Composites Science and Technology 152 (2017) 101–110

Contents lists available at ScienceDirect

Composites Science and Technology

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

High performance quasi-isotropic thin-ply carbon/glass hybrid composites with pseudo-ductile behaviour in all fibre orientations

Mohamad Fotouhi [a, b, *], Meisam Jalalvand [c, b], Michael R. Wisnom [b]

[a] Department of Design and Mathematics, University of the West of England, Bristol BS16 1QY, UK
[b] Bristol Composites Institute (ACCIS), University of Bristol, Bristol BS8 1TR, UK
[c] Department of Mechanical and Aerospace Engineering, The University of Strathclyde, 75 Montrose Street, Glasgow G1 1XJ, UK

A R T I C L E   I N F O

Article history:
Received 26 May 2017
Received in revised form
19 August 2017
Accepted 21 August 2017
Available online 24 August 2017

Keywords:
Carbon fibres
Glass fibres
Thin-ply
Hybrid composites
Delamination
Fragmentation

A B S T R A C T

This study exploits the potential of thin-ply carbon/glass hybrid laminates to generate high performance Quasi-Isotropic (QI) composite plates that show pseudo-ductility in all fibre orientations under tensile loading, overcoming the inherent brittleness of conventional composites. Two types of QI lay-ups with 45° and 60° intervals, i.e. [45/90/-45/0] and [60/-60/0], were used to fabricate novel architectures of a QI T300-carbon laminate sandwiched between the two halves of a QI S-glass laminate. The fabricated plates were then loaded in all their fibre orientations. The laminates were designed by choosing an appropriate ratio of the carbon thickness to the laminate thickness using a robust analytical damage mode map. The experimental results verified the analytical predictions and showed a desirable pseudo-ductile failure in all the fibre orientations. Microscope images taken through the laminates thickness showed fragmentations (fibre fractures in the carbon layer) appearing only in the 0° carbon plies. A hybrid effect was observed, with an increase in strain and stress to failure of the carbon fibres, which was found to be dependent on the stiffness of the plies separating the 0° carbon plies and the plies adjacent to the 0° carbon plies. Altering the stacking sequence changes the stiffness of the separator and adjacent plies, therefore, leads to changes in the pseudo-ductile characteristics such as the initiation and final failure strains.

1. Introduction

Polymer-matrix composites use has been continuously increased in engineering applications due to their superior mechanical properties. However, polymer composites show sudden brittle failure, with linear elastic response and little warning before failure. This drawback leads to large values of safety factors in their design.

Hybridisation of different types of fibres is one of the methods that can introduce gradual failure in composite materials [1–13]. Possible failure modes in a three-layer Uni-Directional (UD) hybrid laminate made from High Strain Material (HSM) and Low Strain Material (LSM) are illustrated schematically in Fig. 1. Two types of catastrophic failure modes occur in conventional hybrid composites; a) a single crack through the whole thickness of the laminate due to a high ratio of LSM to HSM thickness (improperly sized hybrid laminate), which results in a linear stress-strain curve (Fig. 1a, and b) a single fracture in the LSM instantaneously followed by unstable delamination, which appears on the stress–-strain graphs as a significant load drop (Fig. 1b). This is a typical failure mode in conventional standard ply thickness hybrid laminates. Fig. 1c shows a desired gradual failure where delamination is suppressed and multiple LSM fractures are obtained followed by stable localised pull-out. This desired pseudo-ductile behaviour is achievable by selecting appropriate material properties, appropriate values of relative thickness (i.e. proportion of the LSM to HSM) and absolute thickness of the LSM. Thin carbon plies have superior mechanical properties and lower energy release rates, delaying the propagation of intra- and interlaminar cracks [14–16]. Recently, thin-ply UD and QI hybrids with different types of low strain and high strain fibres were introduced that generated the desired nonlinear stress–strain response and pseudo-ductility that avoids the catastrophic failure in laminated composites [17–19].

Fig. 2 shows four main features of a pseudo-ductile laminate with a thin layer of low strain fibre plies; (i) Pseudo-yield strain

* Corresponding author. Department of Design and Mathematics, University of the West of England, Bristol BS16 1QY, UK.
E-mail address: m.fotouhi@bristol.ac.uk (M. Fotouhi).

