Is fracture toughness applicable as a material property for composites?

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In our first series of workshops, we focused on the strength of composites. We defined strength as the maximum stress the material can sustain under uniform uniaxial loading and in the absence of other stress components [1]. Strength is often regarded as a material property, but the various strength workshops highlighted potential complicating factors. For example, the size scaling of longitudinal tensile strength would imply it is not a material parameter unless the Weibull scaling parameters are used to define the strength.

Although strength is important in defining when failure will initiate, fracture toughness determines whether the created crack can or will grow. We will not get into the discussion which of the two parameters matters more, but it is clear that both are important. The question then becomes whether toughness is a material parameter, which implies a range of requirements. The three most relevant requirements are that the property should (1) be independent of lab, operator or machine, (2) not depend on the layup, and (3) be size independent. It is not obvious whether fracture toughness of composites satisfies these requirements.

Fracture toughness is controlled by the energy dissipation mechanisms, several of which occur at the microscale. For this workshop, however, we will focus on the mesoscale. Different morphologies of the fracture process have to be considered at this scale. Unfortunately, there is no uniformity yet on the terminology. We propose that two features must be distinguished: the crack growth direction and the crack surface orientation with respect to the laminate. The combination of these possibilities leads to six cases (see Fig. 1), where the first word (longitudinal, transverse, or through-thickness) refers to the growth direction and the second (interlaminar, intralaminar, or translaminar) to the crack surface orientation. The envisioned series of workshops associated with fracture toughness of composites concentrate on these situations, typically labelled "translaminar fracture toughness" and "interlaminar fracture toughness". We will not address intralaminar fracture in this paper and only partially in the workshops given the limited research on this particular type.

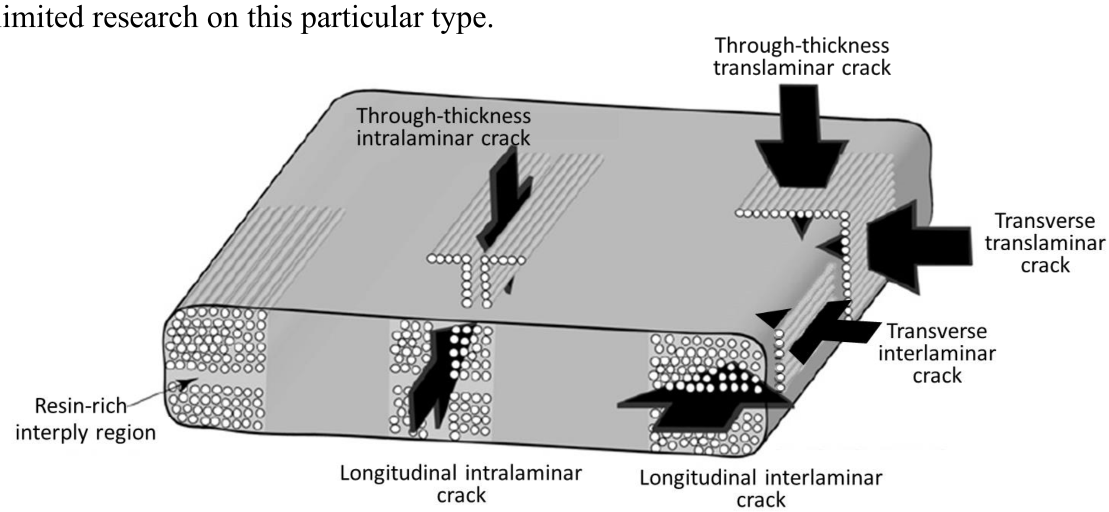

Figure 1.- Representation of independent types of fracture, and associated fracture toughnesses in a unidirectional laminate (reworked based on Laffan et al.[2], with permission from Elsevier).

A common issue in all fracture toughness tests is the definition of the crack initiation point. Various approaches have been proposed, and they all yield somewhat different results [3]. Non-destructive testing or SEM may lead to an even earlier initiation point, but both are difficult to perform during the test and time-consuming. Clearly, the initiation point depends on the utilised method or criterion.

The most common test for translaminar fracture is the compact tension test, along with some variants like the overheight compact tension test. While some standards have been developed (ASTM E1922), many academic labs have developed their own methods and data reduction schemes [2]. This is problematic in terms of their reproducibility, which is a crucial requirement to be considered a material parameter.

