CAPTURING THE OFF-AXIS BEHAVIOR OF THIN-PLY LAMINATES

Anatoli Mitrou

Albertino Arteiro, Pedro P. Camanho, José Reinoso

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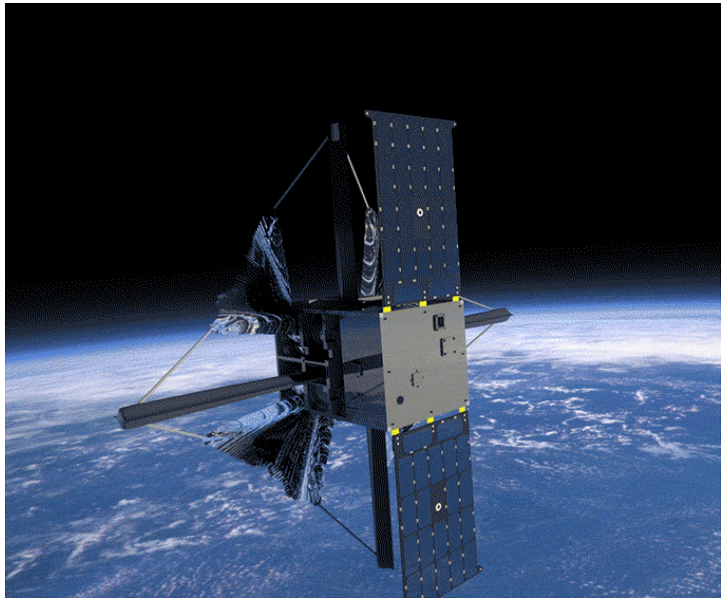
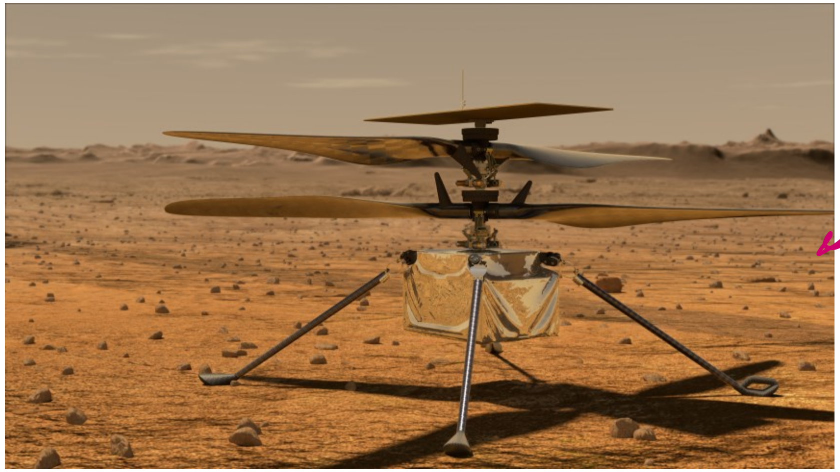
Why thin- ply composites?

- High Versatility
- Tailored design
- Superior strength to weight ratio

The ACS3 spacecraft will showcase the ability to use composite deployable booms





Thin-ply composites made it to and flew on Mars in 2021

What's new...

The difference

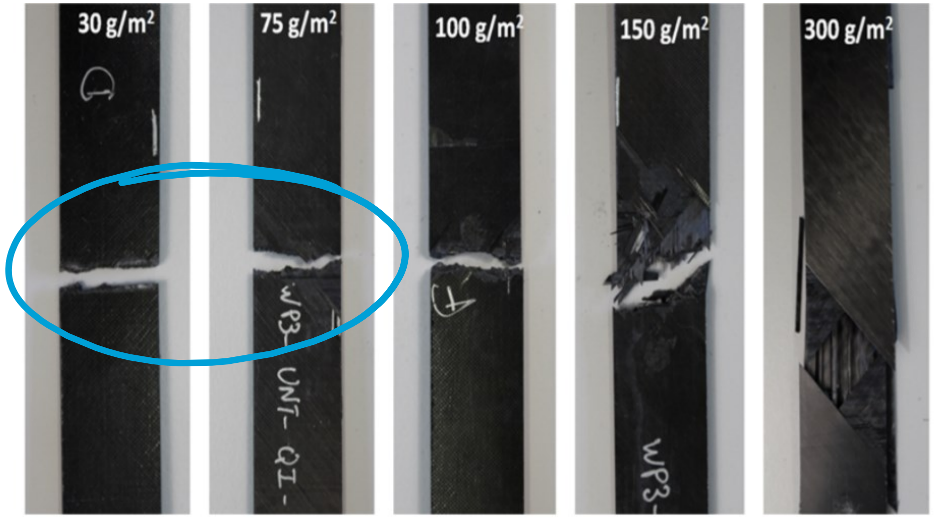
Ply thickness $\geq 100\ \mu m$

Matrix dominated
and
Fiber dominated

Interlaminar
and
Intralaminar

Decreasing ply thickness

Ply thickness $\leq 100\ \mu m$



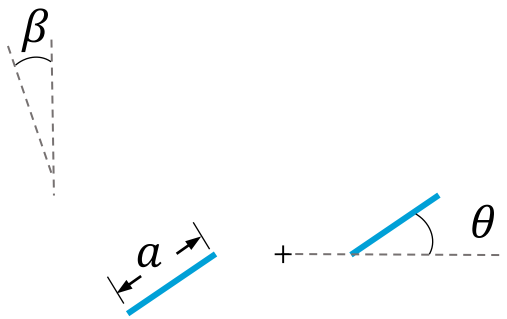
Amacher et al. (2014)

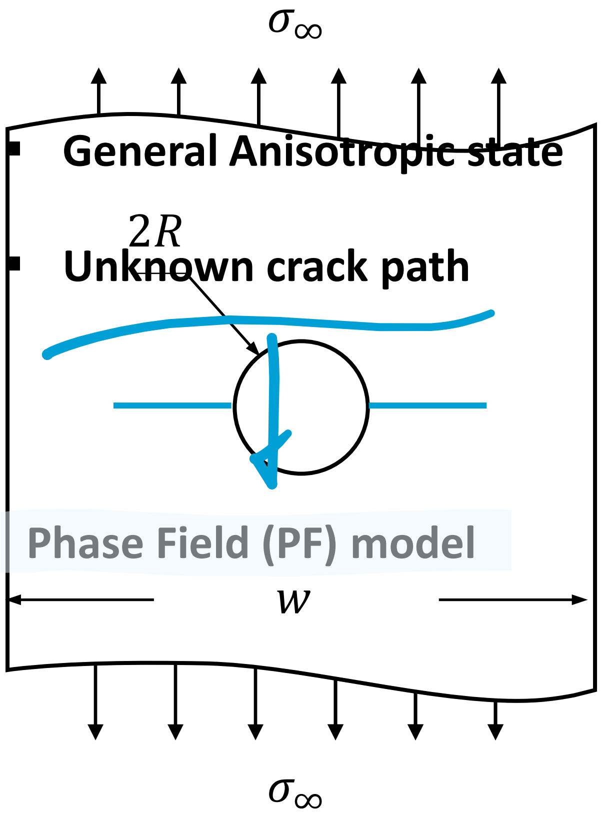
Options

An **Equivalent Single Layer (ESL) approach** seems fit.

