Mode I interlaminar fracture toughness and the factors affecting it

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In our paper introducing the concept of toughness in composites [1], we classified all potential situations where toughness may play a role in interlaminar, intralaminar and translaminar fracture to define the crack surface orientation. We added a term, longitudinal and transverse, to indicate the crack growth direction. Translaminar implies the breaking of fibres, whereas inter- and intralaminar refers to whether the cracks grow in between the plies or through the thickness, respectively. The conditions for toughness to be a material parameter were also considered in [1].

The present workshop is devoted to interlaminar fracture toughness with a nominal mode I component. It is evident that the type of mode refers to a mesomechanical view of the material, which is the level at which predictions on the behaviour of the laminate in an actual component are performed. The absence of fibre breakage in the fracture mode implies that the mechanism consists of interfibre damage formed by connected debonds, as represented in Figure 1. However, this damage may grow in a direction parallel to the fibres (see Figure 1a) or transverse to the fibres (see Figure 1b). In both cases, local modes I and II are involved at the micromechanical level.

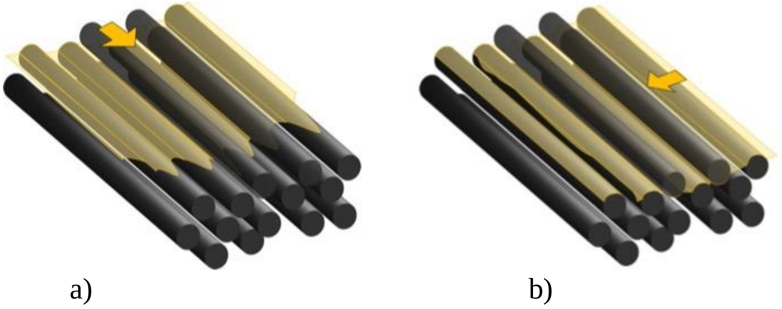

Figure 1.- Two different types of interlaminar crack growth: a) longitudinal, and b) transverse.

ISO and ASTM have developed standards for the double cantilever beam test [2, 3], both involving a double cantilever beam specimen with a symmetric configuration and a precrack. The determination of interlaminar properties has attracted attention from the scientific community with many reviews, from the classical review of Berthelot [4] to many recent publications like the one of Huang and Bobyr [5].

Despite being standardised, there are still many open experimental issues. First, the standards assume that the crack front is straight so that either the crack length can be monitored from the specimen's edge or simple equations can be applied to determine the crack length. Experimental investigations have revealed that this assumption is incorrect [6], but analytical work showed that the effect on the measured interlaminar fracture toughness is small [7]. This approach also assumes that the crack is a 2D feature, even though it follows a tortuous path in reality (see Fig. 1).

Second, there are many ways to measure or estimate the crack length. The ASTM standard suggests three approaches: visual observation, onset of non-linearity, and 5% offset from linearity. In practice, however, researchers also use techniques like digital image correlation and electrical capacitance [8].

Third, many different data reduction schemes have been developed. Katalagarianakis et al. [9] compared ten different analytical and numerical schemes and reported differences of up to 21%.

Fourth, there is often a need to test specimens that do not adhere to the standards. Although the standards require symmetric layups with only 0° plies, testing asymmetric layups with non-0° plies provides access to the interlaminar fracture toughness for other interfaces than 0°/0°. Whenever the tested interface deviates from 0°/0°, the tested specimen will be asymmetric. Such interfaces are crucial to improve the representativeness of the mode I DCB results for use in laminate-level models. Garulli et al. developed an elegant approach to minimise the resulting asymmetry via fully uncoupled laminates

[10]. Some researchers have also used adhesively bonded stiffeners Simaafrookhteh et al. [11] so that the laminate can be artificially stiffened.

Fifth, the initiation toughness is particularly difficult to measure accurately. It tends to be significantly lower than the propagation toughness [12], and sensitive to the data reduction and crack observation method. There may also be R-curve behaviour, which can be affected by different amounts of fibre bridging.

In addition to experimental issues, there is often also a need to characterise more than just the mode I interlaminar fracture toughness. For example, the mode I intralaminar fracture toughness is often assumed to be the same as its interlaminar counterpart. However, Cepero et al. [13] found that the intralaminar fracture toughness was up to two times higher than the interlaminar value. They also found significant differences between the values for transverse and longitudinal intralaminar fracture toughness. Some models also require the cohesive law to be extracted, and various experimental methods have been developed to achieve this [14].

