Coupled stress-energy criterion for composite materials

Rami Hamze

Thiago V Birro

Benoit Gely

Thiago.vasconcellos-birro@capgemini.com

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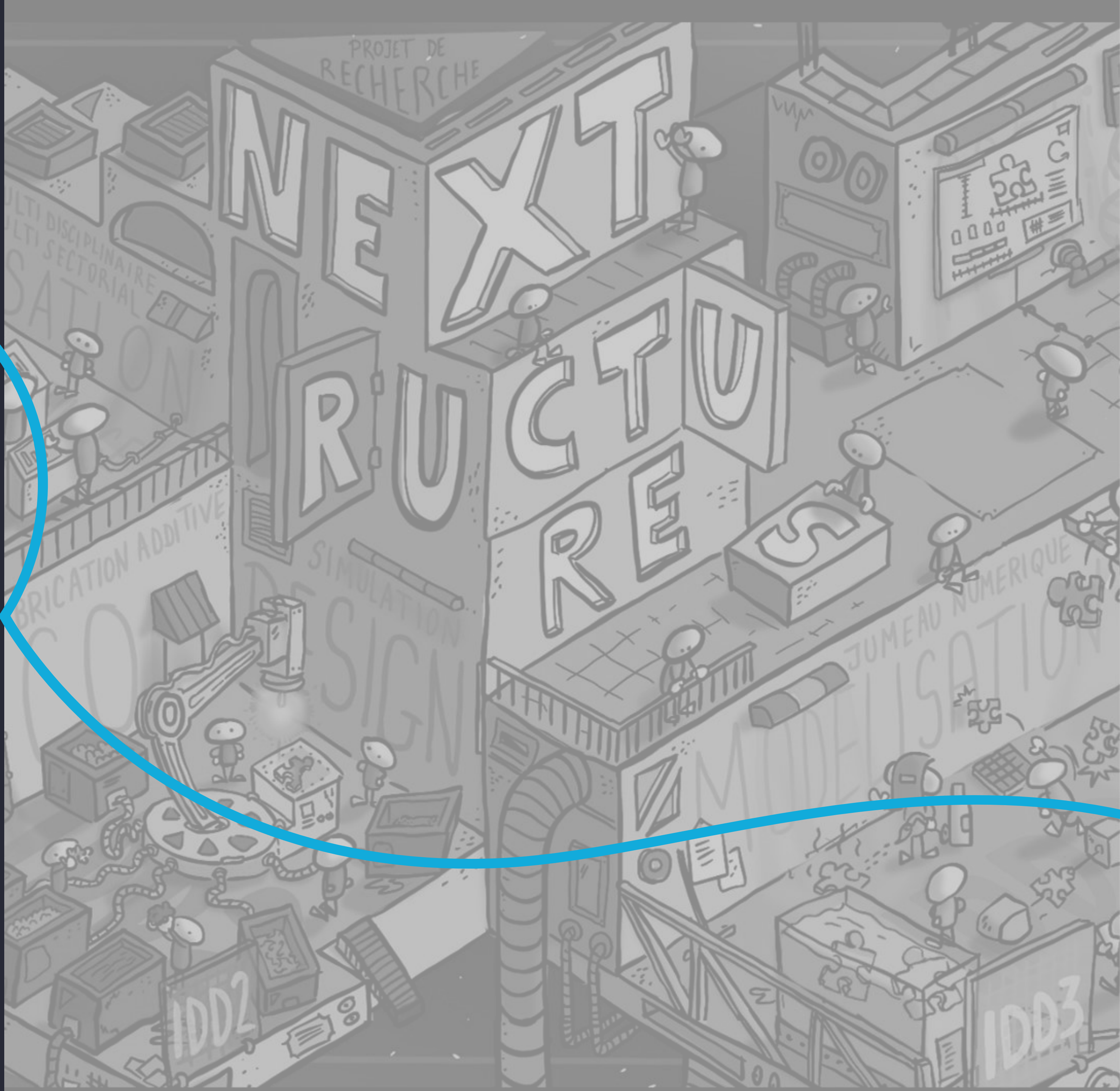

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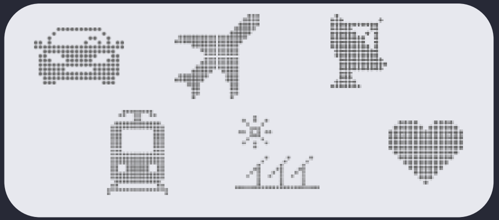

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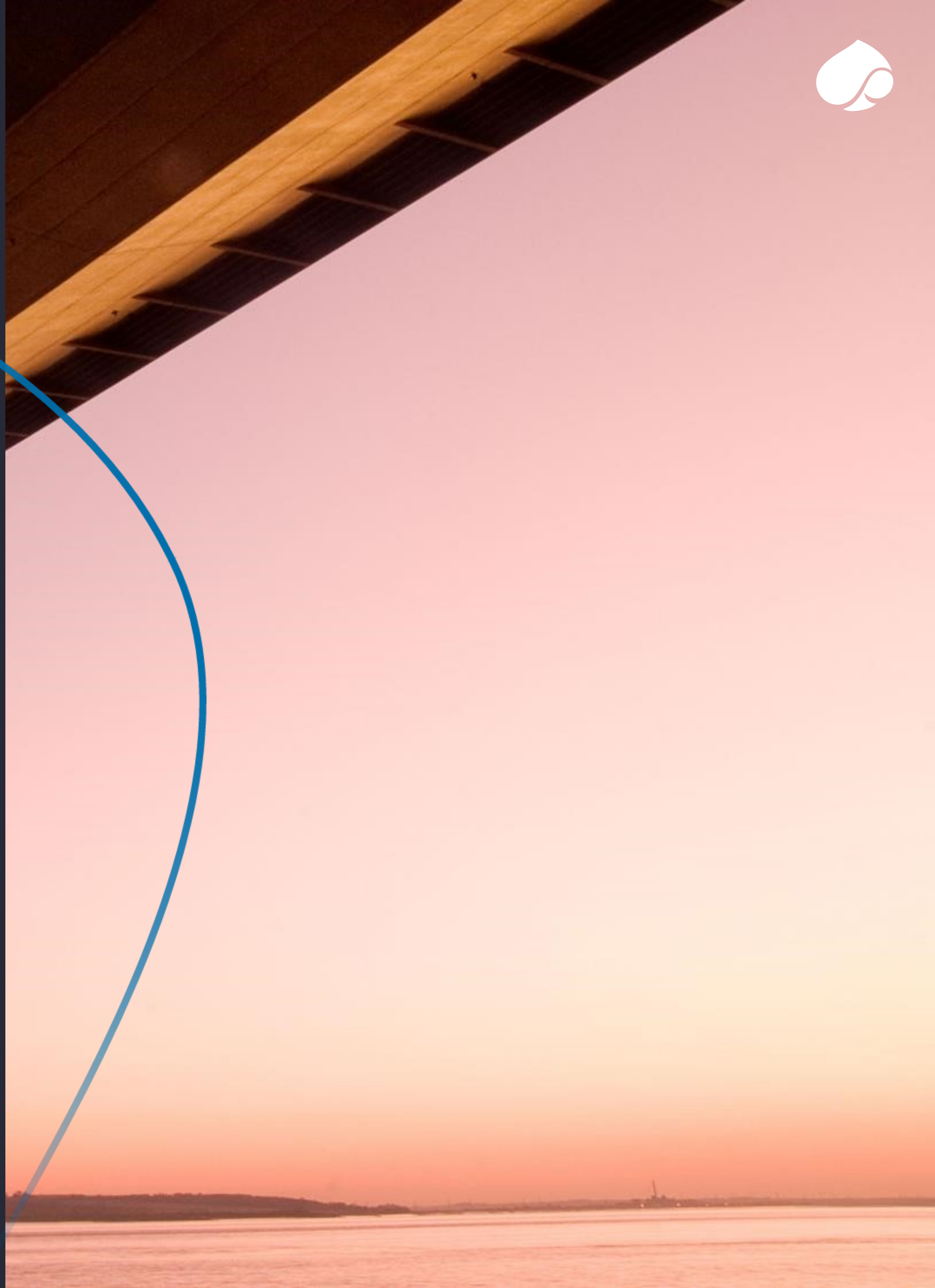
AGENDA

1

INTRODUCTION



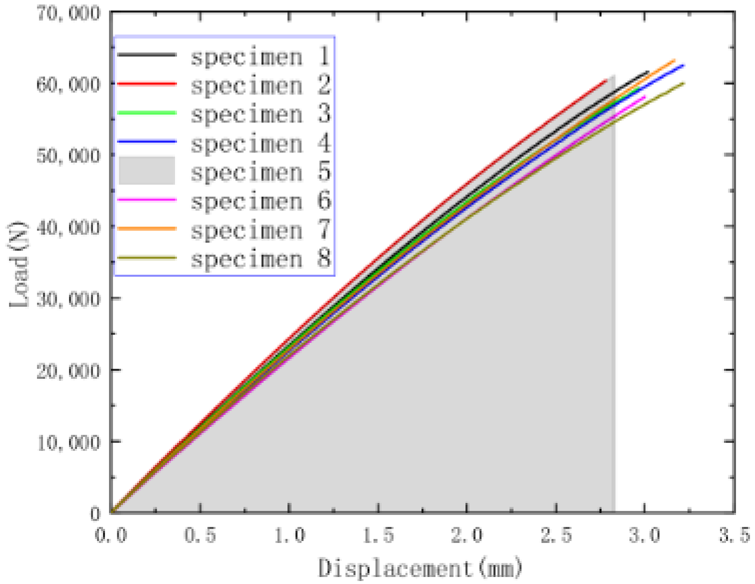
INTRODUCTION

- With all the benefits that the composite materials provide, there are always difficulties and hardships in modelling their behavior and trying to predict it . Green, Wisnom & Hallett (2007). *Compos. Part A Appl. Sci.*, *38*, 867-878.

- Going into practice, most of the composite applications in aircraft structures for example contain notches and joints.

- In the context of **faster design**, this presentation showcases the work on predicting the failure of an open and filled hole composite plate subjected to both tension and compression.

Safe life prediction



J Shi, M Tong,C Zhou, C Ye, X Wang, 2021, Appl Sci, 11, 185.

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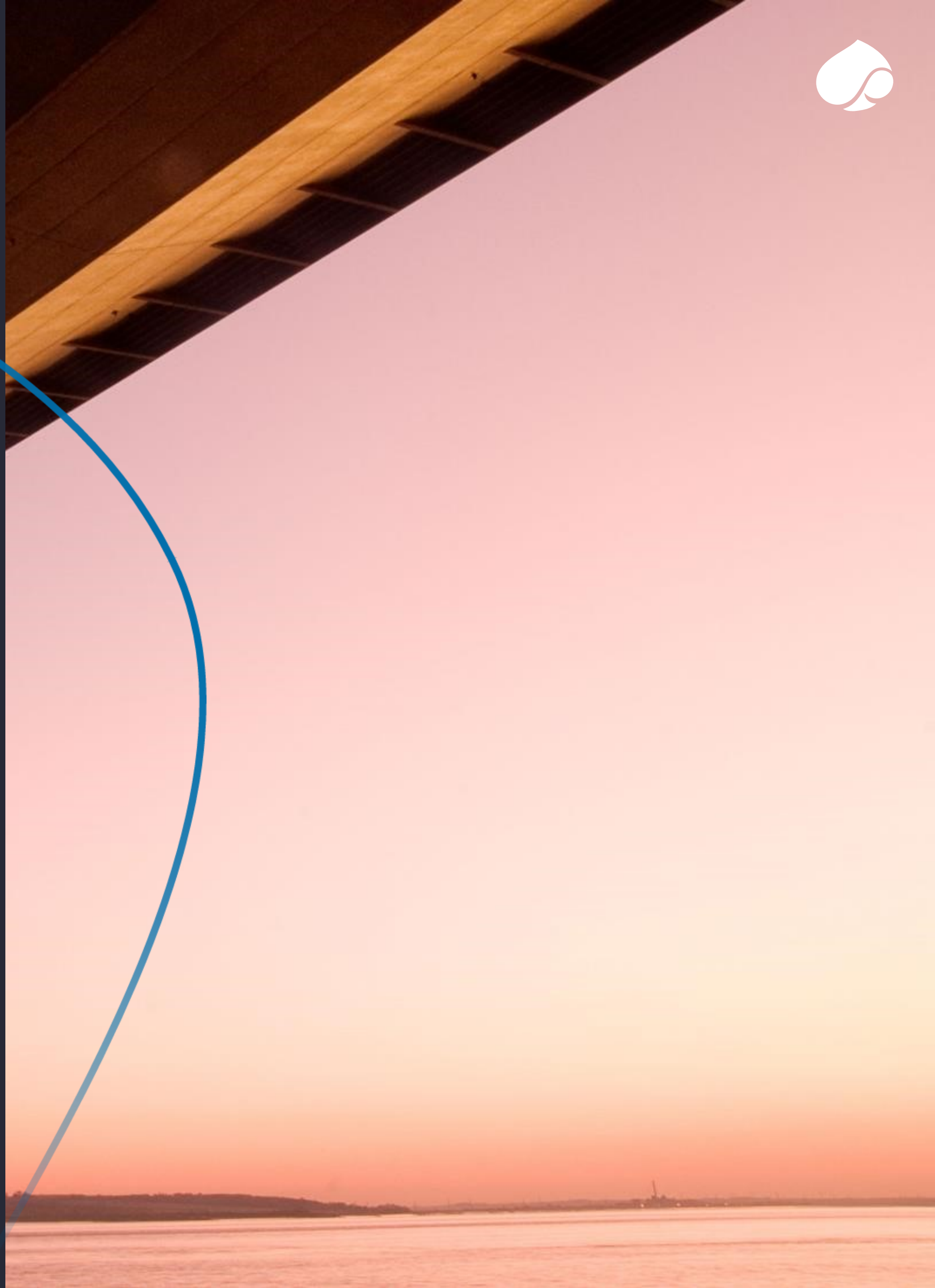
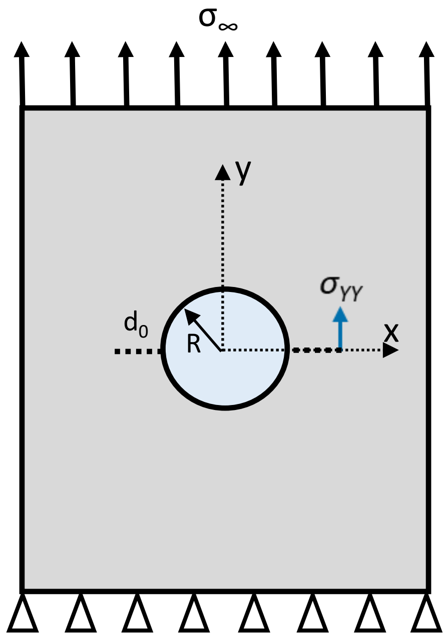
STATE OF THE ART