The problem

A simple problem: **Open Hole Tension**





- **General Anisotropic state**
- **Unknown crack path**

Phase Field (PF) model

Elastic

Proper representation of the material at the ESL level:

- Macro-mechanical homogenization effects. ([A]=[D], [B]=0)
- CLPT or other continuum approaches can represent the material with a homogenized compliance matrix

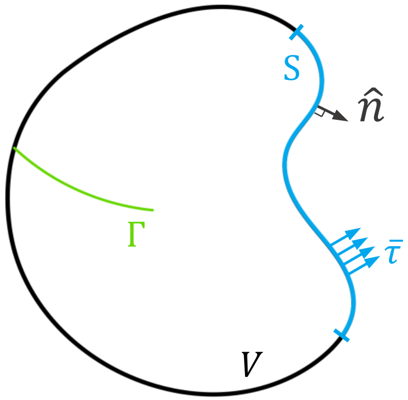
$$\varepsilon = \mathbf{S}\sigma \text{ or } \sigma = \mathbf{C}\varepsilon$$

Fracture

How can directional toughness be defined ?

PF in a nutshell

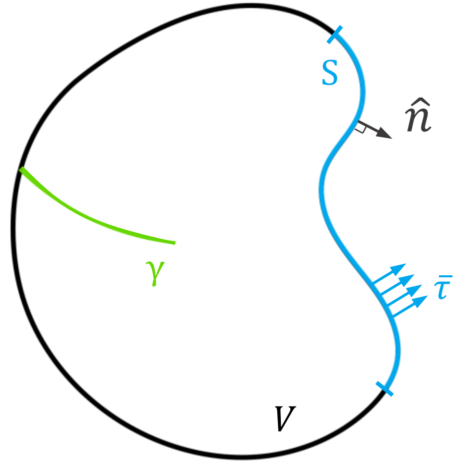
It is a method relies on the **total potential energy minimization** linked to the variational expression of Griffith's energy balance.



$$\Pi(u) = U_e + U_f - W$$

U

$$U_f = \int_\Gamma G_c d\Gamma$$



$$U_e = g(\varphi) \int_V \frac{1}{2} \mathbf{C}\boldsymbol{\varepsilon}^2 dV$$

$$U_f = \int_\Gamma G_c d\Gamma \approx \int_V g_c \gamma(\boldsymbol{\varphi}, \nabla\varphi) dV$$

crack surface density function

The PF variable acts like a damage variable:

- $\boldsymbol{\varphi} = \mathbf{0}$ undamaged state
- $\boldsymbol{\varphi} = \mathbf{1}$ damaged state

Governing equations:

$$\nabla\sigma = 0 \qquad \text{in } V$$

$$\nabla \cdot \left(\frac{\partial U}{\partial \nabla\varphi}\right) - \frac{\partial U}{\partial \varphi} = 0 \quad \text{in } S$$

Evolution equation

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Incorporating Fracture Energy Anisotropy

The crack surface density function:

length scale

$$\gamma(\varphi, \nabla\varphi) = \frac{1}{2l}\left(\varphi^2 - \frac{l}{2}\nabla\varphi \cdot \mathbf{A} \cdot \nabla\varphi\right)$$

structural tensor

$$\mathbf{A} = 1 + a_1 \boldsymbol{a}_1 \otimes \boldsymbol{a}_1 + a_2 \boldsymbol{a}_2 \otimes \boldsymbol{a}_2$$

scaling constants

The new toughness:

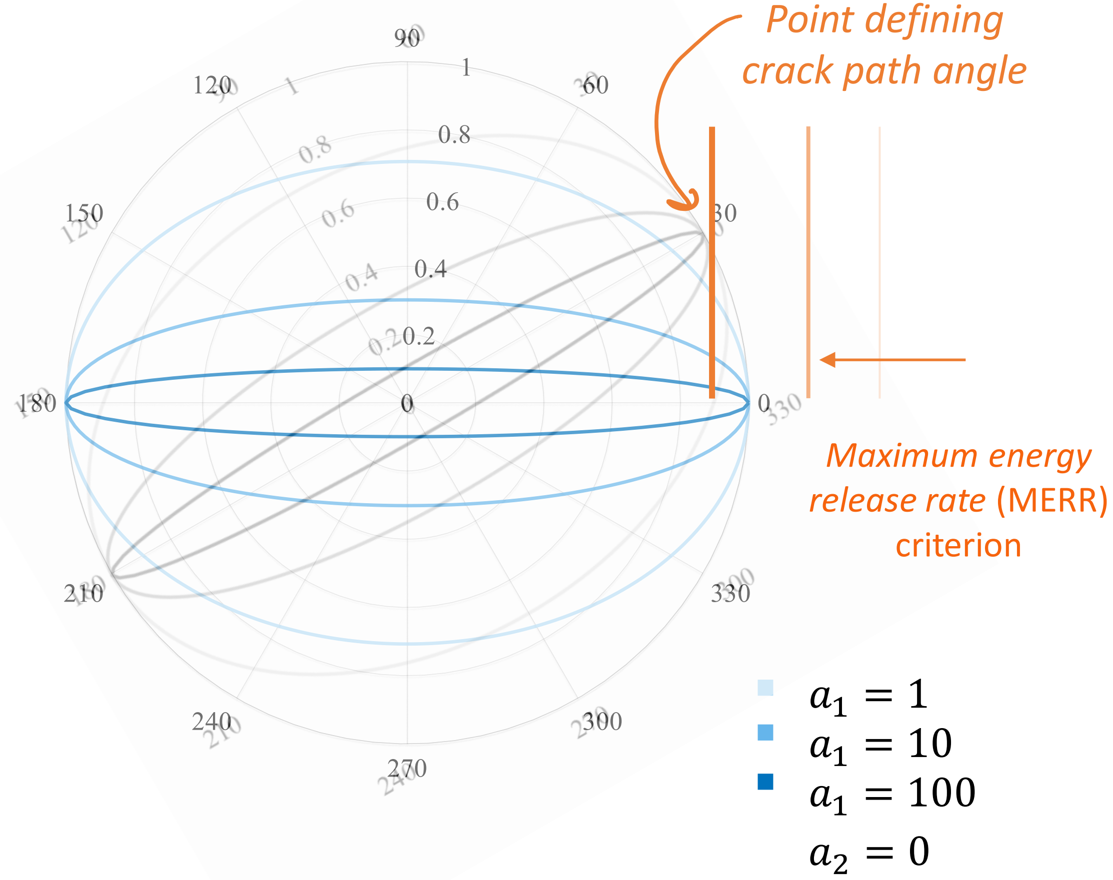
effective length scale

Angle of crack with respect to the preferred $\boldsymbol{a}_1$ direction

$$G_C(\theta) = g_c \sqrt{\frac{l^*}{l}} \qquad l^* = l\left(1 + a_1 \sin^2(\theta) + a_2 \cos^2(\theta)\right)$$

$$G_c(\theta) = g_c \sqrt{1 + a_1 \sin^2(\theta) + a_2 \cos^2(\theta)}$$

Inverse toughness, $G_c(\theta)^{-1}$, plot:



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Teichtmeister et al. (2017)

