Interlaminar fracture tests: why we love UD specimens, why we hate multidirectional ones, and can this change?

Torquato Garulli

Part of the workshop: *Mode I interlaminar fracture toughness and the factors affecting it*. 14th May 2024 • Online

Universitat de Girona
U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO
AMADE ANALYSIS AND ADVANCED MATERIALS FOR STRUCTURAL DESIGN
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Why even ask?

Structural applications → **MD** laminates

But

Interlaminar fracture standards → **UD** specimens

Why?

Is this conservative? → Not obvious

Is toughness the same? → Not obvious

Is it that we like UD specimens more?
If so, why?

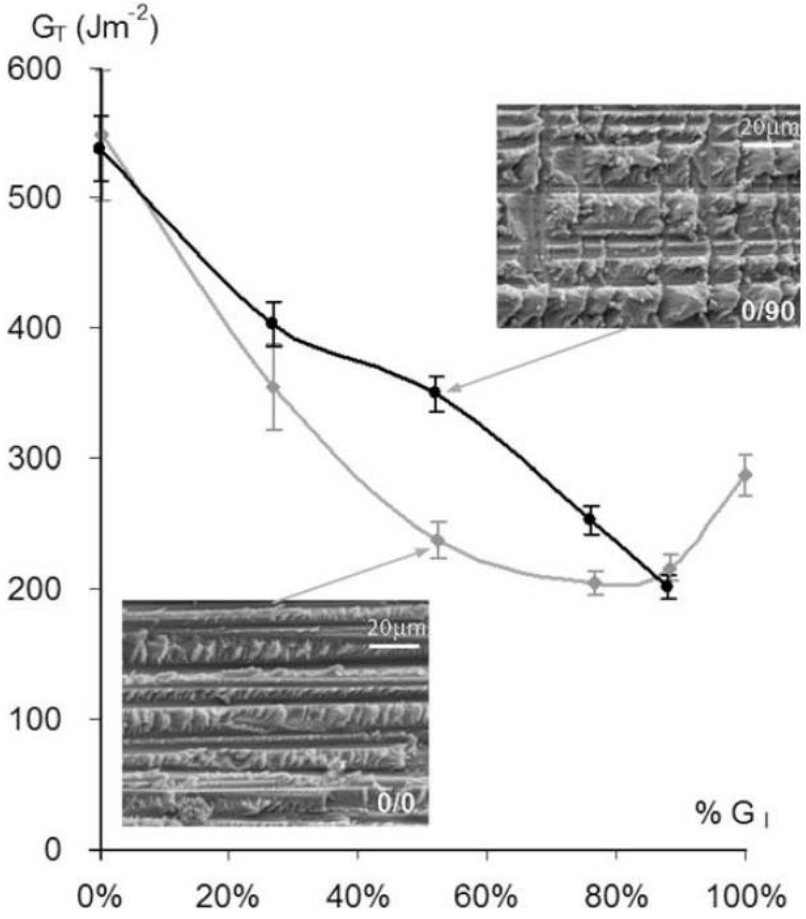
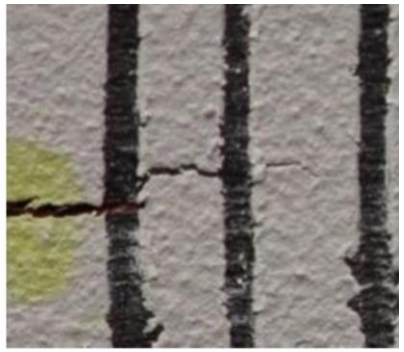


Fig. 5. Failure loci for 0/0 and 0/90 ply interfaces for T800/924.

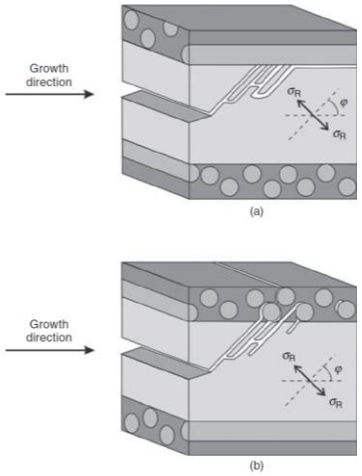
Greenhalgh et al. 2009

Why we love UD specimens, why we hate multidirectional ones?

