IMPROVING DAMAGE TOLERANCE OF CARBON FIBRE LAMINATES VIA BIO-INSPIRED MICRO-STRUCTURAL DESIGN

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ABSTRACT

A bio-inspired micro-structure design technique was used to increase the translaminar fracture toughness and the notch strength of Quasi Isotropic carbon fibre laminates. Patterns of laser-engraved micro-cuts were inserted in the micro-structure of the laminate to promote crack deflection and force the formation of large bundle pull-outs during crack propagation. The design of the patterns of micro-cuts was defined following the predictions of a newly developed Finite Fracture Mechanics criterion. The technique allowed to achieve a 20% increase in the laminate notched strength and an 190% increase in the laminate translaminar work of fracture when compared with the un-modified baseline material.

1 INTRODUCTION

The translaminar fracture toughness is an important property to improve the damage resistance and damage tolerance of Carbon Fibre Reinforced Plastics (CFRP) structures [1–3]. This is particularly important for thin-ply composites because the translaminar fracture toughness of composite laminates has been shown to decrease substantially with ply thickness [4].

Many biological composites have been able to overcome the brittleness of their constituent phases via the evolution of optimized micro-structure designs [5–7]. In these micro-structures, the mechanism of crack deflection is often used to trap cracks in tortuous paths, and a hierarchical architecture of the hard reinforcement phase is used to promote the formation of hierarchical pull-out geometries; both effects increase the energy dissipated, therefore the toughness of the composite [8–11].

Taking inspiration from these biological micro-structures, Bullegas et al. [12,13] created Carbon Fibre Reinforced Plastics (CFRP) laminates with engineered micro-structure by inserting patterns of laser-engraved micro-cuts into the single plies of the laminate. In [12], the patterns of micro-cuts have been used to promote the formation of hierarchical bundle pull-outs in the 0° plies of a thin-ply (30 µm) laminate with cross-ply lay-up during translaminar crack propagation. The bundle pull-outs dissipated energy through debonding and friction, and led to an increase of 214% in the translaminar fracture toughness of the 0° plies. In [13], the role of crack deflection and the interaction of failure mechanisms between neighbouring plies with different fibre orientations in cross-ply laminates were explored, and a 460% increase in the translaminar fracture toughness was obtained.

In the present work, the micro-structure design technique is applied to Quasi-Isotropic (QI) thin-ply (20 µm) CFRP laminates, and both mechanisms of crack deflection and hierarchical pull-outs are exploited to increase energy dissipation during translaminar crack propagation. The Finite Difference