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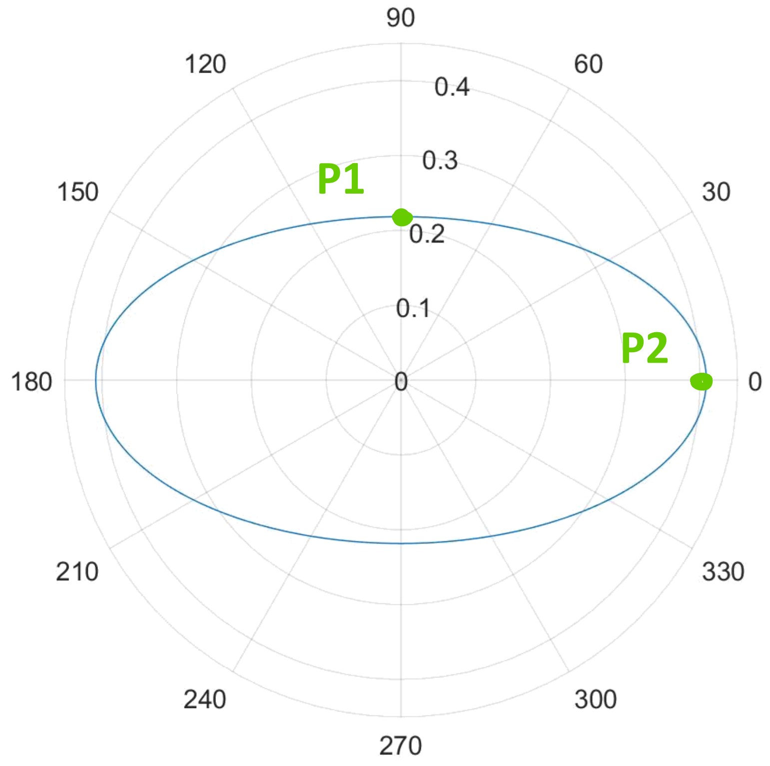
The "proper" scaling constants

If the path is **unknown or a predefined link to a direction exists**, then the toughness distribution will produce the crack angle as an output…

Inverse toughness:



$$G_c(\theta) = g_c\sqrt{1 + a_1 \sin^2(\theta) + a_2 \cos^2(\theta)}$$

Known Points **P1, P2**

$$\boldsymbol{a_1} = \left(\frac{G_c(90°)}{g_c}\right)^2 - 1 \qquad \boldsymbol{a_2} = \left(\frac{G_c(0°)}{g_c}\right)^2 - 1$$

Mitrou et al. (2023)

Application to off-axis tests

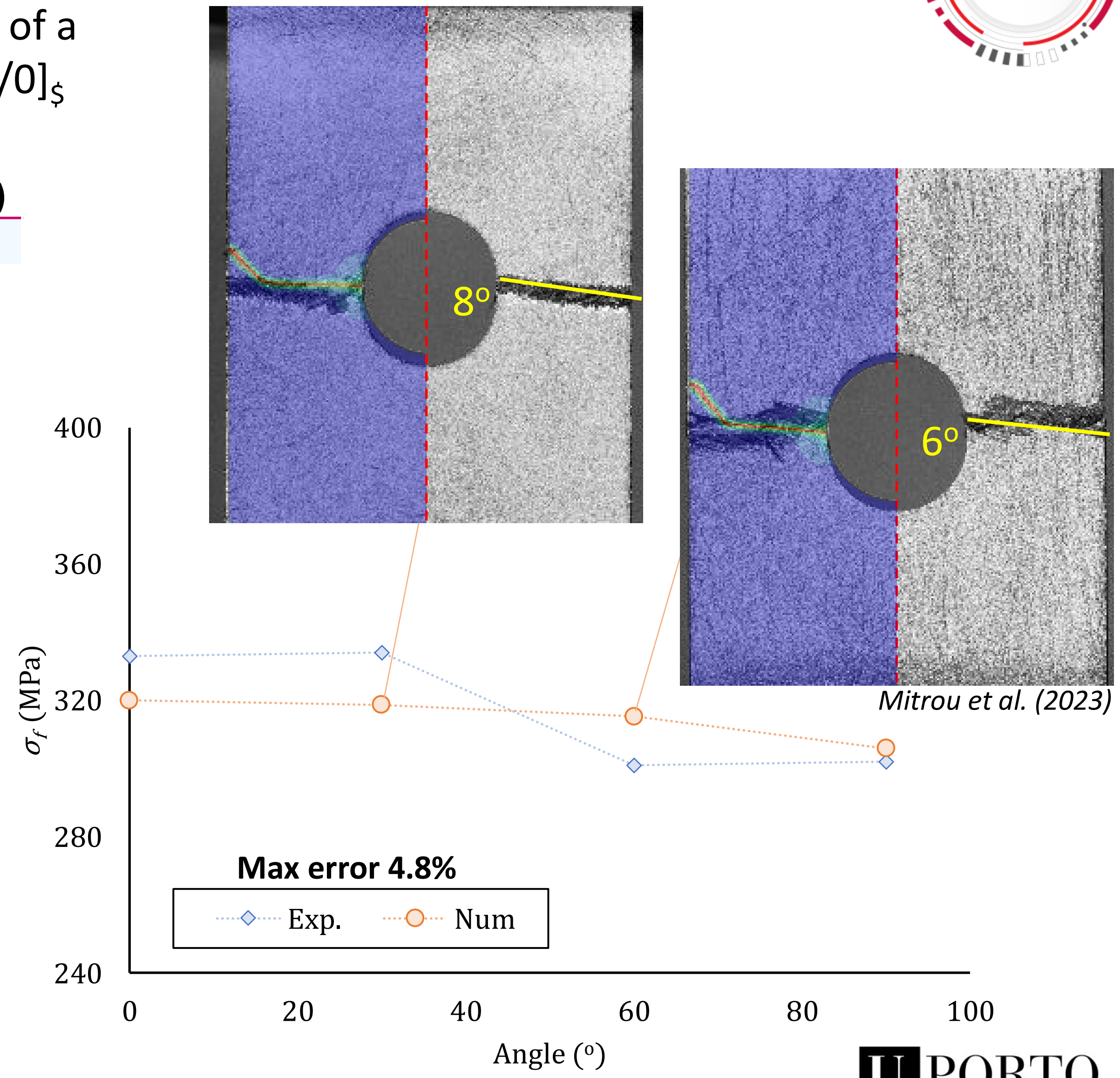
Experimental results from Furtado et al. (2021) for the off-axis OHT of a hard thin-ply laminate of lay-up: $[45/-45/0/45/-45/90/0/45/-45/90/0]_S$

	E_x (GPa)	E_y (GPa)	G_{xy} (GPa)	ν_{xy}	$G_c^{0^o}$ (N/mm)
Lamina	146.6	8.7	4.6	0.34	67
Laminate	54.0	48.3	4.6	0.39	19.7

Scaling constants: $a_1 = -0.9171, \; a_2 = -0.9399$

	Exp. Av.	FEA Prediction	Error (%)
On-axis (0º)	333.00	319.98	4.07
30º	334.00	318.62	4.83
60º	301.00	315.20	-4.51
90º	302.00	305.87	-1.27

Values of strength in MPa



Mitrou et al. (2023)

