DEMONSTRATION OF PSEUDO-DUCTILITY IN ALL FIBRE DIRECTIONS OF HIGH PERFORMANCE QUASI-ISOTROPIC THIN PLY CARBON/GLASS HYBRID COMPOSITES

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ABSTRACT

Hybridisation is one of the approaches to introduce pseudo-ductility to brittle composite materials. In this approach, two or more different types of fibre are combined and if the configuration and material constituents are well selected, the tensile response shows a gradual failure and a metal-like stress-strain curve with a pseudo-yield point. Different types of unidirectional and quasi-isotropic (QI) hybrid composites with continuous layers have been studied to produce pseudo-ductile tensile behaviour in one loading orientation when subjected to tension. However, real composite structures are subjected to multiple loading orientations, therefore, the aim of this paper is to exploit the potential of thin-ply carbon/glass hybrid laminates and the dispersed orientation method to generate high performance QI composite plates that show pseudo-ductility in all the fibre orientations under tensile loading. QI sub-laminates were used to fabricate novel architectures made up of a QI Skyflex thin ply high strength T300-carbon/120˚C epoxy sub-laminate sandwiched between the two QI Hexcel and standard thickness S-glass/913 epoxy sub-laminates. The results show that by choosing an appropriate ratio of the carbon thickness to the laminate thickness and material properties, a desirable pseudo-ductile failure can be achieved in all the fibre orientations.

1 INTRODUCTION

Due to the high stiffness and low density of polymer matrix composites, these materials are being increasingly used in various applications such as aerospace, automotive, etc. However, composites are usually brittle and their failure can be sudden and catastrophic, with little or no warning and usually poor residual load-carrying capacity if any.

Hybridisation of different types of fibres is one of the methods that can introduce gradual failure in composite materials [1]. Recently, thin-ply unidirectional and quasi-isotropic (QI) hybrids of different types of low strain and high strain fibres were introduced that generated a nonlinear stress–strain response and pseudo-ductility that avoids the catastrophic failure in laminated composites [2-4]. The nonlinear stress–strain response is caused by multiple fractures of the low strain fibre, and the stable delaminations caused due to the low energy release rate of the thin plies. Until now, the pseudo-ductility in tension has been achieved in the hybrids in one loading orientation, whereas, real composite structures are subjected to multiple loading orientations.

The present study focuses on exploiting the potential of thin-ply carbon/glass hybrid laminates to generate high performance QI composite plates that show pseudo-ductility in all the fibre orientations under tensile loading.

2 EXPERIMENTAL PROCEDURES

2-1- Materials, manufacturing and testing

Investigated QI hybrid laminates were made from UD S-glass/913 epoxy prepreg and T300 carbon/ epoxy prepreg. Table 1 gives information about the properties of the utilised prepregs. The resin systems in the hybrid laminates were 120 ºC curing epoxies, which were found to be compatible. The laminates were cured in an autoclave at the recommended cure temperature and pressure cycle for the Hexcel 913 resin (60 min at 125 ºC, 0.7 MPa), which was also satisfactory for the carbon. Specimens

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were cut using a diamond-cutting wheel. End tabs made of 2 mm thick woven glass/epoxy plates supplied by Heathcotes Co. Ltd. were bonded to the specimens using a two component Araldite 2000 A/B epoxy adhesive supplied by Huntsman, the components were mixed with the volume fraction ratio of 100: 50 for A: B respectively and cured for 120 minutes at 80 ºC inside a Carbolite oven.

Tensile testing of the hybrid laminates was performed under uniaxial tensile loading and displacement control using a crosshead speed of 2 mm/min on a computer controlled Instron 8801 type 100 kN rated universal hydraulic test machine with wedge-type hydraulic grips. The nominal specimen dimensions for this testing were 240/160/20/h mm overall length/free length/width/variable thickness respectively. To measure the strains with a nominal gauge length of 130 mm, an Imetrum video gauge system was used by tracking the dotted pattern applied on the specimen face.

Prepreg type	S-glass/epoxy [3]	USN020A (T300/epoxy) [2]
Fibre failure strain (%)	5.5	1.5
Cured nominal thickness (mm)	0.155	0.029
Fibre mass per unit area (g/m^2)	190	21
Fibre volume fraction (%)	50	40.5
E1 (GPa)	45.7	101.7

Table 1: Characteristics of the prepregs and fibres applied.

2-2- Specimen design

Table 2 shows the hybrid specimen types and the sequences that they were laid up. From Table 2 and as is shown in Figure 1, adding the specified angles to the orientation of each sub-laminate, in the ±60QI/0° laminate, produces the other layups, when the 0 direction is defined as the loading direction.

