Composites Science and Technology 165 (2018) 290–306

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

Towards quasi isotropic laminates with engineered fracture behaviour for industrial applications

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ARTICLE INFO

Keywords:
Fracture toughness
Damage tolerance
Engineered micro-structure
Crack deflection

ABSTRACT

Carefully placed patterns of micro-cuts have been inserted in the microstructure of Cross-Ply (CP) and Quasi-Isotropic (QI) thin-ply CFRP laminates to engineer their translaminar fracture behaviour with the purpose of increasing their damage resistance under different loading conditions. A novel Finite Fracture Mechanics model has been developed to predict the translaminar crack propagation behaviour and to guide the microstructure design. This technique led to a 68% increase in the laminate notched strength, and a 460% increase in the laminate translaminar work of fracture during Compact Tension tests for CP laminates. It also allowed to achieve a 27% increase in the laminate notched strength, and a 189% increase in the translaminar work of fracture during Compact Tension tests for QI laminates. Furthermore, an increase of 43% in the total energy dissipated, and of 40% in maximum deflection at complete failure was achieved during quasi-static indentation tests on QI laminates. Given the significant improvements in the mechanical performance under different loading conditions, and the industrial relevance of QI laminates and the increasing industrial interest in thin-ply laminates, these results demonstrate that microstructure design can be used effectively to improve the damage tolerance of CFRP structures in industrially-relevant applications.

1. Introduction

Carbon Fibre Reinforced Polymers (CFRPs) are a material of choice for the latest generation of lightweight structures in the aeronautical and transportation industries. This is due to their remarkable specific strength and stiffness when compared with conventional metallic materials. However, CFRP structures are characterised by a comparatively low damage tolerance with respect to typical metallic structures. They are particularly sensitive to the presence of mechanical defects and highly localised loads which can create sharp cracks in the structure, leading to sudden and catastrophic failure [1–5].

Propagation of through-the-thickness cracks along an in-plane direction in CFRP laminates under longitudinal tensile load is usually referred to as translaminar fracture [6–9]. The energy per unit area necessary to propagate this type of damage in the laminate is the translaminar work of fracture. Since the strength and modulus of CFRP laminates are strongly degraded by the translaminar failure of the load-aligned plies, increasing the translaminar work of fracture can lead to a significant improvement in the damage resistance of CFRP structures.

Many biological composites have been able to achieve high toughness by using a suitable micro-structure design [10–12]. In these composites, a hierarchical organization of the hard reinforcing phase promotes the formation of hierarchical pull-out geometries, while deflecting and smearing the crack front into tortuous paths. Both these effects increase the energy dissipated during crack propagation and lead to an increase in toughness without compromising stiffness and strength significantly [13–20].

Taking inspiration from these biological composites, we previously developed thin-ply CFRP laminates with a hierarchical organization of the microstructure [21]. These laminates had a Cross-Ply (CP) lay-up ($[(90,0)_n, 90]_s$) in which the 0° plies were laser engraved with patterns of micro-cuts during the lamination process, while the 90° plies were left un-touched. The patterns of micro-cuts promoted the formation of hierarchical bundle pull-outs in the 0° plies, therefore increasing energy dissipation via debonding and friction, and allowed to achieve up to 214% increase in the translaminar work of fracture of the 0° plies.

In one of the patterns desings for CP laminates previously tested [21], the presence of the micro-cuts in the 0° plies, in addition to

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https://doi.org/10.1016/j.compscitech.2018.07.004
Received 11 March 2018; Received in revised form 3 June 2018; Accepted 1 July 2018
Available online 04 July 2018
0266-3538/

promoting the formation of pull-outs in the 0° plies themselves, also caused multiple splitting and tensile failures of the fibres in the 90° plies. This result suggests that patterns of micro-cuts can be used not just to promote the formation of bundle pull-outs in the 0° plies, but also to cause crack deflection in the laminate and to promote the interaction of the failure mechanisms between neighbouring plies. This idea prompted a "laminate-level" type of approach to microstructure design which is explored in this work.

The test methods and manufacturing procedures used in this paper are detailed in Section 2. In the first part of the paper (Section 3 and Section 4), we explored the hypothesis that the interaction of the failure mechanisms between neighbouring plies, if suitably harnessed, can further increase energy dissipation and the translaminar work of fracture of the laminate. This is achieved by using patterns of aligned micro-cuts in the 0° plies of a CP laminate to steer the crack from its original fracture plane and force it along a tortuous path, causing the interaction of failure mechanisms in the 0° and 90° plies.

A novel Finite Fracture Mechanics model is developed in Section 3.2 to predict the crack deflection behaviour caused by the patterns of micro-cuts and to guide the microstructure design. The increase in translaminar work of fracture of CP laminates with the new microstructure design is tested using Compact Tension (CT) specimens in Section 4.1. The experimentally measured work of fracture is then compared with modelling results to quantify the contribution of the interaction of the failure mechanisms between neighbouring plies to the toughness of the laminate and the results are discussed in Section 4.4.

