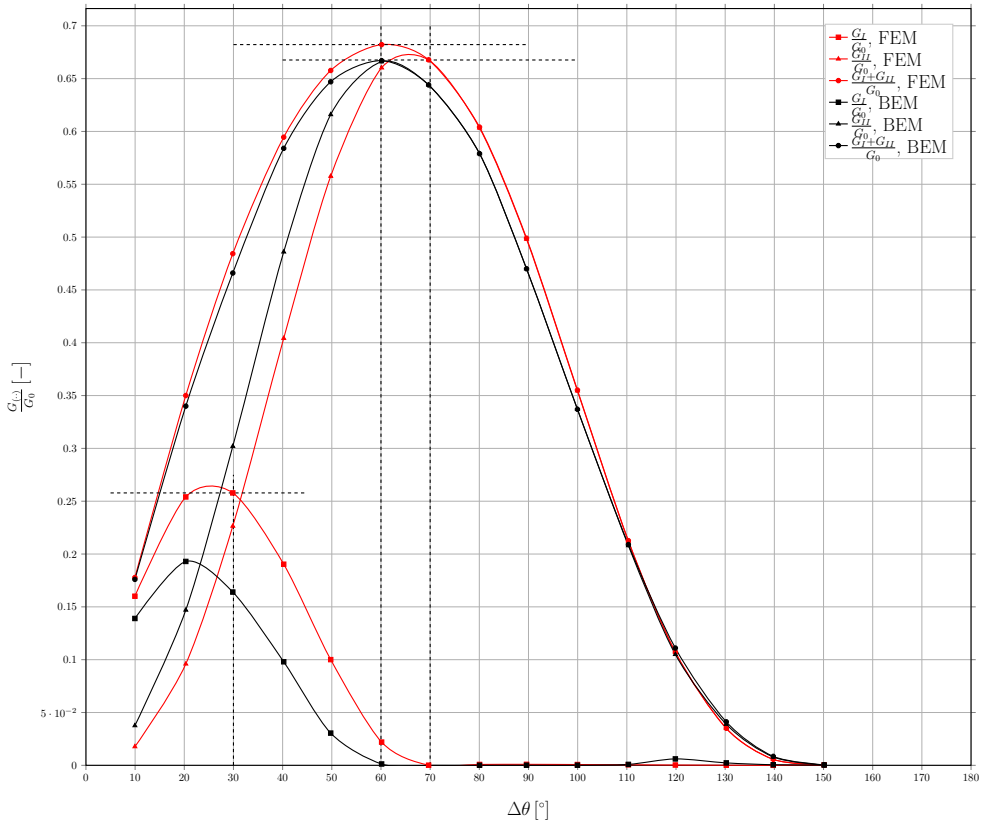
VCCT in forces (in-house Python routine), $\delta = 0.8°$

Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT post-processing routine



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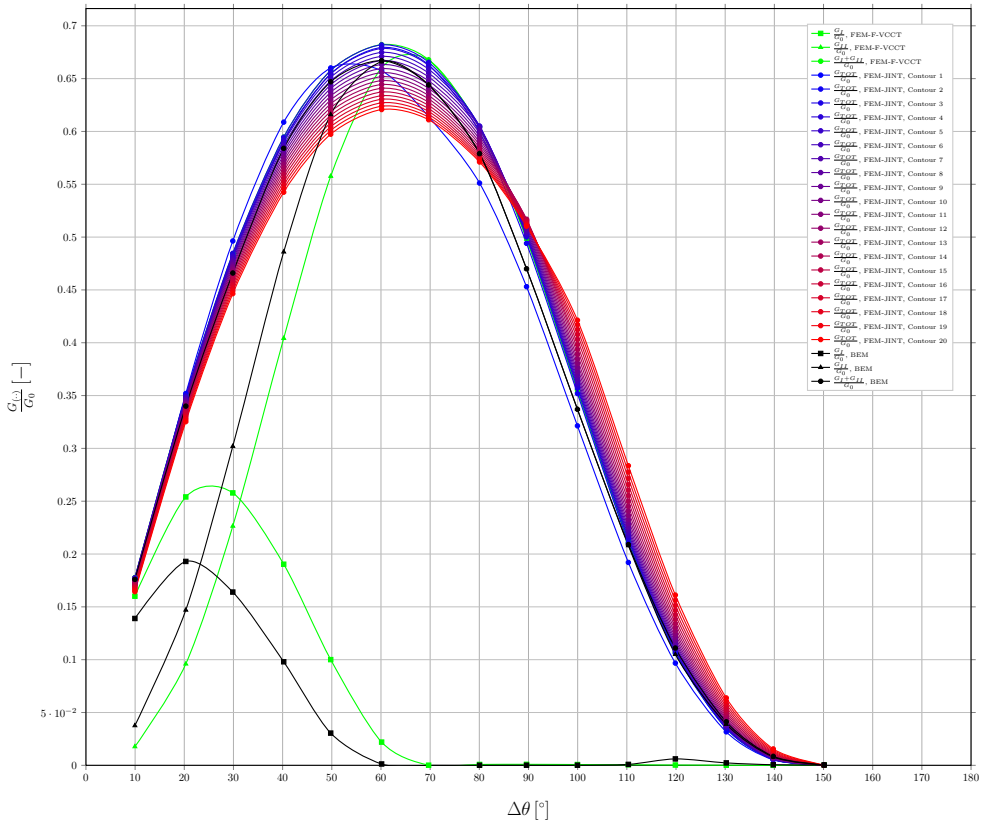

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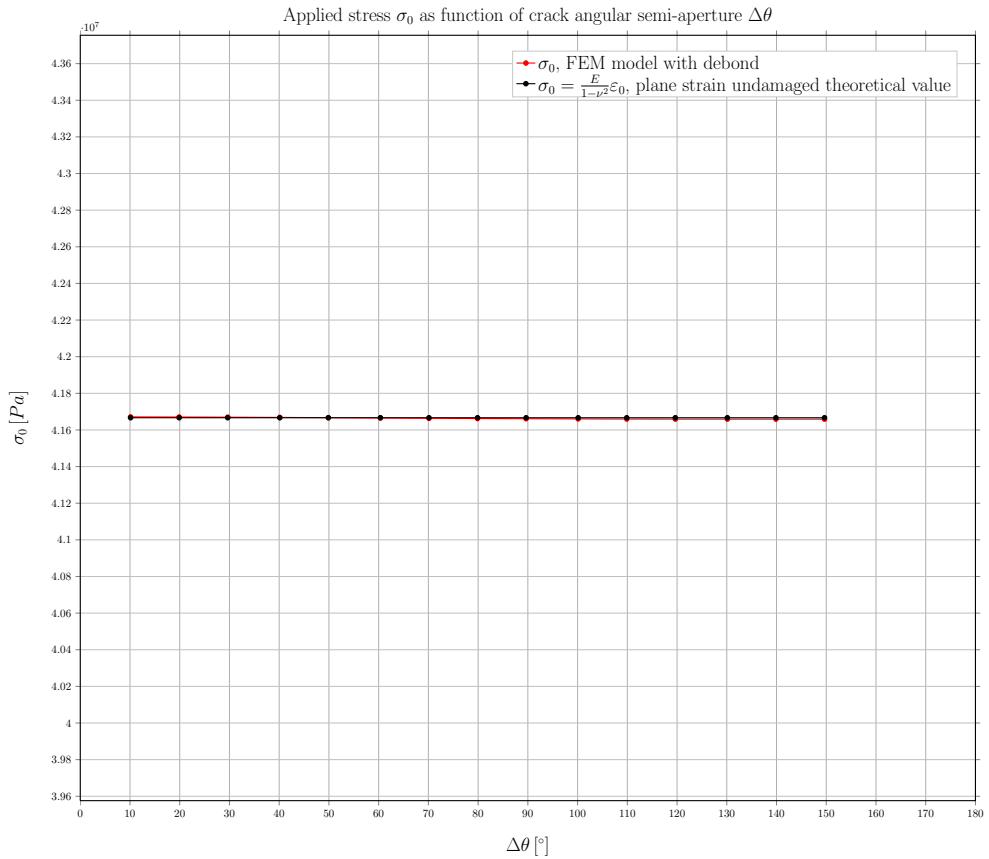

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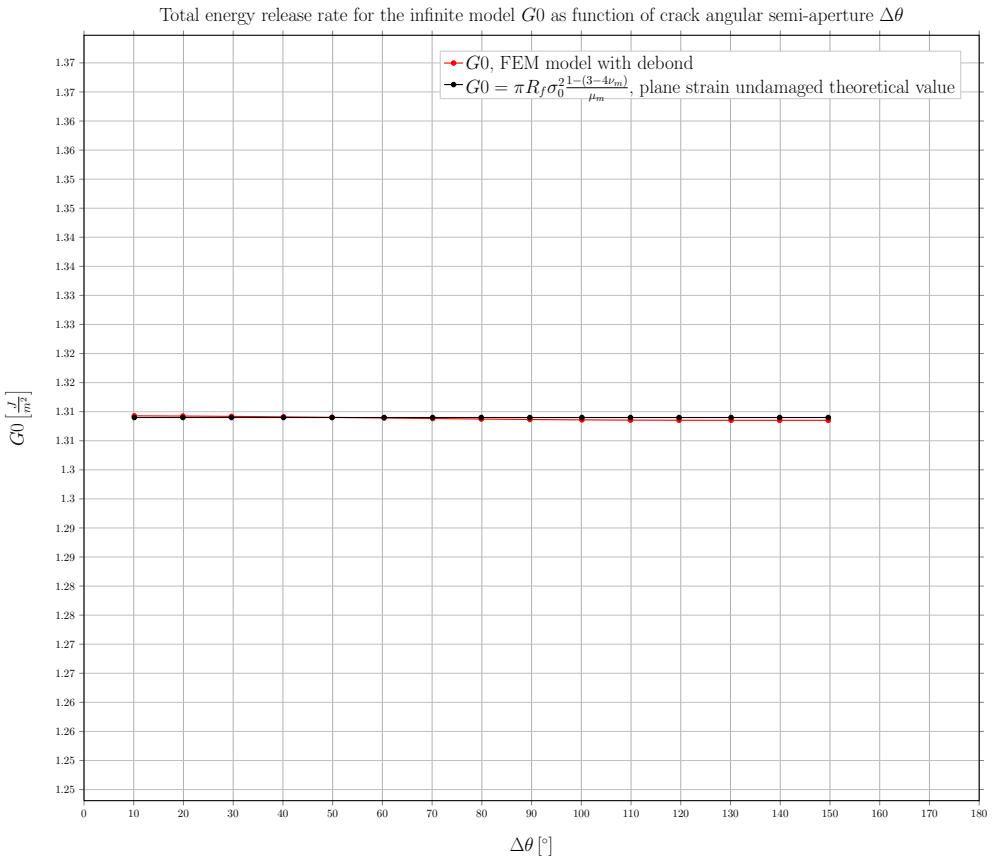
G_0, $\delta = 0.7°$



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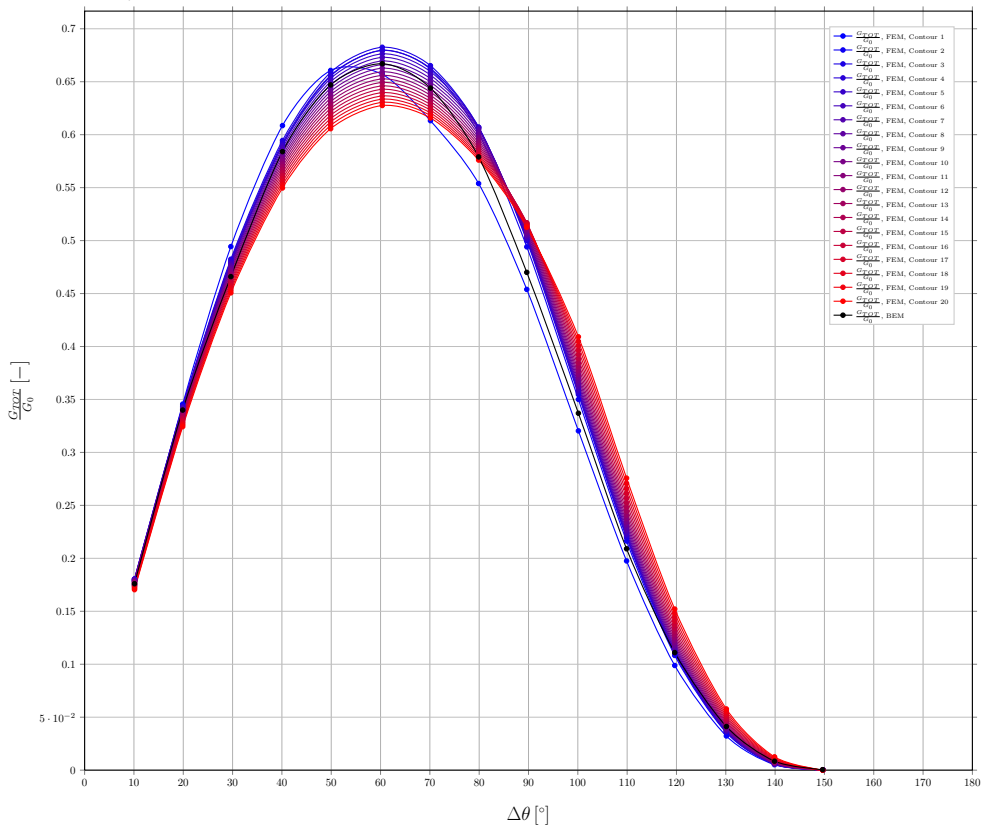
Normalized total energy release rate $\frac{G_{TOT}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with Abaqus built-in J-Integral post-processing routine (*CONTOUR INTEGRAL)