1. Delamination migration



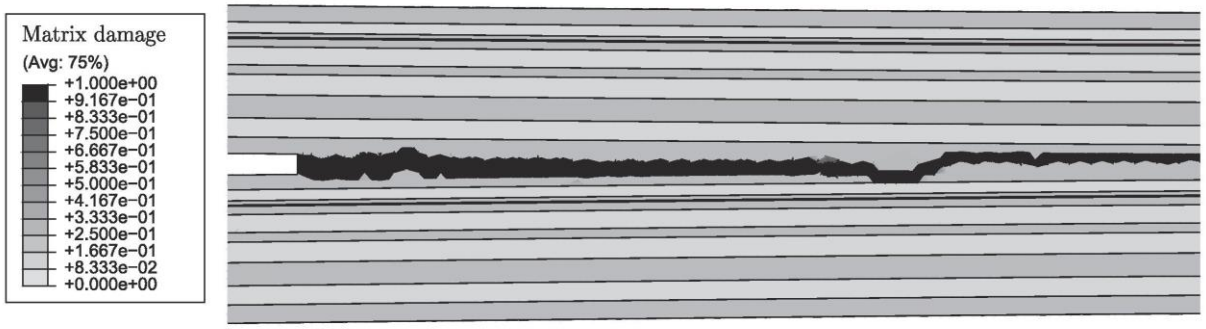
Santos et al., 2023



Greenhalgh, 2009

UD specimens: migration does not occur

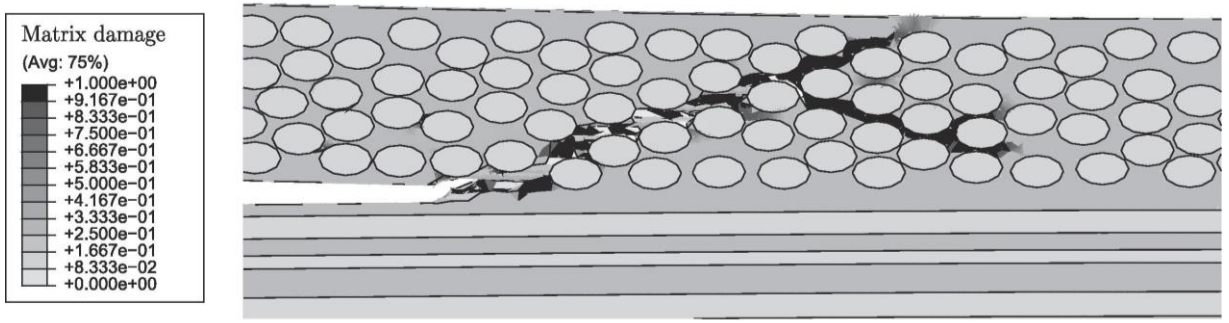
Varandas et al., 2019



(a) 0°/0° UC.

