AN EXPERIMENTAL STUDY OF THE MODE I INTERLAMINAR FRACTURE TOUGHNESS OF VECTRAN/EPOXY COMPOSITES

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Abstract

Aircraft structures are susceptible to delamination from forward facing High Velocity Impact (HVI) in all regimes during service. Advanced composite fibres, such as Vectran could improve HVI performance on aircraft structures, hence creating a safer air travel environment. Vectran fibre are considerably tougher compared to Carbon Fibre Reinforced Plastic (CFRP). In this study, the interlaminar fracture toughness G_{IC} of Vectran/Epoxy laminates is investigated from a Double Cantilever Beam (DCB) test, and compared to monolithic CFRP (T800s/M21). It was found that the interlaminar fracture toughness for Vectran/Epoxy material is significantly higher than that of T800s/M21 ($G_{IC,Vectran} \approx 1.5\ kJ/m^2$; $G_{IC,T800s} \approx\ 0.246\ kJ/m^2$).

1. Introduction

Fibre Reinforced Plastics (FRPs) are widely used today in various applications across many industries. The new Boeing 787 Dreamliner and its European counterpart, Airbus A350 XWB use more than 50% of composites by weight, due to the higher strength-to-weight ratio offered by composite materials compared to other conventional materials such as aluminum. However, the vulnerability of composite aircraft structures to High Velocity Impact (HVI) damage induced by foreign objects are evident, and highly costly. These damages have cost the aerospace industry an estimated $4 billion per year in maintenance costs [1]. Thus, improvement of FRPs in HVI is necessary to increase its performance in HVI hence ultimately reducing the cost required to maintain the aircraft.

The most common method to measure the Mode I interlaminar fracture toughness of FRPs is by performing a Double Cantilever Beam (DCB) test (see Figure 2). In this test, pre-delaminated laminates are loaded in tension, and the crack growth is monitored and recorded, including the applied load (P) and the load line displacement (δ) to calculate the fracture toughness of a particular FRP. However, the fracture toughness measurement is invalid if one of the arms deformed plastically, invalidating the laws of Linear Elastic Fracture Mechanics (LEFM). Thus, adequate out of plane stiffness (i.e. bending stiffness) is required to ensure that the fracture toughness measurement is valid. ASTM [2] suggest a minimum laminate thickness (each arm thickness = 1/2 total laminate thickness) of 3 mm for a Carbon Fibre Reinforced Plastics (CFRP) system and 5 mm for a Glass Fibre Reinforced Plastics (GFRP) system so as to provide adequate bending stiffness for each arm during the DCB test. However, no recommendations were made for other type of fibres (i.e. Aramid, Polyethylene, etc.). Also, the compression modulus of these type of fibres are generally low, hence a low bending stiffness is expected. For this, a hybrid system is proposed,

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where FRPs which possess high bending stiffness will be bonded with low bending stiffness FRP, so as to provide adequate bending stiffness for a valid Mode I interlaminar fracture toughness measurement.

Extensive literature can be found on Mode I interlaminar fracture toughness of Carbon Fibre/Epoxy system in Unidirectional (UD), Cross-Ply (CP), and multidirectional orientation [2–4]. The CP orientation yielded the highest interlaminar fracture toughness, followed by multidirectional and UD orientation. This is due to the extensive fibre bridging found in CP and multidirectional specimens. The fibre bridging phenomenon act as an energy absorbing mechanism, resisting crack to grow along the intended plane. Hence, a higher load (compared to UD configuration) is required to break the bridged fibres, allowing the crack to grow further along the intended plane. However, unstable propagation values must be expected due to the "load drop" occuring in CP and multidirectional laminates (see figure 3(a)) for an example of an unstable propagation). Several efforts have been made to reduce the "load drop" phenomenon including side delamination [5], on top of the front delamination (made by placing an insert, typically made from non-stick film approximately no greater than 13 μm thick). However, few studies can be found on Mode I G_{Ic} of polymer fibres such as Aramid, or Polyethelene. Briscoe et al. [5] investigated the interlaminar fracture toughness of Aramid/Epoxy laminates and found out that the G_{Ic} values are as high as 2 kJ/m^2, due to the extensive fibre bridging phenomenon in the laminate.

