Micromechanical models of transverse cracking in ultra-thin Fiber-Reinforced Composite laminates

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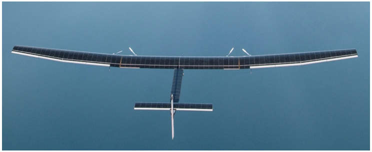
Journée de l'Équipe 304, Nancy (FR), July 5, 2017

Outline

Thin Ply FRP Laminates

Spread Tow Technology: Introduction

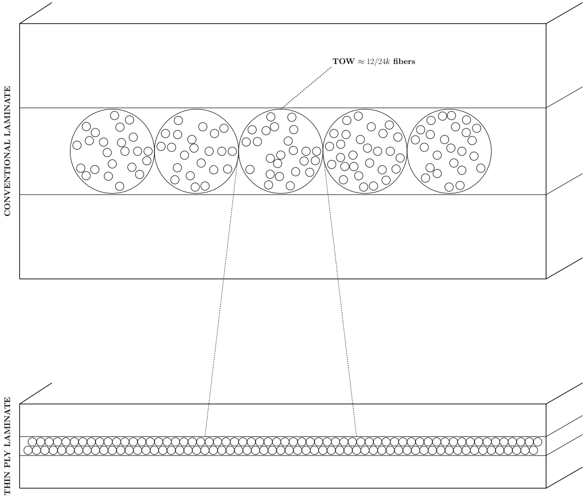
- Firstly developed for commercial use in Japan between 1995 and 1998
- In the last decade its use has been spreading, from sports' equipments to mission-critical applications as in the *Solar Impulse 2*
- Only a few producers wolrdwide: NTPT (USA-CH), Oxeon (SE), Chomarat (FR), Hexcel (USA), Technomax (JP)



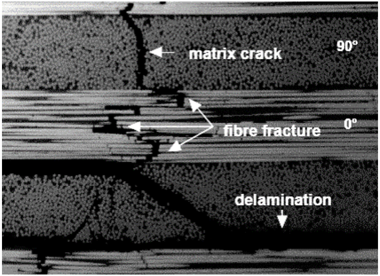
(a) By North Thin Ply Technology.

(b) By TeXtreme.

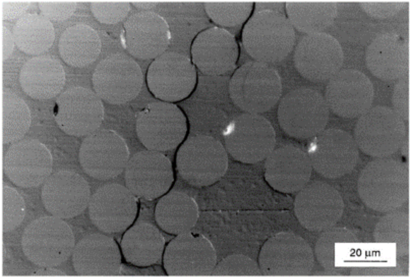
Spread Tow Technology: Foundations



Visual Definition of Transverse Cracking



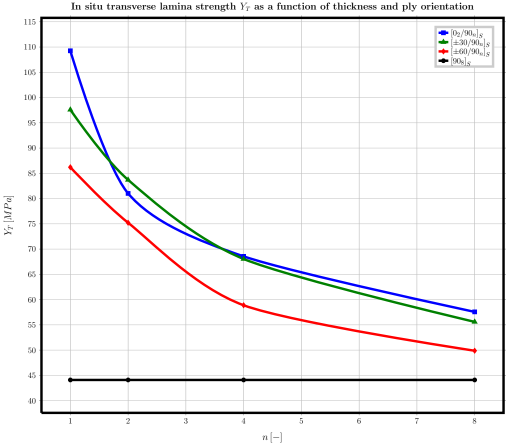
(c) By Dr. R. Olsson, Swerea, SE.



(d) By Prof. Dr. E. K. Gamstedt, KTH, SE.

For a visual definition of intralaminar transverse cracking.

The Thin Ply Effect



Measurements of in-situ transverse strength from D. L. Flaggs & M. H. Kural, 1982 [1].