MD specimens: migration can occur

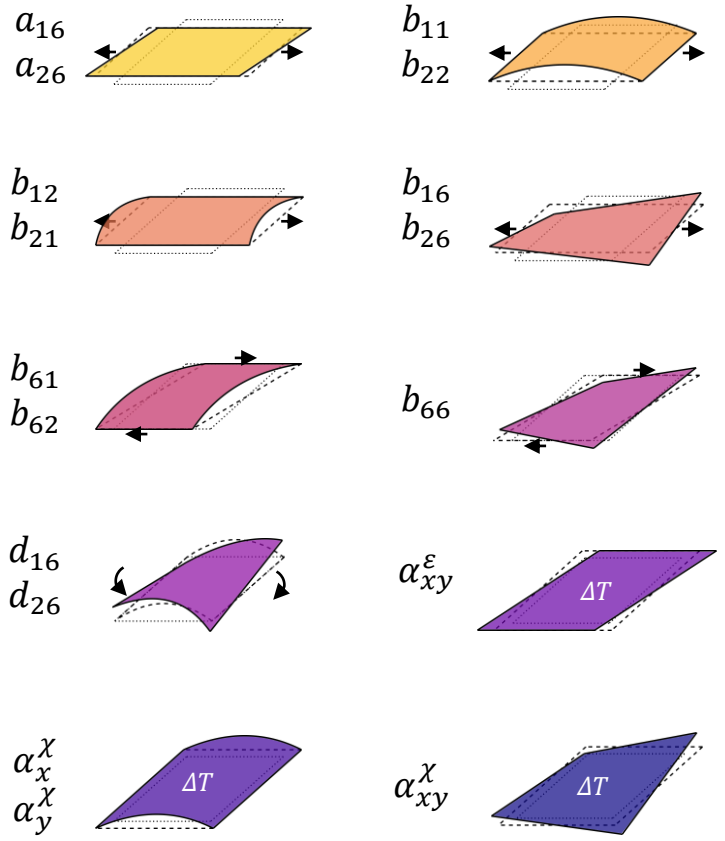
Varandas et al., 2019



(b) 45°/0° UC.

Why we love UD specimens, why we hate multidirectional ones?

2. Thermoelastic couplings



$$B_t = \left|\frac{D_{16}}{D_{11}}\right|$$

UD laminate

$$\begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \\ \chi_x \\ \chi_y \\ \chi_{xy} \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} & 0 & 0 & 0 & 0 \\ a_{12} & a_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & a_{66} & 0 & 0 & 0 \\ 0 & 0 & 0 & d_{11} & d_{12} & 0 \\ 0 & 0 & 0 & d_{12} & d_{22} & 0 \\ 0 & 0 & 0 & 0 & 0 & d_{66} \end{bmatrix} \begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} + \Delta T \begin{Bmatrix} \alpha_x^{\varepsilon} \\ \alpha_y^{\varepsilon} \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

Inverse constitutive law (CLPT)

MD laminate

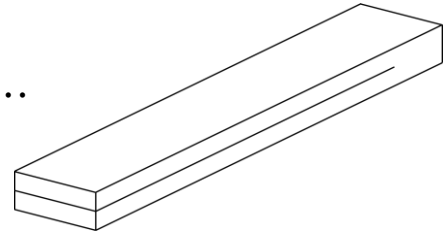
$$\begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \\ \chi_x \\ \chi_y \\ \chi_{xy} \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{16} & b_{11} & b_{12} & b_{16} \\ a_{12} & a_{22} & a_{26} & b_{21} & b_{22} & b_{26} \\ a_{16} & a_{26} & a_{66} & b_{61} & b_{62} & b_{66} \\ b_{11} & b_{21} & b_{61} & d_{11} & d_{12} & d_{16} \\ b_{12} & b_{22} & b_{62} & d_{12} & d_{22} & d_{26} \\ b_{16} & b_{26} & b_{66} & d_{16} & d_{26} & d_{66} \end{bmatrix} \begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} + \Delta T \begin{Bmatrix} \alpha_x^{\varepsilon} \\ \alpha_y^{\varepsilon} \\ \alpha_{xy}^{\varepsilon} \\ \alpha_x^{\chi} \\ \alpha_y^{\chi} \\ \alpha_{xy}^{\chi} \end{Bmatrix}$$

Inverse constitutive law (CLPT)

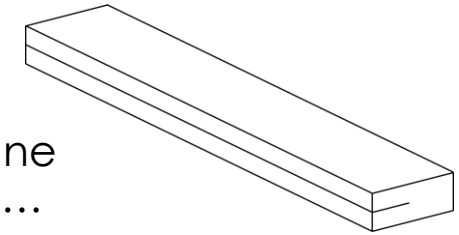
Why we love UD specimens, why we hate multidirectional ones?

3. Finite width effect

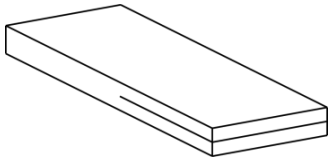
Plane stress …



… plane strain …

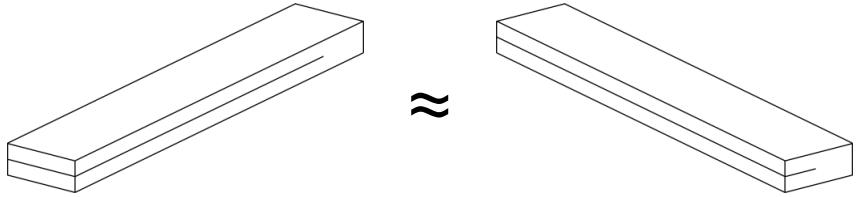


… or ?



