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Compressive crack resistance analysis of unidirectional thermoplastic composites

F. Danzi, P. Silva Campos, A. Arteiro, D. Dalli, C. Furtado, J. Chevalier, R. Tavares, F. Laní, P.P. Camanho.

U.PORTO

SOLVAY

Motivations

Thermoplastic composites:

- Green-revolution in aircraft structures
- Fracture characterization of thermoplastic composites for the aerospace sector

- Limited industrial experience
- High sensitivity to process parameters

Fracture testing improvement:

- Towards the compressive intralaminar fracture testing standardization and uncertainty reduction using the Combined Loading Compression (CLC) rig

Materials and methods

Material:

- APC AS4/PEKK UD thermoplastic
- Hot-press consolidation
- Degree of crystallinity > 30%
- Lay-up $[90/0]_{8S}$
- Laminate thickness = 4.4mm

AS4/PEKK Lamina elastic properties.

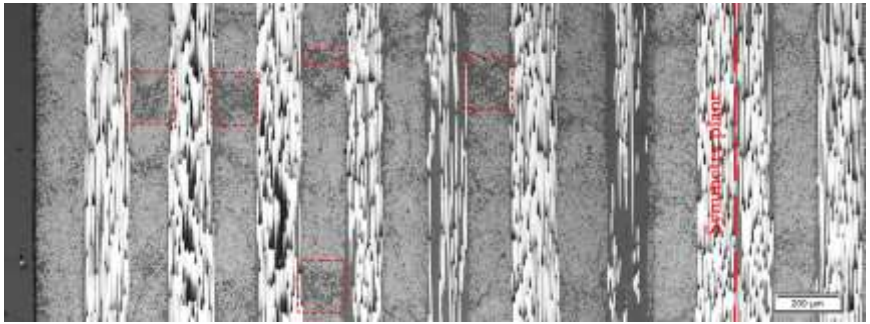
Lamina	E_1 [GPa]	E_2 [GPa]	G_{12} [GPa]	ν_{12} [-]
AS4/PEKK	132.0	9.20	5.08	0.28

Laminate elastic properties.

Layup	E_x [GPa]	E_y [GPa]	G_{xy} [GPa]	$\nu_{xy} = \nu_{yx}$ [-]
$[90/0]_{ns}$	70.9	70.9	5.08	0.037

Methods:

- Size effect methodology (scaled specimen geometries) [1]
- Double-Edge notched coupon
- Edge-Loading (DENC)
- Combined Loading Compression (DENCLC)

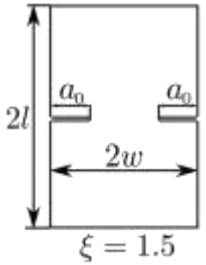


[1]: Bazant Z and Planas J. Fracture and size effect in concrete and other quasi-brittle materials. New directions in civil engineering. Taylor & Francis, 1997.

The DENC set-up

Edge-loaded DENC test:

- 6 tested characteristic size (x5 coupons): (widths from 10 to 35 mm)
- Constant shape parameter: $\xi = \frac{l}{w} = 1.5$
- Constant notch length to specimen characteristic size ratio: $\alpha_0 = \frac{a_0}{w} = 0.6$
- Loading rate: 0.5 mm/min
- Self-aligning spherical hinge base



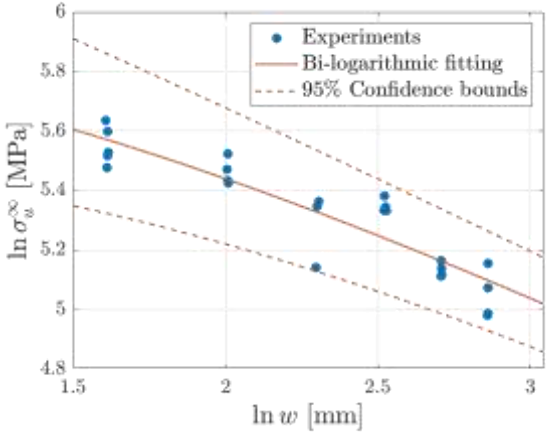
	$2l$ [mm]	$2w$ [mm]	a_0 [mm]	ξ [-]
DENC				
A	15	10	3.0	1.5
B	22.5	15	4.5	1.5
C	30	20	6.0	1.5
D	37.5	25	7.5	1.5
E	45	30	9.0	1.5
F	52.5	35	10.5	1.5