Vectran fibres are similar to Aramid fibres; both fibres are Liquid Crystal Polymers (LCPs). The only difference between Vectran and Aramid fibres lies on the processing method, whereAramid fibres are spun from polymer solutions, until a phase separation occurs between anisotropic liquid crystalline and isotropic phases (lyotropic LCP). Whereas, Vectran fibres are thermotropic LCPs; fibres are made by melting the polymer above its glass temperature point (T_g) [6]. Therefore, the mechanical properties of Vectran and Aramid fibres are expected to be similar, with both having high strain-to-failure and low density.

In this study, G_{Ic} of Vectran/Epoxy laminates will be investigated. Due to the low compression modulus Vectran/Epoxy ($\approx$ 10 GPa), a hybrid configuration will be made where CFRP (T800s/M21) laminates will be bonded with Vectran/Epoxy to provide adequate bending stiffness to the Vectran/Epoxy laminates. The obtained interlaminar fracture toughness values of Vectran/Epoxy will be compared to that of T800s/M21.

2. Experimental Procedure

2.1. Laminate Manufacturing

Two sets of 200 x 250 mm T800s/M21 pre-pregs (herewith known as Laminate A and Laminate B) supplied by Hexcel corporation were laid up with a $[0\,^{\circ}]_{18}$ configuration. A 13 μm teflon insert was placed in the middle of the laminate to create a starter delamination of approximately 60 mm. After curing, the first set of monolithic T800s/M21 (herewith known as Laminate A) was then cut into specimens as shown in Figure 1 (a) and (b) (Top).

The manufacture of the second laminate (herewith known as Laminate B) is slightly more involved. The second set of T800s/M21 laminates were cured separately, without any insert in the first cure round. One ply of 200 x 250 mm MTM57 (319 gsm) epoxy film was placed in between the two stitched 0 °/90 ° NCF Vectran fabric, and then sandwiched in between the two cured T800s/M21 laminates. An insert of approximately 60 mm was placed in between the two Vectran fabric to create a starter delamination. Completed lay-up is then cured for the second time in the autoclave. When cured, Laminate B was then cut into specimens as shown in Figure 1 (a) and (b) (Bottom).

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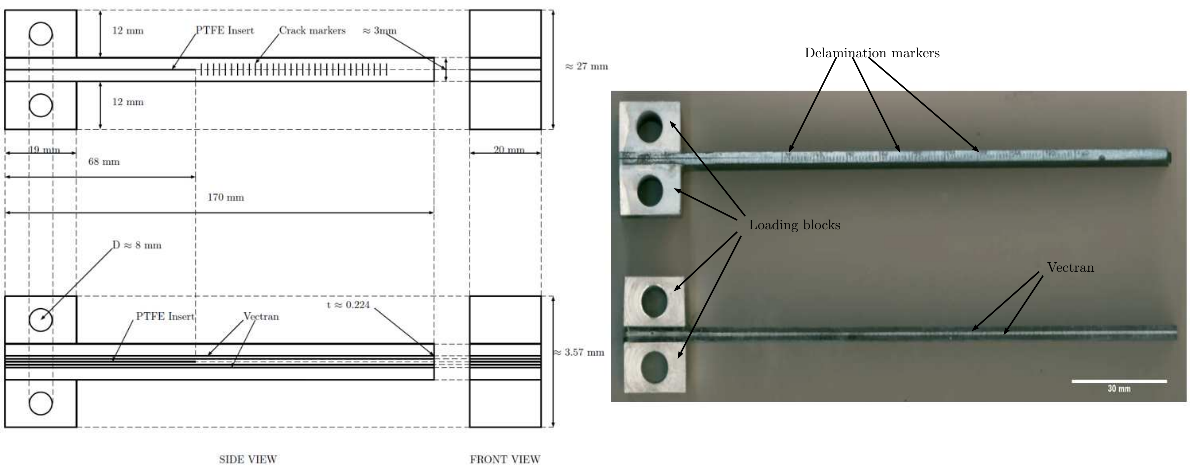
End blocks (6082-T6, aerospace grade aluminium alloy) were bonded on top and bottom of all specimens, using Araldite 2011, a two-part epoxy-hardener and left overnight to ensure good adhesion. Both end blocks and specimens were surface treated by grid blasting before bonding. The specimens were then sprayed with a water based white cellullose paint, to coat one side of the specimen to create a white ‘base’. Delamination markers were then marked on the white‘base’, 50 mm from the edge of the specimen with 1 mm intervals up to 140 mm (see Figure 1).