FAILURE CRITERIA BASED ON FINITE FRACTURE MECHANICS

- A stress concentration factor (SCF) is a dimensionless factor that is used to quantify how concentrated the stress. Whitney and Nuismer, 1974, *J Compos Mater*, 8, 253-265.

$$SCF = \frac{\sigma_{yy}}{\sigma_\infty} = \frac{1}{2}\left(2 + \left(\frac{R}{x}\right)^2 + 3\left(\frac{R}{x}\right)^4\right)\ with\ x \geq R$$



- Point Stress Criteria
  - The Criteria assumes that the failure occurs when the stress over a certain distance, d_0, is equal or greater than the strength of the unnotched material, σ_c.

- Average Stress Criteria
  - This criterion assumes that the failure occurs when the average stress over a specific distance d_0, is equal to the strength of the unnotched specimen, σ_c.

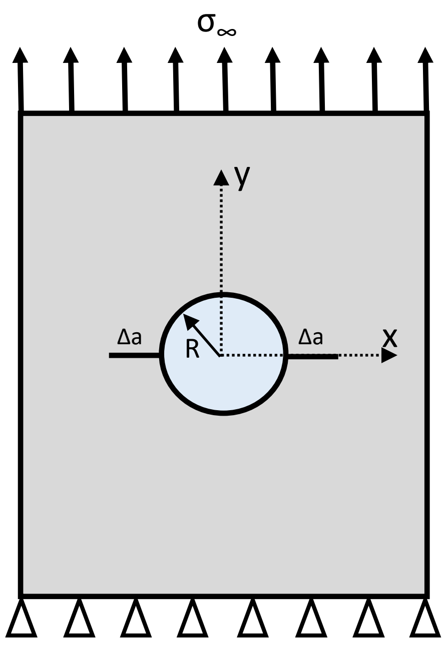
$$\frac{1}{d_0}\int_R^{R+d_0} \sigma_{yy}(x)\, dx \geq \sigma_c$$

FAILURE CRITERIA BASED ON FINITE FRACTURE MECHANICS

This criterion assumes that a failure takes place when the incremental energy release rate, *G*, for a critical crack length, a_c, has reached the critical fracture energy value of the material, G^c. Waddoups, Eisenmann & Kaminski, 1971. J. Compos. Mater. 5, 446–454.

$$\breve{G}(a_c) = \frac{1}{\Delta a} \int_{R}^{R+\Delta a} G(a)\, da = G^c$$

But of course, a new unknown appears in this formulation the finite crack size, *Δa*. This is what led to the energy criteria to also depend on experimental testing to obtain the empirical coefficients.



FAILURE CRITERIA BASED ON FINITE FRACTURE MECHANICS

Point Stress Criterion	Average Stress Criterion	Energy Criterion
✔ Solved by analytical solutions	✔ Solved by analytical solutions	✔ Relatively fast method to predict failure
✔ Fast method to predict failure	✔ Relatively fast method to predict failure	✕ Limited analytical solutions
✕ Not accurate for highly plastic materials	✕ Not accurate for highly plastic materials	✕ Not accurate for brittle materials
✕ Requires empirical parameters to predict failure	✕ Requires empirical parameters to predict failure	✕ Requires empirical parameters to predict failure

COUPLED CRITERION LITERATURE

Both stress and energy criteria are necessary conditions for the fracture but **neither of them is sufficient alone.** Leguillon, 2002, *Eur J Mech A Solids, 21*, 61-72

Due to the singularity on the tip of the notch:

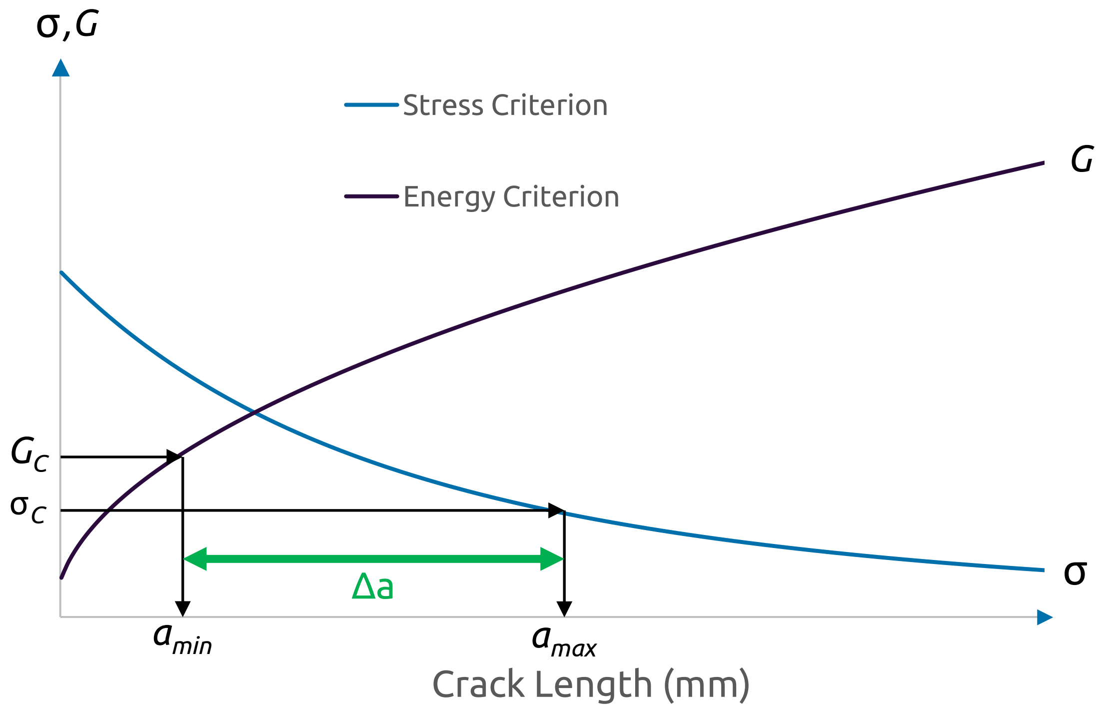
- The Energy Criterion provides a Lower Bound.
- The Stress Criterion provides an Upper Bound.

Coupled Criterion is satisfied upon the simultaneous fulfillment of both the Stress and Energy criteria.

The coupled criterion has already been successfully applied to quasi-isotropic laminates using **analytical equations** for open-hole and filled-hole cases.

Weißgraeber, Felger, Geipel & Becker, 2016, *Eur J Mech A Solids, 55*, 192-198.

Martin, Leguillon, Carrère, 2012 , *Int J. Solids Struct*, 49, 3915-3922.



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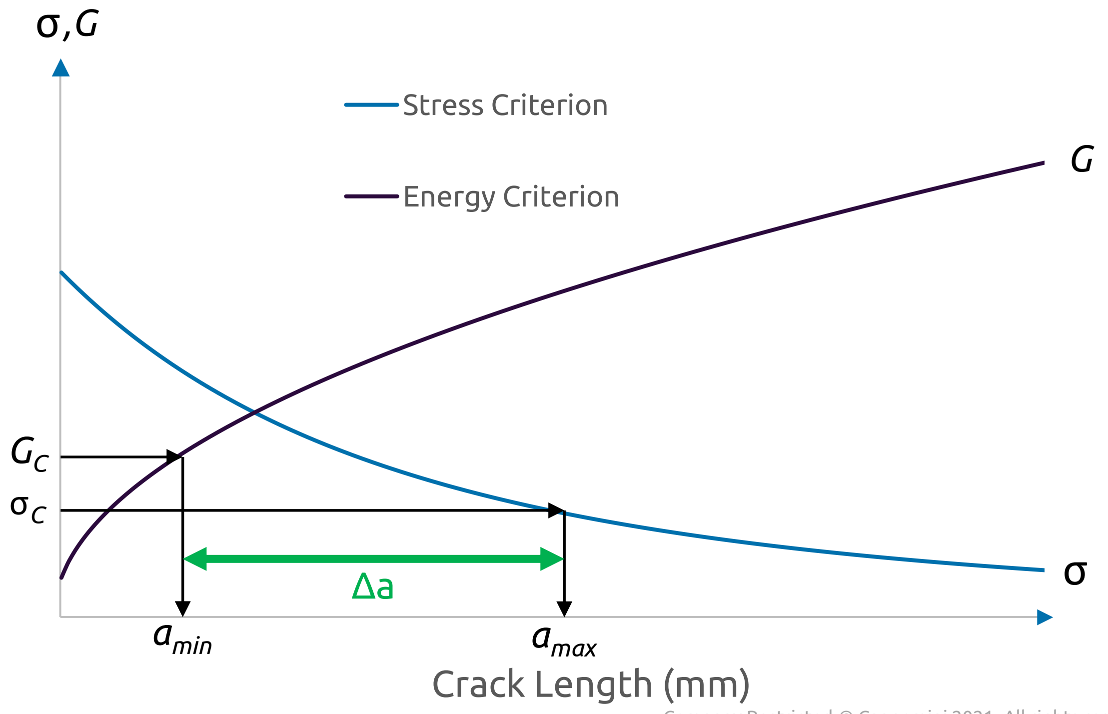
Is it possible to expand the scope and generalize the criterion for anisotropic laminates?

Coupled Criterion is satisfied upon the simultaneous fulfillment of both the Stress and Energy criteria.



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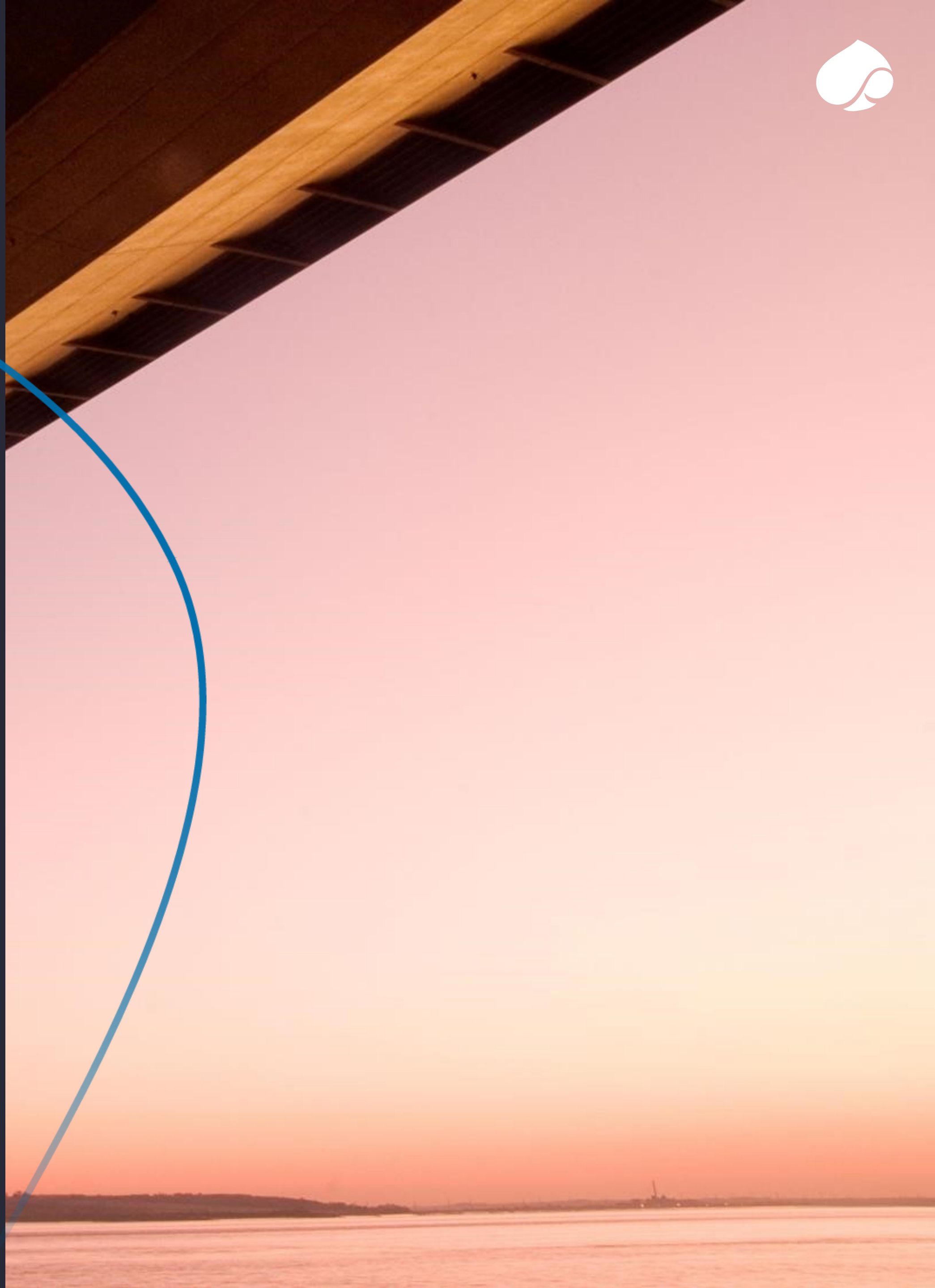
METHODOLOGY



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The direction of the crack onset depends on the stacking sequence

Felger, Stein, Becker, 2017, *Int J. Solid Struct*, 122–123, 14-24.

