Mode II interlaminar fracture toughness and the factors affecting it

Michael R. Wisnom[1], Federico Paris[2], Yentl Swolfs[3]

[1]*Bristol Composites Institute, University of Bristol, UK*, M.Wisnom@bristol.ac.uk
[2]*Escuela Superior de Ingeniería, Universidad de Sevilla, Spain*, fparis@us.es
[3]*Department of Materials Engineering, KU Leuven, Belgium*, yentl.swolfs@kuleuven.be

Our earlier paper and workshop discussed the concept of toughness in composites and whether it is applicable as a material property [1], and then a second workshop was held on mode I fracture toughness [2]. This paper gives a short introduction to the challenges of defining and measuring mode II toughness, and the factors affecting it.

Mode II fracture usually occurs in the resin layers between fibres or plies. Shear deformations take place due to matrix plasticity and tensile cracks then form at 45° to the fibres, in the direction of maximum principal stress. Under further deformation these extend and distort into sigmoidal shaped microcracks, as illustrated in Fig. 1, eventually coalescing into a macroscopic crack. Since failure results from tensile cracks in the matrix, it could be argued that it is not really shear failure at all [3]. There is also a theoretical difficulty that from equilibrium considerations, right at the very crack tip the shear stress must go to zero, meaning that the crack initiation must be mode I.

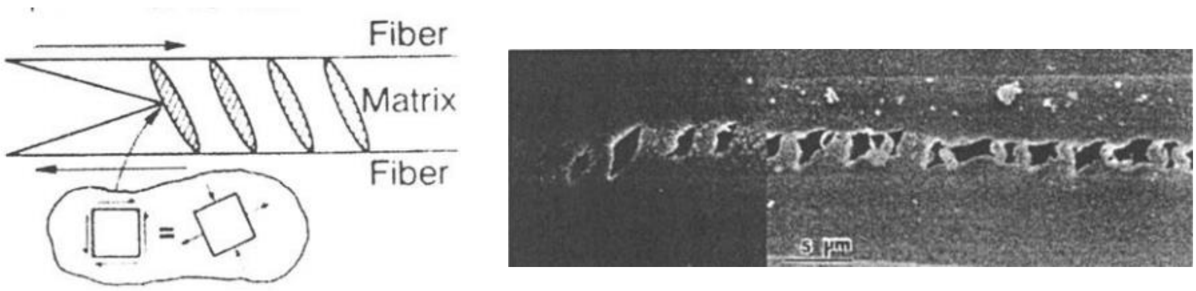

Fig. 1. Schematic and micrograph of tensile cracks forming in mode II delamination [3]

Process zones in mode II can be very long, making it difficult to define and measure the crack length. It is hard to determine visually as there is not significant crack opening and the crack front is not necessarily straight, so the length is normally calculated from the specimen compliance. The most appropriate data reduction method is the subject of debate. There are also questions as to whether the mode II fracture toughness can be considered as a fixed value, with scaled tests indicating an increase with increasing specimen size [4]. Through-thickness compression across a mode II crack can also substantially increase the effective fracture energy [5].

Mode II fracture toughness is most commonly measured with the End Notch Flexure test, ASTM D7905 [6], as shown in Fig. 2. The main drawback of this test is that it is unstable, and so only generates an initiation toughness. There are a number of potential complications, many of which are discussed in the standard. An initial test is carried out from the polymer film, generating a true pre-crack that is used for the main tests. This process normally gives a lower, more conservative value than for specimens that are not precracked.

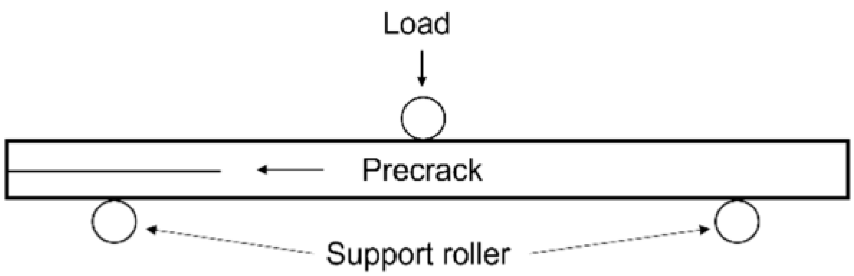

Fig. 2. End notch flexure specimen for mode II fracture toughness

Stable delamination and determination of R-curves can be achieved by loading ENF specimens in 4-point rather than 3-point bending. A number of potential concerns have been raised with this test, including the increased effect of friction [7]. An alternative stable configuration is the end-loaded split, ISO 15114 [8], where a specimen with a mid-plane crack is clamped and loaded as a cantilever, Fig. 3. Blackman et al evaluated this test, and presented experimental results reporting that the R-curve effect was small [9].