In the second part of this paper (Section 5), we apply the engineered microstructure concept to improve the fracture performance of CFRP laminates with a Quasi-Isotropic (QI) layup ($[(90,0)_n, 90]_s$). We initially focused on CP laminates because this layup offers a clean and reliable test case to investigate different failure modes and to validate modelling approaches. However, CP laminates have limited applications in the design of composite structures for practical applications. QI laminates are widely used in composite structures, and therefore of high practical interest. Due to major designing and experimental challenges related to the strong dependency of the crack deflection behaviour on the lay-up sequence, this represents a significant step forward in the development of composite laminates with engineered fracture behaviour for practical applications.

The Finite Fracture Mechanics model developed in Section 3.2 is also used to guide the microstructure design for QI laminates, and the limit of applicability of this model is explored through a parametric study. The increase in translaminar work of fracture of QI laminates with engineered microstructure is tested using Compact Tension (CT) specimens in Section 5.1.3. The best performing microstructure design is then applied to a QI laminate subject to a Quasi-Static Indentation (QSI) test in Section 5.1.4. Finally, the results for QI laminates are discussed in Section 5.3 and the overall conclusions of the paper are presented in Section 6.

2. Test methods and specimens manufacturing

2.1. Test methods

CT tests were used to study the translaminar crack propagation behaviour in laminates with engineered microstructures. The specimen geometry and the test rig setup are shown in Fig. 1 (a). This type of specimen design has been widely used in the literature [7,22–27].

The CT tests were carried out 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. The relative displacement of the load application points in the specimens was recorded using a DIC measurement system (Imetrum). Data reduction was performed to calculate the laminate work of fracture from the experimental load vs. displacement data using the modified compliance calibrated method [7,22,25].

QSI tests were performed to measure the response of composite laminates with engineered microstructure under localised out-of-plane loading. The designs of the specimen and of the fixture used for this test are shown in Fig. 1(b). The fixture design for the QSI test was based upon the ISO 6603-2 standard [28] for impact tests. The indenter head was hemispherical with a 20 mm diameter and was lubricated before each test to avoid friction with the surface of the specimens. The specimens were clamped on a support rig with an inner diameter of 40 mm.

The indentation tests were carried out using an Instron load frame with a 10 kN load cell at a displacement rate of 1 mm/min. During the test, the indentation force was measured via the load cell, and the displacement of the indenter was measured using a DIC measurement system (Imetrum) at a position 20 mm from the contact point (Fig. 1(b)). Data reduction was performed by integrating the force vs. displacement diagram to obtain the total energy dissipated by the specimen during the test. The integration was stopped when the residual indentation load fell below 0.1 kN. At this point, the specimen was considered to be completely broken and the residual load was due essentially to the friction between the specimen and the sides of the indenter.

2.2. Specimens manufacturing

All specimens were manufactured by hand lamination using the procedure developed by Bullegas et al. [21]. Each single ply of the laminate was laser-engraved with patterns of micro-cuts before lamination using a micro-milling laser machine (Oxford Lasers, Series A). Each laser micro-cut perforated through the entire thickness of the ply. During lamination, a special alignment system was used to guarantee that the patterns of micro-cuts precisely overlapped in the final laminate to form the designed microstructure.

After curing the laminate in an autoclave in accordance to the manufacturer specifications, a CNC water-jet machine was used to cut the plate into the final specimens geometry. The same alignment system was used to guarantee the alignment of the patterns of micro-cuts in the laminate plate with the test section of the corresponding specimen.

3. Microstructure design technique

3.1. Design concept

The microstructure design concept used in this paper is shown in Fig. 2 for the case of a 0° ply. It is based on the idea of using the micro-cuts to steer the incoming translaminar crack from its original propagation plane and cause crack deflection. When the deflected crack reaches the maximum height $h_{\max}$, the direction of the pattern of micro-cuts is inverted, and the crack is deflected in the opposite direction. The full pattern is defined following this rule periodically for the entire test section of the specimen. With this type of approach we aim not just to cause the formation of large pull-outs in the plies with the micro-cuts, but also to promote the interaction of failure mechanisms with the neighbouring plies. This type of patterns of micro-cuts and the resulting microstructure design is going to be referred to hereafter as "shark-teeth" microstructure.

3.2. Finite Fracture Mechanics model for crack deflection

Fig. 3(a) shows a 0° ply of thickness t included in a CFRP laminate with a translaminar crack propagating from left to right at the initial coordinate $y = 0$ in the local reference system. The ply has been engraved with an array of micro-cuts, each perpendicular to the fibre direction (Fig. 3(b)). The geometrical parameters of the pattern of micro-cuts are the single cut length (w), the space between the micro-cuts (p), and the vertical distance between the micro-cuts (s).

Fig. 3(c) shows the crack deviating from its original plane and propagating along the array of micro-cuts; each micro-cut defines a bundle which pulls out of its neighbour. It is assumed that the