Average Stress – Energy criteria:

$$\frac{\Delta a \int_0^{\Delta a} \widehat{K}^2 \, d\widetilde{\Delta a}}{\left(\int_R^{R+\Delta a} \widehat{\sigma_{eq}} \, dx\right)^2} = \frac{K_c^2}{{\sigma_c}^2}$$

Mechanical properties of the laminate

Use the mechanical properties of the ply to determine the whole laminate

Testing the whole laminate

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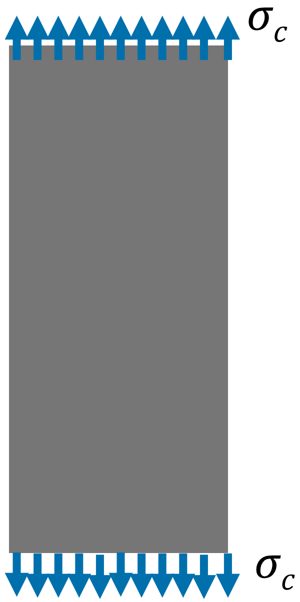
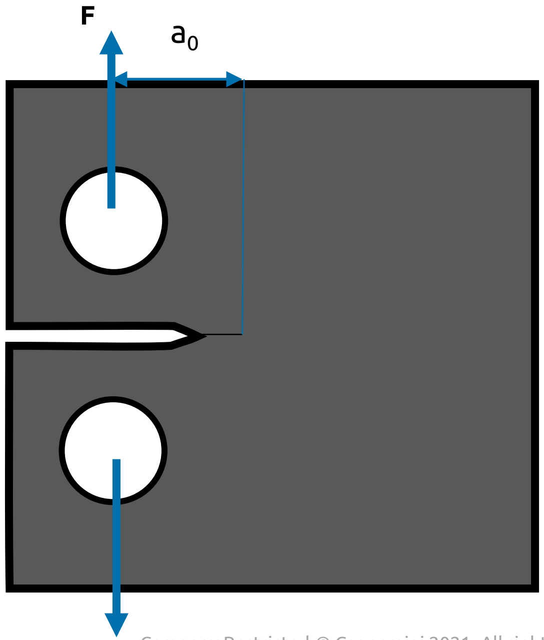
Testing the whole laminate

Unotched test (σ_c)



Compact tension (K_c)



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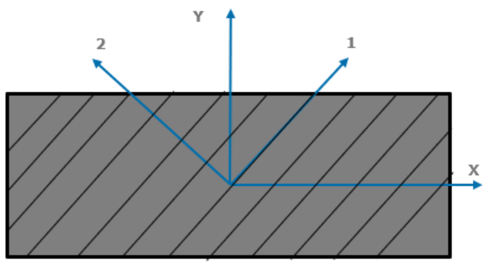
Use the mechanical properties of the ply to determine the whole laminate



Principal and global coordinate system of a lamina

Elastic properties of the ply (transverse isotropic)

E_1, E_2, E_3 -Young's modulus in the three principal planes
G_{12}, G_{13}, G_{23} Shear modulus in the three principal planes of the shell
$\nu_{12}, \nu_{23}, \nu_{13}$ - Poisson's ratios

Fracture properties of the ply

X^T, X^C: the tensile and compressive strengths in the fibers direction
Y^T, Y^C: is the tensile and compressive strengths in the transverse direction
S^T, S^L: transverse and longitudinal shear strengths of the composite

Classical lamination theory + failure criterion (Hashin or Puck)

Determination of σ_c

Li & F Han, 2022, Materials, 15, 2227.

COUPLED CRITERION LITERATURE

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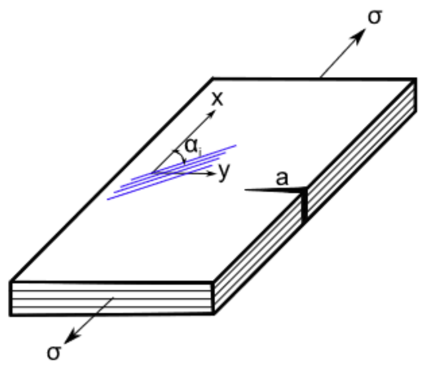

Camanho & Catalanotti, 2011, *Eng Fract Mech*,78, 2011, 2535-2546.

Elastic properties of the ply (transverse isotropic)

E_1, E_2, E_3 -Young's modulus in the three principal planes
G_{12}, G_{13}, G_{23} Shear modulus in the three principal planes of the shell
ν_{12}, ν_{23}, ν_{13} - Poisson's ratios

Fracture properties of 0° ply

K^0_c – fracture toughness of the 0° ply

Determination of K_c

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$$\frac{\Delta a \int_0^{\Delta a} \widehat{K}^2 \, d\widetilde{\Delta a}}{\left(\int_R^{R+\Delta a} \widehat{\sigma_{eq}} \, dx\right)^2} = \frac{{K_{IC}}^2}{{\sigma_c}^2}$$

$$\widehat{\sigma_{eq}} = \frac{\sigma_{eq}(x)}{\sigma_\infty}$$

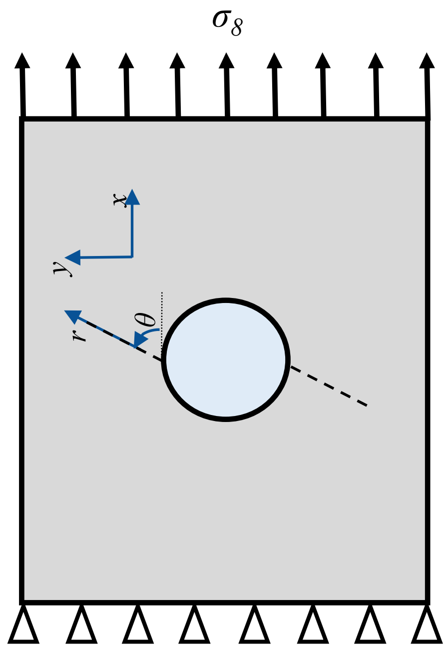
$$\sigma_r = \sigma_x \cos\theta^2 + \sigma_y \sin\theta^2 + 2\,\sigma_{xy}\cos\theta\sin\theta$$

$$\sigma_\theta = \sigma_x \sin\theta^2 + \sigma_y \cos\theta^2 - 2\,\sigma_{xy}\cos\theta\sin\theta$$

$$\sigma_{r\theta} = (\sigma_y - \sigma_x)\cos\theta\sin\theta + \sigma_{xy}\cos\theta^2 - \sigma_{xy}\sin\theta^2$$

$$\sigma_{eq} = \sqrt{{\sigma_\theta}^2 + {\sigma_{r\theta}}^2}$$

Non-cracked model, but along the direction of the crack



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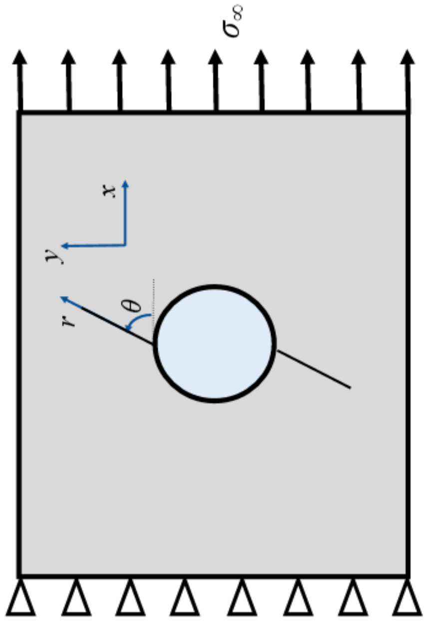
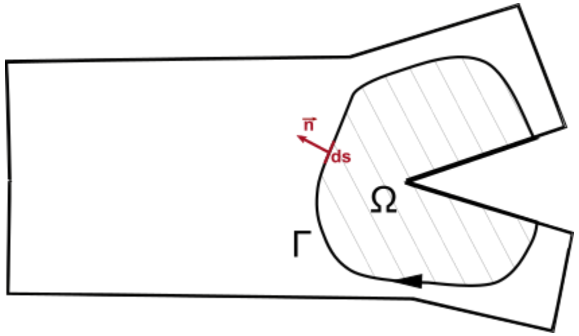
$$\hat{K} = \frac{K(x)}{\sigma_\infty}$$

Cracked model, but along the direction of the crack





Exemple of contour surrounding a crack tip

K can be obtained via J-integral around the crack tip :

$$J = \frac{K^2}{\sqrt{2E_xE_y}} \sqrt{\sqrt{\frac{E_x}{E_y}} + \frac{E_x}{2G_{xy}} - \upsilon_{xy}}$$

Pinho, Robinson & Iannucci, 2006, *Compos Sci Technol*, 66, 2069-2079.

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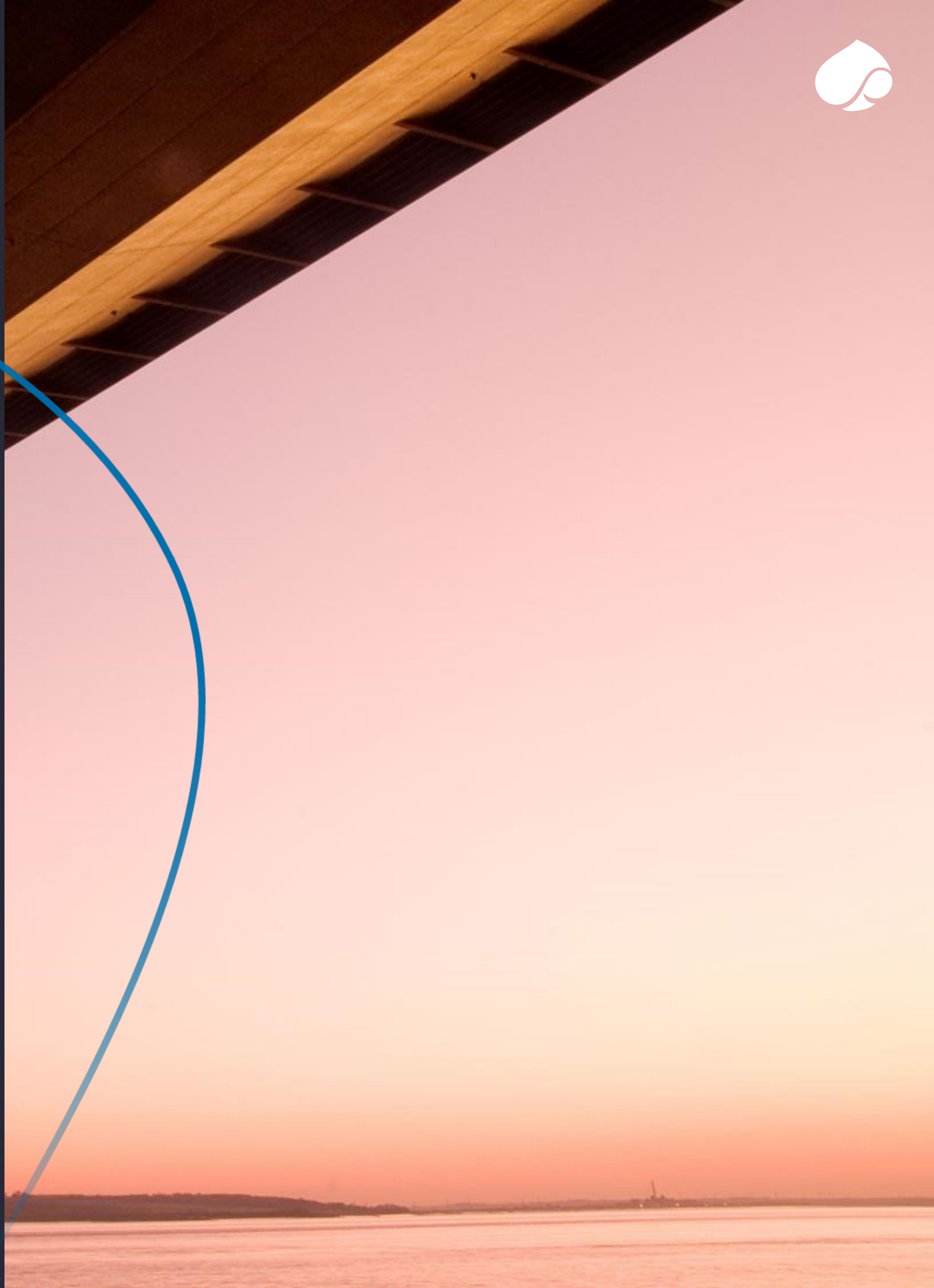
RESULTS



OPEN HOLE STRENGTH USING COUPLED CRITERION

Free Crack Direction – Application

The Experimental tests was presented by:
O Falcó., RL Ávila, B Tijs, CS Lopes, 2018, *Comp Struct*, 190, 137-159.