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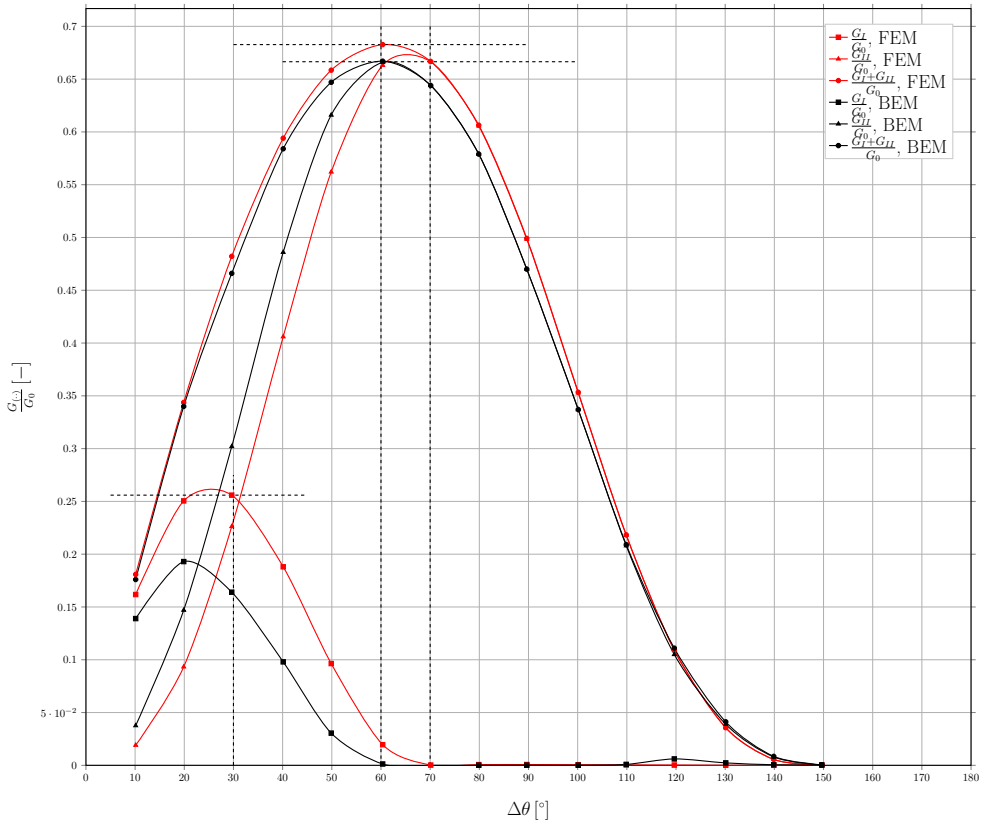
VCCT in forces (in-house Python routine), $\delta = 0.7°$

Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT post-processing routine



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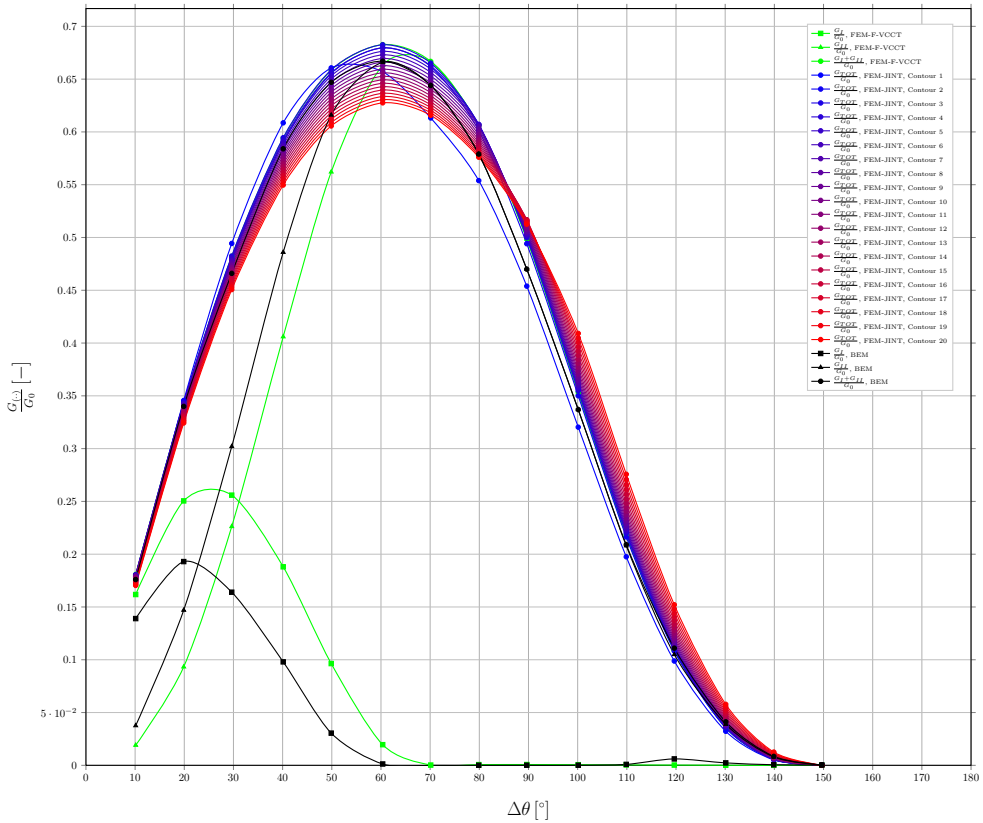
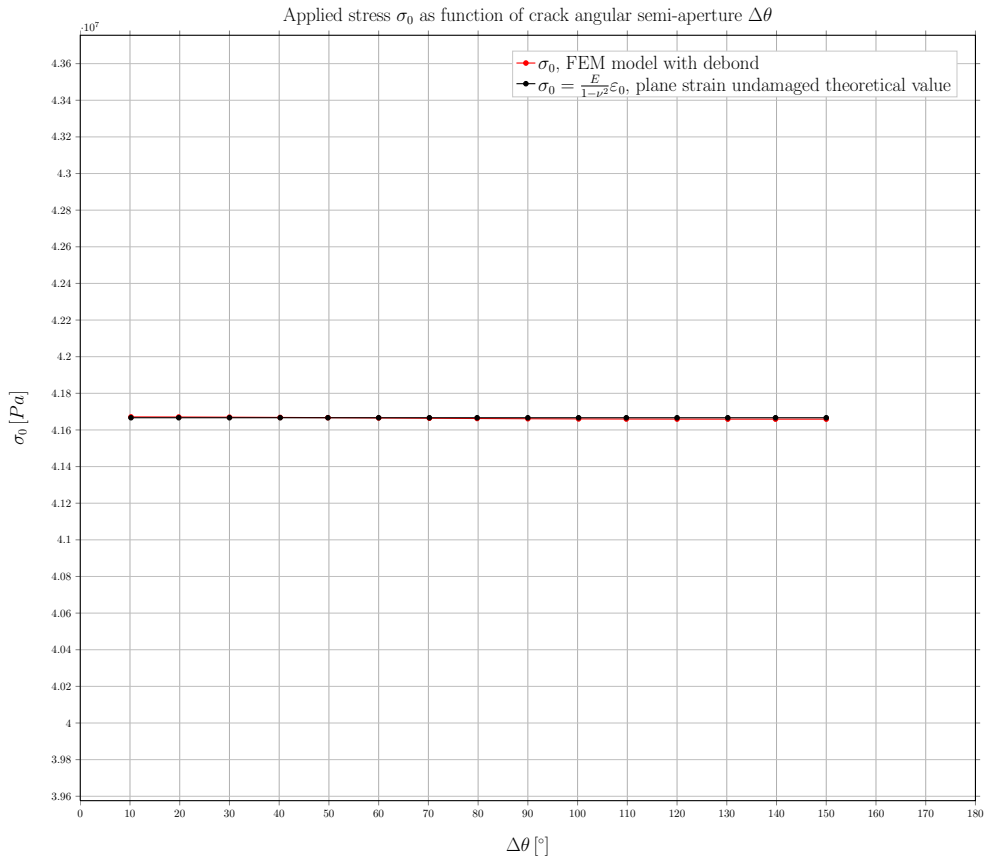
J-Integral and VCCT in forces, $\delta = 0.7°$

Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT and Abaqus built-in J-Integral (*CONTOUR INTEGRAL) post-processing routines



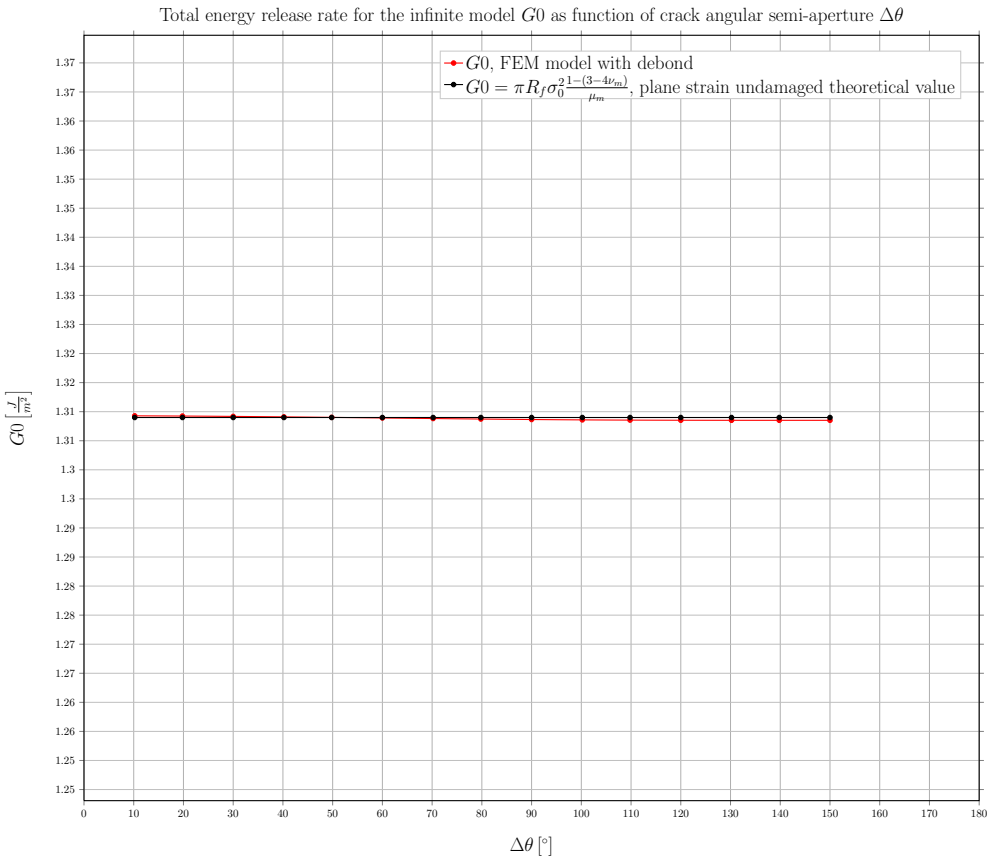
Fading from blue to red for contours further from the crack tip, J-Integral from FEM results; in green VCCT from FEM results; in black BEM results.

σ_0, $\delta = 0.6°$



In red small strain FEM, in black analytical plain strain value.