Objectives & Approach

Objectives & Approach

Objectives

- Investigate the influence of volume fraction, thin ply thickness and bounding plies' thicknesses on crack initiation
- To infere a relationship like

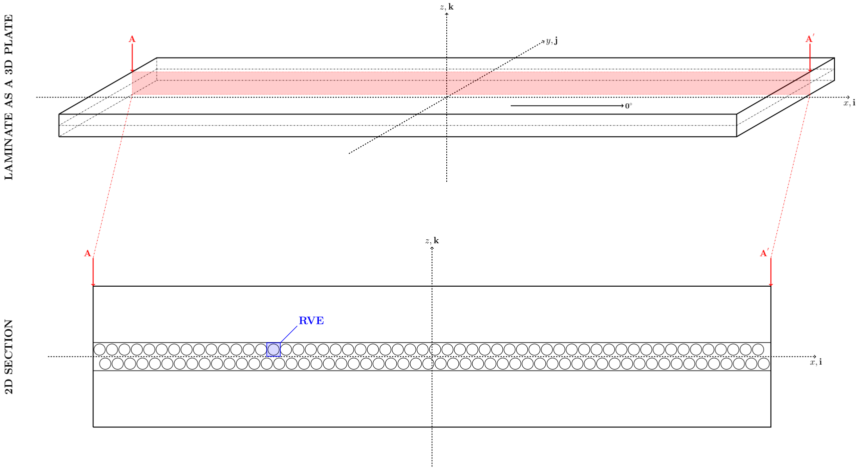
$$G_{*c} = G_{*c}\left(\theta_{debond}, \Delta\theta_{debond}, E_{(..)}, \nu_{(..)}, G_{()}, VF_f, t_{ply}, \frac{t_{ply}}{t_{bounding\ plies}}\right)$$

Approach

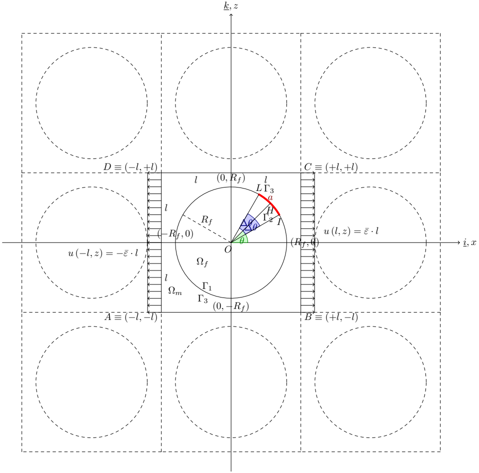
- Design and categorization of different Representative Volume Elements (RVEs)
- Automated generation of RVEs geometry and FEM model
- Finite Element Simulation (in Abaqus)

↘ MICROMECHANICAL MODELING

From macro to micro



Representative Volume Elements (RVEs)



- ✓ 2D space
- ✓ Linear elastic materials
- ✓ Displacement control
- ✓ Dirichlet-type boundary conditions
- ✓ Linear elastic fracture mechanics
- ✓ Contact interaction

Mesh Design and Generation

Why a good mesh is fundamental

1. Geometric discretization has a strong effect on non-linear FEM simulations
2. Damage is a process that implies changes in geometry, i.e. generation of surfaces and domain splitting
3. Fracture mechanics quantities depends on the local mesh topology and refinement

4-step procedure for mesh generation

1. The boundary is generated patching analytical parameterizations
2. The boundary is split into a set of 4 corners (c_i) and 4 edges (e_i)
3. Interior nodes are created applying transfinite interpolation using multi-dimensional linear Lagrangian interpolants

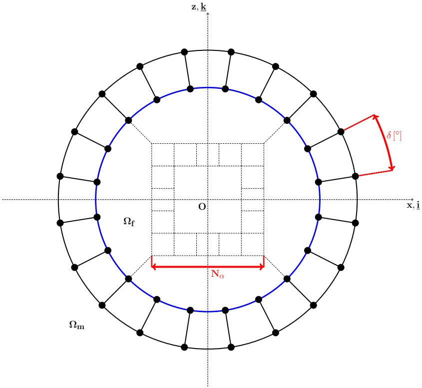
$$P_1(x, p_j) = \sum_{j=1}^{n} p_j \prod_{k=1\ k\neq j}^{n} \frac{x - x_k}{x_j - x_k} \quad P_2(x, y, p_j, q_j) = P_1(x, p_j) \otimes P_1(y, q_j)$$

$$r(\xi, \eta) = P_1(\xi, e_2, e_4) + P_1(\eta, e_1, e_3) - P_2(\xi, \eta, c_1, c_2, c_3, c_4)$$