- Three different types of composites are studied.
- Each composite is subjected to compressive and tensile forces at a time.
- The direction of crack propagation is provided.
- Material: HexPly AS4/8552 unidirectional prepreg CFRP

Property	Unnotched Failure Stress (MPa)	Notched Failure Stress (MPa)	Direction of Crack Orientation (Degrees)
Tension			
Hard Composite	1105.5	526.7	90
Quasi_Isotropic Composite	651.1	370.9	Not Visible
Soft Composite	421.9	289.3	135
Compression			
Hard Composite	787.2	425.7	Not Visible
Quasi_Isotropic Composite (QI)	554.5	301.8	90
Soft Composite	414.1	269.8	Not Visible

Soft Composite in Tension

Hard Composite in Tension

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OPEN HOLE STRENGTH USING COUPLED CRITERION

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Property	Notched Failure Stress (MPa)
Tension	
Quasi_Isotropic Composite	370.9
Compression	
Quasi_Isotropic Composite (QI)	301.8

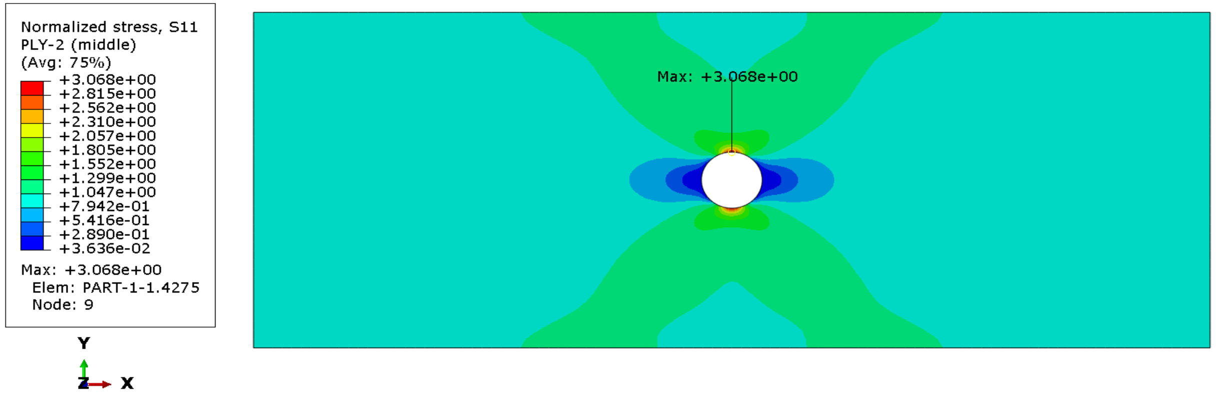
These values were adopted from the quasi-isotropic configuration + analytical equation OH as a first approach.

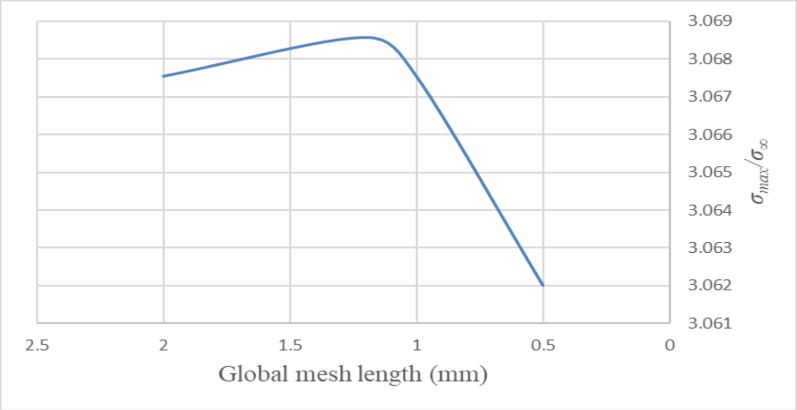
Property	Mean Value
Ply Elastic Properties	
E_{1t} (GPa)	137.1
E_{1c} (GPa)	114.4
E_{2t} (GPa)	8.8
E_{2c} (GPa)	10.1
$G_{12} = G_{13}$ (GPa)	4.9
$\upsilon_{12} = \upsilon_{13}$	0.314
υ_{23}	0.487
Ply Strength Properties	
X^T (MPa)	2106.4
X^C (MPa)	1675.9
Y^T (MPa)	74.2
Y^C (MPa)	322.0
S^L (MPa)	110.4
Fracture toughness	
Kc – tension ($MPa.m^{0.5}$)	48
Kc - compression($MPa.m^{0.5}$)	38
Ply Configuration	
Hard Composite	$[0,45,0,90,0,-45,0,45,0,-45]_S$
Quasi-Isotropic Composite (QI)	$[-45,0,45,90]_{2S}$
Soft Composite	$[45,-45,0,45,-45,90,45,-45,45,-45]_S$

OPEN HOLE STRENGTH USING COUPLED CRITERION

Convergence test using uncracked (stress) and cracked (energy) configuration – 2D geometry