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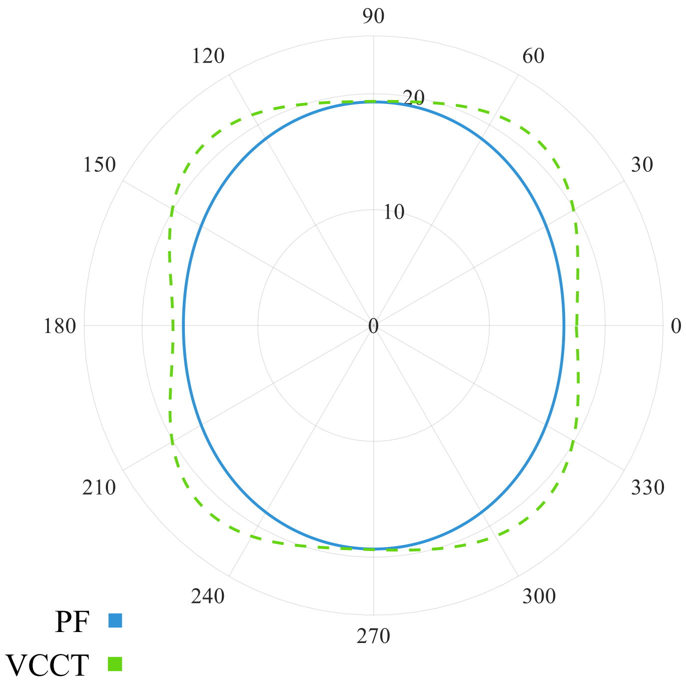
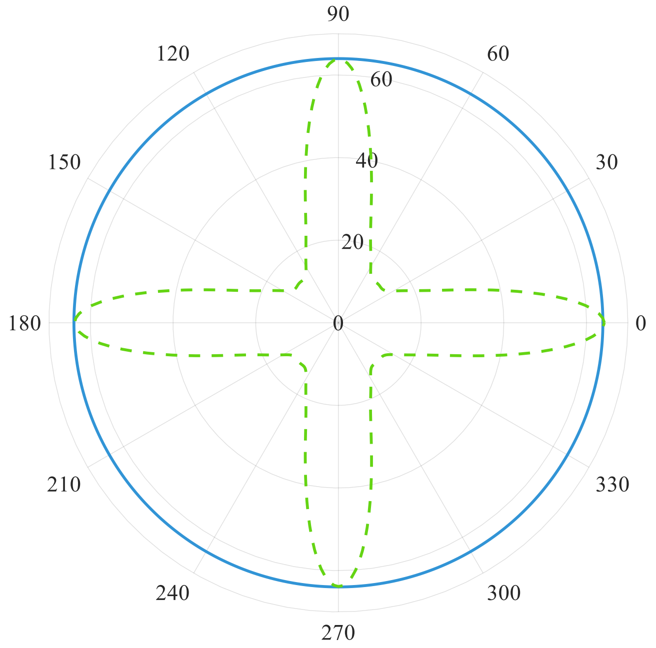
But…

The accurate predictability for the off-axis MD OHT seems be linked to the **weak level** of anisotropy the plate has:



What is to be expected in **strongly anisotropic** plates?

e.g., the cross-ply…



There is a discrepancy in most angles

Assuming the SERR distribution is a valid indicator of a fracture toughness distribution

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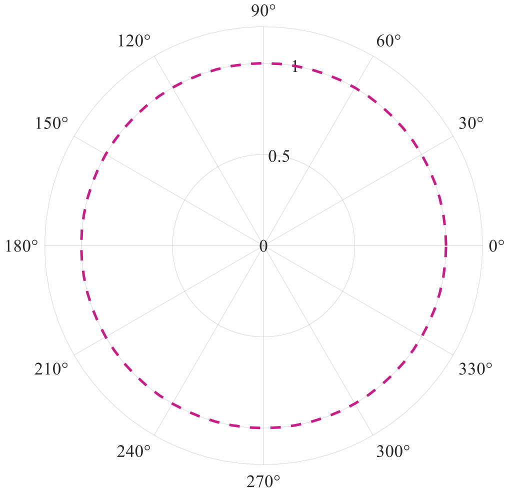
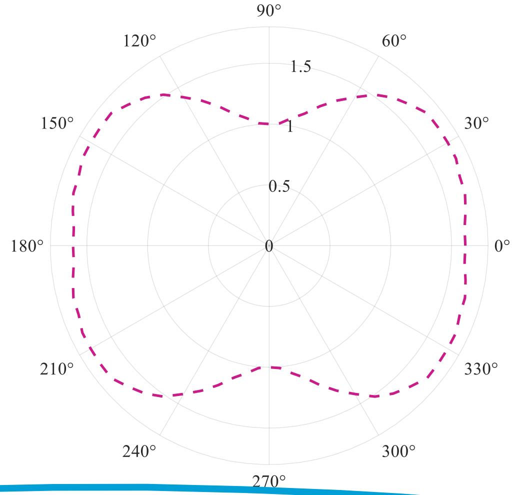
Testing for validation…

