ON THE MODE-I FRACTURE TOUGHNESS OF FILAMENT WOUND CURVED LAMINATES

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Abstract – This work aims to measure the mode-I fracture toughness of curved beams manufactured by filament winding. The methodology consists of experimental tests on specimens made of carbon/epoxy and glass/epoxy materials wound at ±55° in relation with the longitudinal axis of a 136 mm diameter mandrel. The specimens were prepared following the recommendations of ASTM D5528-01 standard. The tests demonstrate a typical mode I fracture toughness behaviour with a slightly better performance observed for the glass/epoxy composite sample compared to the carbon/epoxy one.

Keywords: *Double cantilever beam, interlaminar fracture toughness, curved beams, filament winding.*

Introduction

Filament winding (FW) is a well-known manufacturing process for composite structures and the most exploited to produce closed surfaces given its high precision on the fibre angle and high reproducibility. Examples of commercial components commonly produced by FW include tubes, drilling risers, transmission shafts, pressure vessels and pipelines in the oil & gas industry [1,2].

Interlaminar fracture (i.e. delamination) is a critical failure mode in fibre-reinforced polymer composites due to the lack of through-thickness reinforcement [3]. Several factors affect the interlaminar strength of a laminate, such as manufacturing defects, impact during production and service, fibre discontinuities, stress concentrations and premature cracks from drilling procedures, among others [4]. Therefore, characterising the fracture toughness behaviour of composite laminates is of utmost importance to design them and to understand their service life.

The literature on fracture toughness tests for flat composite specimens is extensive, however reports on curved beams are scarce. Among them, Guedes et al. [6] carried out an experimental study on curved beams and modelled them using the traditional virtual crack closure technique (VCCT) approach. Ghadirdokht and Heidari-Rarani [7] developed analytical and numerical models of composite beams to describe their behaviour. Beckert et al. [8] developed finite element (FE) models of curved double cantilever beam (CDCB) for filament wound thermoplastic composites, reaching an energy release rate (ERR) of 1.2 kJ/m^2.

In this context, this work aims at experimentally investigating the mode-I fracture toughness of carbon/epoxy and glass/epoxy curved composites manufactured by FW. The suitability of the developed CDCB testing apparatus is herein also exploited.

Experimental

Materials and manufacturing

Two towpregs systems are used here: carbon/epoxy - one is composed of Toray T700-12K-50C carbon fibre pre-impregnated with UF3369 epoxy resin from TCR Composites; whereas the glass/epoxy towpreg has glass fibre type Toray 158B-AB-450 impregnated with the same epoxy resin. The cylinders were designed using CadWind software and manufactured through filament winding using a KUKA robot with 7 degrees of freedom. A stainless steel mandrel with an outer diameter of 136 mm is used to produce the cylinders.

Angle-ply layer laminates are produced through FW, in which the winding is paused after the $+\theta$ sub-layer is deposited, then the 50-mm PTFE release film is inserted to act as the pre-crack, and then the $-\theta$ sub-layer is deposited on top of it. A cylinder with a winding angle of ±55° is considered, which has a winding pattern of 1/1.

The cylinder was cured in an oven with air circulation for 5 h at 120 °C, cooled down to room temperature and removed from the mandrel. The tubes were cut into rings 25-mm long using a diamond saw with water cutting disc. One-quarter of the ring circumference is cut off, polished and painted in white on the sides with black marks, following the recommendations of ASTM D5528-01 standard. The carbon fibre and the glass fibre specimens are 2.75 mm and 3.40 mm thick, respectively.

Testing

Curved loading blocks were designed and machined in steel 1020 material. The samples were attached to the loading blocks with epoxy adhesive. The tests were recorded in order to measure the crack growing and recorded to allow the synchronization of the crack length with results from the Instron universal testing machine. The tests were performed at a speed rate of 4 mm/min as recommended by the referred standard. Figure 1 shows an assembly of an ongoing test.