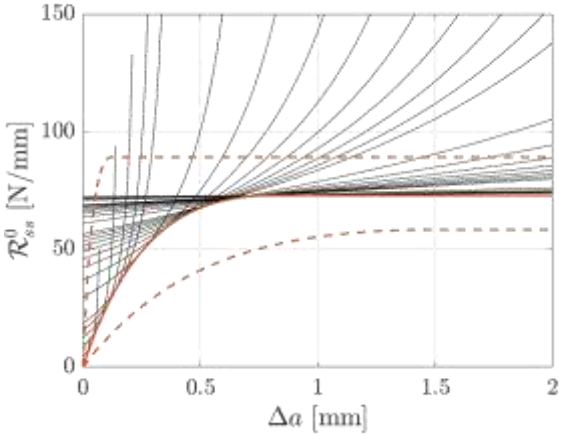
Results and limitations of DENC setup

DENC results:

- Large scatter in notched strength
- Pure compressive loading difficult to achieve:
  - High sensitivity to loading edges parallelism
  - High sensitivity to specimen centering
- Wide uncertainty bounds in intralaminar compressive fracture toughness

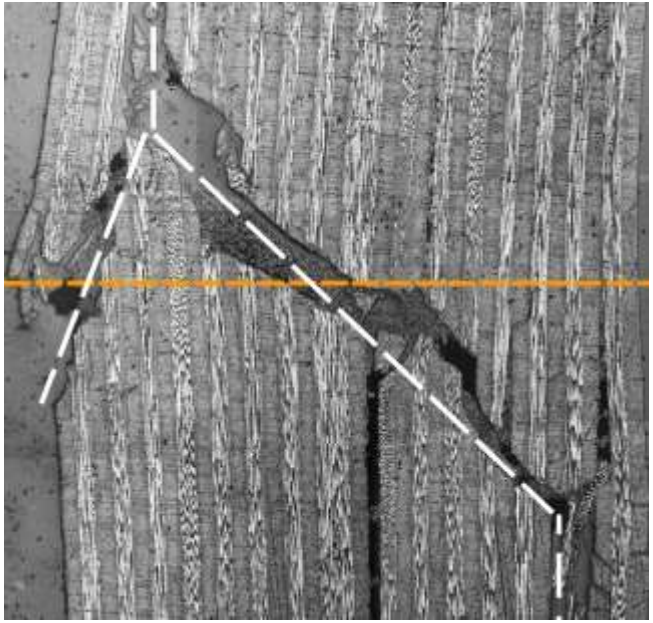
$$R_{SS}^{0} = 73.36 \frac{N}{mm} \ (\pm 22\%)$$



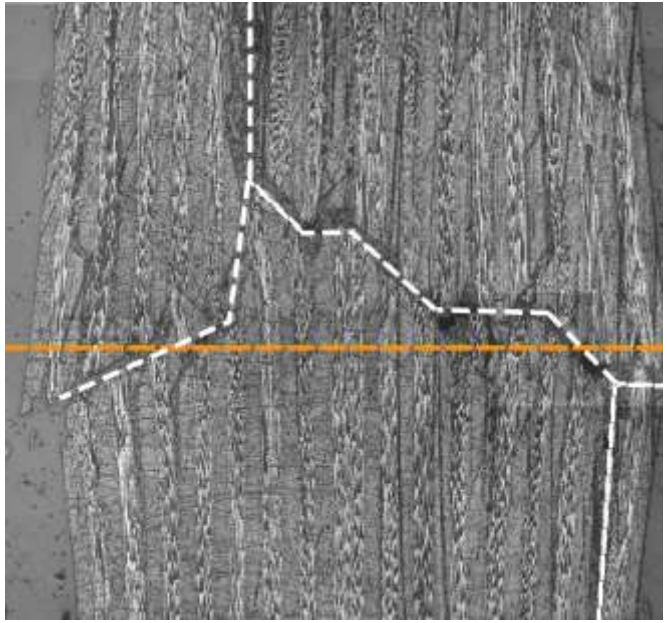


Typical DENC failure modes

Single inclination fracture plane:



Wedge failure cross-section:



DENCLC motivation

DENCLC test:

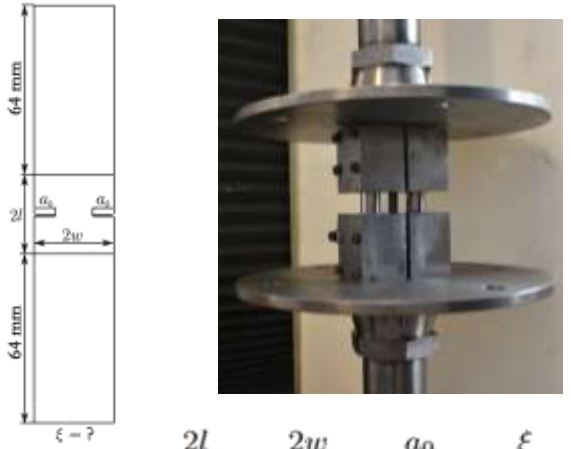
- 5 tested characteristic size (x3 coupons):
  (widths from 10 to 35 mm, 30 mm excluded)
- Constant notch length to specimen characteristic size ratio: $\alpha_0 = 0.6$
- Loading rate: 0.5 mm/min

Advantages:

- Easy to ensure specimen verticality and centering with respect to the loading platens

Drawbacks:

- Unknown constraint effect on in-plane deformation
- Shape parameter ξ determination more complex



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B	143	15	4.5	9.5
C	148	20	6.0	7.4
D	153	25	7.5	6.1
E	-	-	-	-
F	163	35	10.5	4.6

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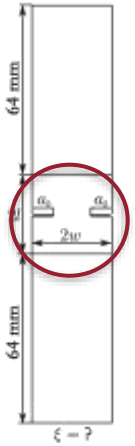

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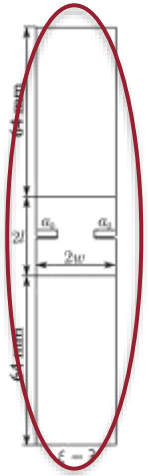

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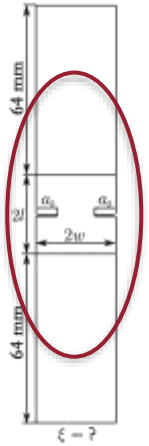

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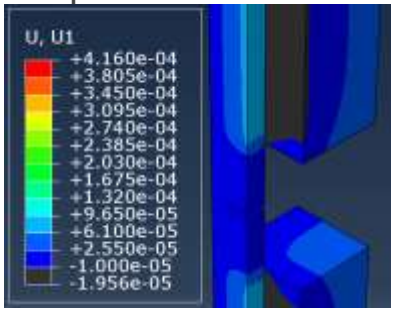
Specimen characteristic length and its constraint-dependency

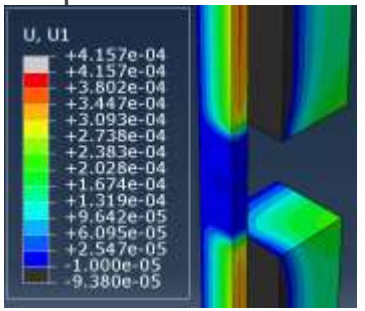
Effect of bolt torque :

- High torque on the 8 bolts (2.5 Nm as per ASTM D6641) would constrain the clamped faces against in-plane deformation, and possibly introduce stress close to the ligament region
- A lower torque of 0.5 Nm, applied using a calibrated torque screwdriver, minimises the clamping effect