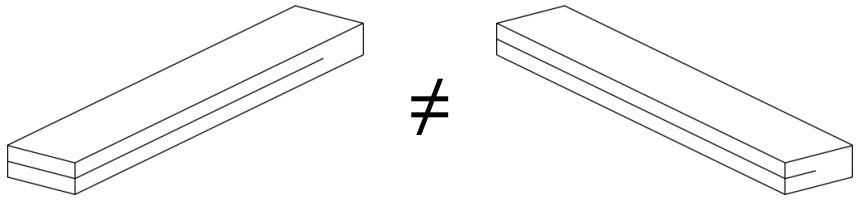
$$D_c = \frac{D_{12}^2}{D_{11} D_{22}}$$

UD specimens



- Low D_c
- Negligible effect

MD specimens

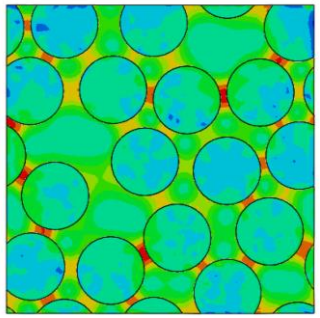


- Potentially high D_c
- Significant effect
  - Uneven ERR at front
  - Curved front
  - Non-self-similar propagation

Why we love UD specimens, why we hate multidirectional ones?

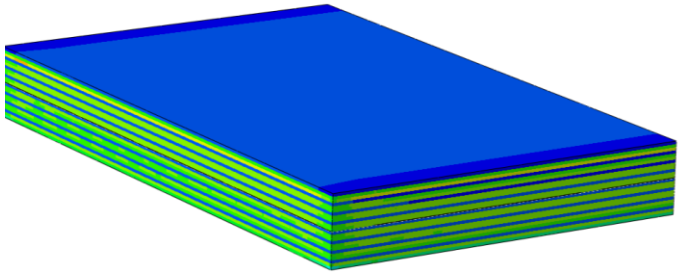
4. Thermal residual stresses

Micro residual stresses

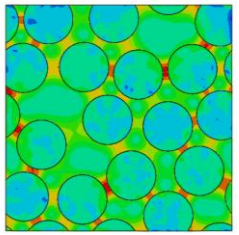


Gonçalves et al., 2022

Ply-level residual stresses

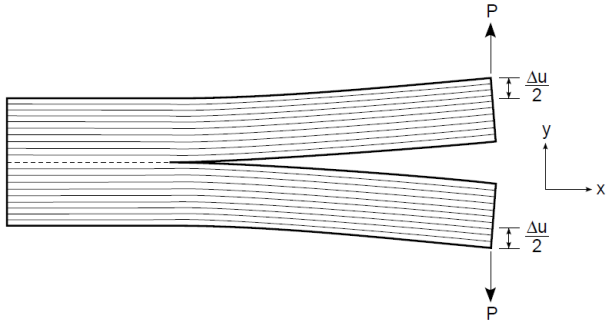


UD specimens



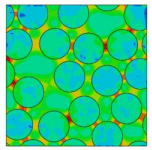
Micro-residual stresses only

Nairn, 1997

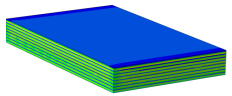


Micro-residual stresses do not release energy during delamination propagation

MD specimens



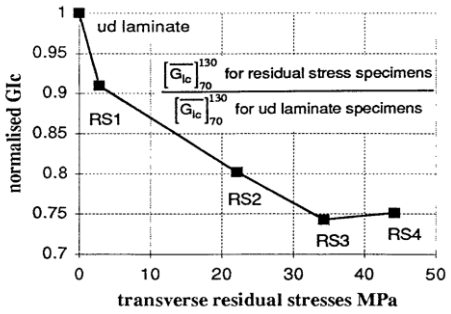
+



Both micro and ply-level residual stresses

Nairn, 2000: suggests double symmetric layups

Robinson et al., 1996



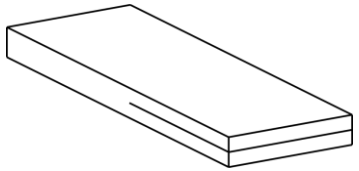
Sebaey et al., 2011: Ply-level stresses facilitate migration

Gonçalves et al., 2023: Micro & ply-level stresses reduce effective strength

Can this change?

