Xu, X., Paul, A., & Wisnom, M. (2016). On the Relationship between Fracture Toughness and Specimen Thickness for Quasi-isotropic Carbon/Epoxy Laminates. In B. D. Davidson, J. G. Ratcliffe, & M. W. Czabaj (Eds.), Proceedings of the American Society for Composites 2016: Thirty-First Technical Conference on Composite Materials. Lancaster, PA ,USA: DEStech Publications Inc.

Title: **On the Relationship between Fracture Toughness and Specimen Thickness for Quasi-isotropic Carbon/Epoxy Laminates**

Authors (names are for example only): Xiaodong Xu
Aakash Paul
Michael R. Wisnom

This is the authors' version. The published version can be find in the Proceedings of the 31st Technical Conference of the American Society for Composites

ABSTRACT

Trans-laminar fracture toughness was measured in a series of centre-notched quasi-isotropic IM7/8552 carbon/epoxy laminates with scaled specimens of thickness between 2 and 8 mm. The aim was to find out if there is a transition laminate thickness at which there is a change in fracture toughness. No dependency on specimen thickness was found for specimens with 12.7 mm and 25.4 mm centre notches. There is a discrepancy compared with the findings of the previous literature. The potential causes are discussed.

INTRODUCTION

Fracture toughness is an important material property for composite structures. Although ASTM standards are available for the measurement of fracture toughness [1, 2], its specimen-thickness dependency for composite laminates is still not well understood. The ASTM E1922 standard [1] does not specify the specimen thickness, and only suggests that a thickness as small as 2 mm works well [1]. In fact, there is no mention of whether the measured trans-laminar fracture toughness depends on the specimen thickness.

Harris and Morris [3] demonstrated that trans-laminar fracture toughness does not depend on central crack length in thin 8-ply and thick 120-ply T300/5208 graphite/epoxy $[0/\pm45/90]_{ns}$ laminates. But they used specimens with variable crack-to-width ratios. The different finite width effects may affect the measured fracture toughness values. They then compared the fracture toughness values for different laminate thicknesses with a fixed crack-to-width ratio of 0.5 and a relatively long 25.4 mm centre-notch length. They concluded that the trans-laminar fracture toughness decreases with increasing specimen thicknesses, with a transition between 32 and 64 plies (check!). Li et al. [4] also reported a decrease in the quasi-isotropic IM7/8552 carbon/epoxy $[45/90/-45/0]_{ns}$ laminate toughness from 16 plies to 32 plies. However, no thicker IM7/8552 laminates, e.g. 64-ply $[45/90/-45/0]_{8s}$, were tested.

Xiaodong Xu, Aakash Paul, Michael R. Wisnom, Advanced Composites Centre for Innovation & Science (ACCIS), University of Bristol, University Walk, Bristol BS8 1TR, UK

In the present study, trans-laminar fracture toughness was measured in two series of width and centre-notch scaled quasi-isotropic IM7/8552 carbon/epoxy laminates with different specimen thicknesses. It was found that the fracture toughness is approximately constant from the 16-ply $[45/90/-45/0]_{2s}$ specimens to the 64-ply $[45/90/-45/0]_{8s}$ specimens in the 12.7 mm centre-notched tests. There is a discrepancy between the current study and the previous work [3, 4]. This may be because the 12.7 mm notch in the current specimens is significantly shorter than the one used in the previous tests. The material used before was more brittle and had a lower trans-laminar fracture toughness value, implying a smaller damage zone. Therefore, the damage process zones in the current centre-notched specimens may not have fully developed at 12.7 mm notch length [5]. As a result, the specimen may not have been big or thick enough to see if there is a laminate thickness effect.

EXPERIMENT CONFIGURATION

A series of small centre-notched quasi-isotropic IM7/8552 carbon/epoxy specimens as shown in Figure 1 were tested under tension. Another set of large specimens with doubled centre-notch length and doubled specimen width were also tested, leaving the notch-to-width ratio constant (0.2). The tested specimen dimensions are shown in Table I. The large centre-notched specimens have their gauge length kept the same as the small specimens. For the shorter specimens, the closer boundaries in the length direction were previously shown not to affect the stress distribution near the notches, justifying the use of the relatively shorter specimens [5]. The machine cut centre notches which have a 0.5 mm radius were sharpened with 0.25 mm-wide piercing saw blades at the notch tip.