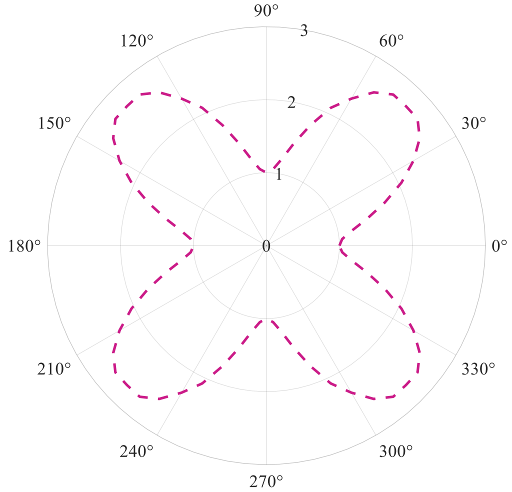
QI - $[90,-45,0,45]_{4s}$



H30 - $[90,0,\pm30,0,90,\pm30]_{2s}$

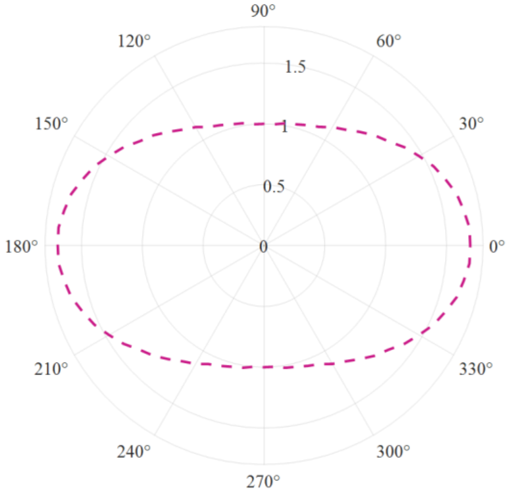


H1575 - $[90,\pm75,0,\pm15,0,90\,]_{2s}$

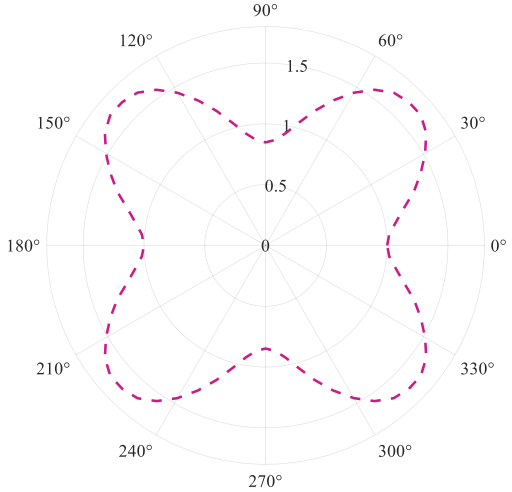


Weakest → *Strongest*

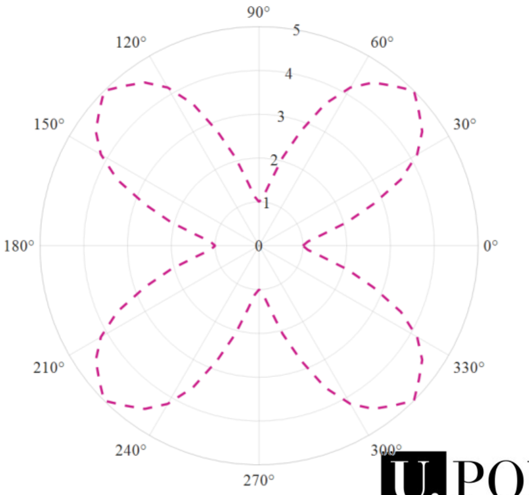
SOFT - $[90,\pm45,90,\pm45,90,0\,]_{2s}$



H6015 - $[90,\pm60,0,\pm15,90,0\,]_{2s}$



CP - $[90,0]_{8s}$



■ $1/G_c(\theta)$

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The soft one

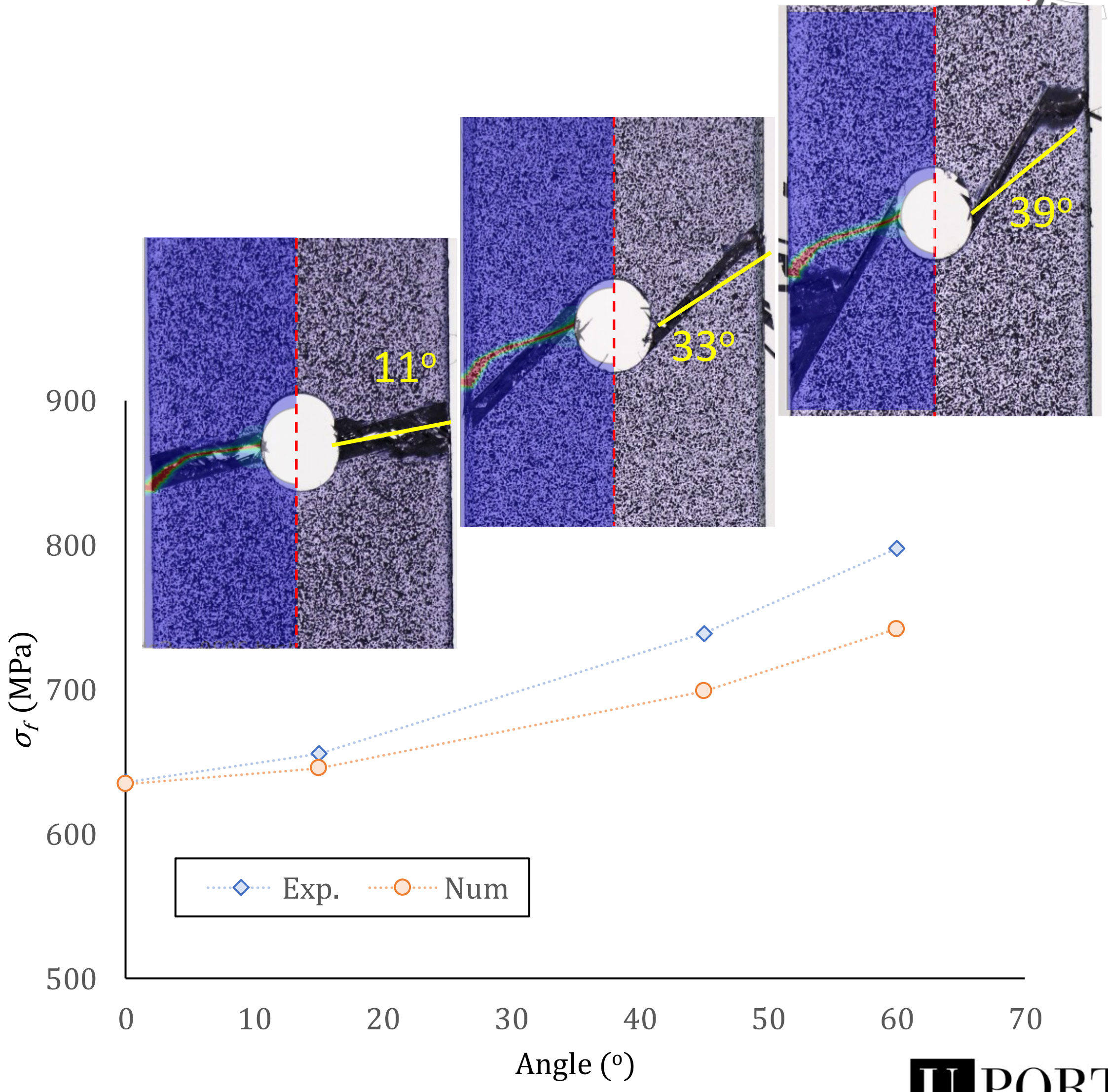
Experimental results for the off-axis OHT of a "soft" thin-ply laminate of lay-up: $[90/\pm45/90/\pm45/90/0]_{2s}$ for T800-736LT from NTPT

	E_x (GPa)	E_y (GPa)	G_{xy} (GPa)	ν_{xy}	$G_c^{0^o}$ (N/mm)
Lamina	143.8	7.85	4.6	0.38	171

Scaling constants: $a_1 = -0.9657,\ a_2 = -0.8382$

	Exp. Av.	FEA Prediction	Error (%)
On-axis (0º)	635.89	634.51	-0.22
15º	655.56	645.45	-1.54
45º	738.75	698.745	-5.42
60º	797.51	741.7	-7.00