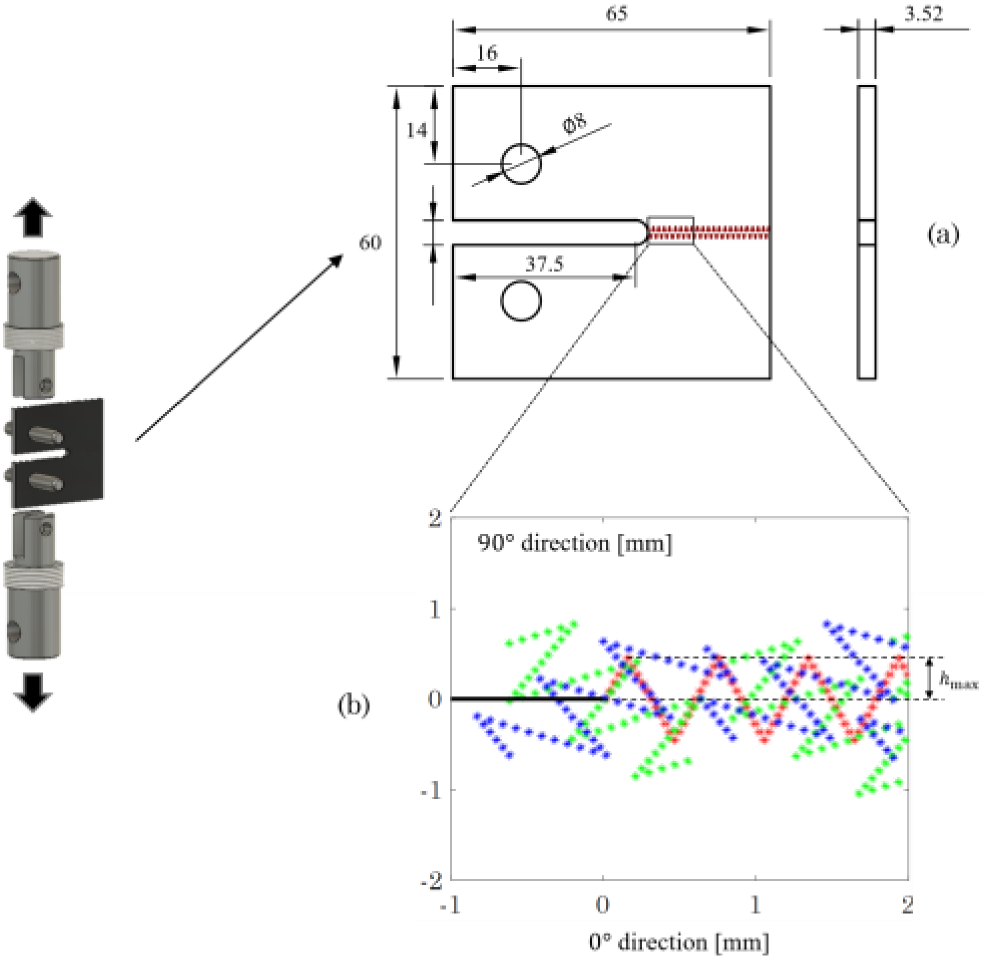


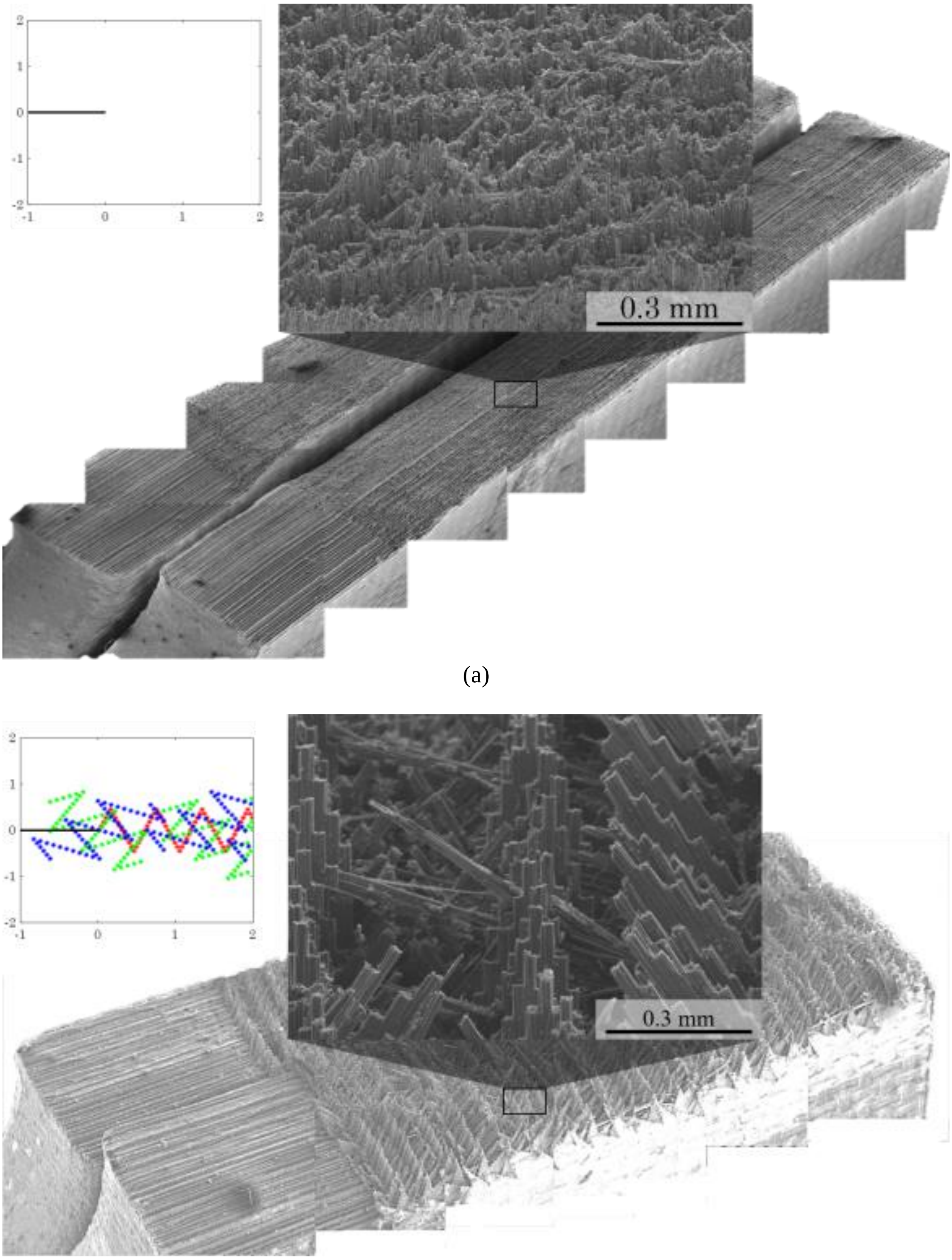
Figure 1 (a) Design of the Compact Tension specimen with quasi isotropic lay-up ($[45^\circ, 0^\circ, -45^\circ, 90^\circ]_{22s}$). Patterns of micro-cuts were laser engraved in each single ply of the laminate before laminations and aligned with the test section of the specimen. (b) Each dot represents a 30 μm micro-cut perpendicular to the local fibre direction. The distribution of the micro-cuts in the different ply orientations is done in accordance with the following colour scheme: red = 0° plies, blue = -45° plies, green = 45° plies. There are no micro-cuts in the 90° plies.