Stress concentration factor of 0° ply of QI composite

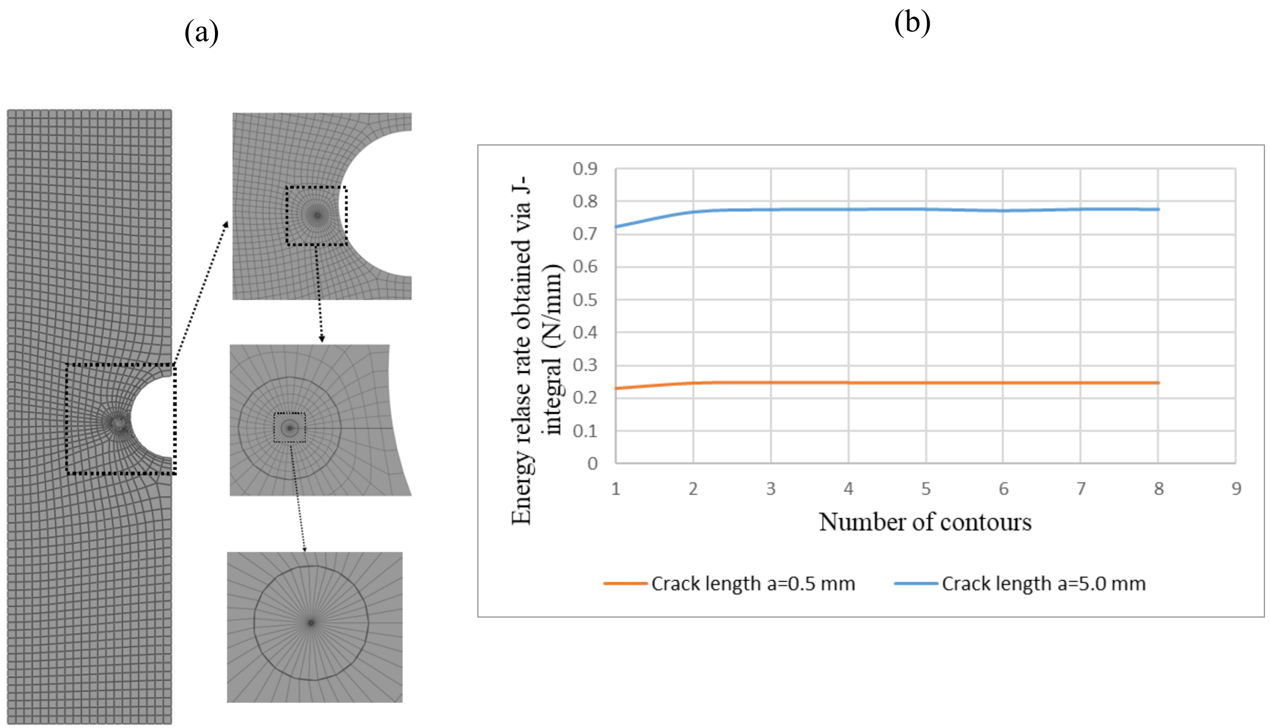




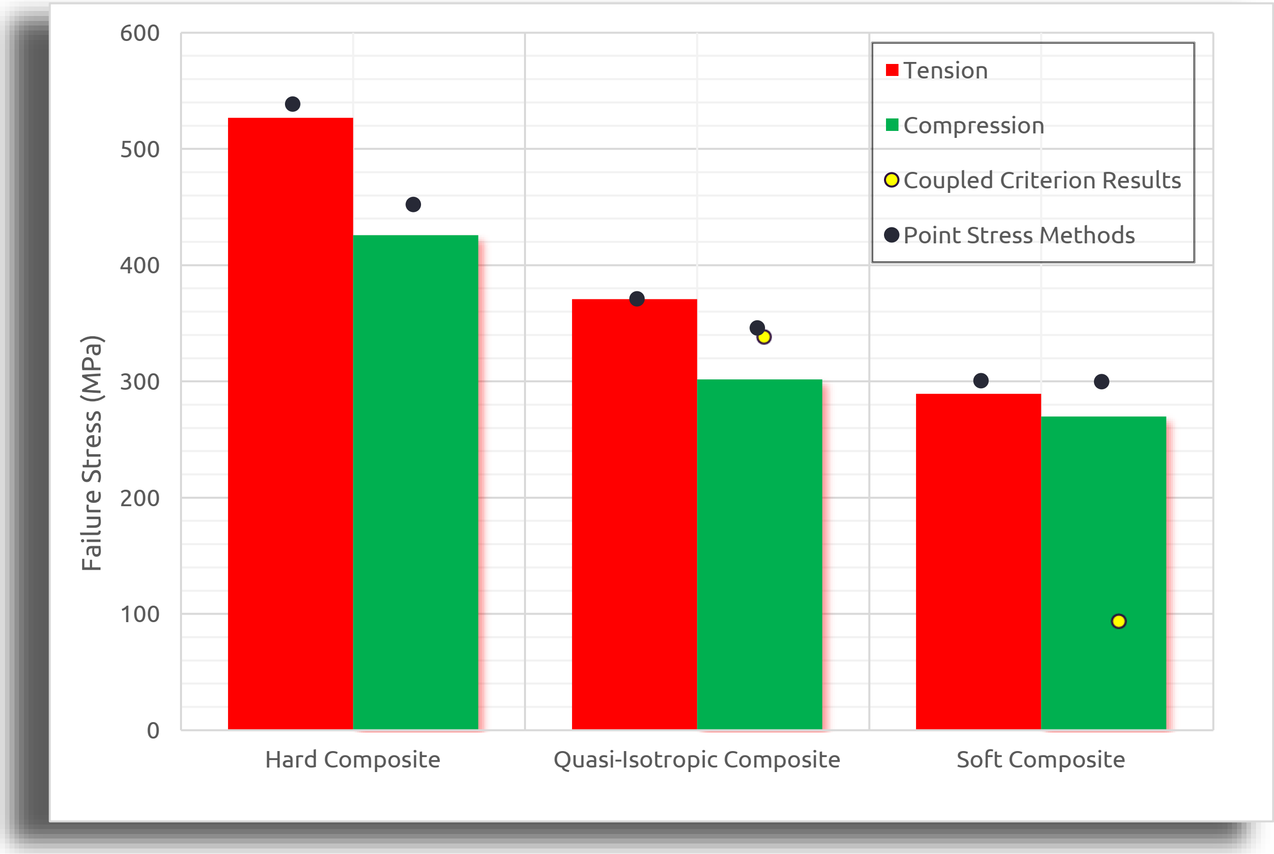
OPEN HOLE STRENGTH USING COUPLED CRITERION

Convergence test using non-cracked (stress) and cracked (energy) configuration

Convergence of energy release rate for QI



COUPLED CRITERION USING COUPLED CRITERION



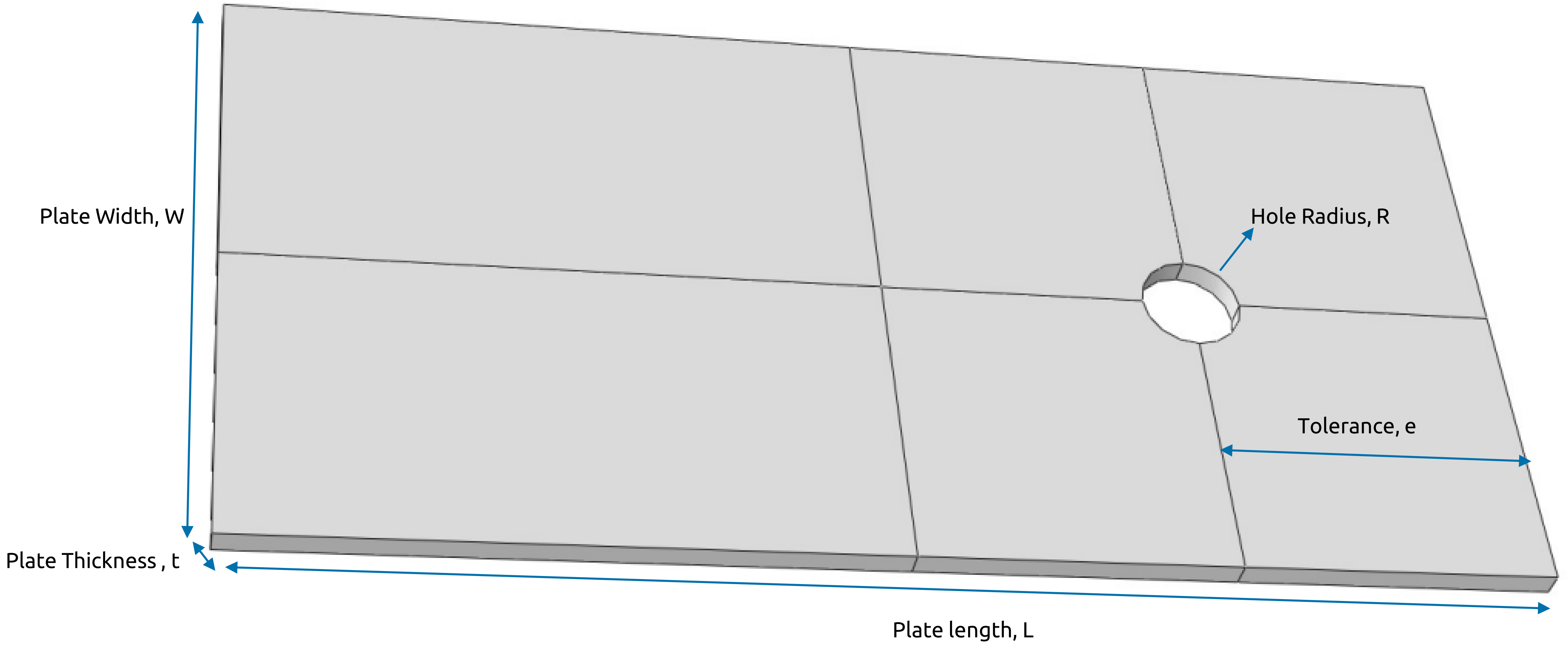
Coupled Criterion predicted the failure in open hole composites for:

- Tension and Compression Loadings.
- Thin Composite Layup
- Any Geometrical Inputs
- Any Orientation of the Crack

FILLED HOLE CONFIGURATION

GEOMETRY AND PARAMETERS

Plate – thin-ply CFRP



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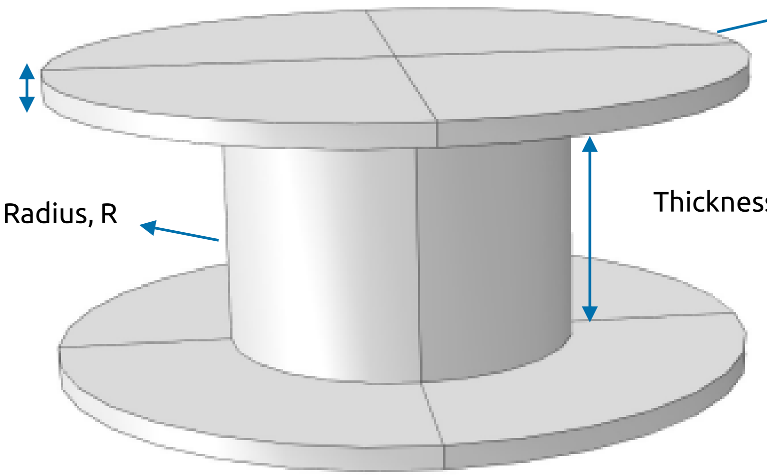
GEOMETRY AND PARAMETERS

Fastener - steel



Young's modulus (E_{steel}): 200 GPa
Poisson's ratio (ν_{steel}): 0.3

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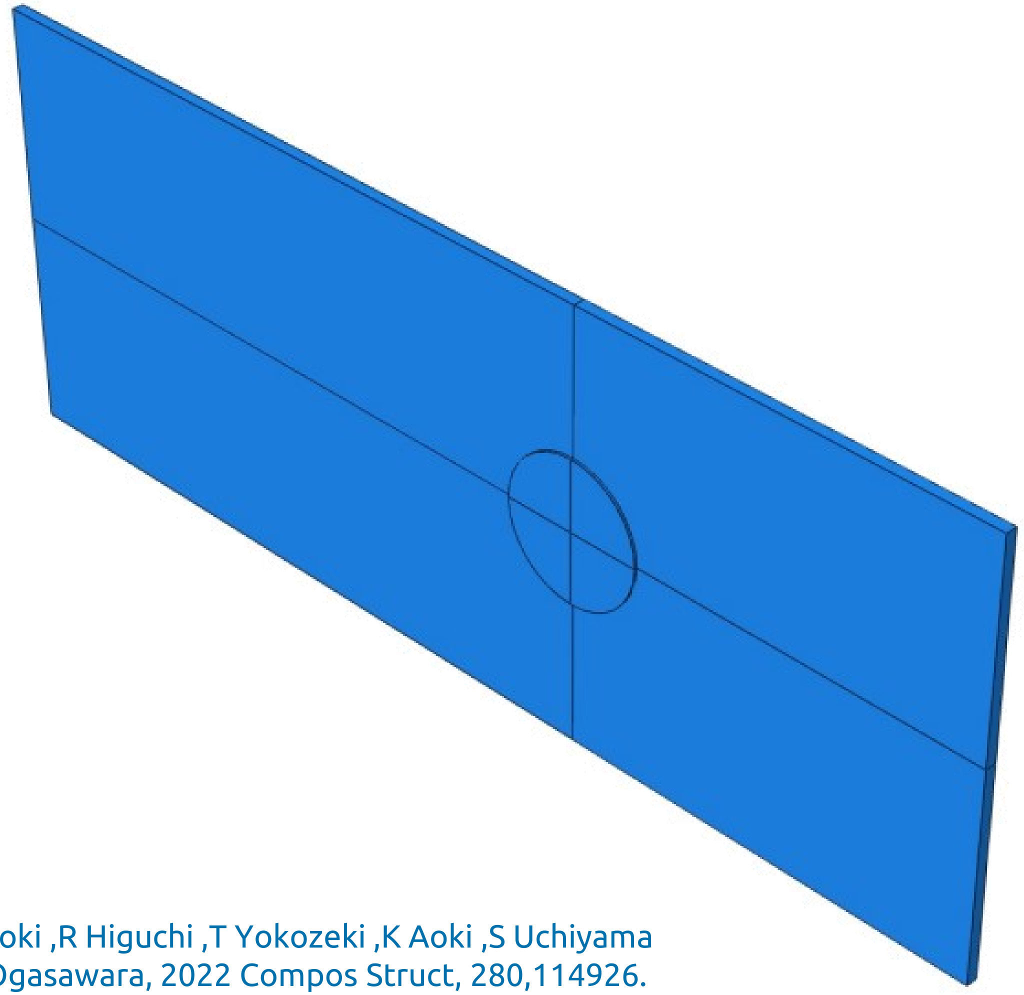
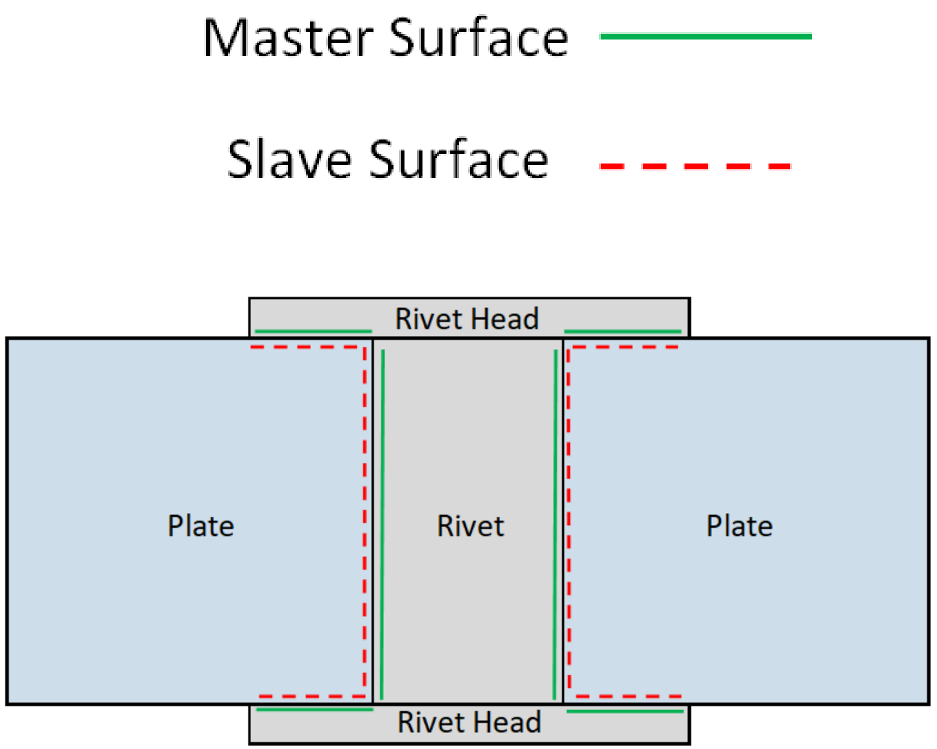
ASSEMBLY CONDITIONS

One Plate-Rivet Assembly





3 Surface to Surface Contacts

Coefficient of friction: 0.2

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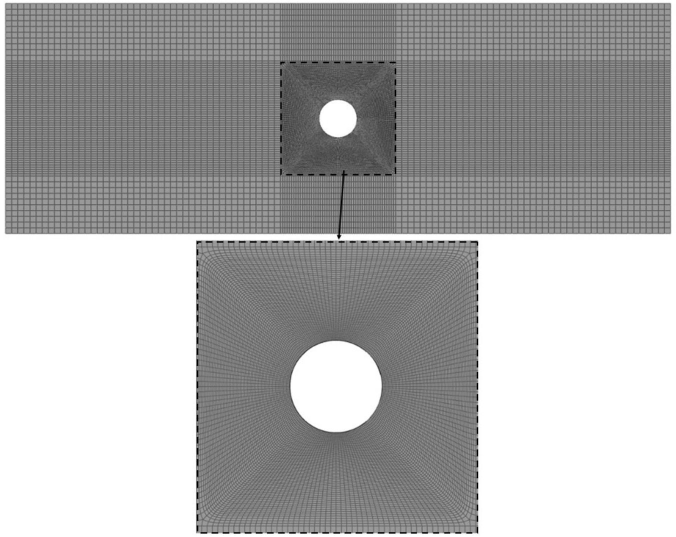
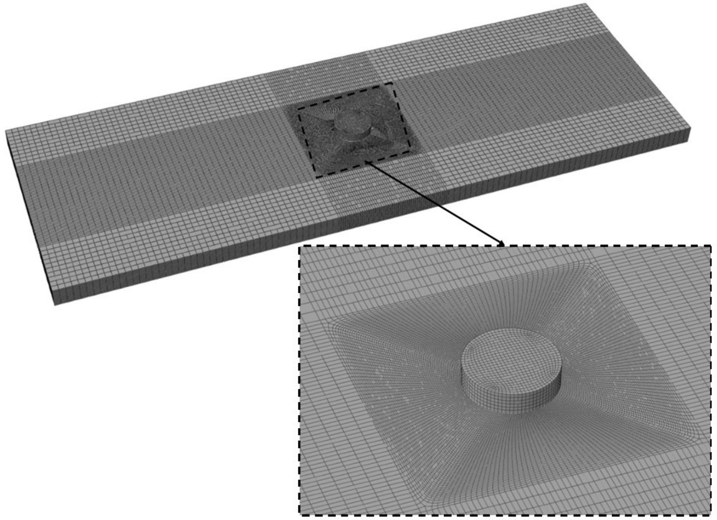
APPLICATION CASE

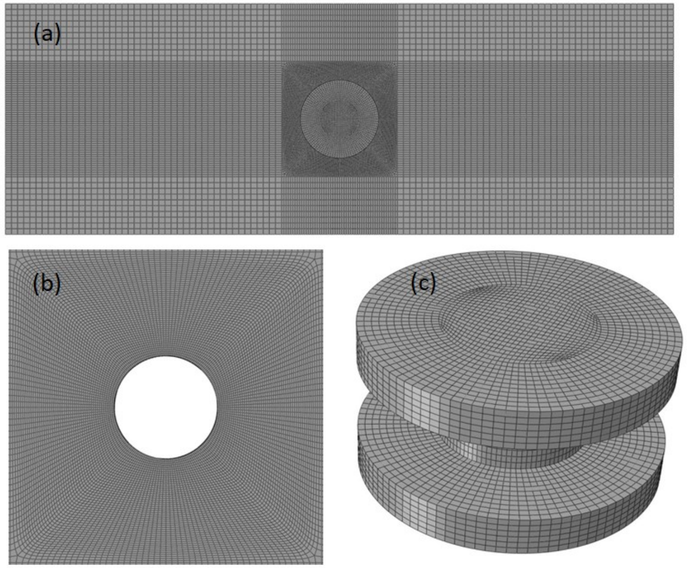
OHT condition
(W/o bolt and washer)