G_0, $\delta = 0.6°$



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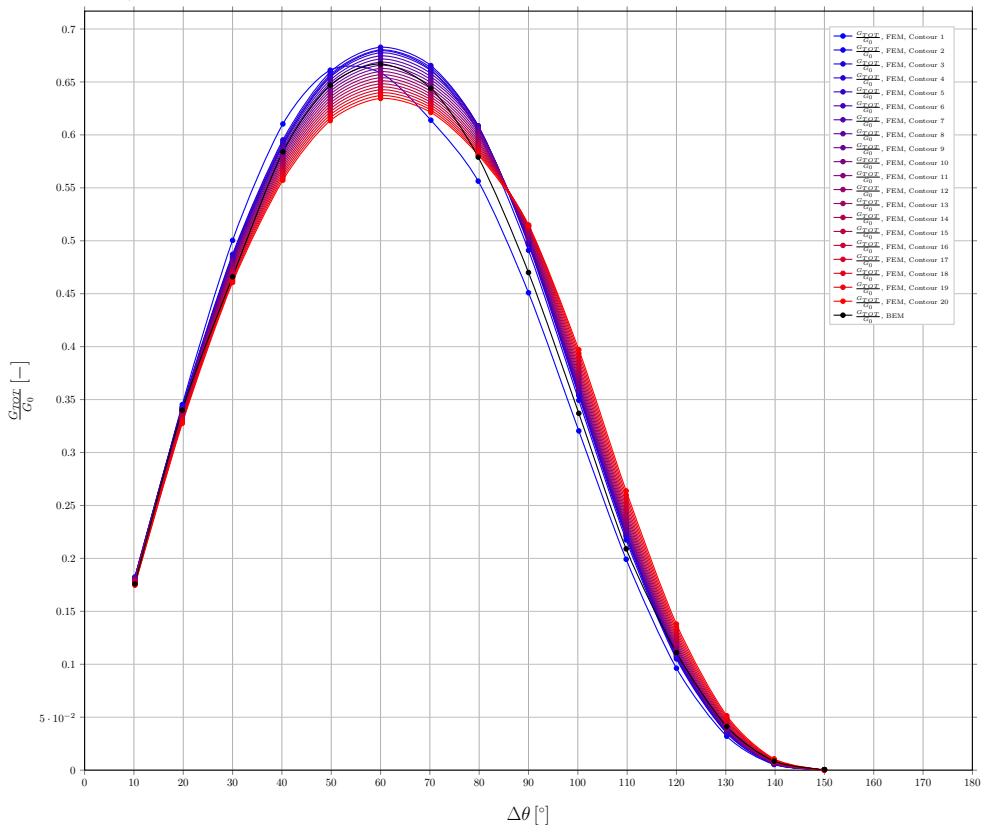
J-Integral (Abaqus built-in routine), $\delta = 0.6°$

Normalized total energy release rate $\frac{G_{TOT}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with Abaqus built-in J-Integral post-processing routine (*CONTOUR INTEGRAL)



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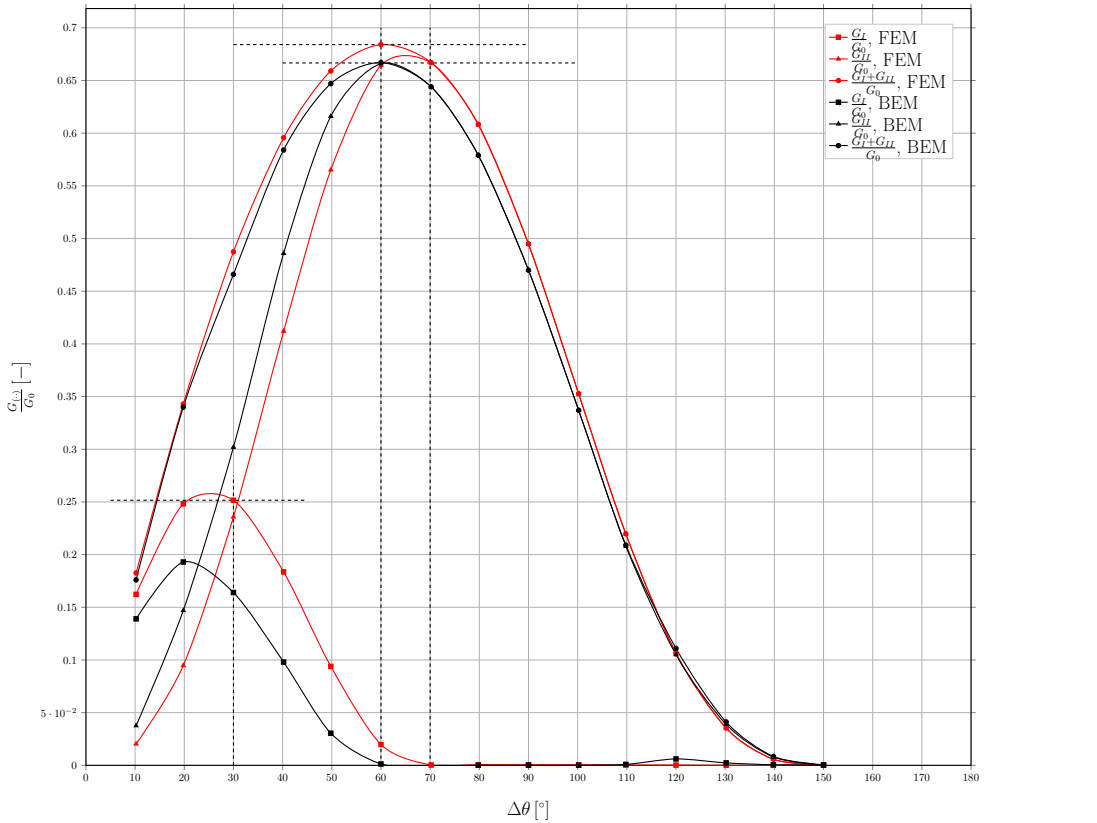
VCCT in forces (in-house Python routine), $\delta = 0.6°$

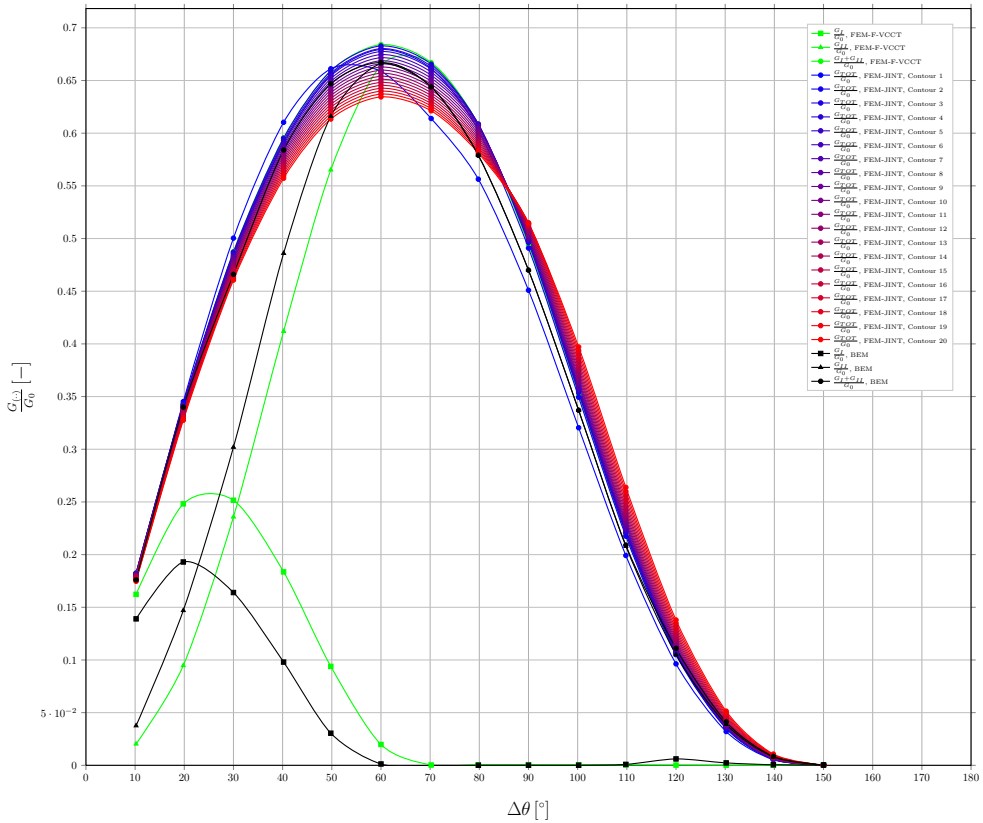
Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT post-processing routine



In green VCCT from FEM results, in black BEM results; positions of maxima highlighted by dashed lines.

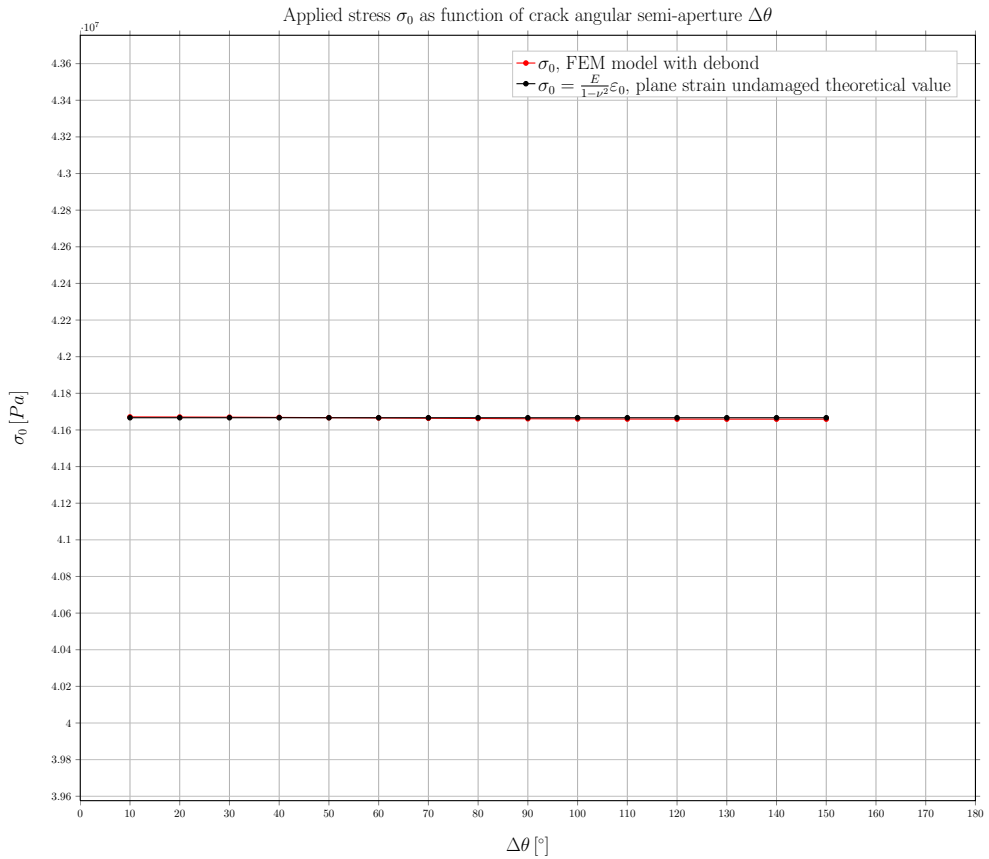
J-Integral and VCCT in forces, $\delta = 0.6°$

Normalized energy release rate $\frac{G_{(-)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT and Abaqus built-in J-Integral (*CONTOUR INTEGRAL) post-processing routines



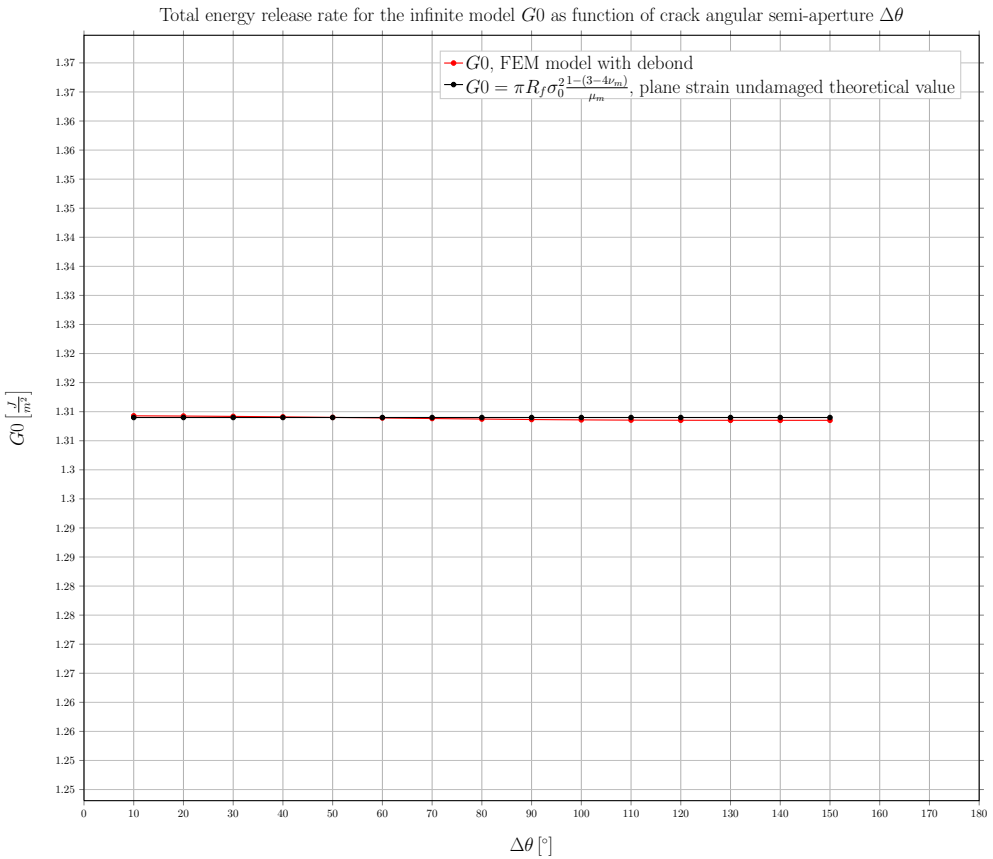
Fading from blue to red for contours further from the crack tip, J-Integral from FEM results; in green VCCT from FEM results; in black BEM results.

σ_0, $\delta = 0.5°$



In red small strain FEM, in black analytical plain strain value.