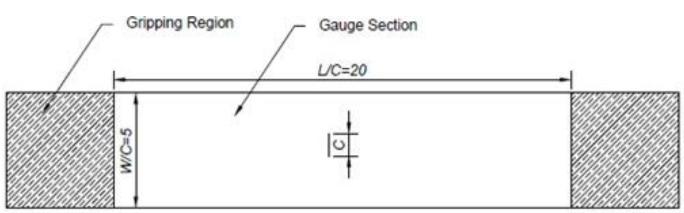

Figure 1. Schematics of the small specimen.

TABLE I. IN-PLANE DIMENSIONS OF TEST SPECIMENS (mm)

Specimens	Notch Length	Gauge Width	Gauge Length	End tab Length
Small	12.7	63.5	254.0	100.0
Large	25.4	127.0	254.0	100.0

The material used for all experiments was Hexcel HexPly© IM7/8552 carbon/epoxy pre-preg with a ply thickness of 0.125 mm. Three quasi-isotropic stacking sequences were tested with a 12.7 mm centre notch: 16-ply $[45/90/-45/0]_{2s}$, 32-ply $[45/90/-45/0]_{4s}$ and 64-ply $[45/90/-45/0]_{8s}$. For the specimens with a 25.4 mm centre notch only 32-ply $[45/90/-45/0]_{4s}$ and 64-ply $[45/90/-45/0]_{8s}$ were tested. The three specimen nominal laminate thicknesses are 2 mm, 4 mm and 8 mm respectively, which are very close to the measured specimen thicknesses.

Hydraulically driven machines were used for the experiments under displacement control. The loading rate for all the experiments was kept at a consistent 1 mm/min.

TEST RESULTS

The load vs. crosshead displacement curves are fairly linear prior to final failure. The trans-laminar fracture toughness is calculated according to Equation 1 using the gross-section stress just before the final load drop. Table II presents all of the test results.

$$K_C = \sigma_n f(\lambda) \sqrt{\frac{\pi C}{2}} \qquad (1)$$

where, K_C is the trans-laminar fracture toughness, σ_n is the average nominal gross section failure stress, $\lambda = C/2W = 0.1$ is the half notch-to-width ratio, C is the initial notch length, W is the specimen width and $f(\lambda) = \sqrt{\sec(\pi\lambda)} = 1.025$ is a geometric parameter to account for the effect of finite width [6].

TABLE II. SUMMARY OF TEST RESULTS

Notch length (mm)	Stacking sequence	Number of specimens	Tensile strength in MPa (CV%)	Fracture toughness (MPa m$^{1/2}$)
12.7	16-ply $[45/90/-45/0]_{2s}$	5	457 (4.5)	66
	32-ply $[45/90/-45/0]_{4s}$	5	456 (0.9) [5]	66
	64-ply $[45/90/-45/0]_{8s}$	5	464 (1.4)	67
25.4	-	-	-	-
	32-ply $[45/90/-45/0]_{4s}$	4	456 (2.7) [5]	71
	64-ply $[45/90/-45/0]_{8s}$	3	464 (5.5)	70

The measured fracture toughness values are constant from the 16-ply to 64-ply quasi-isotropic laminates with a 12.7 mm centre notch, and are also constant from the 32-ply to 64-ply quasi-isotropic laminates with a 25.4 mm centre notch, although slightly higher than for the 12.7 mm notch case. One case still missing is the 16-ply 25.4 mm centre-notched test.

RESULTS ANALYSIS

A linear elastic FE analysis has been carried out to understand the overall in-plane stress distribution through the specimen thickness. One eighth of the baseline specimen was modelled. A unit gross section stress was applied to the end of the model. Symmetrical boundary conditions were applied at the symmetry planes. The 8-node solid elements have homogenized orthotropic material properties as shown in Table III. It was found that the in-plane loading-direction stress distribution is not dependent on the mesh size through the 8 mm specimen thickness away from the surface as shown in Figure 2. A refined mesh (0.125 mm) was used for the rest of the FE analyses. The in-plane mesh was kept the same with a minimum mesh size of 0.2 mm. No attempt was made to compare different in-plane meshes, since the simulated stress concentration factors were only used for comparison purposes. The in-plane stress distribution in Figure 3 indicates that there is not much variation through the thickness or change with different thicknesses.