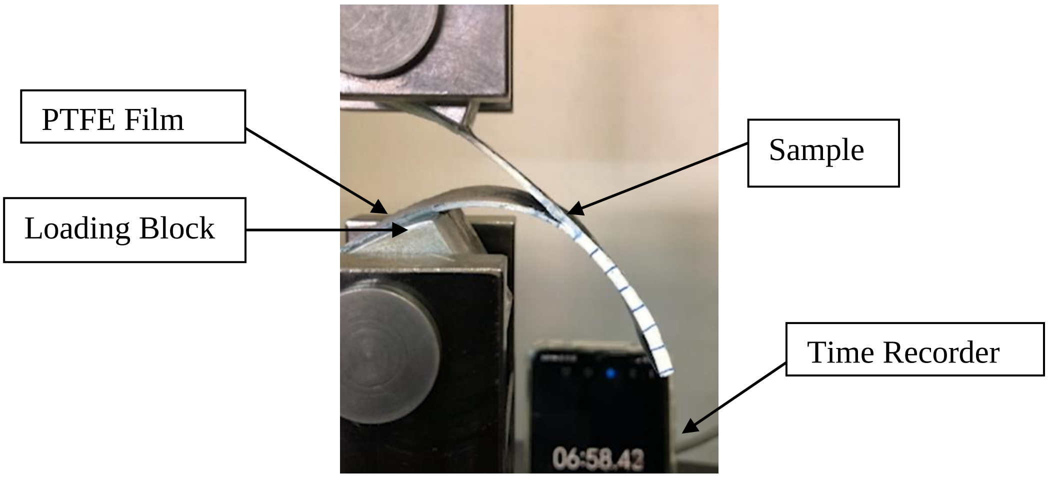

Figure 1 – The CDCB testing.

The strain energy release rate, G_1, is calculated using Equation 1, where P is the applied load, δ is the displacement, b is the specimen width, a is the delamination length and $|\Delta|$ is the correction factor to the rotation of the beam on the delamination point. To compensate this rotation, a slightly longer crack, $a + |\Delta|$, is considered. Considering the ASTM D5528-01 is applicable for flat unidirectional specimens, the Δ parameter can be determined using the Timoshenko's beam theory for curved beams, by plotting the cubic root of the compliance, $C^{1/3}$, as a function of the delamination length, as follows [7]

$$G_1 = \frac{3\mathrm{P}\delta}{2\mathrm{b}(\mathrm{a}+|\Delta|)} \tag{1}$$

$$\Delta = C^{1/3} \text{ and } C_{curved} = C_{curved\ top} + C_{curved\ bottom} \tag{2}$$

with

$$C_{curved\ bot} = \frac{1}{2}\,\frac{H}{E_\theta}\,\left(\cos\frac{a^-}{R}\sin\frac{a^-}{R} - \frac{a^-}{R}\right) + \frac{6}{5b}\,\frac{R/h - 1/2}{G_{\theta z}}\cos\frac{a^-}{R}\sin\frac{a^-}{R} \tag{3}$$

where

$$H^- = \frac{R/h - 1/2}{B - B(R/h - 1/2)\log\left(\frac{R/h}{R/h - 1)}\right)}\ and\ \frac{a^-}{R} = \frac{R/h - 1/2}{(R/h)^2}\,\frac{a}{h}$$

and

$$C_{curved\ top} = \frac{1}{2}\,\frac{H^+}{E_\theta}\left(\cos\frac{a^+}{R}\sin\frac{a^+}{R} - \frac{a^+}{R}\right) + \frac{6}{5b}\,\frac{R/h + 1/2}{G_{\theta z}}\cos\frac{a^+}{R}\sin\frac{a^+}{R} \tag{4}$$

where

$$H^+ = \frac{R/h + 1/2}{B - B(R/h + 1/2)\log\left(\frac{R/h + 1}{R/h}\right)}\ and\ \frac{a^+}{R} = \frac{R/h + 1/2}{(R/h)^2}\,\frac{a}{h}$$

In order to determine G_1 at the beginning of the delamination, there are three methods recommended by the standard. The first one is the non-linearity (NL) method, where G_1 is taken at the point of the deviation from linearity to non-linearity of the load-displacement curve; The second one is the visual observation (VIS), which consists on visually detecting crack initiation and calculate G_1 at this moment; The third one is at a 5% offset of the maximum load (5%/max) and consists of a line drawn from the origin of the load-displacement curve and offset by 5% of the linear portion. If the maximum load occurs before the point of intersection, then the maximum load and corresponding displacement should be used to calculate G_1.