4. The mesh is smoothed applying elliptic mesh generation

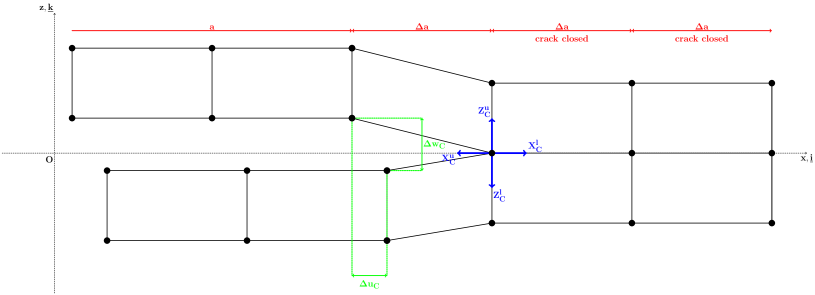
$$g^{11}\underline{r}_{,\xi\xi} + 2g^{12}\underline{r}_{,\xi\eta} + g^{22}\underline{r}_{,\eta\eta} = 0$$

Angular discretization



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

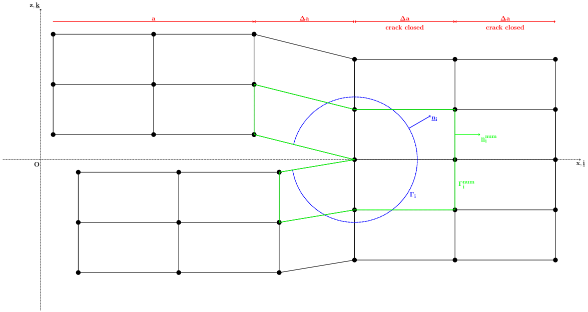
Virtual Crack Closure Technique (VCCT)



$$G_I = \frac{Z_C \Delta w_C}{2B\Delta a} \quad G_{II} = \frac{X_C \Delta u_C}{2B\Delta a} \quad \Longleftrightarrow$$

In-house routine and Abaqus

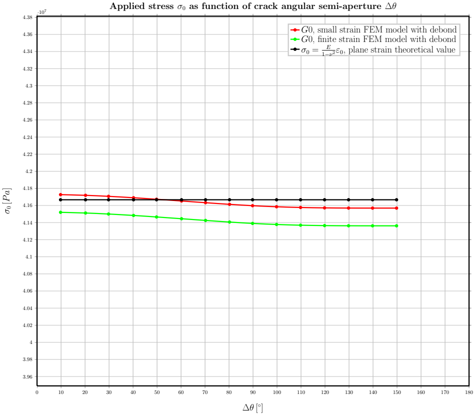
J-integral evaluation



$$J_i = \lim_{\varepsilon \to 0} \int_{\Gamma_\varepsilon} \left(W(\Gamma)\, n_i - n_j \sigma_{jk} \frac{\partial u_k (\Gamma, x_i)}{\partial x_i} \right) d\Gamma \iff \text{*CONTOUR INTEGRAL in Abaqus}$$

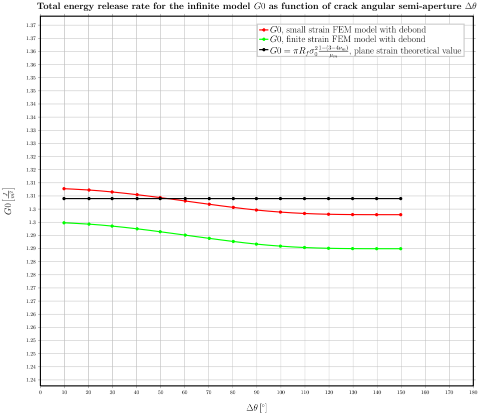
Results

σ_0 for $Vf_f = 0.001$, $\frac{L}{R_f} \sim 28$ and $\delta = 0.4°$



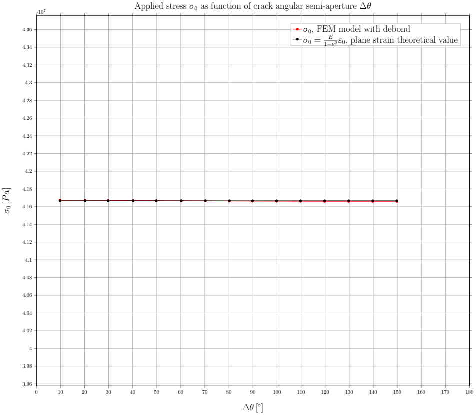
In red small strain FEM, in green finite strain FEM, in black $\sigma_0 = \frac{E}{1-\nu^2}\varepsilon$.