Fully-Uncoupled Multidirectional (FUMD) specimens, concept

Garulli et al., 2019



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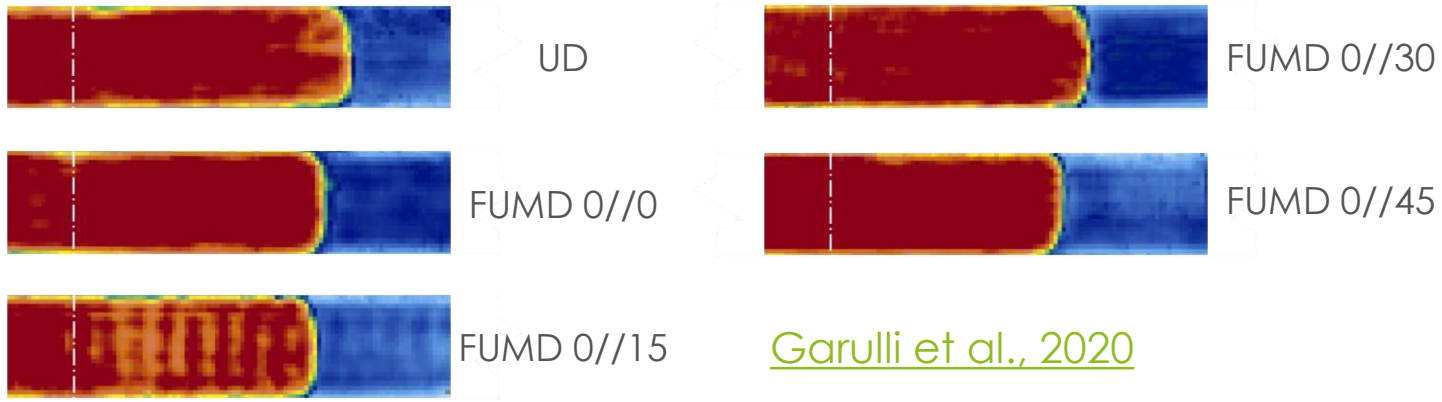
Set of MD specimens with UD-like thermoelastic behaviour

- No couplings (in arms or uncracked region)
- Free orientations choice
- Arbitrary interface

FUMD preliminary experimental results

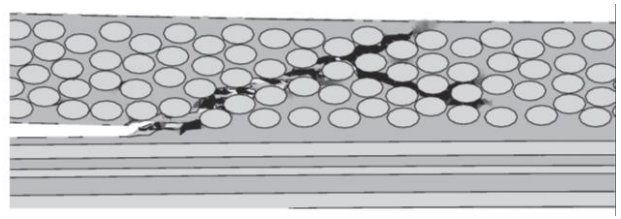


Garulli et al., 2020

What may be missing?

Migration:

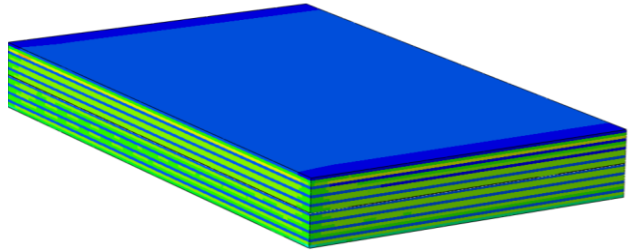
Can we avoid it in mode I tests?



Varandas et al., 2019

Residual stresses:

Can we fully understand their effects?



Conclusions

There are many (reasonable) reasons to love UD specimens

- As easy and as convenient as it gets
- Allow reasonable structural predictions (surprisingly)

There are (still) a few reasons to hate MD specimens:

- More complex behaviour
- Unsolved issues

Can this change?

- Potentially, with some research effort
- If it does, it will enable us to deliberately choose whether to use UD or MD specimens!

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