G_0, $\delta = 0.5°$



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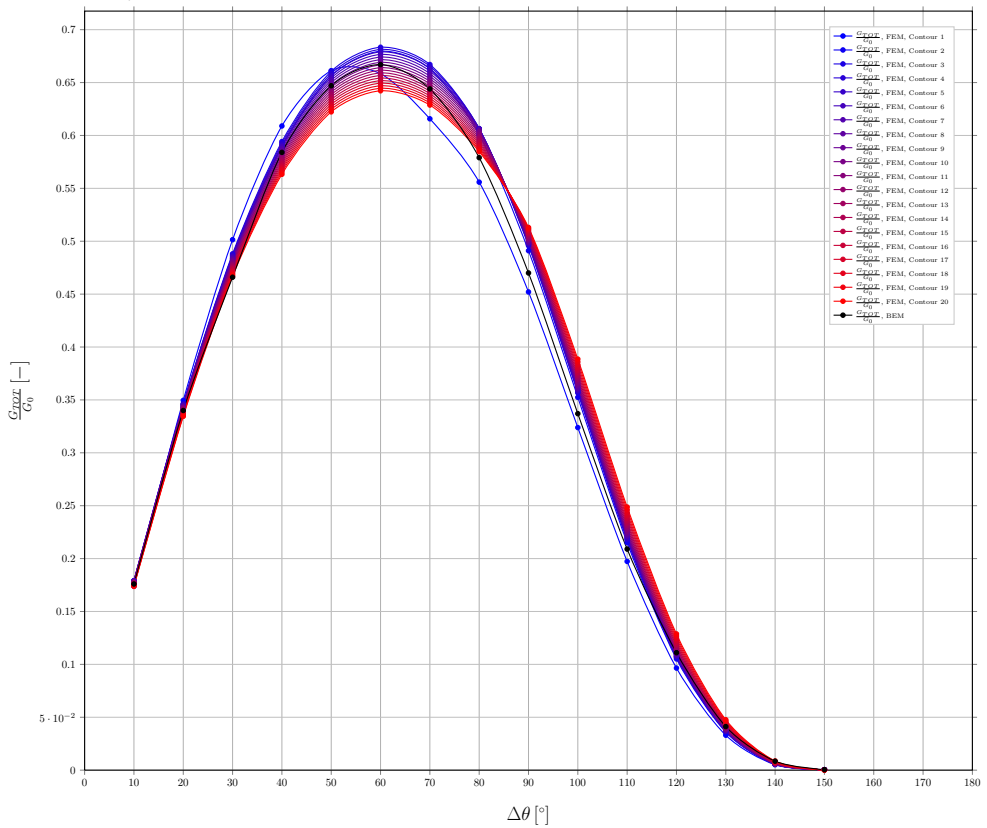
J-Integral (Abaqus built-in routine), $\delta = 0.5°$

Normalized total energy release rate $\frac{G_{TOT}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with Abaqus built-in J-Integral post-processing routine (*CONTOUR INTEGRAL)



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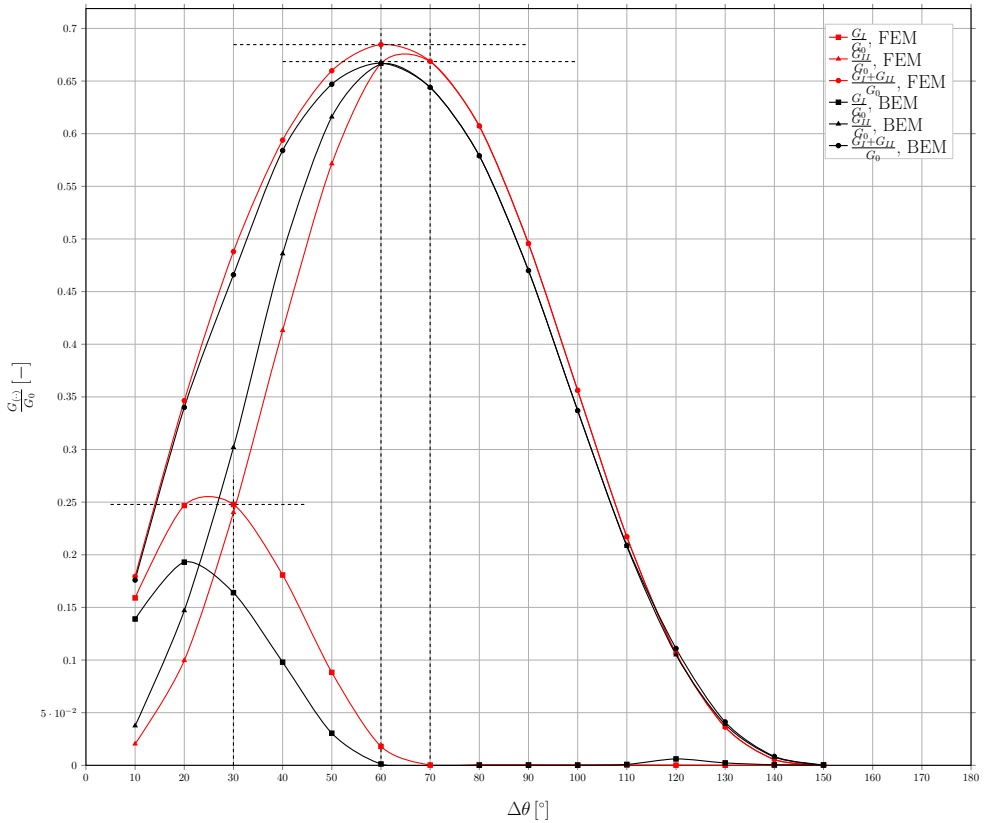
VCCT in forces (in-house Python routine), $\delta = 0.5°$

Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT post-processing routine



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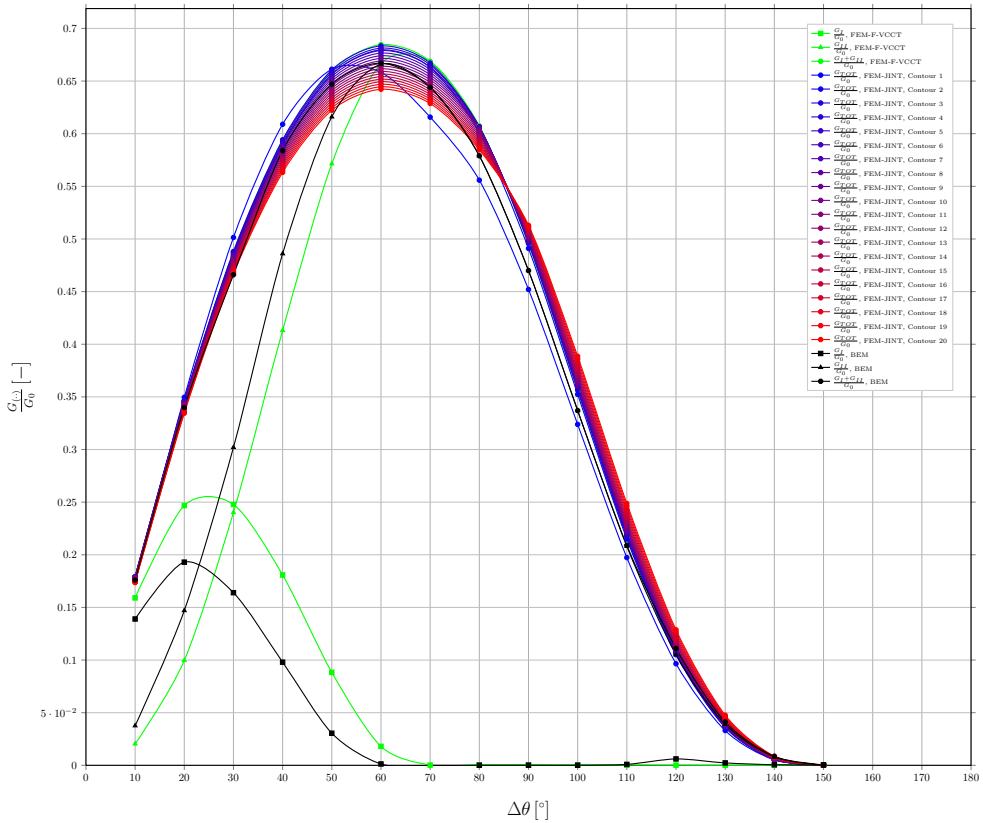
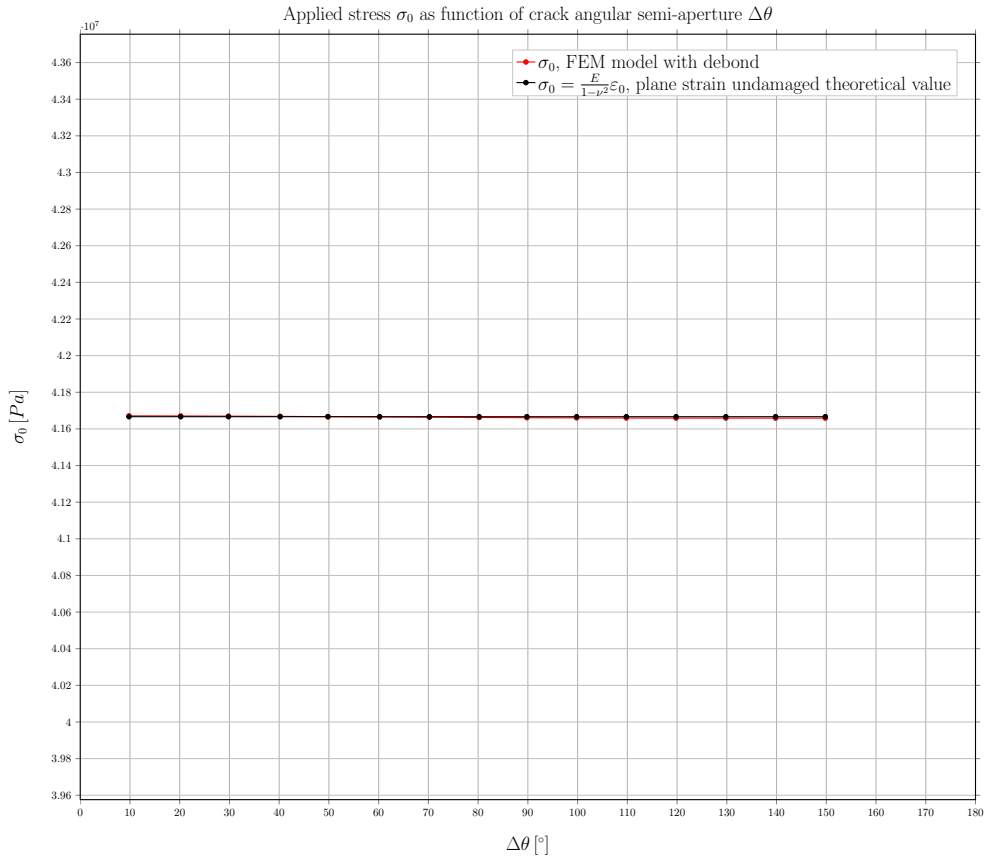
J-Integral and VCCT in forces, $\delta = 0.5°$

Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT and Abaqus built-in J-Integral (*CONTOUR INTEGRAL) post-processing routines



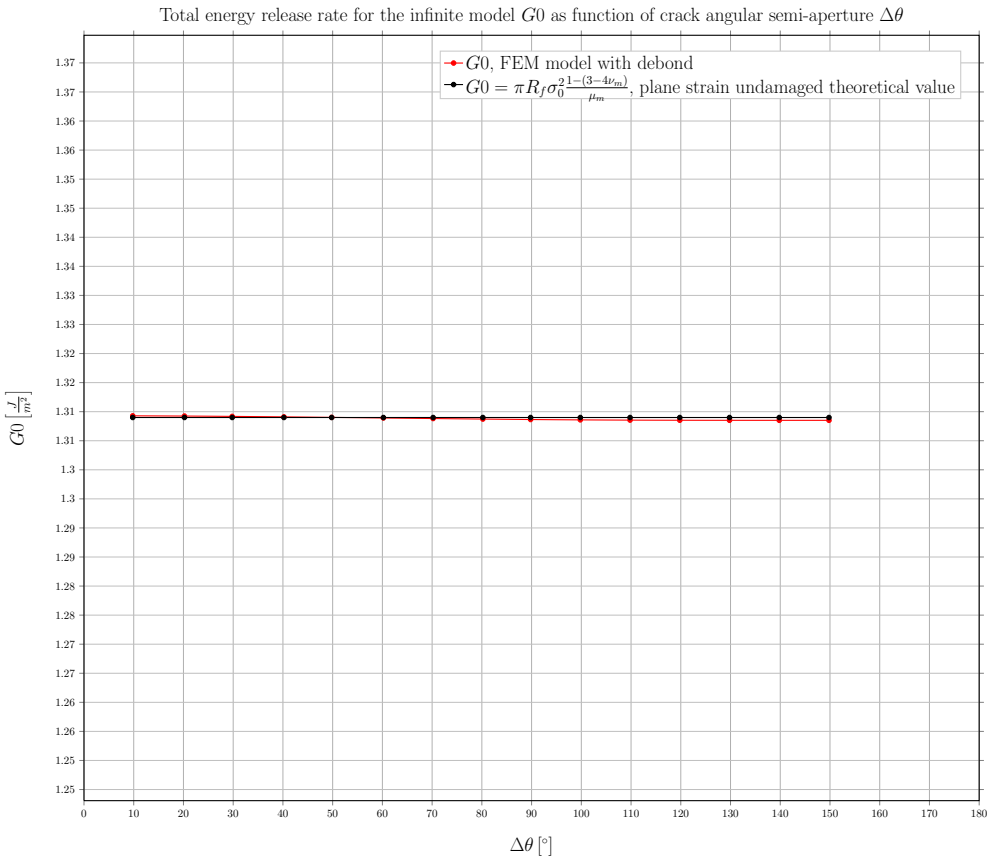
Fading from blue to red for contours further from the crack tip, J-Integral from FEM results; in green VCCT from FEM results; in black BEM results.