Values of strength in MPa



The H30

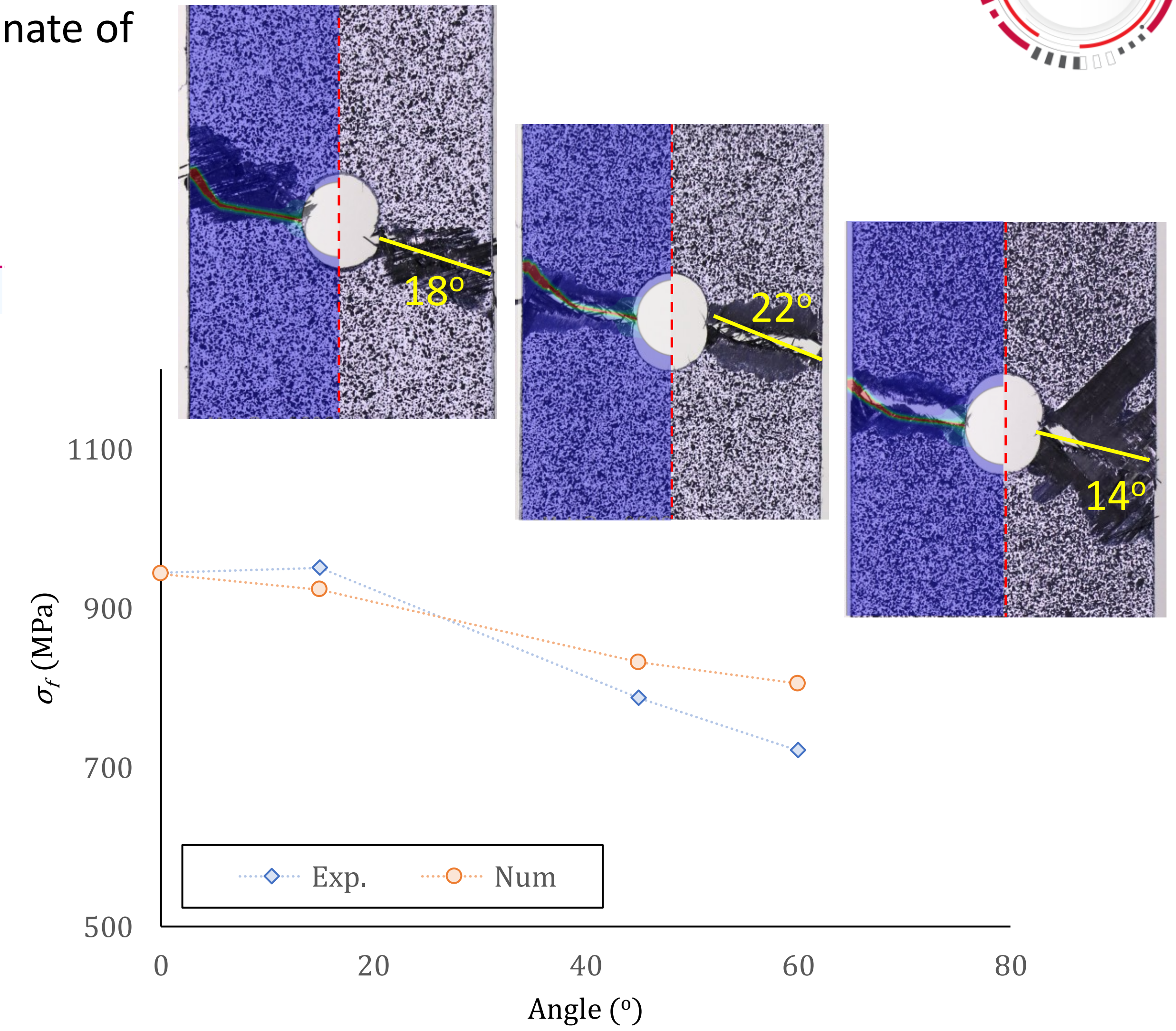
Experimental results for the off-axis OHT of a "hard" thin-ply laminate of lay-up: $[90/\pm30/0/90/\pm30]_{2s}$ for T800-736LT from NTPT

	E_x (GPa)	E_y (GPa)	G_{xy} (GPa)	v_{xy}	$G_c^{0^o}$ (N/mm)
Lamina	143.8	7.85	4.6	0.38	171

Scaling constants: $a_1 = -0.8332,\ a_2 = -0.9330$

	Exp. Av.	FEA Prediction	Error (%)
On-axis (0º)	944.52	943.065	-0.15
15º	950.82	923.38	-2.89
45º	787.13	831.995	5.70
60º	721.61	805.18	11.58

Values of strength in MPa



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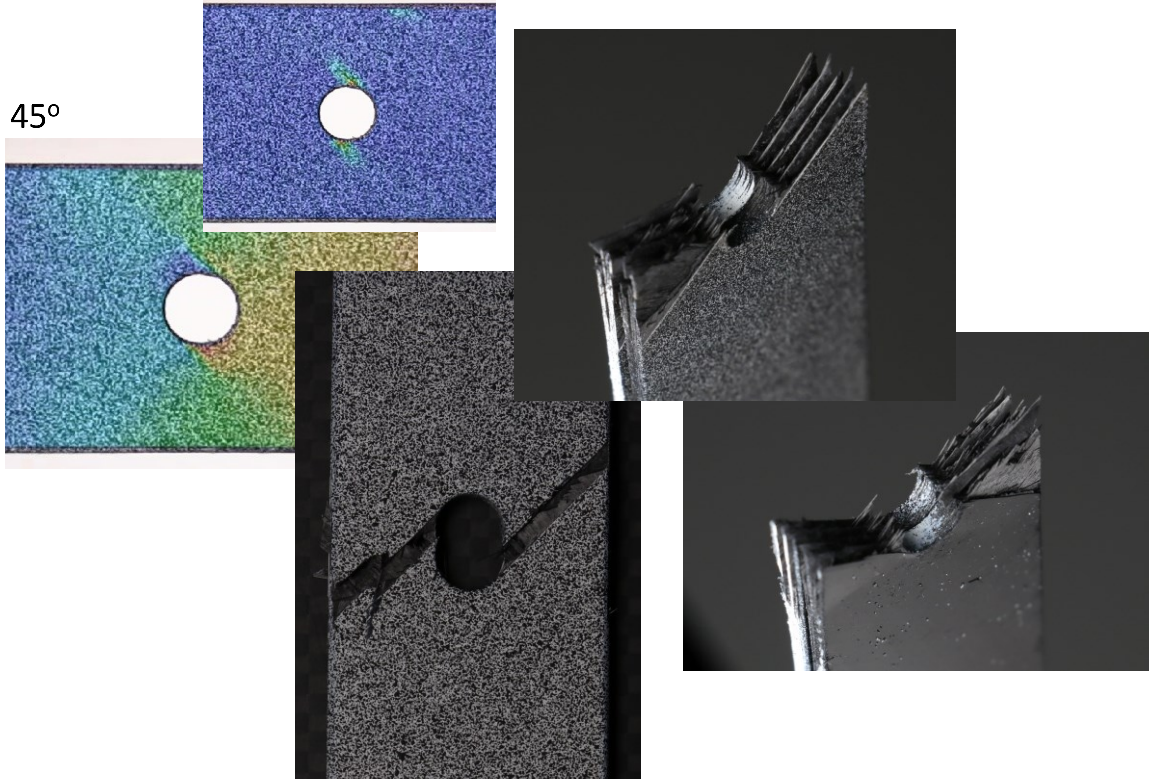
The rest…