Torque 0.5Nm



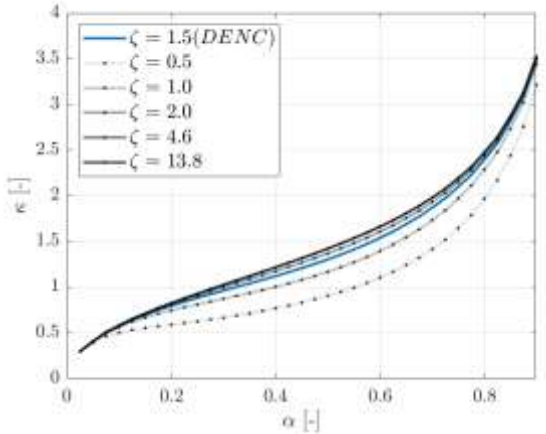
Torque 2.5Nm



Effect of ξ on the correction factor κ :

- Higher ξ values would correspond to lower notched strength values, since the fracture toughness is an independent ply/laminate parameter

$$\mathcal{K}_I^0 = \sigma_u^\infty \sqrt{w}\kappa(\alpha, \rho, \xi)$$



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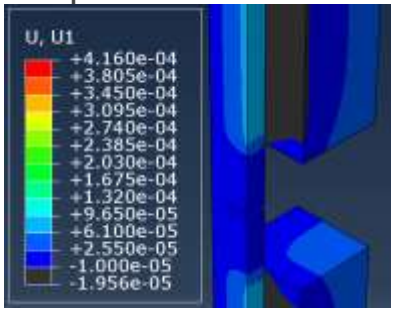

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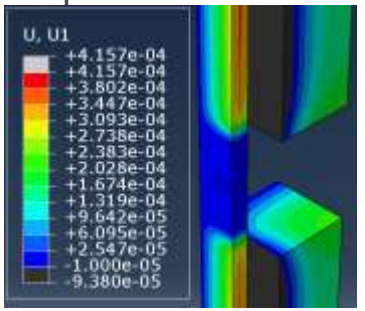

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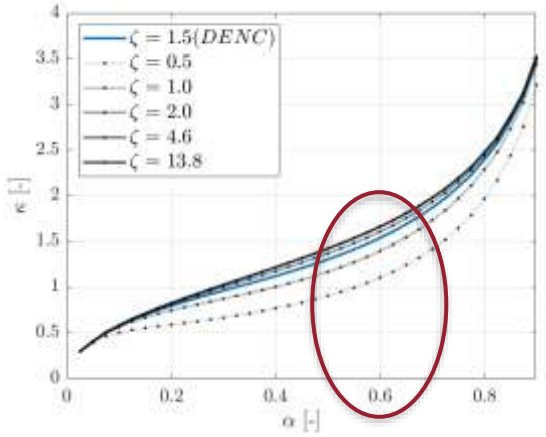


Investigating the constraint effect on the notched strength of DENCLC coupons

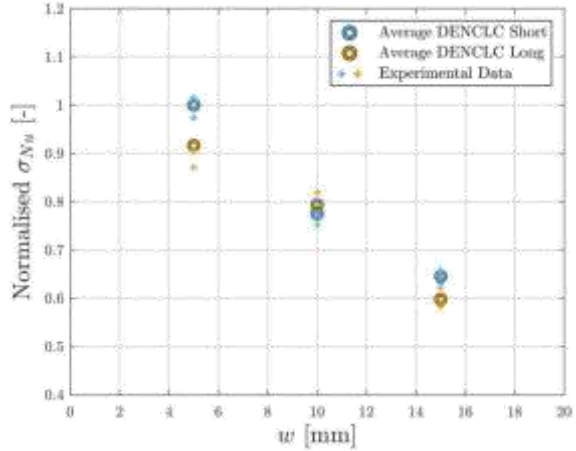
Validation study parameters:

- Two different material systems:
  - Unidirectional thermoplastic
  - Woven thermoset
- Different shape parameters in the free gauge section:
  - $\xi = 0.5$ (Short)
  - $\xi = 2 - 1.5 - 1$ for w $= 5 - 10 - 15$ mm (Long)
- Constant bolt torque 0.5 of Nm