σ_0, $\delta = 0.4°$



In red small strain FEM, in black analytical plain strain value.

G_0, $\delta = 0.4°$



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J-Integral (Abaqus built-in routine), $\delta = 0.4°$

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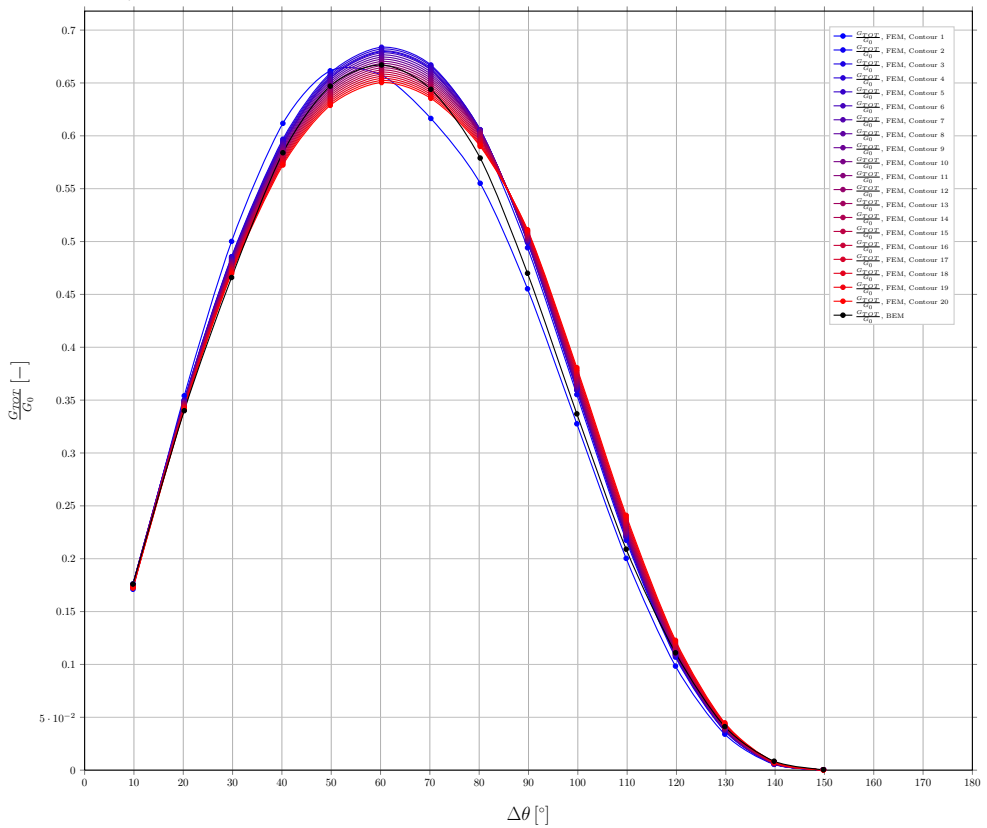
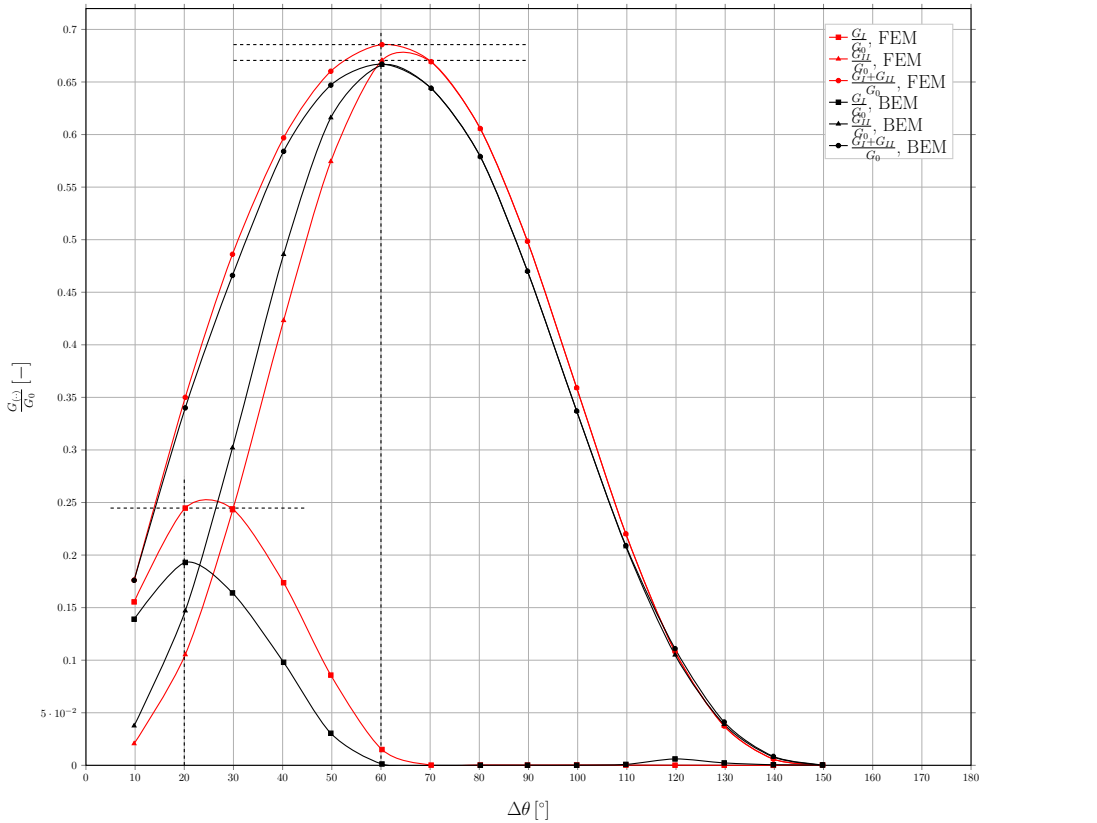


Fading from blue to red for contours further from the crack tip, FEM results; in black BEM results.

VCCT in forces (in-house Python routine), $\delta = 0.4°$

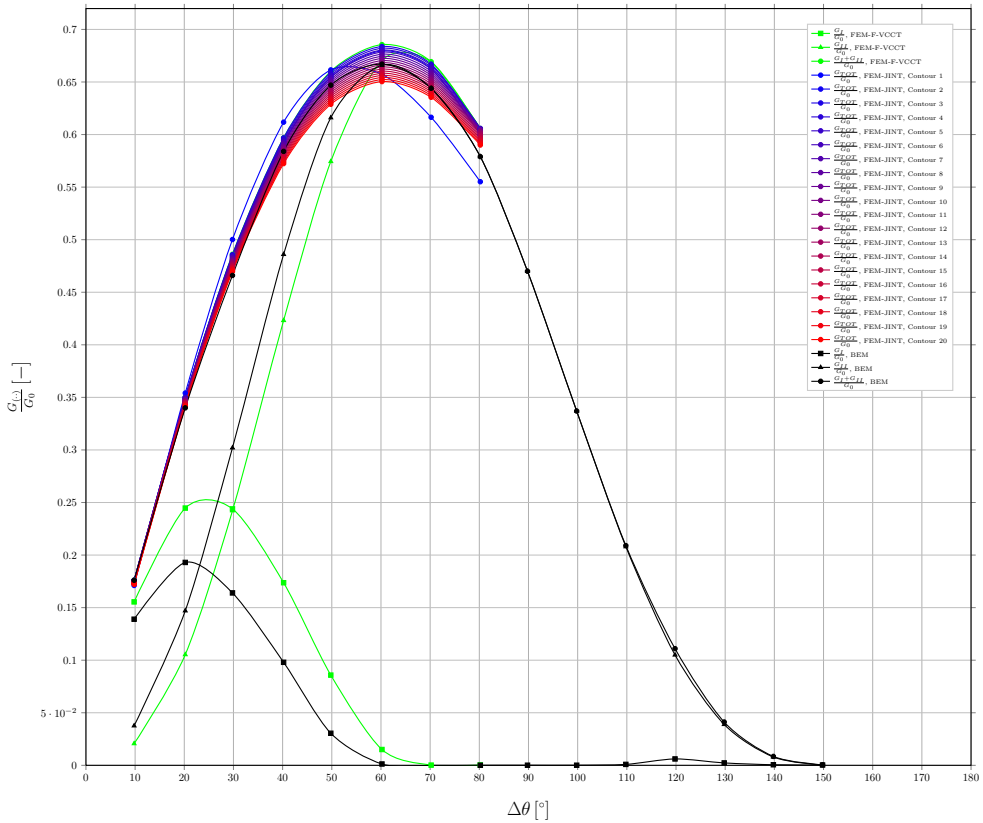
Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT post-processing routine



In green VCCT from FEM results, in black BEM results; positions of maxima highlighted by dashed lines.

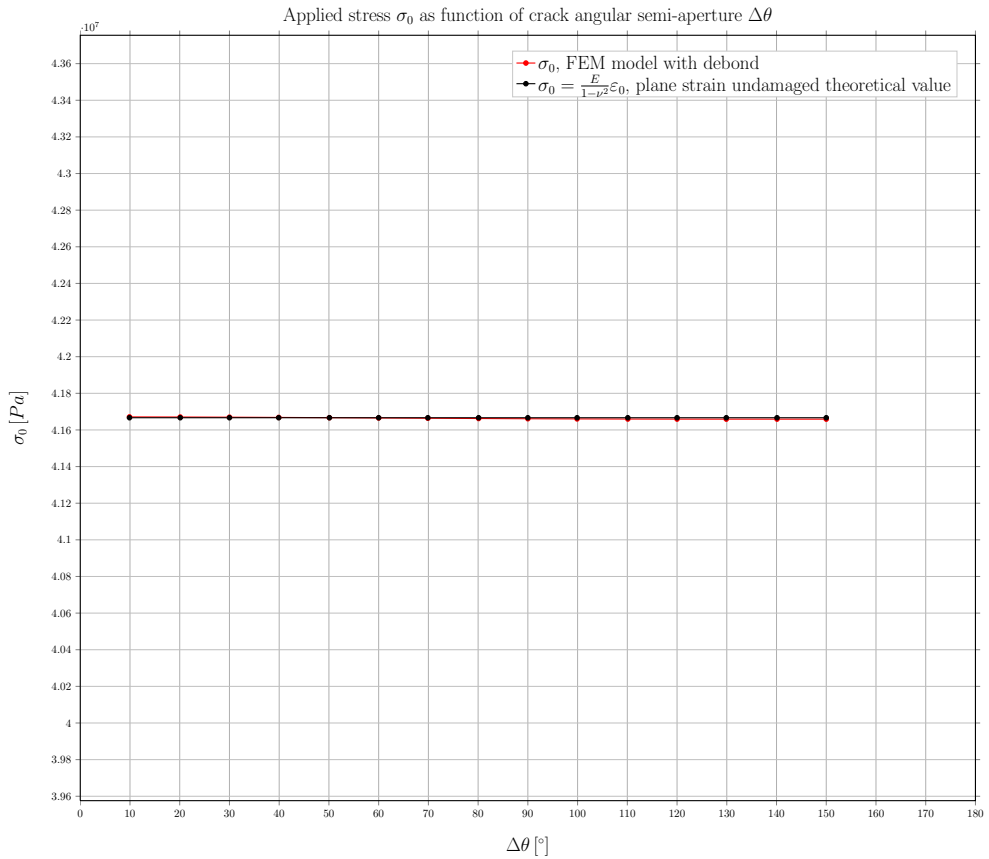
J-Integral and VCCT in forces, $\delta = 0.4°$

Normalized energy release rate $\frac{G_{(-)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT and Abaqus built-in J-Integral (*CONTOUR INTEGRAL) post-processing routines