Pin FHT(3D)
(With bolt)



Pin FHT(3D)
(With bolt and washed – P=41.8 MPa)



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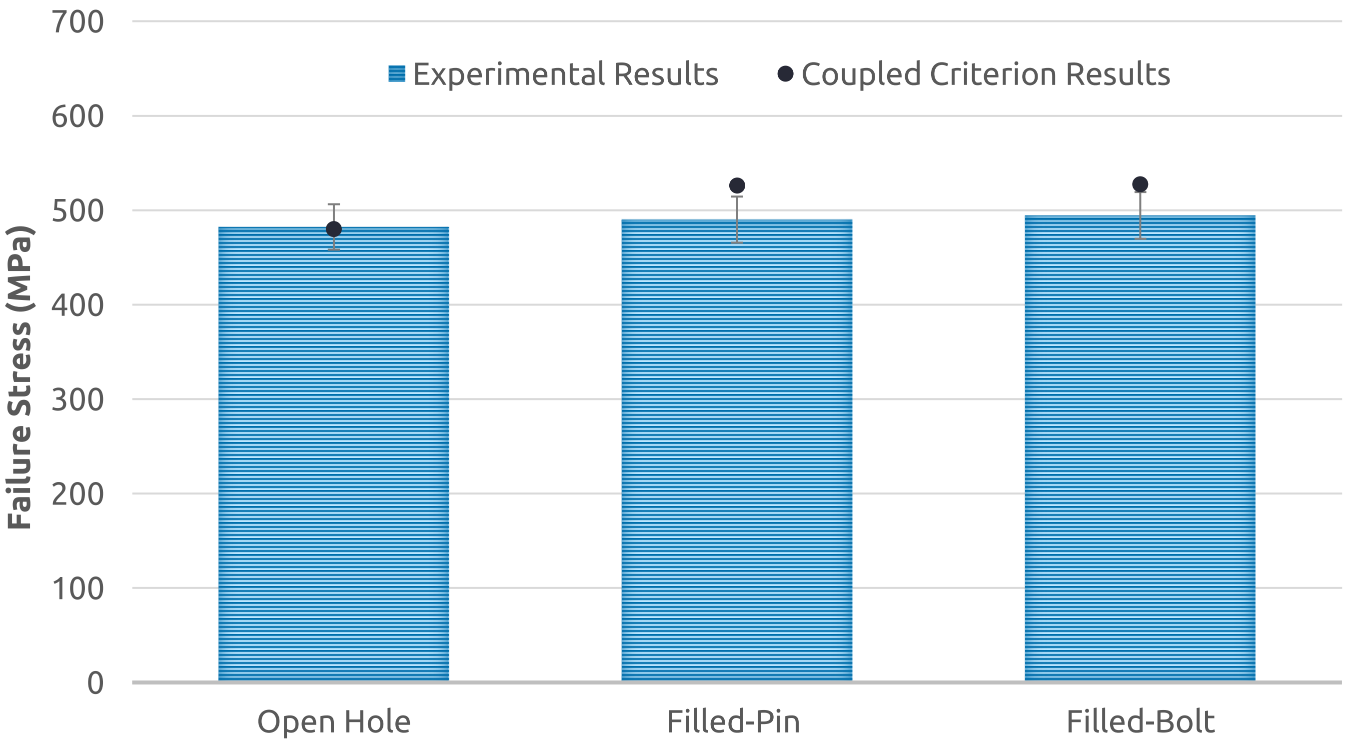
APPLICATION CASE

Coupled Critertion Results

Properties and Parameters	Value
E_1 (GPa)	139
E_2 (GPa)	7.88
G_{12} (GPa)	3.99
υ_{12}	0.33
σ_c (MPa)	1250.1
K_C (MPa/mm^-0.5)	1344.1
F (N/mm)	1000
L (mm)	110
W (mm)	38
R (mm)	3.175
h (mm)	0.05
Number of Plies	64
Stacking sequence QI	$[45,67.5,90,-67.5,-45,-22.5,0,22.5]_{4s}$

Failure Stress (MPa)		
Open Hole	Pin Filled Hole	Rivet Filled Hole
482.2	490.1	494.6



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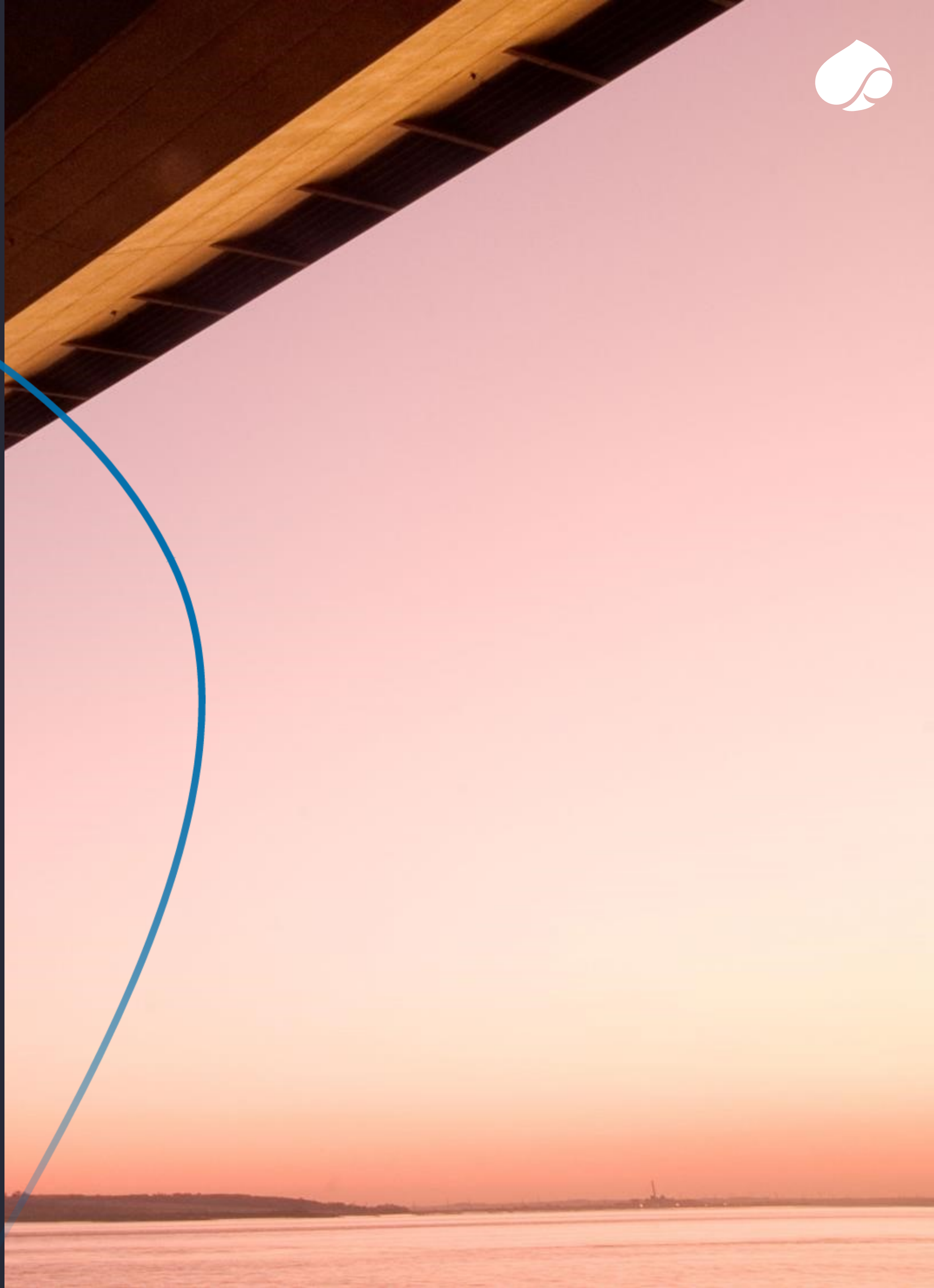
CONCLUSION AND PERSPECTIVES



CONCLUSION AND PERSPECTIVES

The Coupled Criterion is able to solve the problem of composite plate failure using only as inputs:

- Material's Property. (E_1, E_2, G_{12}, v_{12})
- Laminate Stacking Sequence.
- Ply Thickness.
- Unnotched Laminate Strength. (σ_c)
- Critical Stress Intensity Factor. (K_C)

The approach taken in this study is able to output the following:

- Equation for the SCF and the SIF.
- Failure Stress in tension or in compression.
- Critical crack length tension or in compression.

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CONCLUSION AND PERSPECTIVES

- Ongoing:
  - Developing a new module for determining the fracture toughness of the 0° ply(K_c)
  - Creating a new module for determining the critical strength using Classical Laminate Theory and Hashin's Criterion.

- Future perspectives:
  - Modeling fracture of multidirectional thin-ply laminates using an anisotropic formulation at the macro-scale $K_c(\theta)$ A Mitrou, A Arteiro, J Reinoso, PP Camanho,2023, *Int. J. Solids Struct*, 273, 2023,112221.
  - Multiaxial loading conditions

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APPENDIX

ANALYTICAL APPROACH

Weißgraeber, Felger, Geipel & Becker, 2016, *Eur J Mech A Solids*, *55*, 192-198.

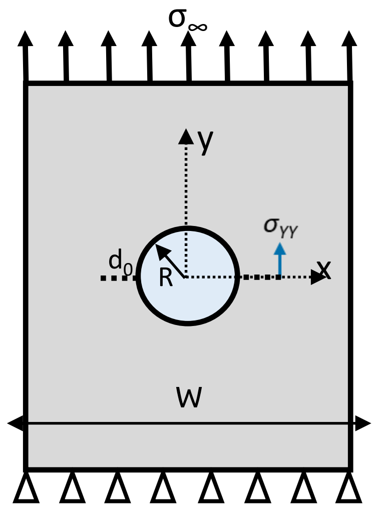
Martin, Leguillon, Carrère, 2012 , *Int J. Solids Struct*, 49, 3915-3922.

Isotropic Plate

The literature provides analytical solution for both the SCF and the SIF. Both cases shows no dependency on material's properties.

- Stress Concentration Factor:

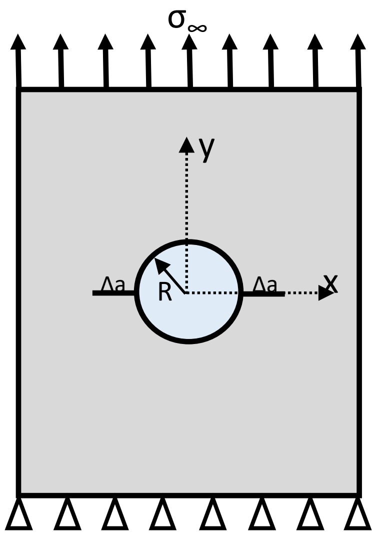
$$SCF = \frac{\sigma_{yy}(x)}{\sigma_\infty} = \frac{1}{2}\,\frac{2+\left(1-\frac{R}{W}\right)^3}{3\left(1-\frac{R}{W}\right)}\left(2+\left(1+\frac{x}{R}\right)^{-2}+3\left(1+\frac{x}{R}\right)^{-4}\right)$$



- Stress Intensity Factor:

$$SIF = \frac{K_I(x)}{\sigma_\infty} = \sqrt{\pi\,\Delta a}\,\frac{1}{\sqrt{\cos\left(\pi\frac{R}{W}\right)}}\,H(\Delta a, R, W)$$

$$H = \frac{1}{\sqrt{\cos\left(\pi\frac{R}{W}\left(1+\frac{\Delta a}{R}\right)\right)}}\left(1+0.358\left(1+\frac{\Delta a}{R}\right)+1.425\left(1+\frac{\Delta a}{R}\right)^2-1.578\left(1+\frac{\Delta a}{R}\right)^3+2.156\left(1+\frac{\Delta a}{R}\right)^4\right)$$

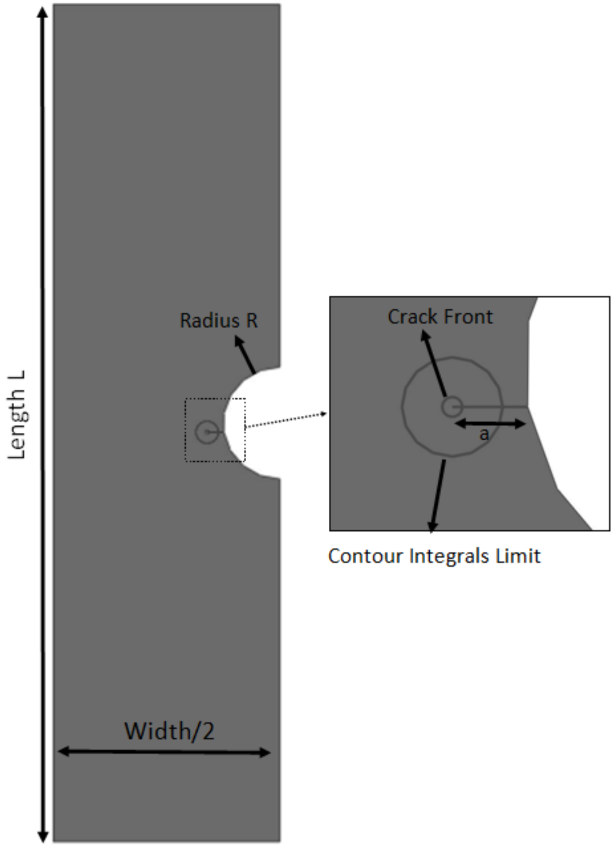


Coupled Criterion can be solved!