Mechanics (FFM) model presented in [**Error! Reference source not found.**] is adapted to laminates with a QI lay-up, and is used to guide the design process.

2 MATERIALS, TEST METHODS AND SPECIMENS DESIGN

The material system used in this work is a thin-ply UD carbon-epoxy prepreg (TR30/K51) with a ply thickness of 20 µm. The prepreg material was manufactured by Skyflex [14], individual fibres and laminate properties can be found in Bullegas et al [13].

In this work, Compact Tension specimens were used to study the translaminar crack propagation behaviour in QI laminates with engineered micro-structure. The CT specimen design is the same described in [12], and is shown in Figure 1(a). The specimens have been cut from a laminate with QI lay-up ($[45^\circ, 0^\circ, -45^\circ, 90^\circ]_{22s}$). Two specimens were manufactured for these study: the first specimen was manufactured without any modification to the prepreg material, this will be referred to as the "baseline" specimen; the second specimen was manufactured with an engineered micro-structure obtained by inserting patterns of micro-cuts perpendicular to the local ply orientation in the 0° and in



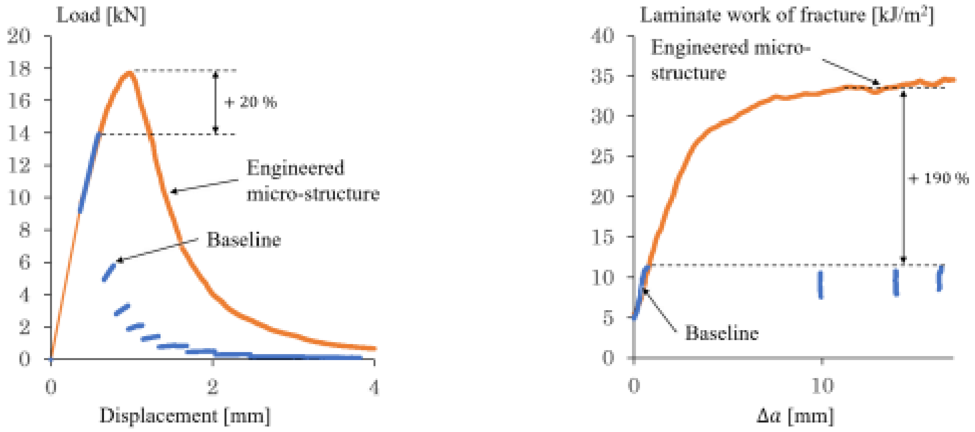
(a)

(b)

Figure 2 (a) TFS of Quasi-Isotropic (QI) ($[45°, 0°, -45°, 90°]_{22s}$) laminate without modifications (baseline). (b) TFS of the same QI laminate with engineered micro-structure.

the ±45° plies. The patterns of micro-cuts in each ply overlap in the final structure of the laminate and coincide with the test section of the CT specimen as shown in Figure 1(a).