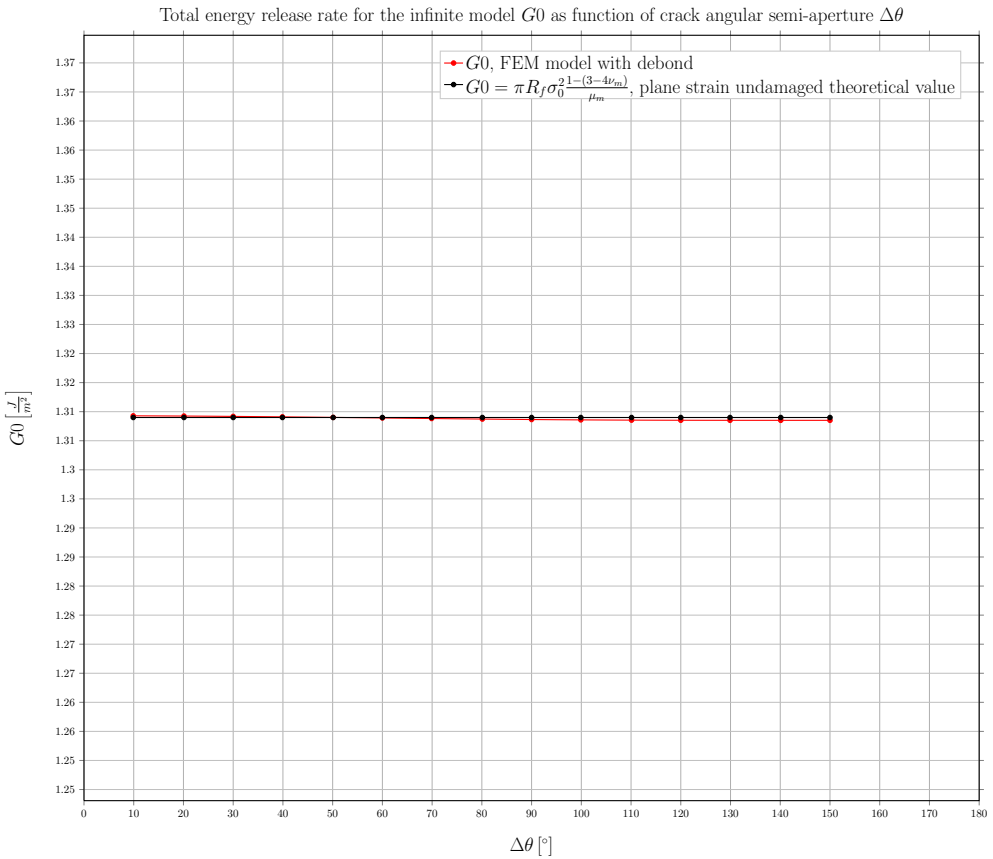
Fading from blue to red for contours further from the crack tip, J-Integral from FEM results; in green VCCT from FEM results; in black BEM results.

σ_0, $\delta = 0.3°$



In red small strain FEM, in black analytical plain strain value.

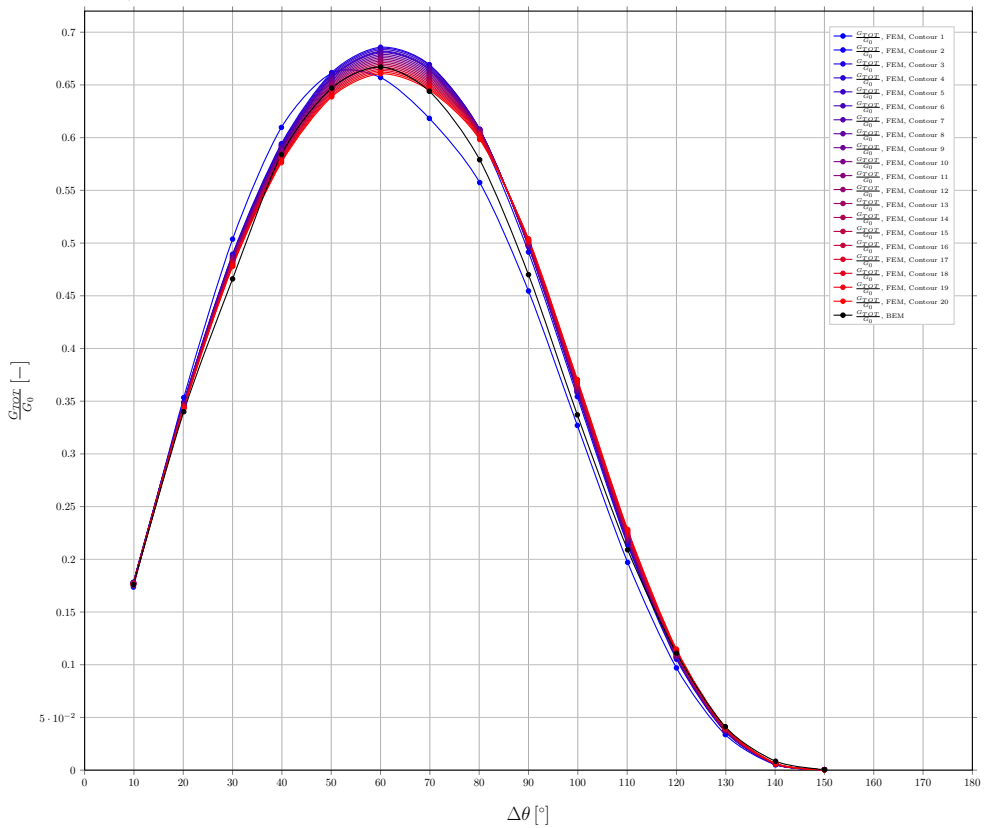
G_0, $\delta = 0.3°$



In red small strain FEM, in black analytical plain strain value.

J-Integral (Abaqus built-in routine), $\delta = 0.3°$

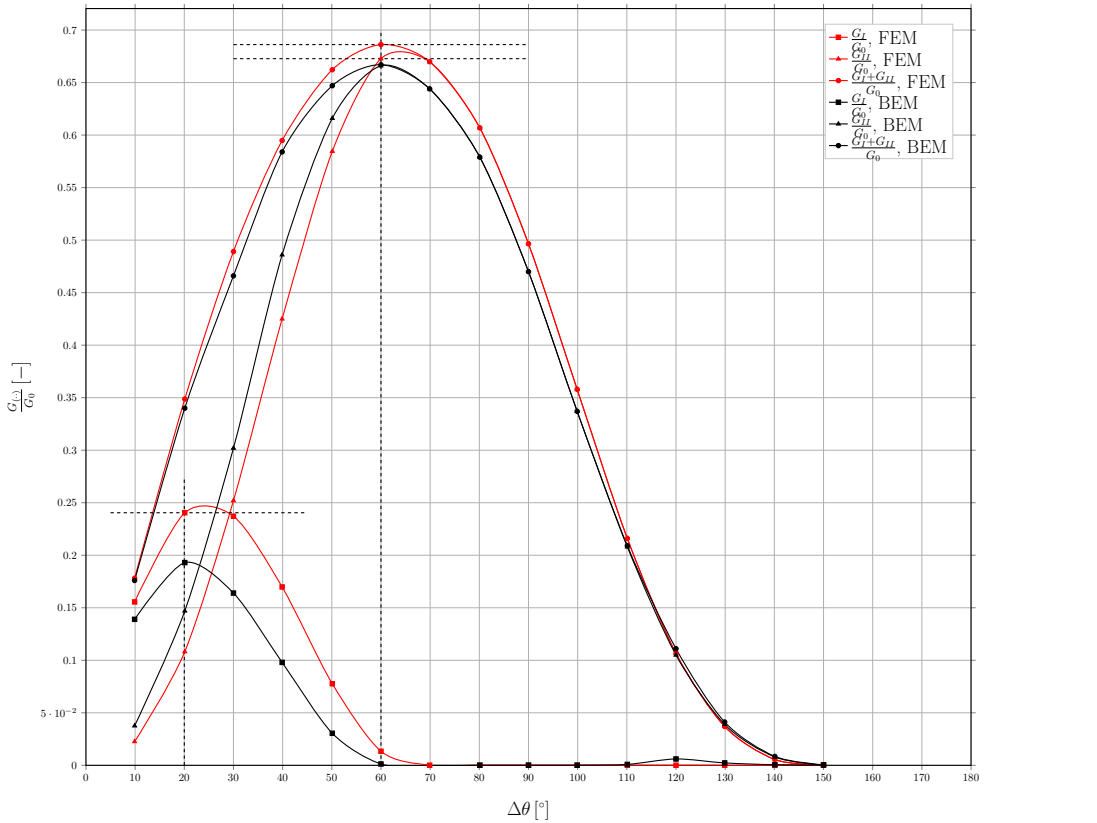
Normalized total energy release rate $\frac{G_{TOT}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with Abaqus built-in J-Integral post-processing routine (*CONTOUR INTEGRAL)



Fading from blue to red for contours further from the crack tip, FEM results; in black BEM results.

VCCT in forces (in-house Python routine), $\delta = 0.3°$

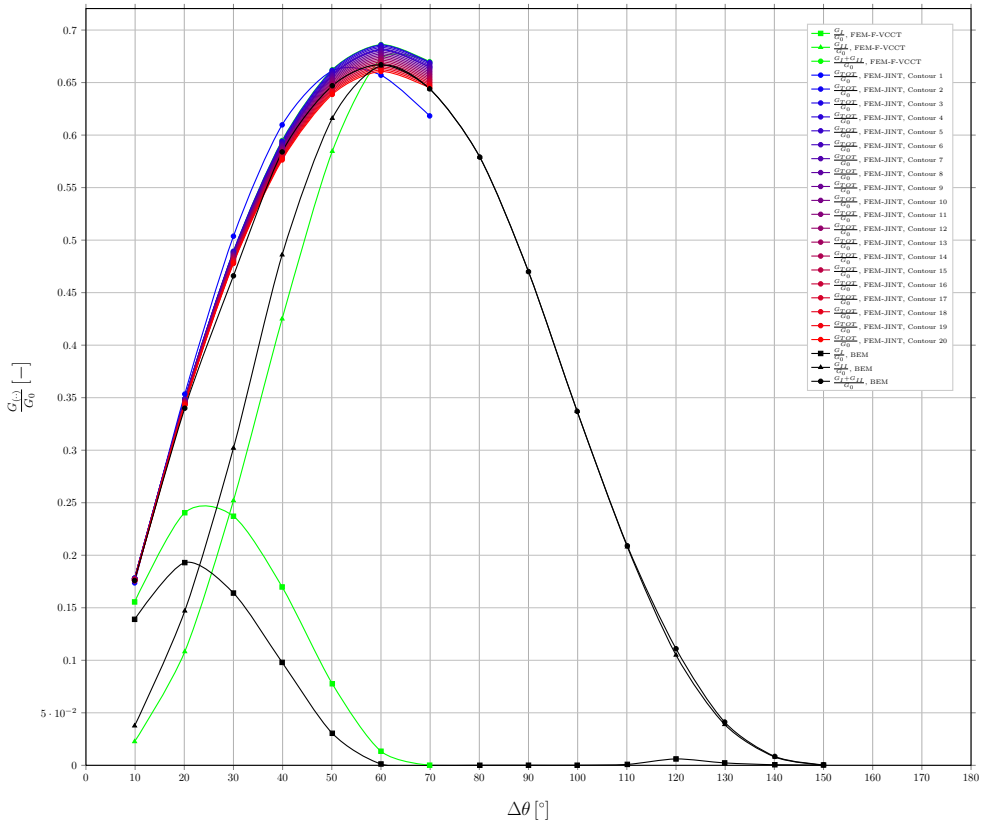
Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT post-processing routine



In green VCCT from FEM results, in black BEM results; positions of maxima highlighted by dashed lines.

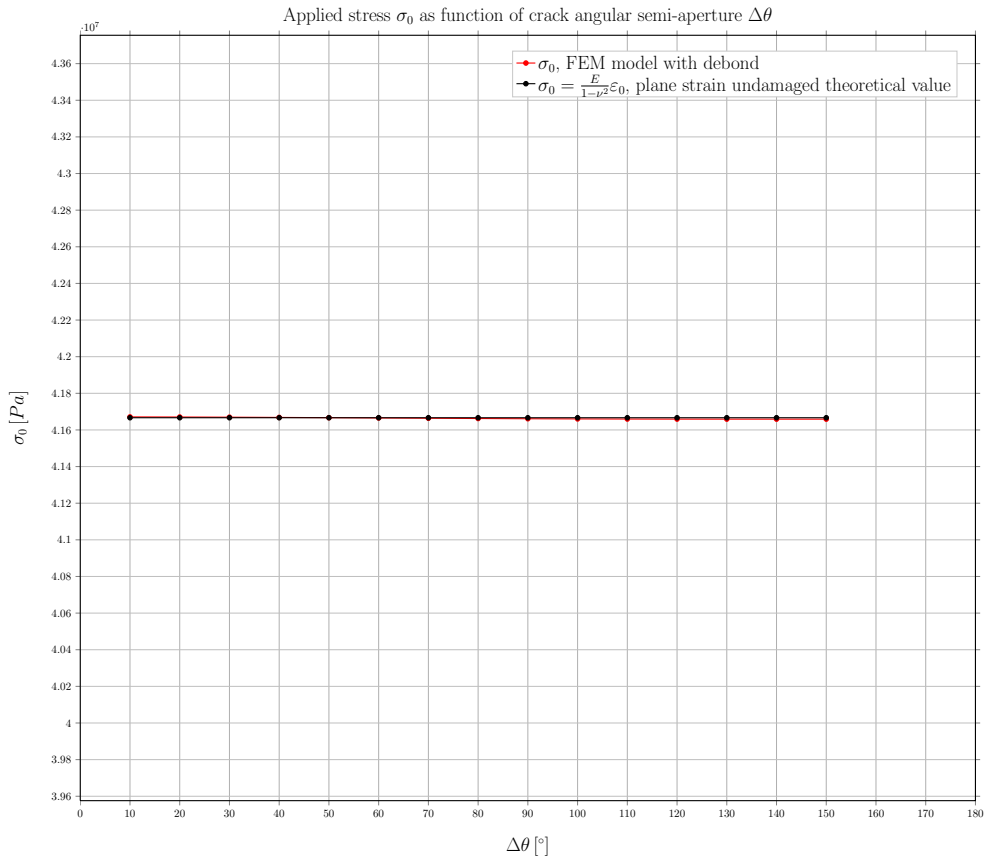
J-Integral and VCCT in forces, $\delta = 0.3°$

Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT and Abaqus built-in J-Integral (*CONTOUR INTEGRAL) post-processing routines



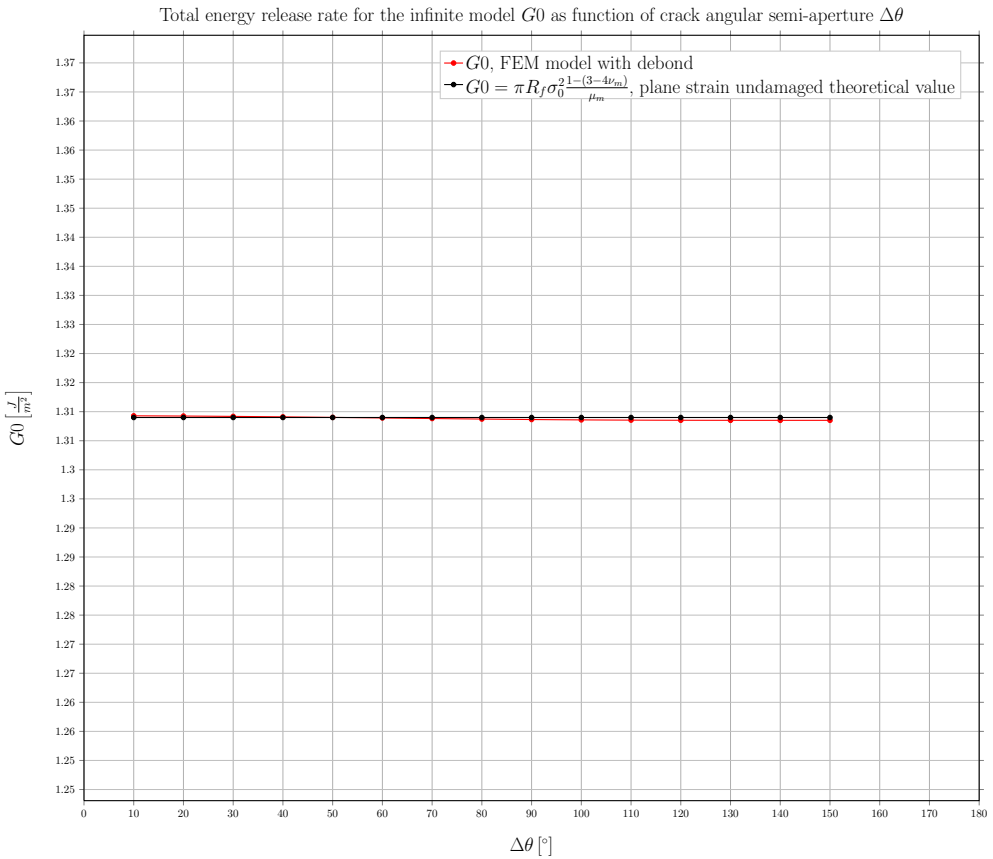
Fading from blue to red for contours further from the crack tip, J-Integral from FEM results; in green VCCT from FEM results; in black BEM results.

σ_0, $\delta = 0.2°$



In red small strain FEM, in black analytical plain strain value.

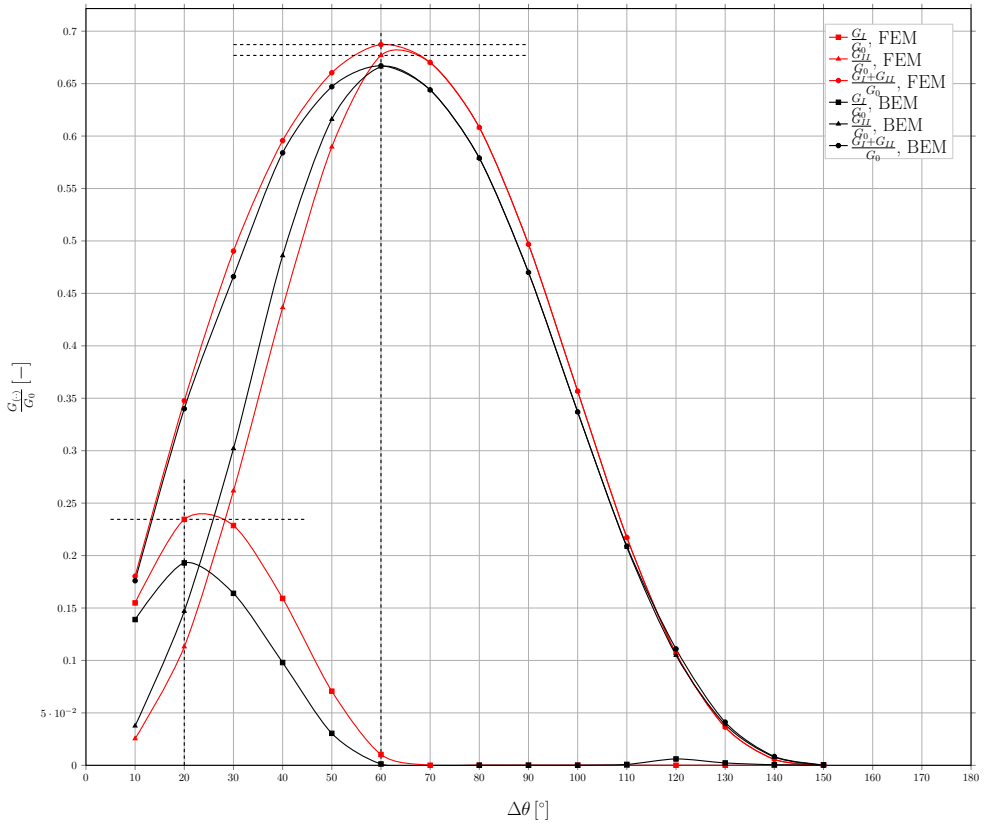
G_0, $\delta = 0.2°$



In red small strain FEM, in black analytical plain strain value.

VCCT in forces (in-house Python routine), $\delta = 0.2°$

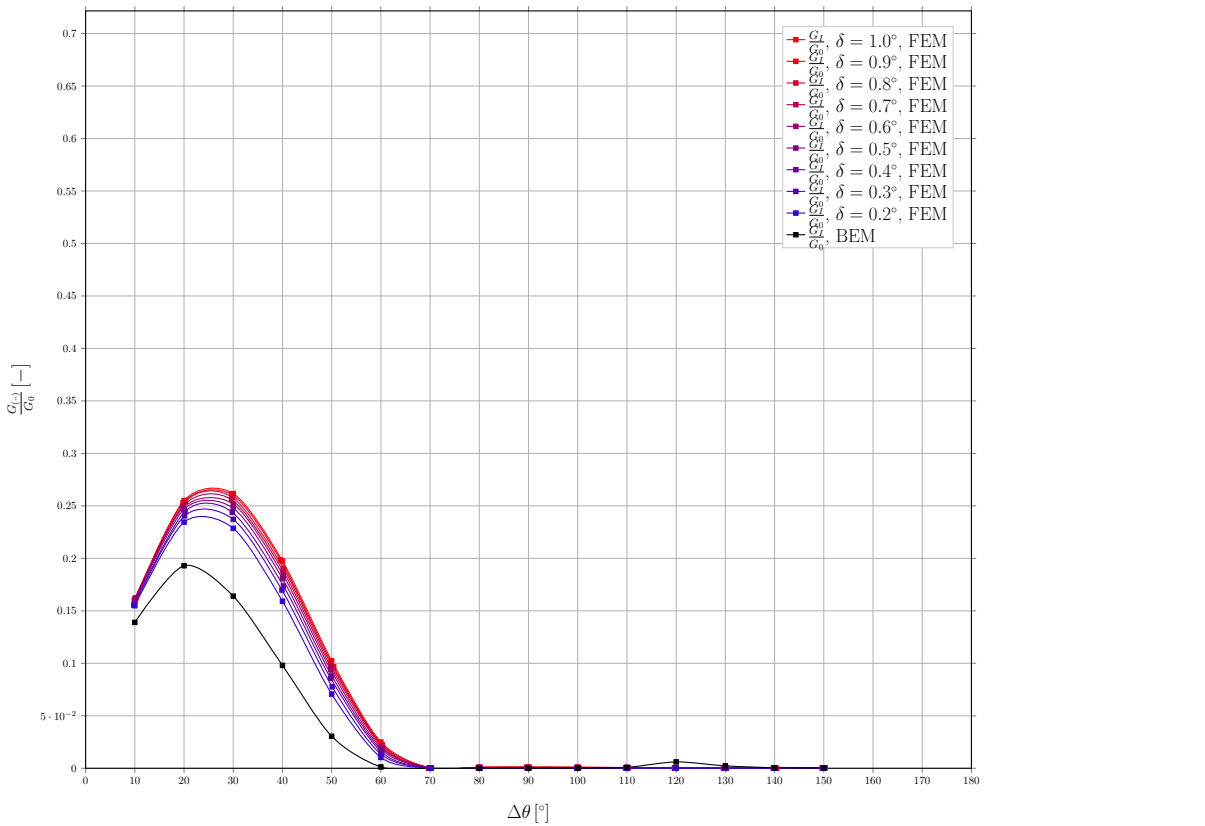
Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house force-based VCCT post-processing routine



In green VCCT from FEM results, in black BEM results; positions of maxima highlighted by dashed lines.

G_I, VCCT in forces

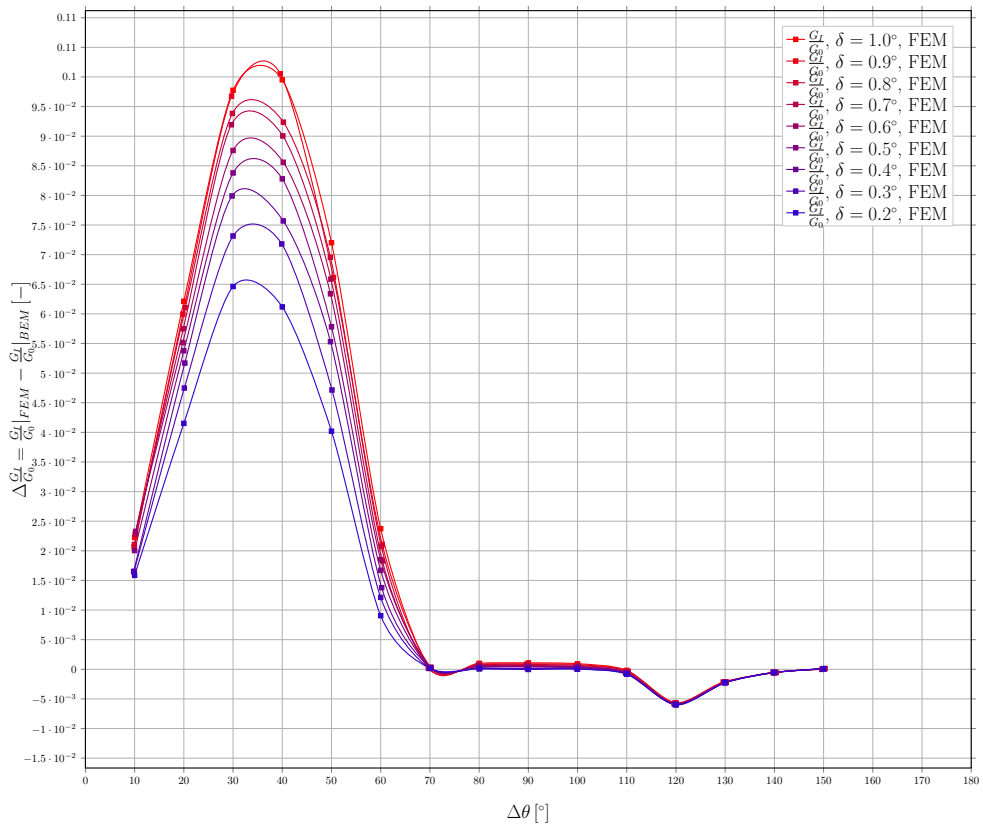
Normalized energy release rate $\frac{G_I}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, $VF_f = 7.9 \cdot 10^{-5}$, $\frac{L}{R_f} \sim 100$ calculated with in-house force-based VCCT post-processing routine



Fading from red to blue for decreasing size of elements at the interface, VCCT from FEM results; in black BEM results.