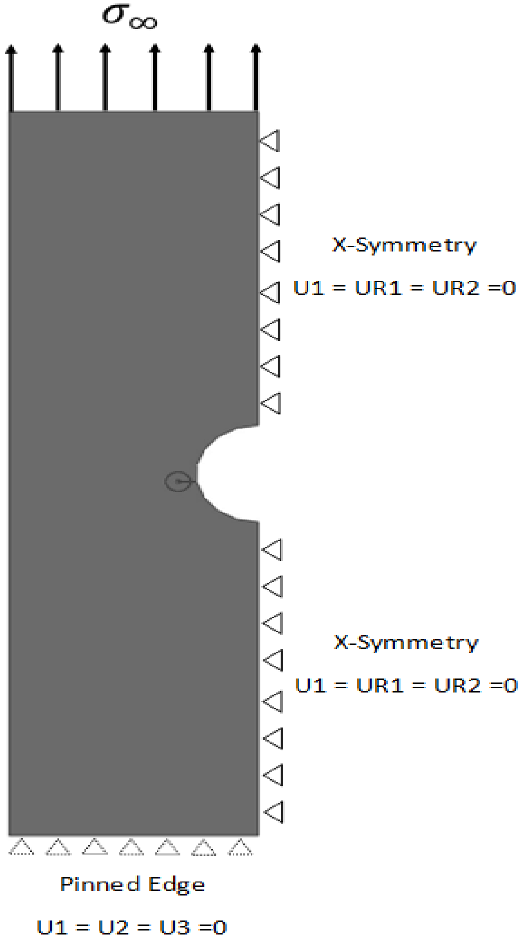
NUMERICAL VALIDATION

Isotropic Plate

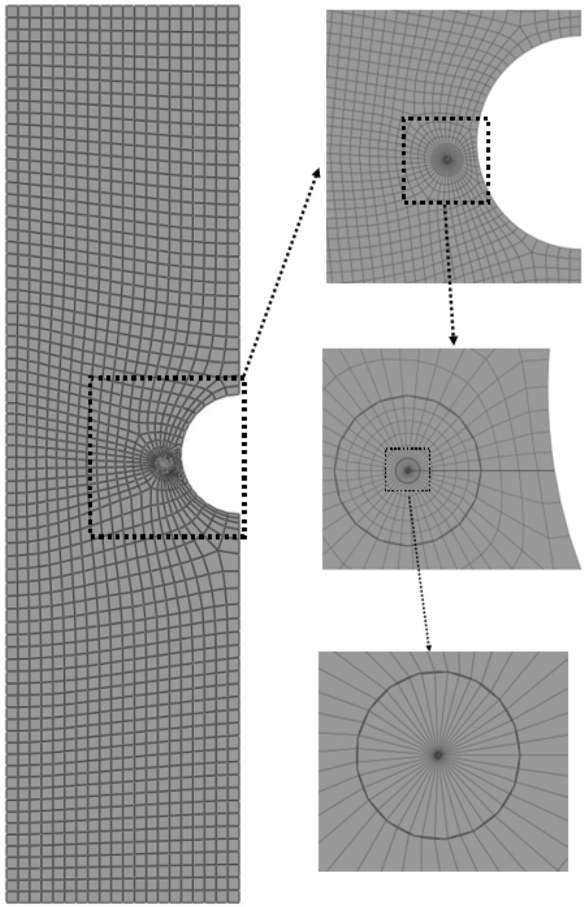
This study was done using the analytical solutions as a reference, to build and prove the validity of the numerical model being used.



Geometry



Boundary Conditions



Mesh

NUMERICAL VALIDATION

Isotropic Plate

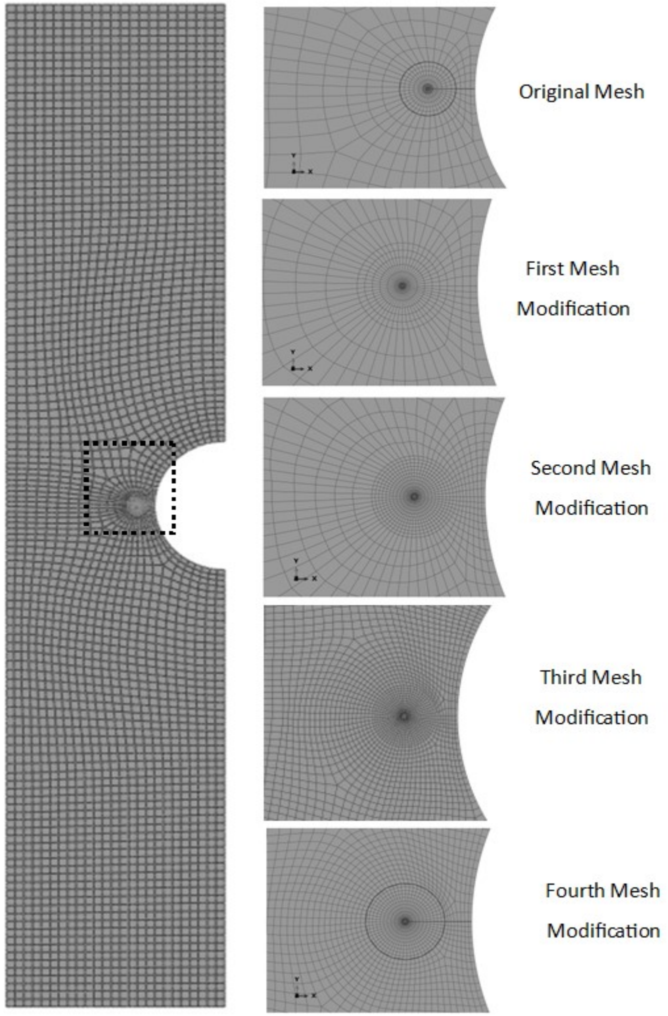
Mesh convergence depended on many factors:

- Size of the contour integrals.
- Local seeding mesh on the crack.
- Global mesh.

	Original Mesh	1st Modification	2nd Modification	3rd Modification	4th Modification
SIF	5.3405	5.342	5.339	5.32	5.34

Different specimens were then tested using this approach.

Length L (mm)	Radius R (mm)	Width W (mm)	Crack Length a (mm)	Analytical value of SIF	Numerical value of SIF
800	15	200	4.5	8.415	8.378
500	5	160	3	6.402	6.39
400	15	150	1.5	4.713	4.725



NUMERICAL VALIDATION

SIF for Quasi-Isotropic Plate

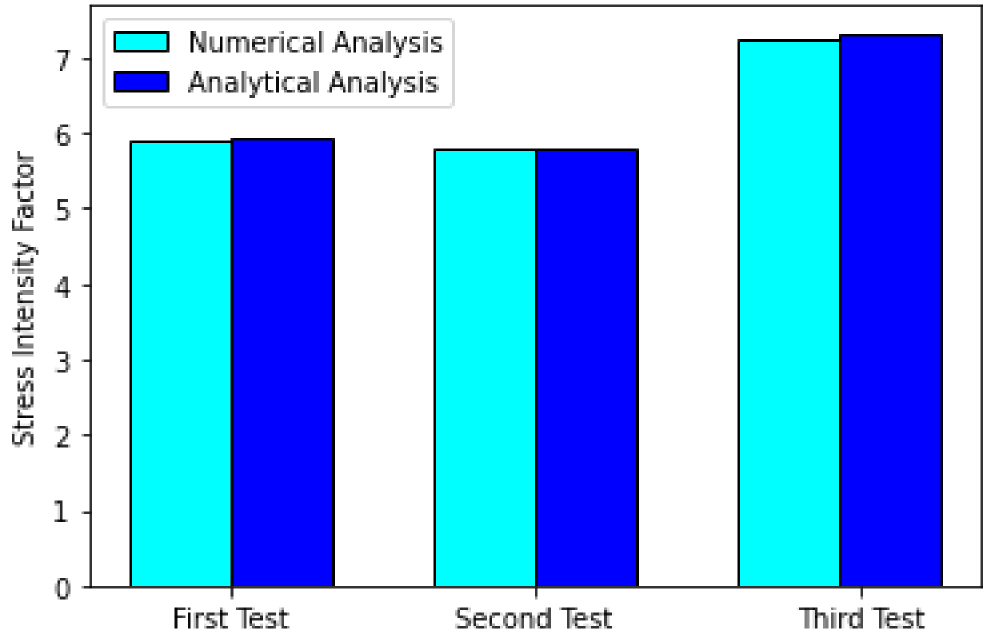
Material Properties →

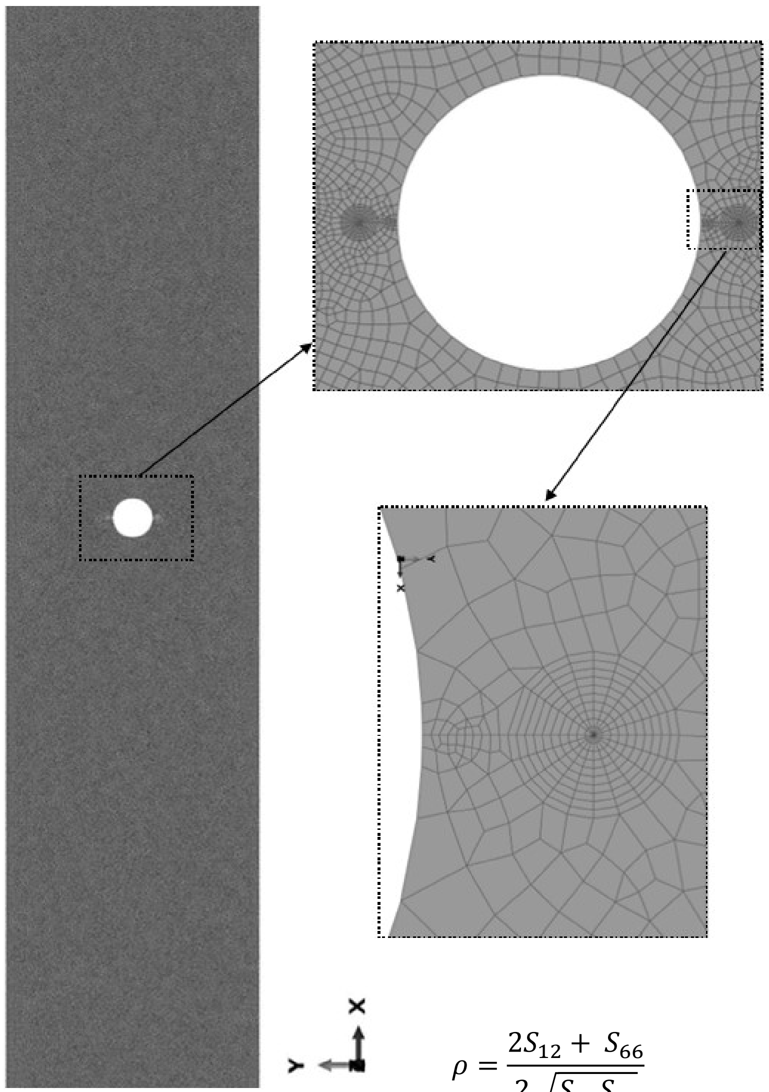
E_1 (MPa)	E_2 (MPa)	υ_{12} (MPa)	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
135000	8500	0.3	4800	4800	3200

Eqauivalent Material Properties →

E_x (MPa)	E_y (MPa)	υ_{xy} (MPa)	G_{xy} (MPa)	ρ	λ
52518	52518	0.295776	20265	1.0002	0.999

Simulation Results →





$$\rho = \frac{2S_{12} + S_{66}}{2\sqrt{S_{22}S_{11}}}$$

$$\lambda = \frac{S_{11}}{S_{22}}$$

NUMERICAL VALIDATION

SIF for Orthotropic Plate

Material Properties →

E_1 (MPa)	E_2 (MPa)	υ_{12} (MPa)	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
135000	8500	0.3	4800	4800	3200

Stacking Sequence →

$[0,0,45,90,90,-45,0]_s$

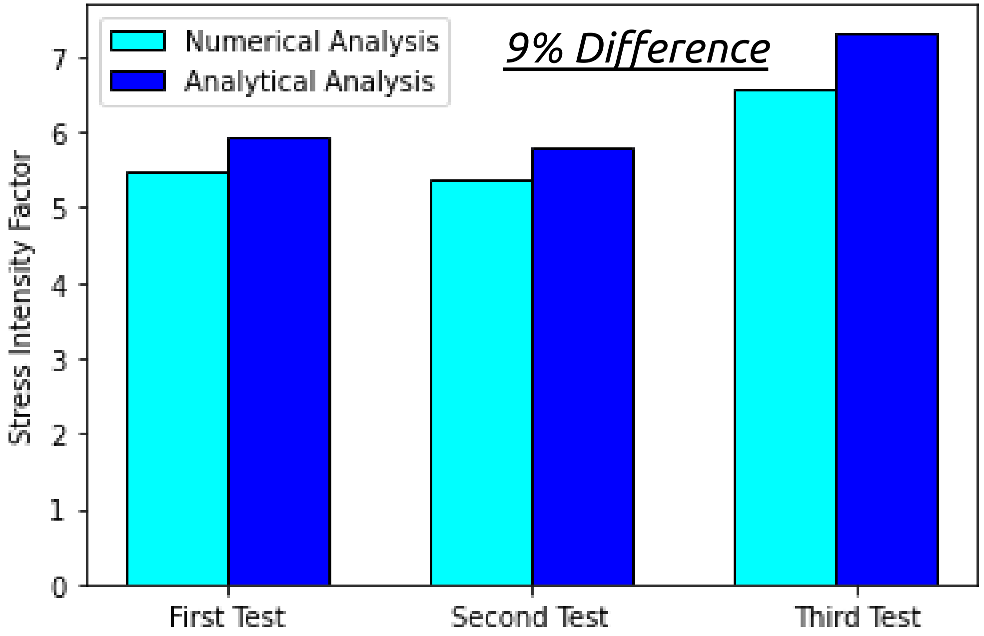
[0,0,0,45,90,-45,0,0,0,-45,90,45,0,0,0]