Translaminar fracture toughness cannot be measured directly on unidirectional composites because the specimen would just split. Most research, therefore, uses cross-ply or quasi-isotropic laminates. The ply thickness effect has been widely debated for translaminar fracture toughness in tension. Thicker plies lead to longer fibre pull-outs that dissipate more energy, leading to a higher translaminar fracture toughness [4]. However, some authors have argued that thicker plies also create more secondary damage [5,6], such as splits, off-axis cracks and delamination, which can also blunt the notch and increase the translaminar fracture toughness. These two explanations do not necessarily contradict each other, as the extra secondary damage creates longer pull-outs. However, both explanations would indicate that translaminar fracture toughness is not a material parameter. In contrast, Furtado et al. [5] revealed that numerical models that incorporate the secondary damage properly can predict laminate strength for a constant value of the translaminar fracture toughness. Their conclusion would imply that translaminar fracture toughness is a material parameter. On the other hand, Xu et al. predicted laminate fracture toughness based on a Weibull failure model with no toughness for fibre failure at all [7].

In contrast, interlaminar fracture toughness tests are much more standardised and established. Nevertheless, some reports still question whether interlaminar fracture toughness can be considered a material parameter. For example, some studies reported that a larger angle difference at the delamination interface decreased the initiation G_{IIc} without any significant effect on the propagation G_{IIc} [8,9], but others contradicted this [10,11]. Several authors have reported that the extent of fibre bridging in mode I depends on the specimen thickness [12]. If the angle at the interface or specimen thickness influences the result, then the fracture toughness is not a material parameter.

Although the debate is not settled, these examples already demonstrate that it is not easy to establish that fracture toughness of composites is a true material parameter. Nevertheless, it is vital to understand which parameters might prevent it from being one so that (1) we can account for them in devising and performing experimental campaigns, and (2) those parameters can be appropriately reflected in simulations. The second point may require the conversion of the R-curve into a cohesive law, which raises some fundamental questions about whether cohesive laws appropriately capture the physics. This first workshop aims to discuss the determination and applicability of fracture properties associated with composites and identify points that deserve to be treated in a separate workshop.

References

[1] Wisnom, Paris, *How do we define and measure strength of a composite?*, www.bristol.ac.uk/media-library/sites/composites/documents/presentations/definition-of-strength.pdf (2020),

[2] Laffan, Pinho, Robinson, McMillan, *Translaminar fracture toughness testing of composites: A review*, Polym Test 31 (2012), 481-489, http://dx.doi.org/10.1016/j.polymertesting.2012.01.002.

[3] Brunner, *Experimental aspects of Mode I and Mode II fracture toughness testing of fibre-reinforced polymer-matrix composites*, Computer Methods in Applied Mechanics and Engineering 185 (2000), 161-172, https://doi.org/10.1016/S0045-7825(99)00257-1.

[4] Teixeira, Pinho, Robinson, *Thickness-dependence of the translaminar fracture toughness: Experimental study using thin-ply composites*, Compos Part A Appl Sci Manuf 90 (2016), 33-44, http://dx.doi.org/10.1016/j.compositesa.2016.05.031.

[5] Furtado, Arteiro, Linde, Wardle, Camanho, *Is there a ply thickness effect on the mode I intralaminar fracture toughness of composite laminates?*, Theoretical and Applied Fracture Mechanics 107 (2020), 102473, https://doi.org/10.1016/j.tafmec.2020.102473.

[6] Xu, Wisnom, Li, Hallett, *A numerical investigation into size effects in centre-notched quasi-isotropic carbon/epoxy laminates*, Compos Sci Technol 111 (2015), 32-39, https://doi.org/10.1016/j.compscitech.2015.03.001.

[7] Xu, Wisnom, Hallett, *Deducing the R-curve for trans-laminar fracture from a virtual Over-height Compact Tension (OCT) test*, Compos Part A Appl Sci Manuf 118 (2019), 162-170, https://doi.org/10.1016/j.compositesa.2018.12.027.

[8] Salamat-Talab, Shokrieh, Mohaghegh, *On the R-curve and cohesive law of glass/epoxy end-notch flexure specimens with 0//θ interface fiber angles*, Polym Test 93 (2021), 106992, https://doi.org/10.1016/j.polymertesting.2020.106992.

[9] Andersons, König, *Dependence of fracture toughness of composite laminates on interface ply orientations and delamination growth direction*, Compos Sci Technol 64 (2004), 2139-2152, https://doi.org/10.1016/j.compscitech.2004.03.007.

[10] Rubbrecht, Verpoest. *The development of two new test methods to determine the mode I and mode II fracture toughness for varying fibre orientations at the interface*. Proc of 38th Int SAMPE symp, Anaheim, CA: SAMPE; **1993**. 875-887.

[11] Lachaud, Piquet, Michel, *Delamination in mode I and II of carbon fibre composite materials: fibre orientation influence*, Proc of 12th Int Conf on Composite Materials, Paris, France, **1999**, https://iccm-central.org/Proceedings/ICCM12proceedings/papers/pap1284.pdf.

[12] Farmand-Ashtiani, Cugnoni, Botsis, *Specimen thickness dependence of large scale fiber bridging in mode I interlaminar fracture of carbon epoxy composite*, Int J Solids Struct 55 (2015), 58-65, https://doi.org/10.1016/j.ijsolstr.2014.03.031.