Results and Discussion

Figure 2 presents the load-displacement curve for both glass/epoxy and carbon/epoxy composites. Both curves present a typical fracture behaviour for composite laminates under mode-I fracture toughness tests, in which the load evolves linearly up to the load peak, and drops progressively following the pre-crack opening. The non-linear load dropping is mainly due to delamination and fibre bridging. Comparing both materials in study, it is noted that glass/epoxy composite has the higher peak of load and hence greater strain energy release rate.

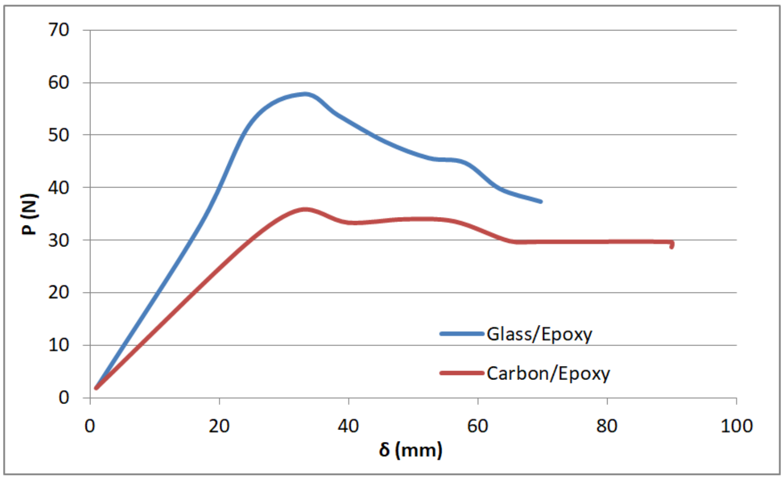

Figure 2 – Mode-I load-displacement curves for both carbon/epoxy and glass epoxy composites.

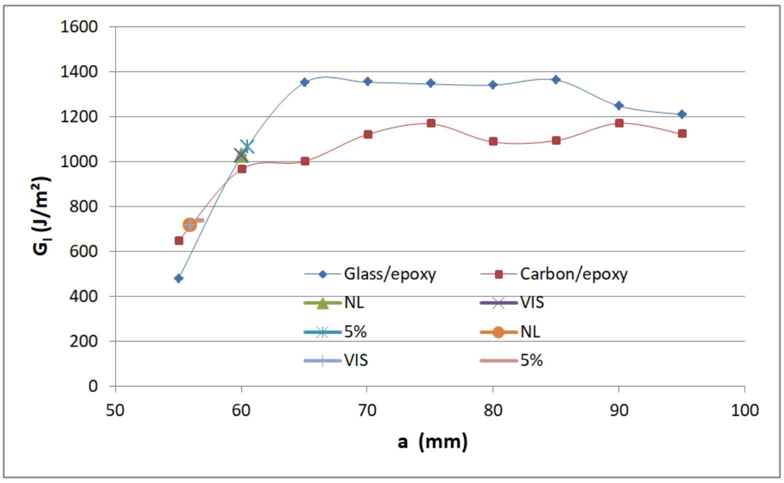

Figure 3 – Strain energy release rate for both carbon/epoxy and glass/epoxy composites.

Conclusions

In this work, curved double cantilever beam (CDCB) tests have been performed on carbon/epoxy and glass/epoxy filament wound composite rings to measure their mode-I fracture toughness. The results show that the glass/epoxy composites have a superior performance compared to carbon/epoxy ones in terms of peak load and strain energy release rate.

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References

1. R. Rafiee *Compos. Struct.* 2016, *143*, 151.
2. L. Sorrentino, E. Anamateros, et al. *Compos. Struct.* 2019, *220*, 699.
3. K. Yildiz, I. Gürkan, F. Turgut, F. Cebeci, H. Cebeci *Compos. Communication* 2020, *21*, 100423.
4. M. Hosseini, F. Taheri-Behrooz, M. Salamat-talab *Polymer Testing* 2019, *78*, 105943.
5. M.M. Shokrieh, M. Salamat-talab, M. Heidari-Rarani *Theoretical and Applied Fract. Mech.* 2016, *86*, 153.
6. R. M. Guedes, A. Sá, M.F.S.F. de Moura *Polymer Testing* 2008, *27*, 985.
7. A. Ghadirdokht, M. Heidari-Rarani *Composites Part B 2019, 175*, 107139.
8. W. Beckert; B. Lauke; K. Friedrich *Appl. Compos. Mater.* 1995, *1*, 395.