a) Drawing Schematics

b) Sample monolithic and hybrid DCB specimen

Figure 1. (a) DCB dimension used in the experiment (Top) Monolithic T800s/M21 (Bottom) T800s/M21/Vectran/MTM57 hybrid (b) Sample monolithic and hybrid DCB specimen

2.2. Test Procedure

Instron 5969 (with load cell capacity of up to 50 kN) was used to load the specimens in tension (see Figure 2). All experimental procedures were performed according to ASTM D5528 [2], with a crosshead speed of 1 mm/min. This speed was selected so that a slow crack growth can be observed, and hence can be recorded accurately. Crack growth observation was made using a travelling microscope which is connected to a monitor to provide a higher-resolution for accurate crack growth recording. A pre-crack of approximately 5 mm was being performed, as suggested by ASTM. This is to eliminate any presence of a resin-rich zone near the crack tip, which would contribute to an artificial G_{Ic} value.

3. Results and Discussion

Experimental crack lengths, a, was recorded and G_{Ic} values were then computed using the Modified Beam Theory (MBT) as suggested by ASTM D5528 [2]. Since load blocks were employed, the computed G_{Ic} values were corrected using the load block correction, N, along with the corrected load line displacement, $\delta_{corrected}$. G_{Ic} was then computed using equation (1) below,

$$G_{Ic} = \frac{3P\delta_{corrected}}{2B(a + \Delta)} \tag{1}$$

where P is the load, B is the specimen width, a is the measured crack length (measured from the load line to the delaminated length), and Δ is the x-axis intersection of the cube root compliance, $(C/N)^{1/3}$. The average G_{Ic} computed for T800s/M21 specimens are approximately 0.246 kJ/m^2, and the average

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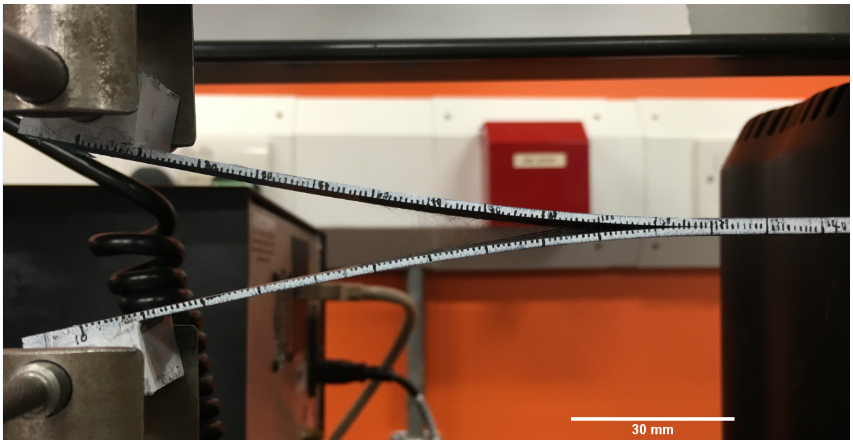
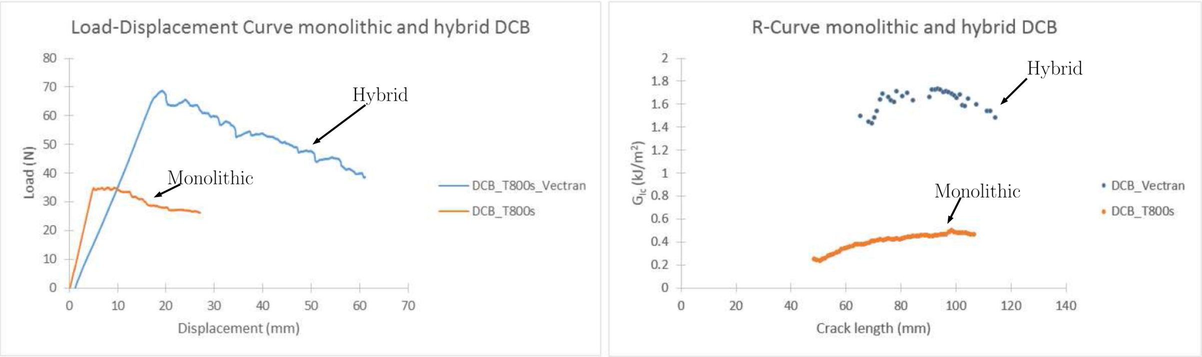