G_0 for $Vf_f = 0.001$, $\frac{L}{R_f} \sim 28$ and $\delta = 0.4°$



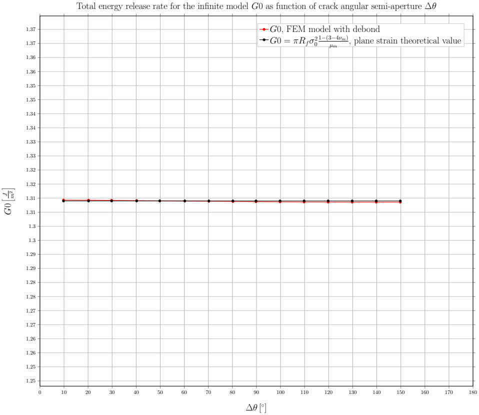
In red small strain FEM, in green finite strain FEM, in black G_0 calculated assuming $\sigma_0 = \frac{E}{1-\nu^2}\varepsilon$.

σ_0 for $Vf_f = 0.000079$, $\frac{L}{R_f} \sim 100$ and $\delta = 0.4°$



In red small strain FEM, in black $\sigma_0 = \frac{E}{1-\nu^2}\varepsilon$.

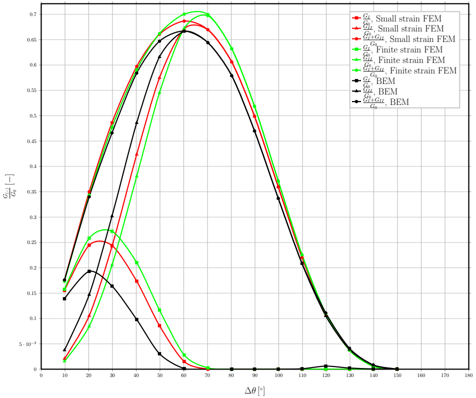
G_0 for $Vf_f = 0.000079$, $\frac{L}{R_f} \sim 100$ and $\delta = 0.4°$



In red small strain FEM, in black G_0 calculated assuming $\sigma_0 = \frac{E}{1-\nu^2}\varepsilon$.

$\frac{G_{(\cdot\cdot)}}{G_0}$ for $V_f = 0.001$, $\frac{L}{R_f} \sim 28$ and $\delta = 0.4°$

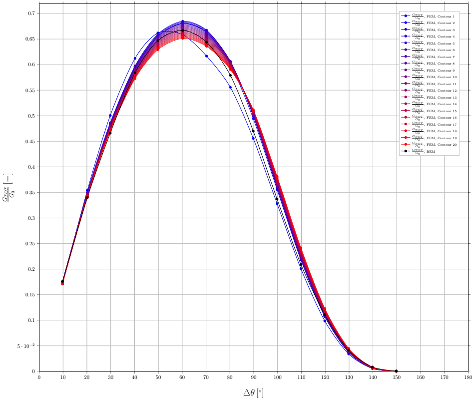
Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house VCCT post-processing routine



In red small strain FEM, in green finite strain FEM, in black BEM results.

$\frac{G_{(\cdot\cdot)}}{G_0}$ for $V_f = 0.001$, $\frac{L}{R_f} \sim 28$ and $\delta = 0.4°$, small strain formulation

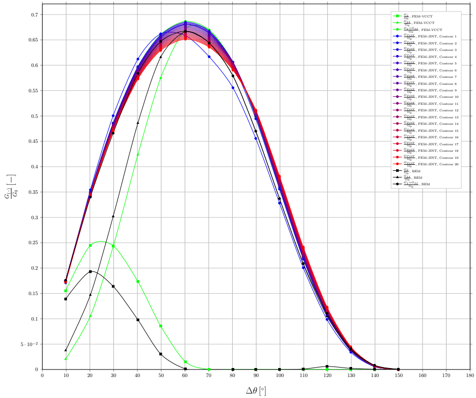
Normalized total energy release rate $\frac{G_{TOT}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with Abaqus built-in J-Integral post-processing routine (*CONTOUR INTEGRAL)



Fading from blue to red J-Integrals evaluated at contours at increasing distance from the crack tip, in black BEM results.