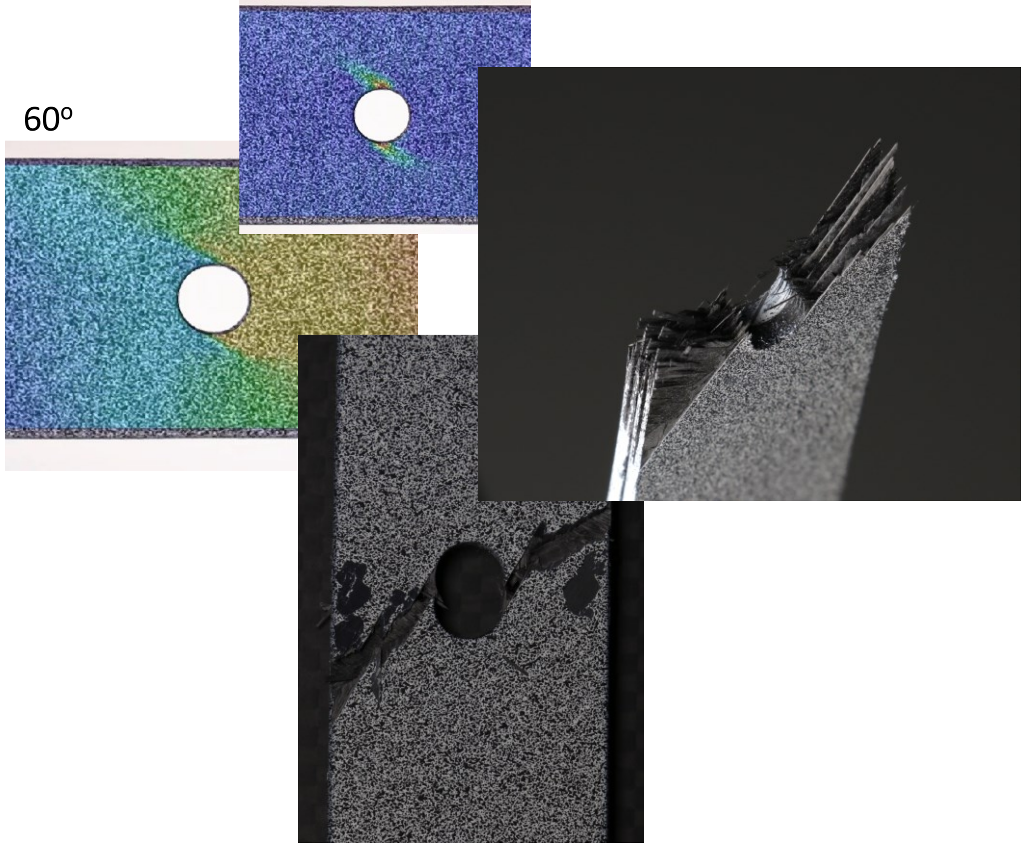
In fact, things get a bit more complicated…

H6015

45º

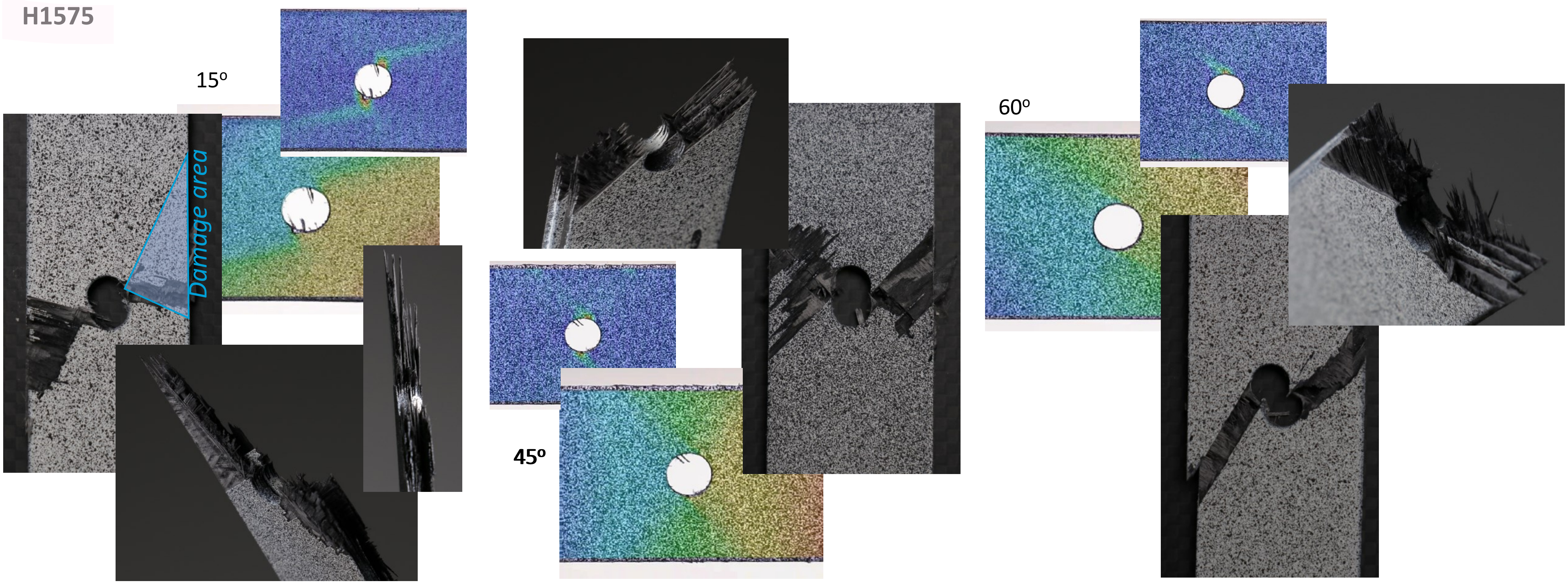


60º



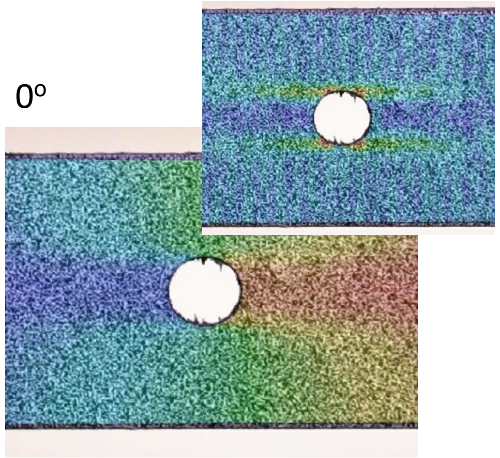
The rest…

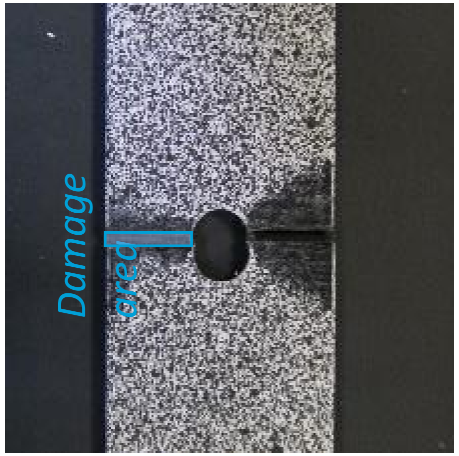
In fact, things get a bit more complicated…