The micro-cuts pattern design devised for this study is shown in Figure 1(b). It is based on the idea of using regular arrays of micro-cuts perpendicular to the local fibre orientation to deflect an incoming translaminar crack and force it dissipate more energy during propagation. The patterns on micro-cuts shown in Figure 1(b) are repeated periodically along the test section of the CT specimen. The maximum



(a) (b)

Figure 3 (a) Comparison of maximum load measured during a Compact Tension (CT) test for the baseline laminate and the laminate with engineered micro-structure. (b) Comparison of Work of Fracture measured with CT test for the baseline laminate and the laminate with engineered micro-structure.

crack deflection height ($h_{\max}$ in Figure 1(b)), which is the most important parameter of the design, was decided upon following the predictions from an original Finite Fracture Mechanics (FFM) criterion developed in [13].

The CT specimens were tested using an Instron load frame with a 10 kN load cell; each specimen was loaded under displacement control at a rate of 0.5 mm/min. A video strain gauge system (Imetron) was used to measure and record the relative displacement of the load application points. The modified compliance calibrated method [2] was used to calculate the laminate work of fracture from the experimental data. Note that the term work of fracture is used here instead of fracture toughness to highlight the diffuse damage introduced by this technique.

3 RESULTS

Figure 2 shows the two different fracture surfaces obtained from the CT tests. By comparing Figure 2(a) and (b), it is possible to notice how the patterns of micro-cuts promoted the formation of large bundle pull-outs in the 0° and in the ±45°. It is also possible to notice that, while the 90° plies in the baseline specimen did not generate any pull-out and are almost not visible in the image; the 90° plies in the specimen with the engineered micro-structure present multiple splits and tensile failures of the fibres.

Figure 3 shows the quantitative results of the CT tests for the two specimens. From the load vs. displacement plot in Figure 3(a), it is possible to notice that the crack propagation behaviour goes from unstable (in the case of the baseline material) to stable (for the specimens with the engineered micro-structure), with a substantial increase in the notched strength (20%). Accordingly, the laminate work of fracture vs. opening displacement plot (Figure 3(b)) shows greatly improved performances for the laminates with engineered micro-structures, with an increase of 190% in the translaminar work of fracture of the laminate

4 DISCUSSION

The patterns of micro-cuts inserted in the 0°, and in the ±45° plies of a Quasi Isotropic laminate have been successful in promoting crack deflection during translaminar crack propagation (Compact Tension test), and allowed to obtain the designed translaminar fracture surface. The change in the micro-mechanic of translaminar crack propagation in the specimen with the engineered micro-structure resulted in a different macro-mechanical response when compared with the baseline specimen without any modification. In facts, an increase of 190% in the work of fracture of the laminate, and of 20% in notched strength have been recorded during the test.

Since the allowable crack deflection height for each pattern design was decided upon using the FFM criterion presented in [13], these experimental results demonstrated that this criterion is useful in identifying a conservative lower boundary of applicability of the crack deflection technique. More studies will be necessary to confirm the upper boundary.

The test demonstrated an interaction between different ply orientations: the presence of the patterns of micro-cuts in the 0° and in the ±45° plies caused multiple splits and tensile failures in the 90° plies. It is plausible to assume that this increased the contribution of the latter to the total work of fracture of the laminate.

9 CONCLUSIONS

These are the main outcomes which emerged from the present study:

- patterns of micro-cuts inserted in the micro-structure before lamination can promote crack deflection during translaminar crack propagation, and cause the formation of large pull-outs in Quasi Isotropic laminates. The energy dissipated through debonding and friction during this process contributes to an increase in the translaminar work of fracture of the laminate;
- the Finite Fracture Mechanics (FFM) criteria can be used to determine maximum allowable crack deflection height and therefore is a useful tool in the design of the patterns of micro-cuts.
- the presence of the patterns of micro-cuts does not just cause crack deflection, but causes also an interaction of failure mechanisms between neighbouring plies with different ply orientation, which can further contribute to energy dissipation during crack propagation.

In conclusion, the results presented in this work demonstrate that the micro-structure design technique here developed can be successfully be used to engineer the translaminar fracture behaviour, and drastically increase the work of fracture of Quasi Isotropic laminates by up to 190%, which corresponds to an increase in notched strength of up to 20%.

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