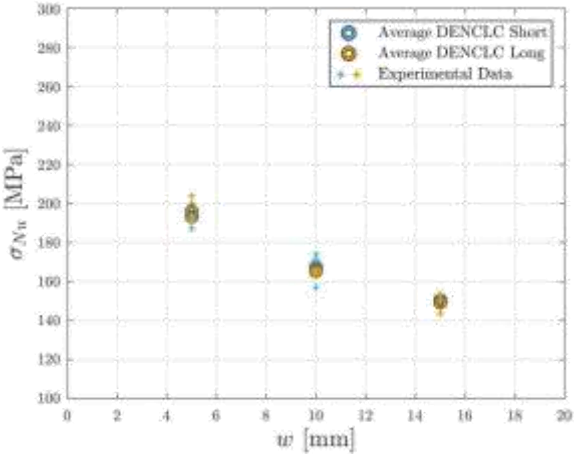
Analysis of notched remote strength: :

- Similar remote strength implies a constraint-insensitivity (Full specimen length L can be used in ξ estimation)

UD Thermoplastic



2D Woven Thermoset



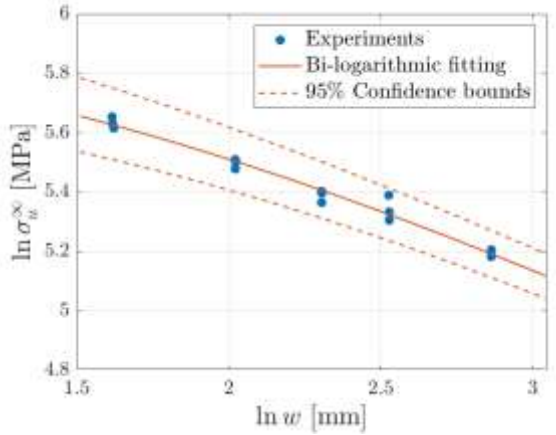
Results and achievements of DENCLC setup

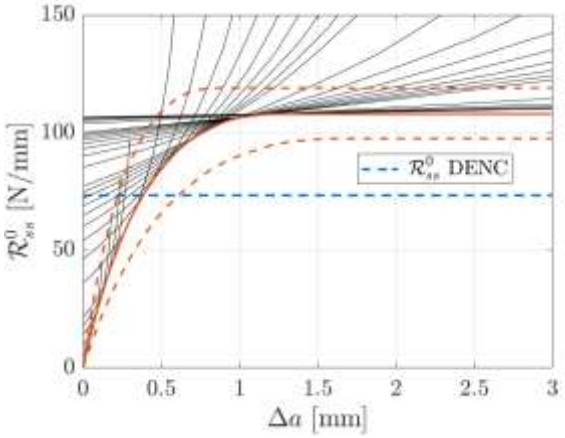
DENCLC results:

- Reduced scatter in notched strength
- Higher measured value of intralaminar fracture toughness:

$$R_{SS}^{0} = 106.9 \frac{N}{mm} (\pm 8.5\%)$$

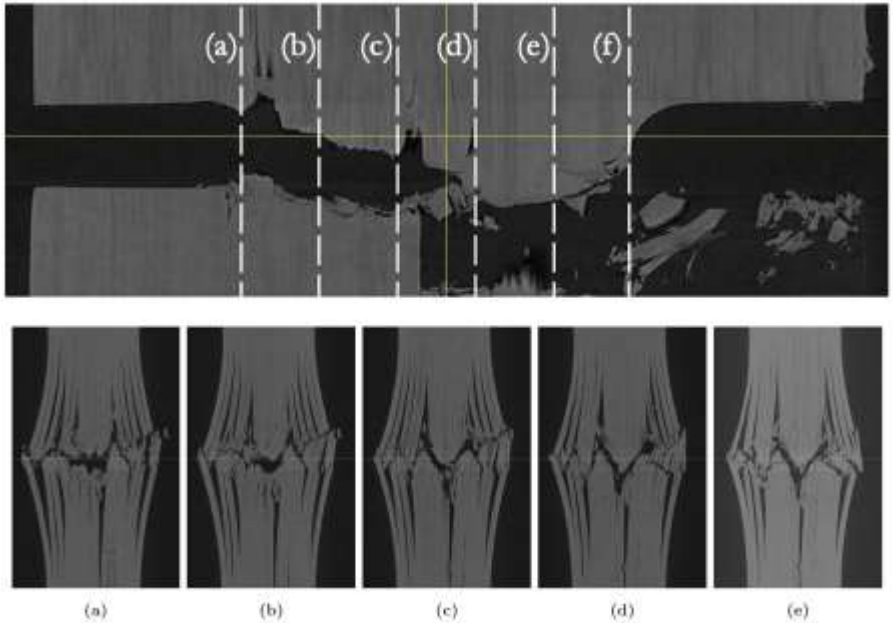
- Under-estimation of fracture toughness using DENC
- Confidence bounds in intralaminar fracture toughness reduced