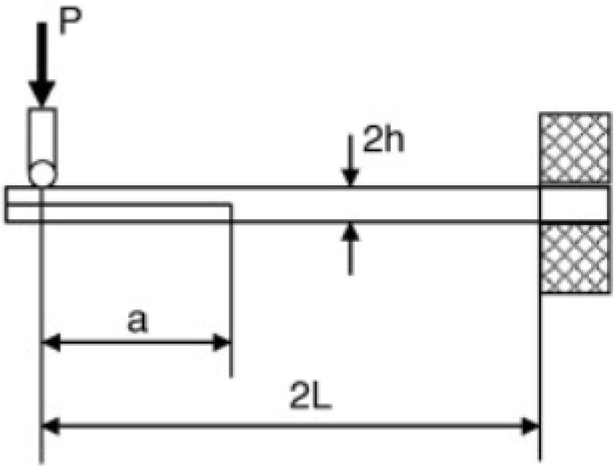

Fig. 3. End-loaded split test for mode II fracture toughness

Multidirectional laminates exhibit more complex damage, typically giving higher mode II toughness for delamination between interfaces at larger angles [10]. Unidirectional composites give the lowest values and so the values obtained should be conservative. Multidirectional composites tend to face issues with delamination migration.

Reductions of G_{IIc} have been reported with both increasing temperature and moisture [11] although there can be conflicting effects due to these conditions increasing plasticity but reducing interfacial strength. The effect of strain rate is also difficult to determine, with conflicting trends reported [12].

These issues on defining and measuring mode II fracture toughness and the factors affecting it will be discussed and debated at the workshop.

REFERENCES

1. Swolfs, Y., F. Paris, and 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. Paris, F., M.R. Wisnom, and Y. Swolfs. *Mode I interlaminar fracture toughness and the factors affecting it.* https://www.bristol.ac.uk/composites/news/2024/international-workshop-on-mode-i-toughness.html. 2024.
3. O'Brien, T.K. *Composite interlaminar shear fracture toughness, GIIc: Shear measurement or sheer myth?* in *7th Symposium on Composites - Fatigue and Fracture*. 1997. St Louis, Mo: American Society Testing and Materials. https://doi.org/10.1520/stp13263s
4. Wisnom, M.R., *On the increase in fracture energy with thickness in delamination of unidirectional glass-fiber-epoxy with cut central plies.* Journal of Reinforced Plastics and Composites, 1992. **11**(8): p. 897-909. https://doi.org/10.1177/073168449201100802
5. Xu, X.D., et al., *Experimental determination of Through-Thickness Compression (TTC) enhancement factor for Mode II fracture energy.* Composites Science and Technology, 2018. **165**: p. 66-73. https://doi.org/10.1016/j.compscitech.2018.06.012
6. ASTM, *ASTM D7905-19 Standard Test Method for Determination of the Mode II Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites.* 2019.
7. Davidson, B.D., X.K. Sun, and A.J. Vinciquerra, *Influences of friction, geometric nonlinearities, and fixture compliance on experimentally observed toughnesses from three and*

four-point bend end-notched flexure tests. Journal of Composite Materials, 2007. **41**(10): p. 1177-1196. https://doi.org/10.1177/0021998306067304

8. ISO, *ISO 15114:2014 Fibre-reinforced plastic composites — Determination of the mode II fracture resistance for unidirectionally reinforced materials using the calibrated end-loaded split (C-ELS) test and an effective crack length approach.* 2014.
9. Blackman, B.R.K., A.J. Brunner, and J.G. Williams, *Mode II fracture testing of composites: a new look at an old problem.* Engineering Fracture Mechanics, 2006. **73**(16): p. 2443-2455. https://doi.org/10.1016/j.engfracmech.2006.05.022
10. Pereira, A.B., et al., *Mode II interlaminar fracture of carbon/epoxy multidirectional laminates.* Composites Science and Technology, 2004. **64**(10-11): p. 1653-1659. https://doi.org/10.1016/j.compscitech.2003.12.001
11. Asp, L.E., *The effects of moisture and temperature on the interlaminar delamination toughness of a carbon/epoxy composite.* Composites Science and Technology, 1998. **58**(6): p. 967-977. https://doi.org/10.1016/s0266-3538(97)00222-4
12. May, M., H. Channammagari, and P. Hahn, *High-rate mode II fracture toughness testing of polymer matrix composites - A review.* Composites Part a-Applied Science and Manufacturing, 2020. **137**: p. 9. https://doi.org/10.1016/j.compositesa.2020.106019