$\frac{G_{(\cdot\cdot)}}{G_0}$ for $V_f = 0.001$, $\frac{L}{R_f} \sim 28$ and $\delta = 0.4°$, small strain formulation

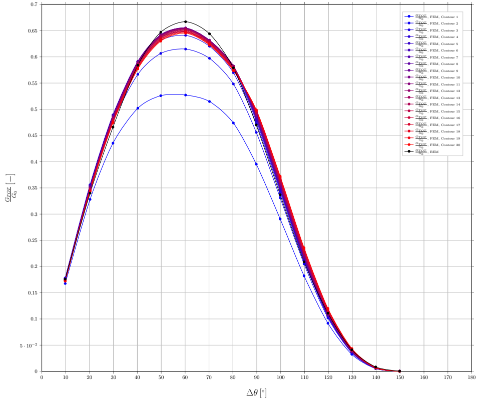
Normalized energy release rate $\frac{G_{(\cdot)}}{G_0}$ as function of crack angular semi-aperture $\Delta\theta$, calculated with in-house VCCT and Abaqus built-in J-Integral (*CONTOUR INTEGRAL) post-processing routines



Fading from blue to red J-Integrals evaluated at contours at increasing distance from the crack tip, in green evaluation with in-house VCCT routine, in black BEM results.

$\frac{G_{(\cdot\cdot)}}{G_0}$ for $V_f = 0.001$, $\frac{L}{R_f} \sim 28$ and $\delta = 0.4°$, finite strain formulation

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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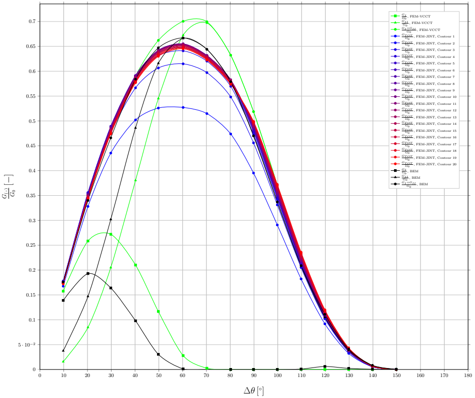


Fading from blue to red J-Integrals evaluated at contours at increasing distance from the crack tip, in green evaluation with in-house VCCT routine, in black BEM results.

Conclusions

Conclusions & Outlook

Conclusions

- 2D micromechanical models have been developed to investigate crack initiation in thin ply laminates
- A numerical procedure has been devised and implemented to automatize the creation of FEM models
- Analyses for $VF_f \rightarrow 0$ (matrix dominated RVE) conducted to validate the model with respect to previous literature

Outlook

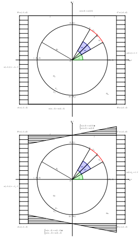
- Investigate the dependence on VF_f, t_{ply}, $\frac{t_{ply}}{t_{bounding\ plies}}$ and different material systems
- Study numerical performances with respect to model's parameters
- Repeat for different RVEs and compare

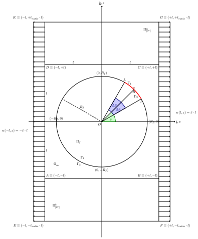
Appendices & References

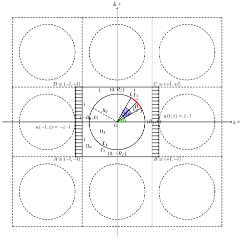
Spread Tow Technology: Implications

- Strong reduction in ply's thickness and weight
- Reduction in laminate's thickness and weight
- Higher fiber volume fraction and more homogeneous fiber distribution
- Ply thickness to fiber diameter ratio decreases of at least 1 order of magnitude, from > 100 to ≤ 10
- Increased load at damage onset and increased ultimate strength, in particular for transverse cracking

RVEs: Variations on a Theme







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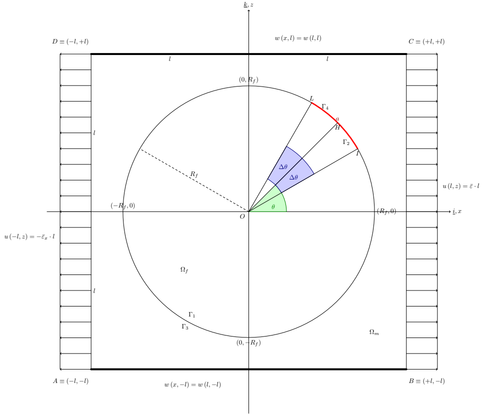
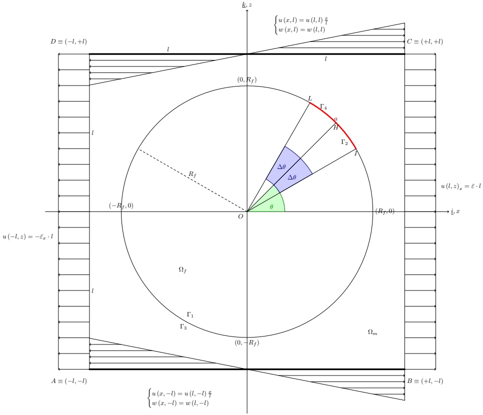
RVEs: First Variation on a Theme