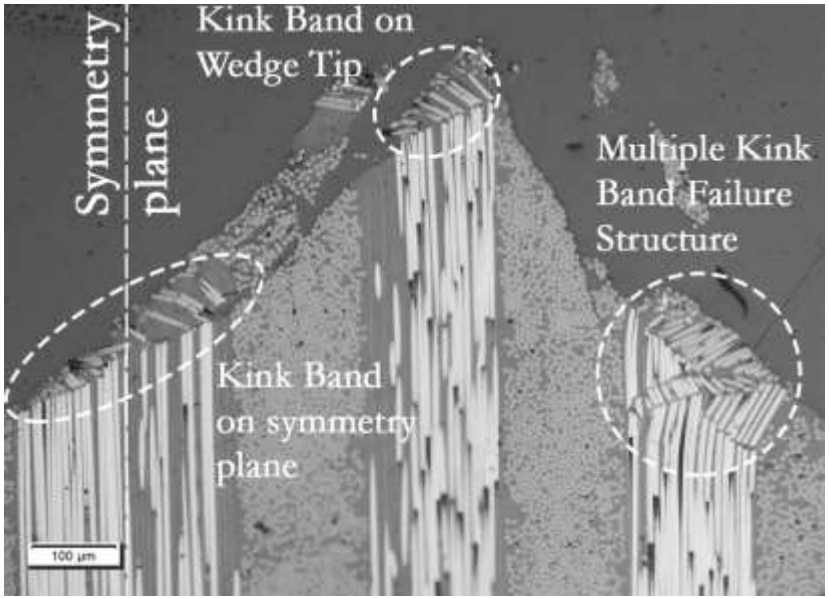


Typical failure modes

Wedge failure cross-sections:



Kink-band at the wedge tip:



Conclusions

- The intralaminar fracture toughness of a unidirectional thermoplastic has been measured
- The inadequacy of the traditional Double-edge notched compressive set-up has been highlighted
- The use of the CLC fixture has been extended to the study of the fracture properties of unidirectional composites
- The results from the DENCLC showed higher intralaminar fracture toughness with a narrower confidence interval

For further details

- Danzi F., Silva Campos P., Arteiro A., Dalli D., Furtado C., Chevalier J., Tavares R.P., Lani F., Camanho P.P., **Longitudinal failure mechanisms and crack resistance curves of unidirectional thermoplastic composites**, Engineering Fracture Mechanics, Volume 282, 2023.

- Dalli D., Danzi F., Silva Campos P., Arteiro A., Camanho P.P., **On the use of the combined loading compression fixture to calculate the intralaminar compressive fracture toughness of composites**, Engineering Fracture Mechanics, 2023 (Under review)

Acknowledgements

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SOLVAY

NXCT National X-Ray Computed Tomography

U.PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Questions?

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Bonus slide

“Some models for composite materials consider the R-curve to start from a certain initial non-zero value, interpreted as a certain small-scale value of the fracture energy. However, this kind of R-curve implies that the crack tip would be able to sustain, up to some value of the stress intensity factor, a singular stress field without showing any damage, which does not seem reasonable.” [1]

[1]: Bazant Z and Planas J. Fracture and size effect in concrete and other quasi-brittle materials. New directions in civil engineering. Taylor & Francis, 1997.