https://doi.org/10.1016/j.compscitech.2017.08.024

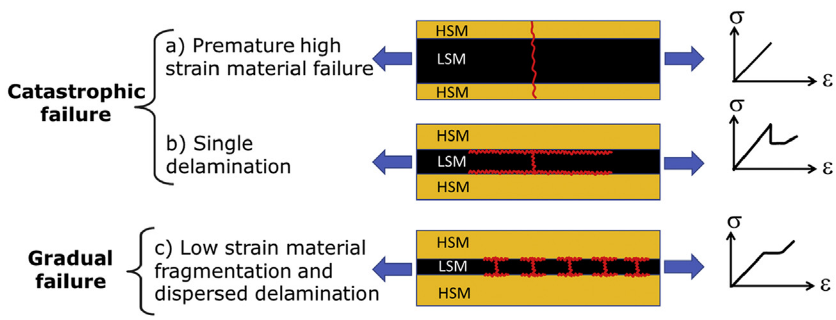

Fig. 1. Possible failure modes in a three layer UD hybrid made from HSM and LSM (red lines show fracture) (a) single crack through the whole specimen, (b) single crack in the LSM followed by instantaneous delamination, and (c) multiple fracture and localised stable pull-out of the LSM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(ε_{py}), (ii) final failure strain (ε_f), (iii) Pseudo-ductile strain (ε_{pd}) and (iv) Hybrid effect. ε_{py} and σ_{py} are the strain and stress levels at which the tensile response deviates from the initial linear elastic behaviour, respectively. ε_f and σ_f are the final failure strain and stress values at which the HSM cannot carry any more load, respectively. It usually corresponds with fibre failure in the high strain material. Pseudo-ductile strain is the enhancement in strain achieved as a result of gradual failure and is calculated as the difference between the final failure strain, and the elastic strain based on the initial modulus at the final failure stress.

Hybrid effects were reported by different researchers [9–11], where they observed higher strain to failure of carbon in their UD glass/carbon hybrids than that of all carbon specimens. Swolfs et al. [20] reviewed the basic mechanisms causing the hybrid effect, with the most significant considered to be thermal residual stresses, altered failure development due to statistical effects on formation of clusters of fibre breaks and dynamic stress concentrations. Wisnom et al. [21] used glass/carbon hybrid composites, rather than all carbon composites, to measure the strain to failure of the baseline carbon plies more accurately, to reduce the variability typically obtained using conventional unidirectional tests and avoid the high values for the hybrid effect values when using these tests as the baseline [9–11]. This method addressed the difficulty in measuring the strain to failure due to stress concentrations at the load introduction regions. They defined hybrid effect as the enhancement in strain and stress to failure of the low strain fibres in the thin-ply hybrid composite, compared to those obtained in hybrid specimens with thick carbon plies where it was found that there is no hybrid effect.

The performance of the pseudo-ductile QI layups is influenced not only by the UD laminates' design parameters, but also by the stacking sequence of the plies. Recently, two different stacking approaches were used to fabricate pseudo-ductile hybrids to make a QI hybrid laminate; (i) orientation-blocked method, where the hybrid laminates were fabricated from optimised UD hybrid sub-laminates [22] and (ii) orientation-dispersed method in which the hybrid laminates were made from different non-hybrid multi-directional sub-laminates [23]. A nonlinear stress–strain response was achieved in both cases, however, using the orientation-blocked concept, there were significant free-edge delaminations. The orientation-dispersed method is considerably better to decrease interlaminar stresses at the free-edges and to suppress free-edge delamination [23].

Previous studies indicated that the pseudo-ductility is achieved in the QI hybrids in one loading orientation when subjected to tension [22,23]. However, most composite structures are subjected to multiple loading orientations, therefore, the aim of this paper is to study the potential of thin-ply carbon/glass hybrid laminates and

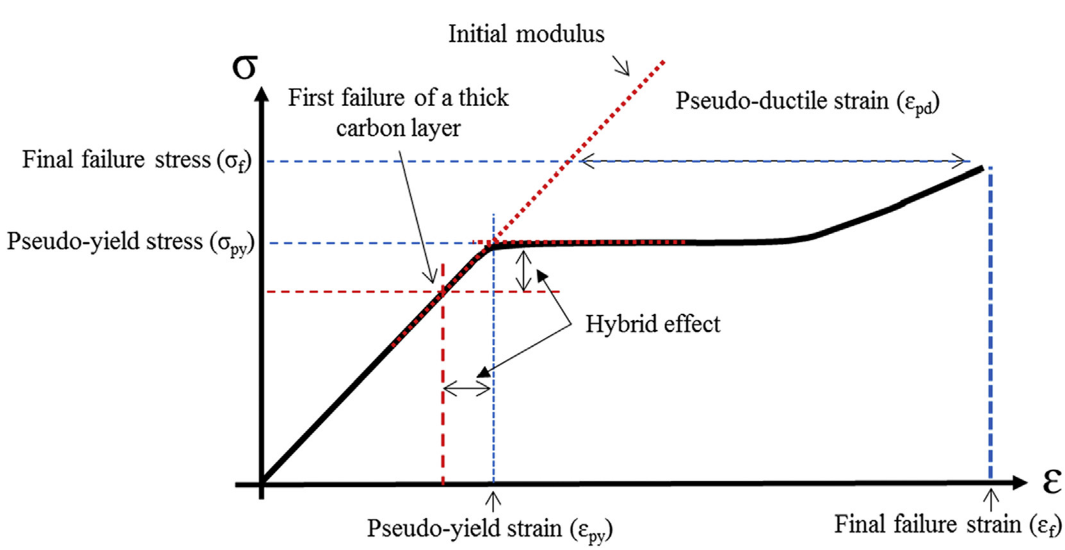

Fig. 2. Schematic of the stress–strain graph of a thin-ply hybrid with pseudo-ductility.