TABLE III. MATERIAL PROPERTIES FOR SOLID ELEMENTS

E_{11}=E_{22} (GPa)	E_{33} (GPa)	G_{12} (GPa)	G_{13}=G_{23} (GPa)	υ_{12}	υ_{13}= υ_{23}
61.6	13.5	23.4	4.5	0.32	0.31

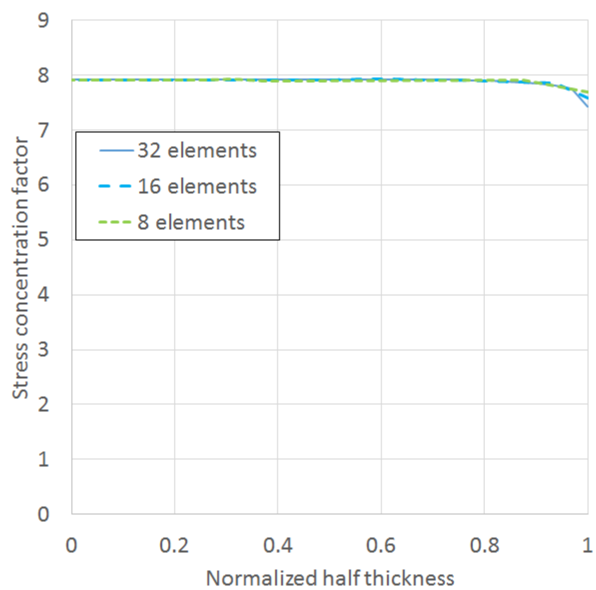

Figure 2. In-plane stress distribution with different numbers of elements through laminate thickness

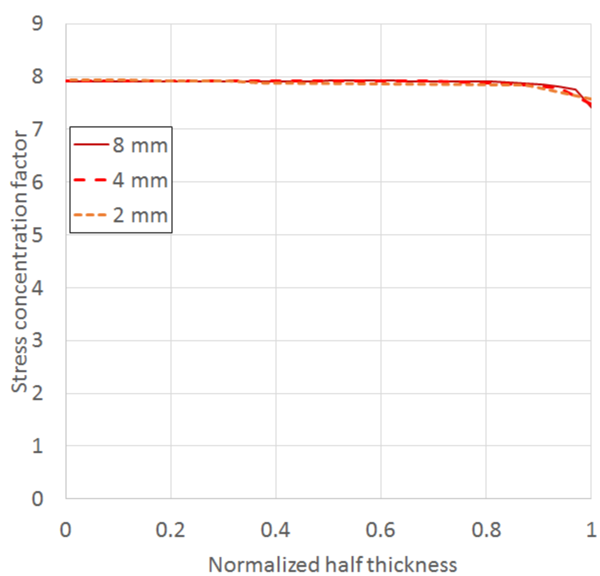

Figure 3. In-plane stress distribution through laminate thickness for different specimen thickness

DISCUSSION

Harris and Morris [3] reported that thicker quasi-isotropic laminates tend to have a lower fracture toughness value, as shown in Figure 4. The transition thickness is between 32 plies and 64 plies for T300/5208 graphite/epoxy $[0/\pm45/90]_{ns}$ laminates.

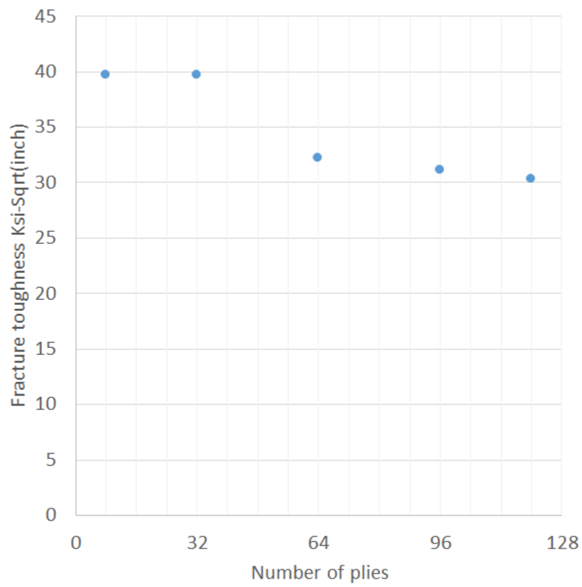

Figure 4. Specimen-thickness dependency of trans-laminar fracture toughness [3].