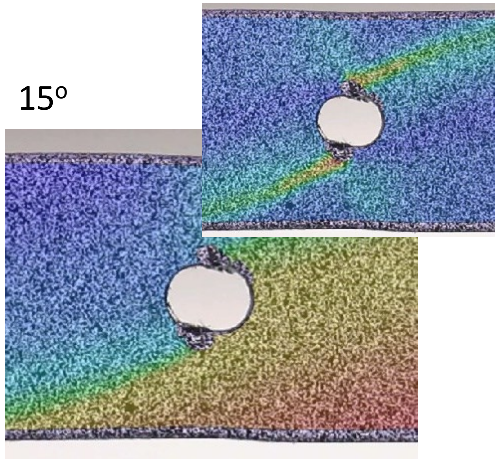
The CP

0°

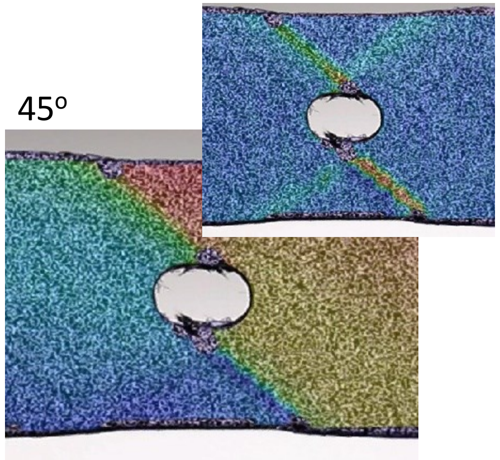


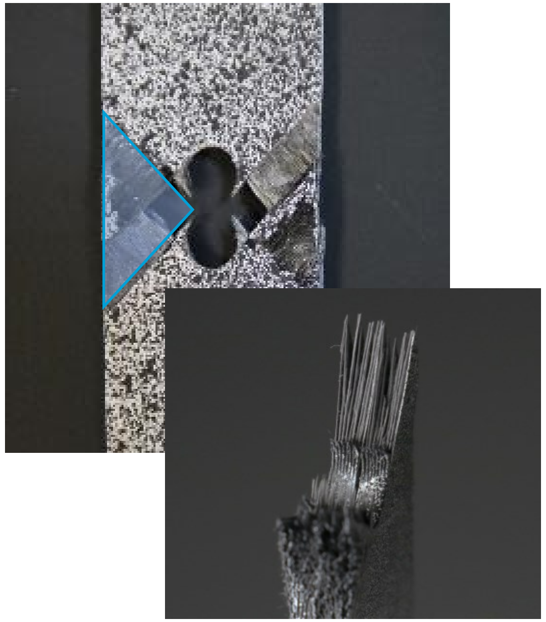


15°

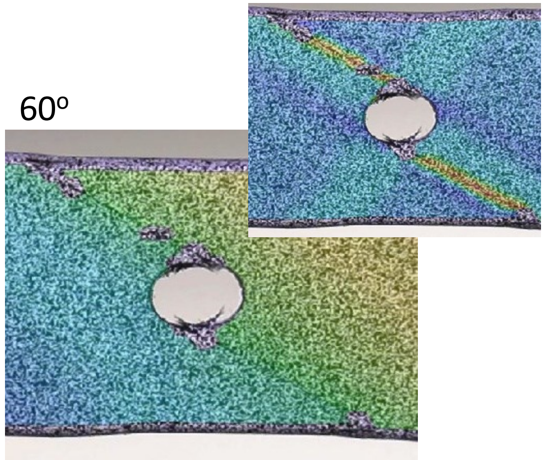


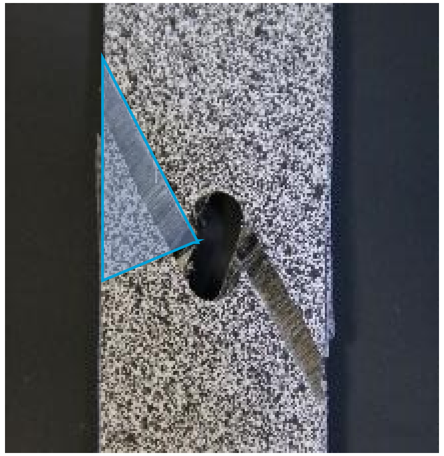
45°





60°





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Conclusions & Now What(s)?

Conclusions

- A PF ESL approach can be used to successfully predict **off-axis** notched strengths of MD thin-ply laminates residing in the weakly anisotropic range.
- There is a clear dependence of the overall behavior of MD thin-ply laminates to the level of anisotropy they exhibit

as for what follows…

- Continue exploring and developing methods and tools….

For listening up to here…

Thank you !

Contact: anatomitrou@fe.up.pt

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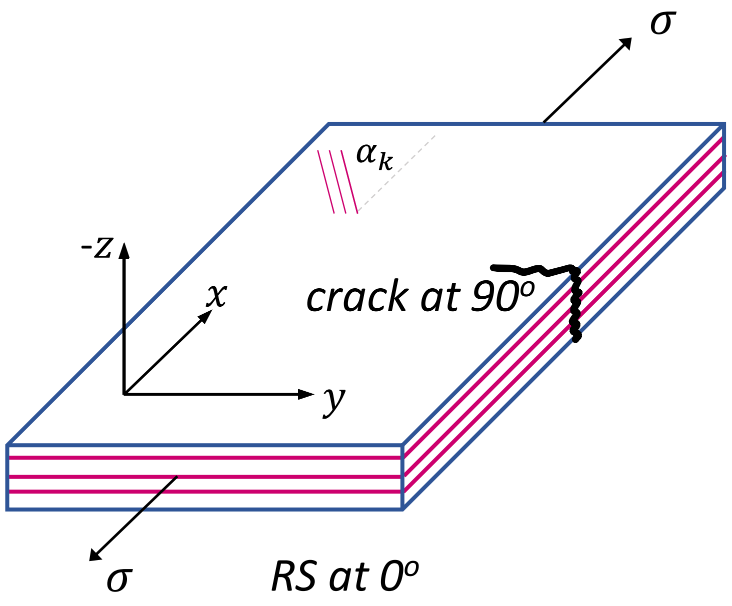
Directional Toughness

The toughness of a MD laminate can be determined by using as an input Camanho and Catalanotti (2011):

- **Lay-up** of the laminate
- **Toughness of the 0º** ply

$$G_c^L = \sum_{k=1}^{n} G_c^k v_k = \cdots = G_c^0 E_{eq}^0 \sum_{k=1}^{n} \left(\Omega_k \frac{\chi_k}{\chi_0}\right)^2 \frac{v_k}{E_{eq}^k}$$

number of balanced sub-laminates

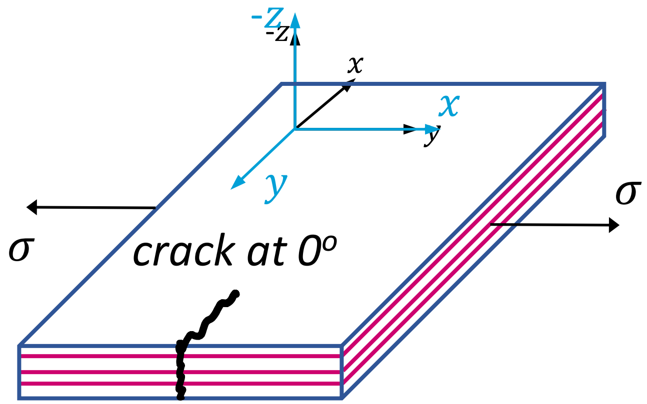


RS at 0º

Scaling constants:

$$a_1 = \left(E_{eq}^0 \sum_{0^\circ} \left(\Omega_k \frac{\chi_k}{\chi_0}\right)^2 \frac{v_k}{E_{eq}^k}\right)^2 - 1$$

$$a_2 = \left(E_{eq}^0 \sum_{90^\circ} \left(\Omega_k \frac{\chi_k}{\chi_0}\right)^2 \frac{v_k}{E_{eq}^k}\right)^2 - 1$$



RS at 90º

Essentially the Lay-up definition is changes to reflect a 90º rotation of the plies

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VCCT technique for ERR distribution

Run the model until a certain u is reached and record the ERR11 and ERR12 components.

Loop for all possible angles θ of the material system

Given a known $G_c(0^o)$ it scales the respective ERR11 value to obtain the $G_c(\theta)$ distribution