As in previous editions of this series of workshops, the emphasis has been put in looking for the factors that affect the nominal value of fracture toughness (interlaminar under mode I in the present case). A question that requires further attention is the representativity of the values obtained from a test when they are used in designing actual composite components, as the mechanisms of damage involved in the damage process in an actual laminate may be different from those involved in a test.

REFERENCES

[1] Y. Swolfs, F. Paris, M.R. Wisnom, Is fracture toughness applicable as a material property for composites? https://bristol.ac.uk/composites/events-and-seminars/events/2023/is-fracture-toughness-applicable-as-a-material-property-for-composites.html, 2023.
[2] ASTM D5528-13 - Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites, ASTM, Philadelphia, USA, 2013.
[3] ISO 15024:2023 - Fibre-reinforced plastic composites-determination of mode I interlaminar fracture toughness, GIc, for unidirectionally reinforced materials, ISO, Geneva, Switzerland, 2023.
[4] J.-M. Berthelot, Transverse cracking and delamination in cross-ply glass-fiber and carbon-fiber reinforced plastic laminates: Static and fatigue loading, Applied Mechanics Reviews 56(1) (2003) 111-147, https://doi.org/10.1115/1.1519557
[5] T. Huang, M. Bobyr, A Review of Delamination Damage of Composite Materials, J. Compos. Sci. 7(11) (2023) 468, https://doi.org/10.3390/jcs7110468
[6] T. Chatziathanasiou, J. Soete, J. Vanhulst, D. Carrella-Payan, L. Gorbatikh, M. Mehdikhani, In-situ X-ray computed tomography of mode I delamination in carbon-epoxy composites: The effect of the interface ply orientation, Compos. Part B Eng. 260 (2023) 110761, https://doi.org/10.1016/j.compositesb.2023.110761
[7] B.D. Davidson, An Analytical Investigation of Delamination Front Curvature in Double Cantilever Beam Specimens, J. Compos. Mater. 24(11) (1990) 1124-1137, https://doi.org/10.1177/002199839002401101
[8] T. Tiedemann, F. Chen, B. Fiedler, New Method for Crack Length Determination in Low-Temperature DCB Tests Based on Electrical Capacitance, 9th Int. Conf. on Fracture of Polymers, Composites and Adhesives, Les Diablerets, Switzerland, 2024.
[9] A. Katalagarianakis, E. Polyzos, D. Van Hemelrijck, L. Pyl, Mode I, mode II and mixed mode I-II delamination of carbon fibre-reinforced polyamide composites 3D-printed by material extrusion, Compos. Part A Appl. Sci. Manuf. 173 (2023) 107655, https://doi.org/10.1016/j.compositesa.2023.107655
[10] T. Garulli, A. Catapano, D. Fanteria, W. Huang, J. Jumel, E. Martin, Experimental assessment of Fully-Uncoupled Multi-Directional specimens for mode I delamination tests,

Compos. Sci. Technol. 200 (2020) 108421,
https://doi.org/10.1016/j.compscitech.2020.108421

[11] S. Simaafrookhteh, P. Tsokanas, T. Loutas, S.V. Lomov, J. Ivens, Measuring the interlaminar fracture toughness of thin carbon fiber/polyamide6 composites using adhesively bonded stiffeners, Compos. Part A Appl. Sci. Manuf. 176 (2024) 107841,
https://doi.org/10.1016/j.compositesa.2023.107841

[12] G. Pappas, J. Botsis, Intralaminar fracture of unidirectional carbon/epoxy composite: experimental results and numerical analysis, Int. J. Solids Struct. 85-86 (2016) 114-124,
https://doi.org/10.1016/j.ijsolstr.2016.02.007

[13] F. Cepero, I.G. García, J. Justo, V. Mantič, F. París, An experimental study of the translaminar fracture toughnesses in composites for different crack growth directions, parallel and transverse to the fiber direction, Compos. Sci. Technol. 181 (2019) 107679,
https://doi.org/10.1016/j.compscitech.2019.107679

[14] R. Erives, B.F. Sørensen, S. Goutianos, Extraction of mix-mode cohesive laws of a unidirectional composite undergoing delamination with large-scale fibre bridging, Compos. Part A Appl. Sci. Manuf. 165 (2023) 107346,
https://doi.org/10.1016/j.compositesa.2022.107346