As discussed in the previsou section, the thickness dependency cannot be explained by the constraint through the thickness on the in-plane stress distribution [7] in the absence of sub-critical damage. However, when sub-critical damage such as delamination is considered, it was previously concluded that higher thickness provides more constraint, suppressing delamination and reducing the size of the damage zone [3]. Such an effect could be further enhanced by the current stacking sequence. This is because there is a larger porportion of the double central 0° ply block in the current thiner laminate (50%) for a 2 mm-thick 16 plies compared against 12.5% for a 16 mm-thick 64 plies. The central double 0° ply block encourages relatively more subcritical damage in thiner laminates, and results in more energy dissipation in the event of fracture propagation, in other words, a higher fracture toughness [8].

However, the damage zone is not only constrained by the specimen thickness, but is also affected by the size of the specimens [5]. The increase in fracture toughness from the 12.7 mm centre notch to the 25.4 mm centre notch in Table II is due to the fact that the damage process zone is not fully developed with the relatively short 12.7 mm notches [5]. This may be the reason why the fracture toughness measured in these tests with a 12.7 mm centre notch is the same from 16 plies to 32 plies, due to constraint on sub-critical damage limiting the already under-developed damage zone. To capture the change in fracture toughness with a fully developed damage zone, the specimens need to be larger. This also raises the question as to whether the observed specimen-thickness dependency of the measured trans-laminar fracture toughness may depend on in-plane dimensions (i.e. notch lengths).

There is also a discrepancy between the test results from the current study and the previous literature for the same material. Previously, 16-ply laminates were studied in an Over-height Compact Tension (OCT) configuration [4]. There was a 23 % higher fracture toughness value for 16 plies than for the 32 plies. In contrast, it has been found that the fracture toughness remains constant in the current study. Further testing of the 16-ply laminates with 25.4 mm notches will be conducted to investigate if there is a transition at a lower thickness.

CONCLUSIONS AND FUTURE WORK

Measured trans-laminar fracture toughness from the available test results of 12.7 mm and 25.4 mm centre notches did not show a dependence on the specimen thickness.

The mechanism behind the previously reported thickness dependency may be the constraint through the laminate thickness on sub-critical damage such as delamination. This may be further influenced by the stacking sequence, in particular, when there is a double 0° ply block at the specimen mid-plane encouraging more damage.

There is still one set of tests missing to confirm if a transition thickness for fracture toughness exists for the current material. 16-ply centre-notched tests with a 25.4 mm notch will therefore be conducted in the future.

REFERENCES

1. ASTM Standard E1922-97. 1997. "Standard test method for translaminar fracture toughness of laminated polymer matrix composite materials," ed. West Conshohocken, PA, USA: ASTM International.
2. ASTM Standard E399-90. 1990 (1997). "Standard test method for plane-strain fracture toughness of metallic materials," ed. West Conshohocken, PA, USA: ASTM International.
3. C. E. Harris and D. H. Morris. 1986. "Effect of laminate thickness and specimen configuration on the fracture of laminated composites," *Composite Materials: Testing and Design (Seventh Conference)*, ASTM STP 893:117-195.
4. X. Li, S. R. Hallett, M. R. Wisnom, N. Zobeiry, R. Vaziri and A. Poursartip. 2009. "Experimental study of damage propagation in Over-height Compact Tension tests," *Composites Part A: Applied Science and Manufacturing,* 40:1891-1899.
5. X. Xu, M. R. Wisnom, Y. Mahadik and S. R. Hallett. 2014. "An experimental investigation into size effects in quasi-isotropic carbon/epoxy laminates with sharp and blunt notches," *Composites Science and Technology,* 100:220-227.
6. J. C. Newman. 1976. "Fracture analysis of various cracked configurations in sheet and plate materials," *Properties Related to Fracture Toughness* ASTM STP 605: 104-123.
7. D. Broek. 1986. *Elementary engineering fracture mechanics*, Fourth revised ed. London: Kluwer Academic Publishers.
8. X. Xu, M. R. Wisnom, S. R. Hallett, N. Zobeiry, S. Leslie, A. Poursartip and R. Vaziri. 2013. "Stacking sequence effects in over-height compact tension tests of quasi-isotropic laminates," presented at the 19th International Conference on Composite Materials, Montreal.