G_I Error with respect to BEM, VCCT in forces

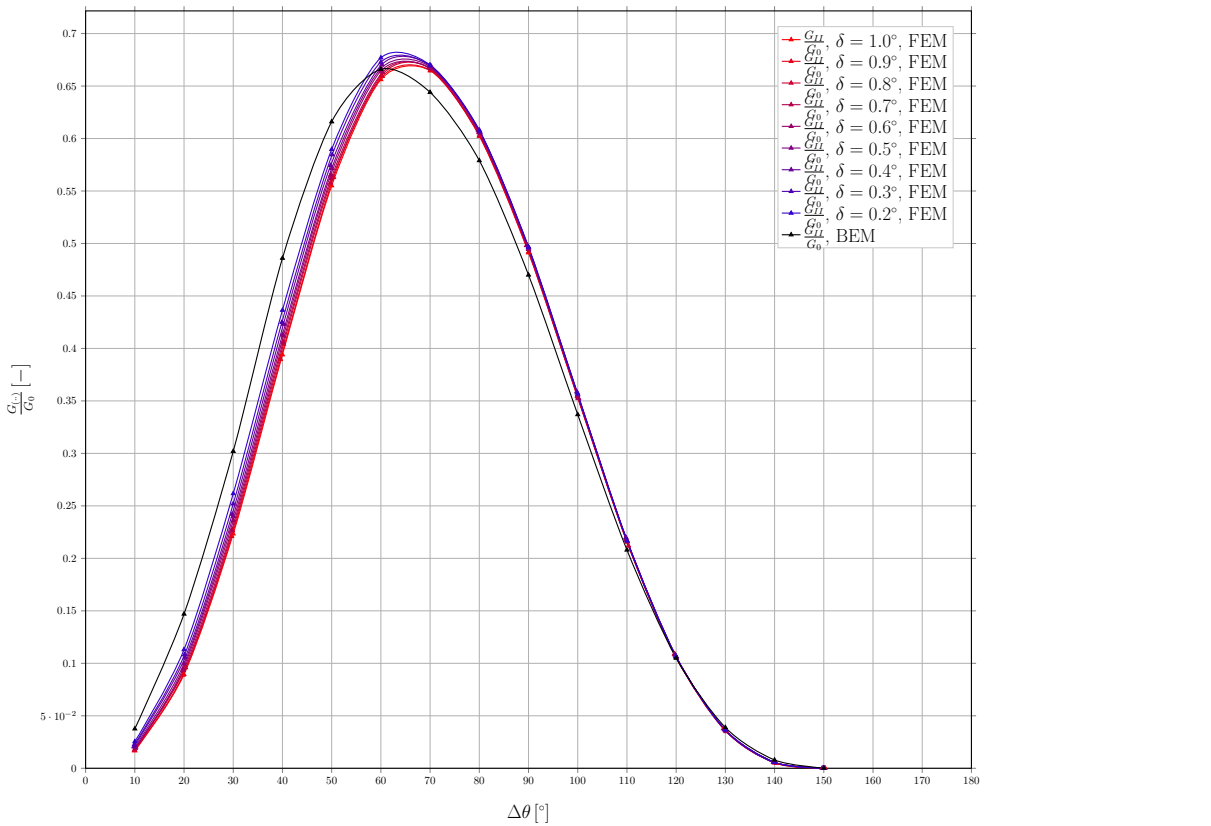
Error of of normalized energy release rate with respect to BEM results $\Delta\frac{G_I}{G_0} = \frac{G_I}{G_0}|_{FEM} - \frac{G_I}{G_0}|_{BEM}$ as function of crack angular semi-aperture $\Delta\theta$, $VF_f = 7.9 \cdot 10^{-5}$, $\frac{L}{R_f} \sim 100$ calculated with in-house force-based VCCT post-processing routine



Fading from red to blue for decreasing size of elements at the interface, VCCT from FEM results.

G_{II}, VCCT in forces

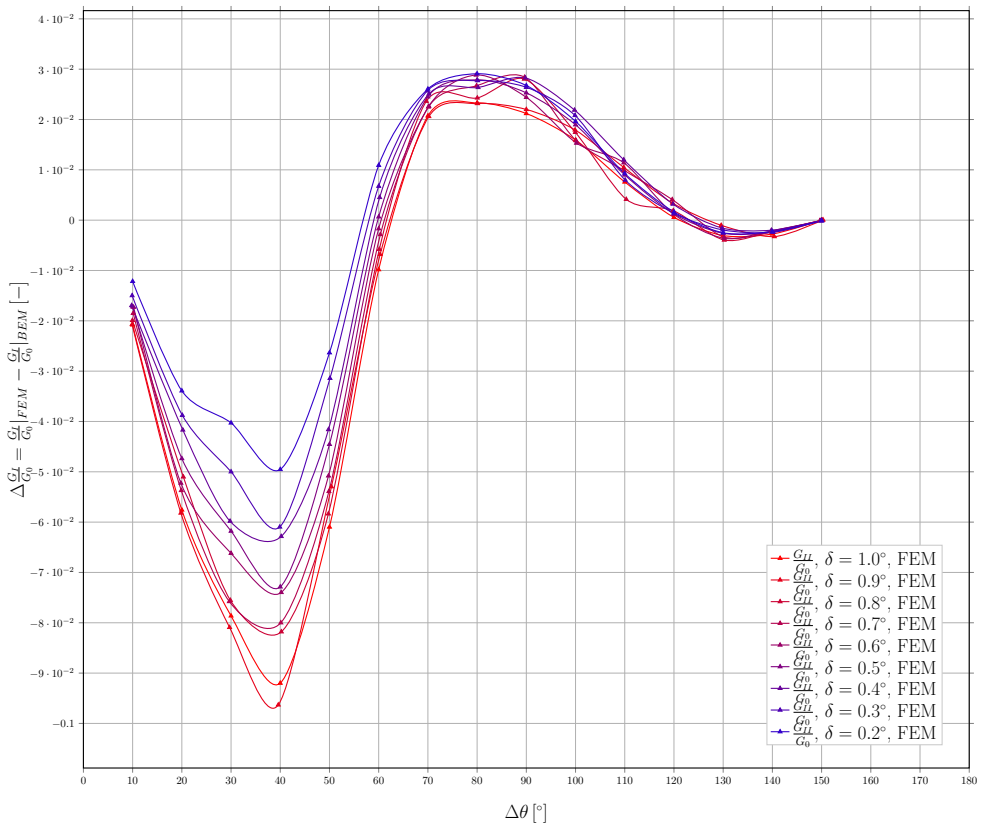
Normalized energy release rate $\frac{G_{II}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, $VF_f = 7.9 \cdot 10^{-5}$, $\frac{L}{R_f} \sim 100$ calculated with in-house force-based VCCT post-processing routine



Fading from red to blue for decreasing size of elements at the interface, VCCT from FEM results; in black BEM results.

G_{II} Error with respect to BEM, VCCT in forces

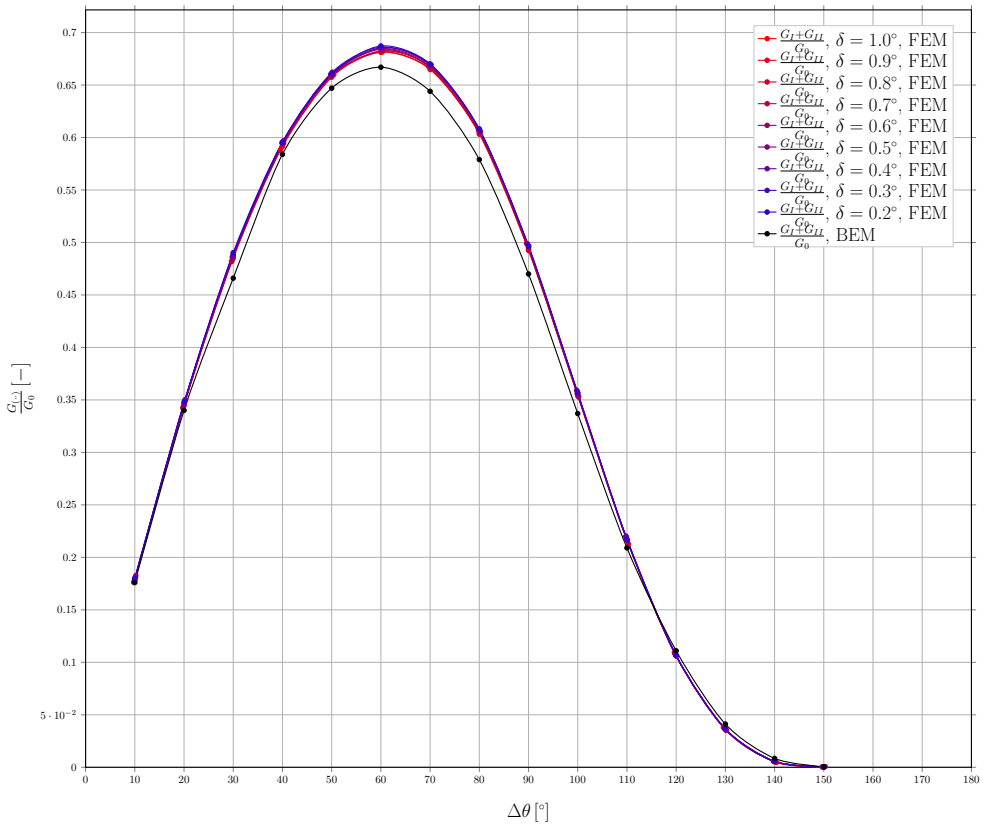
Error of of normalized energy release rate with respect to BEM results $\Delta\frac{G_I}{G_0} = \frac{G_I}{G_0}|_{FEM} - \frac{G_I}{G_0}|_{BEM}$ as function of crack angular semi-aperture $\Delta\theta$, $VF_f = 7.9 \cdot 10^{-5}$, $\frac{L}{R_f} \sim 100$ calculated with in-house force-based VCCT post-processing routine



Fading from red to blue for decreasing size of elements at the interface, VCCT from FEM results.

G_{TOT}, VCCT in forces

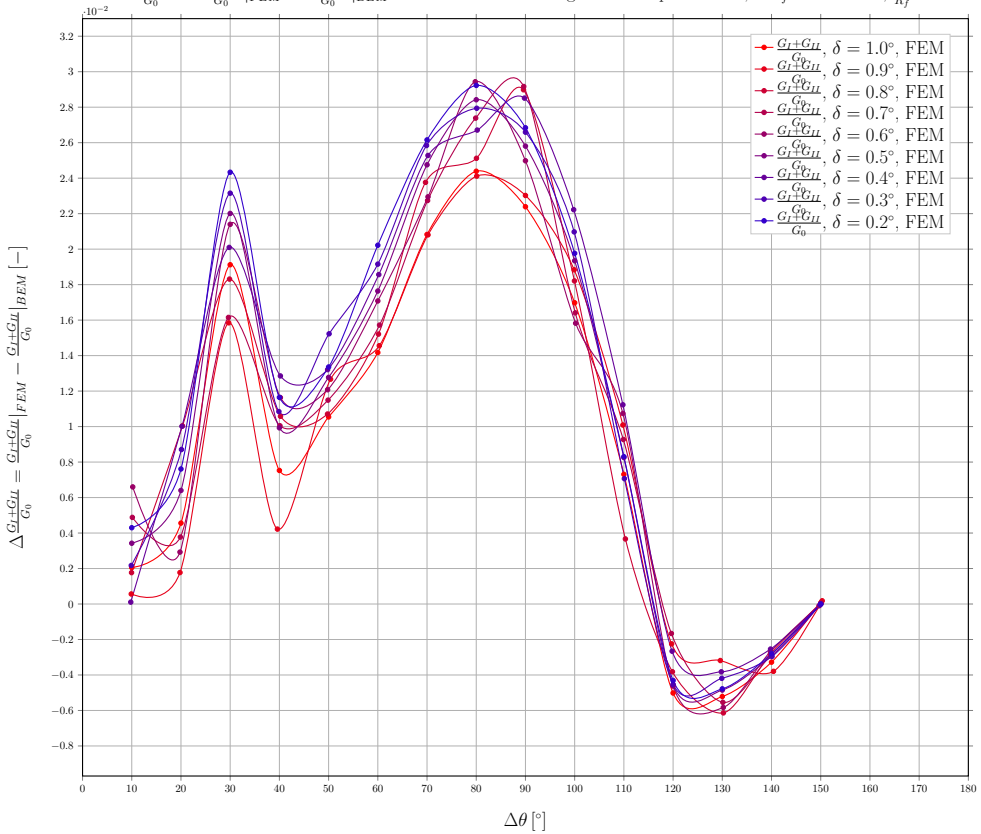
Normalized energy release rate $\frac{G_I+G_{II}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, $VF_f = 7.9 \cdot 10^{-5}$, $\frac{L}{R_f} \sim 100$ calculated with in-house force-based VCCT post-processing routine



Fading from red to blue for decreasing size of elements at the interface, VCCT from FEM results; in black BEM results.

G_{TOT} Error with respect to BEM, VCCT in forces

Error of of normalized energy release rate with respect to BEM results $\Delta\frac{G_I+G_{II}}{G_0} = \frac{G_I+G_{II}}{G_0}|_{FEM} - \frac{G_I+G_{II}}{G_0}|_{BEM}$ as function of crack angular semi-aperture $\Delta\theta$, $VF_f = 7.9 \cdot 10^{-5}$, $\frac{L}{R_f} \sim 100$ calculated with in-house force-based VCCT post-processing



Fading from red to blue for decreasing size of elements at the interface, VCCT from FEM results.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