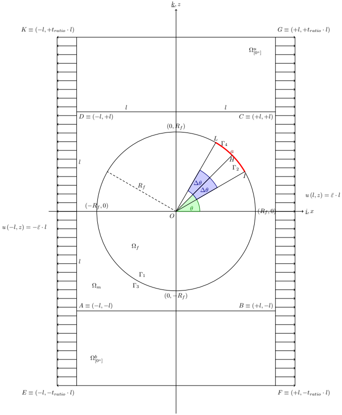
Isolated RVE with zero vertical displacement BC.

RVEs: Second Variation on a Theme



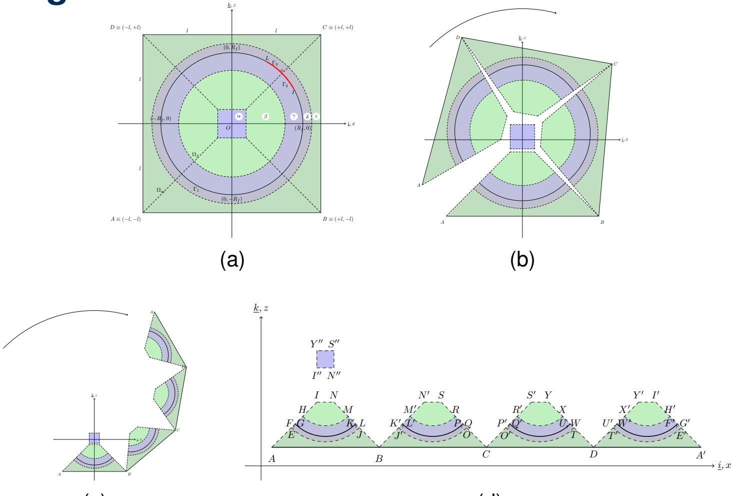
Isolated RVE with homogeneous displacement BC.

RVEs: Third Variation on a Theme



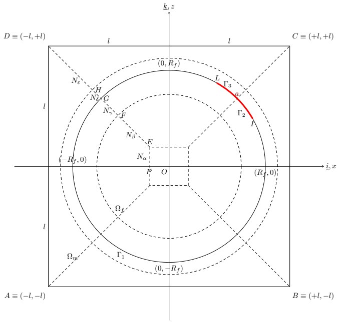
Bounded RVE.

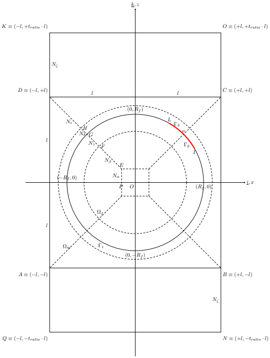
Topological transformation



(a) (b) (c) (d)

Mesh parameters





$E \equiv (-f_1 \cdot R_f, +f_1 \cdot R_f)$ $F \equiv f_2 R_f\,(-\cos 45°, \sin 45°)$

$G \equiv R_f\,(-\cos 45°, \sin 45°)$

$H \equiv (R_f + f_3\,(l - R_f))\,(-\cos 45°, \sin 45°)$

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$G \equiv R_f\,(-\cos 45°, \sin 45°)$

$H \equiv (R_f + f_3\,(l - R_f))\,(-\cos 45°, \sin 45°)$

Finite Element Model in Abaqus

Method	ABAQUS/STD static analysis + VCCT + J-integral.
Type	Static, i.e. no inertial effects. Relaxation until equilibrium.
Elements	CPE4/CPE8
Interface	Tied surface constraint & contact mechanics
Input variables	R_f, V_f, material properties, interface properties.
Control variables	θ, $\Delta\theta$, $\bar{\varepsilon}_x$.
Output variables	Stress field, crack tip stress, stress intensity factors, energy release rates, a.

Evaluation of G_0

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

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

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

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