Figure 2. Sample monolithic DCB specimen during experiment

computed G_{Ic} for Vectran/Epoxy specimens are approximately 1.5 kJ/m^2.



(a) Load-Displacement Curve monolithic and hybrid DCB

(b) R-Curve monolithic and hybrid DCB

Figure 3. Load-Displacement curve and R-Curve for monolithic and hybrid specimens

Figure 3 (a) presents the Load-Displacement curve for both monolithic and hybrid DCB specimen. A relatively high load (≈ 70 N) was required to delaminate the specimen, compared to the monolithic DCB specimen (≈ 37 N). Also, an unstable crack propogation can be observed on the hybrid specimen, compared to the monolithic. Figure 3 (b) shows the Resistance Curve (R-Curve) for both monolithic and hybrid DCB specimen . Similarly, a stable crack propagation can be seen for T800s/M21 specimen, and the opposite can be seen for the hybrid specimen.

high interlaminar fracture toughness value can be attributed to the presence of extensive fibre bridging, shown in Figure 4 (b), influencing the crack openings at each interval. This result is consistent with Briscoe et al. [5], which found the G_{Ic} value of Aramid/Epoxy based laminates to be in the range of 1-2 kJ/m^2. Also, fabric stitching present in the Vectran fabric (shown in Figure 4 (a)), contributes to the high G_{Ic} values, although the percentage contribution of both mechanisms (fibre bridging and stitching) are unknown.

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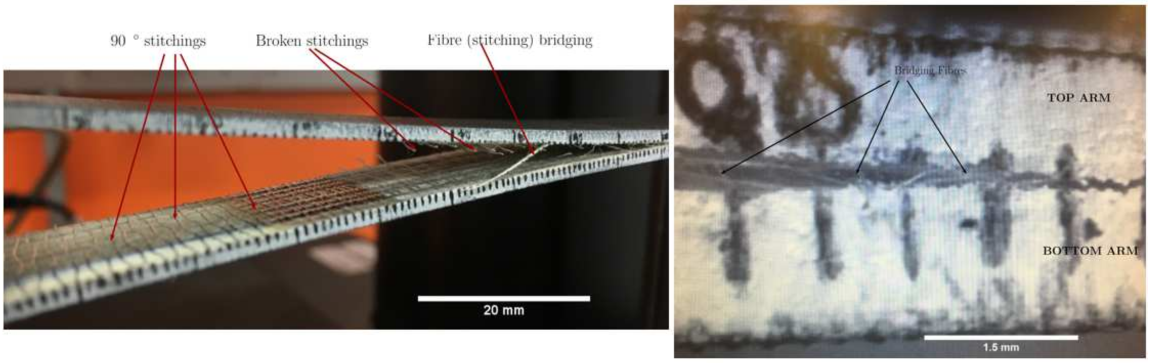

(a) Hybrid DCB specimen during experiment

(b) Close up image of DCB hybrid specimen from travelling microscope

Figure 4. Hybrid DCB specimen during testing

4. Conclusion and Recommendation

The high Mode I G_{Ic} values obtained in the hybrid specimen are an indication of substantial toughening, with respect to Mode I fracture. This is an indication of a tougher system (Vectran/Epoxy laminates), which could provide a better protection on impact from foreign objects, due to the higher interlaminar fracture toughness (in this case, Mode I). It is however recommended for future research that the Mode I interlaminar fracture toughness could be investigated for Vectran/Epoxy laminates on CP and multidirectional orientation specimens, since these orientation are often the type of orientations used in designing laminates for structural applications.

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