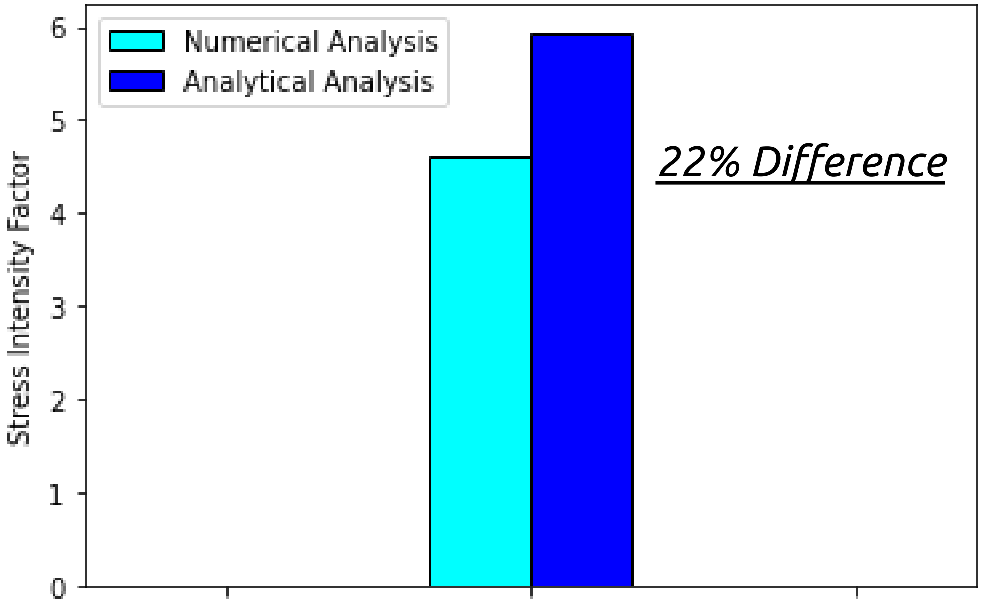
Eqauivulant Material Properties →

E_x (MPa)	E_y (MPa)	υ_{xy} (MPa)	G_{xy} (MPa)	ρ	λ
70400	52794	0.204	13370	0.749	2.108

E_x (MPa)	E_y (MPa)	υ_{xy} (MPa)	G_{xy} (MPa)	ρ	λ
90607	33285	0.3064	12799	0.367	1.959

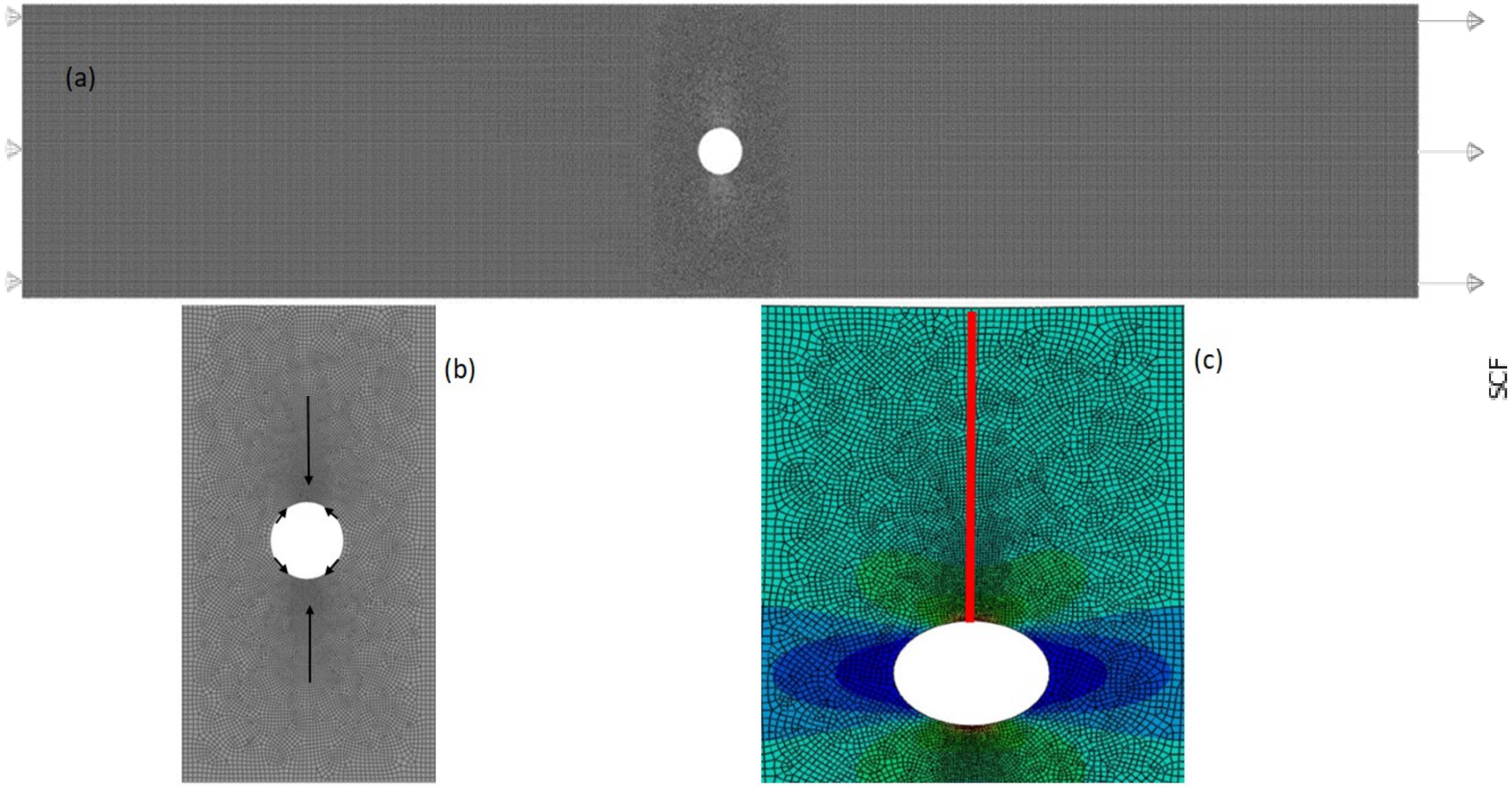
Simulation Results →

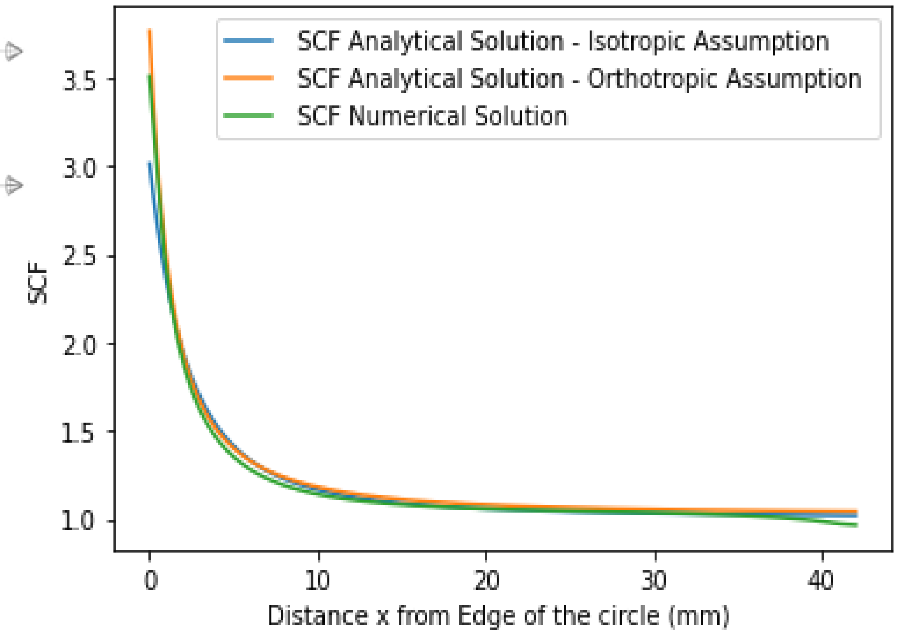




NUMERICAL VALIDATION

SCF for Orthotropic Plate





(a) – Overall Specimen Configuration

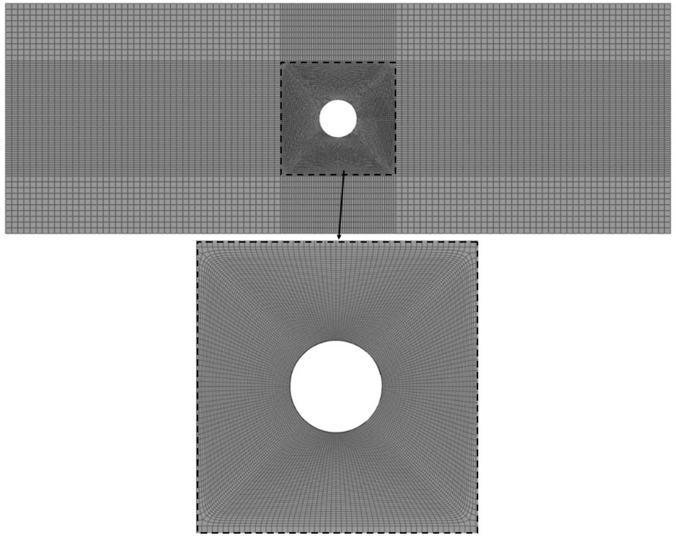
(b) – Mesh Technique Utilized

(c) – Path Used to Perfom Analysis

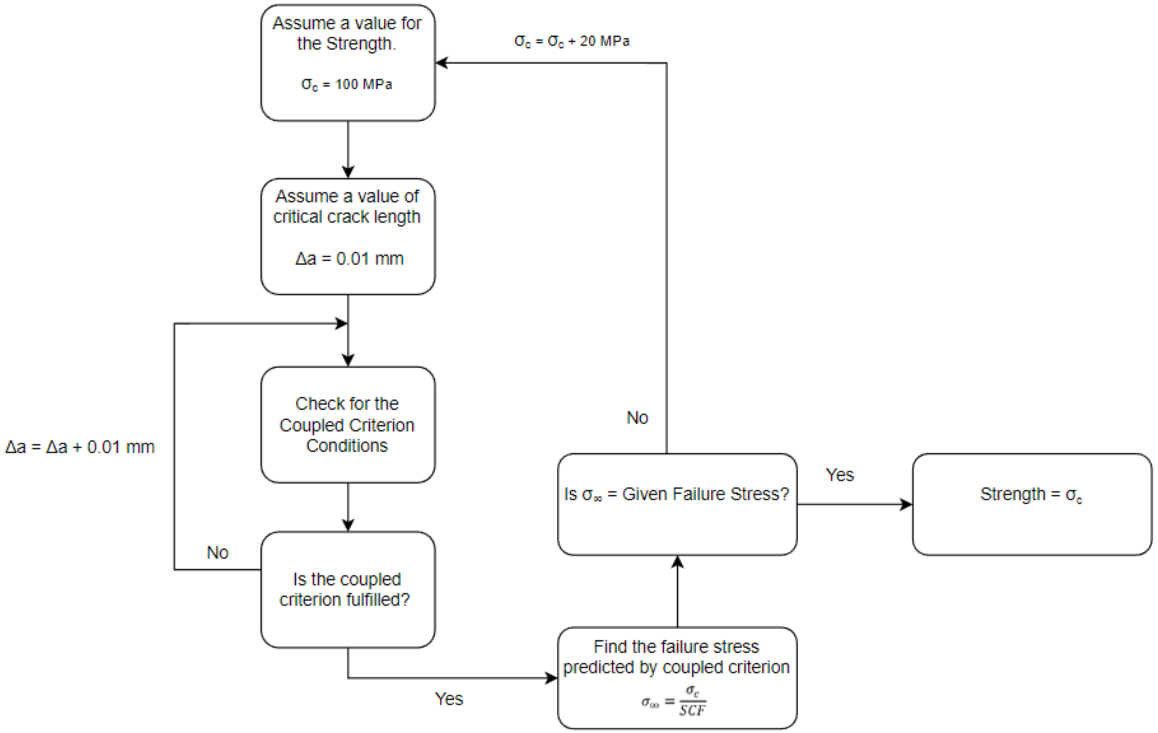
Simulation Results

APPLICATION CASE – FILLED HOLE 3D

OHT condition
(W/o bolt and washer)



For a given K_c is known, the following approach is undertaken:



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