Specimen type	Resulting layup
±60QI/0°	$[60_{S\text{-}glass}/-60_{S\text{-}glass}/\underline{\mathbf{0_{S\text{-}glass}}}/\underline{\mathbf{0_{C\text{-}T300}}}/60_{C\text{-}T300}/-60_{C\text{-}T300}]_s$
±60QI/+60°	$[-60_{S\text{-}glass}/\underline{\mathbf{0_{S\text{-}glass}}}/60_{S\text{-}glass}/60_{C\text{-}T300}/-60_{C\text{-}T300}/\underline{\mathbf{0_{C\text{-}T300}}}]_s$
±60QI/-60°	$[\underline{\mathbf{0_{S\text{-}glass}}}/60_{S\text{-}glass}/-60_{S\text{-}glass}/-60_{C\text{-}T300}/\underline{\mathbf{0_{C\text{-}T300}}}/60_{C\text{-}T300}]_s$

Table 2: Layups of the investigated laminates, 0 plies highlighted in red.

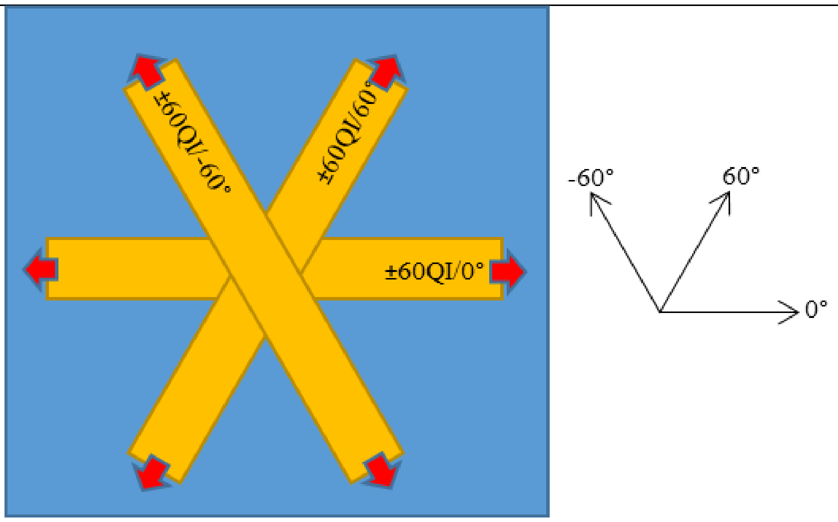

Figure 1: Schematic of the investigated laminates in a QI composite sheet, the red arrows showing the loading directions.

The layups were chosen using appropriate values of relative thickness (i.e. proportion of the low strain fibre plies) and absolute thickness of the carbon fibre plies. Pseudo-ductile response is achieved by suppression of catastrophic delamination and appearance of damage modes of (i) fragmentation in the carbon plies and (ii) local delamination. This has been done through using damage mode maps, similar to those for UD laminates [3]. To do so, the multi-directional glass and carbon laminates were assumed to be homogenised. The damage mode map with calculated boundaries between the different regions is illustrated in Figure 2. The thickness of carbon plies and the proportion of carbon plies in the investigated hybrid layups were chosen in the Frag. & Del. region to get the desired damage scenario.

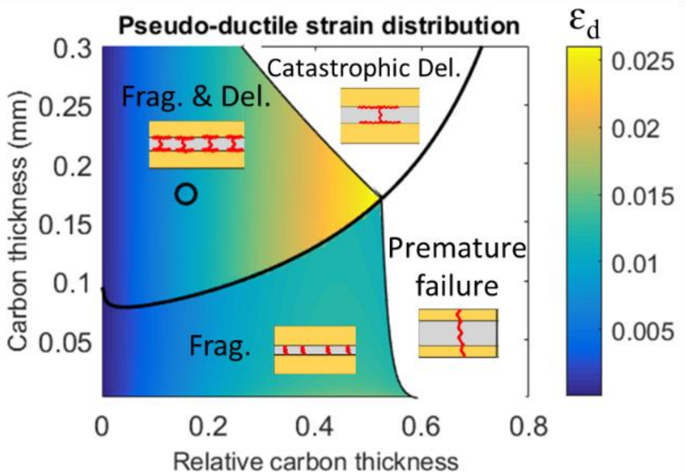

Figure 2: Distribution of pseudo-ductile strain for the investigated ±60QI and ±45QI specimens.

3 RESULTS AND DISCUSSION

3-1- Mechanical results:

Figure 3 shows the overall tensile stress–strain graphs obtained from the investigated hybrid specimens, based on the average stress calculated using the measured specimen. Analysing the curves, all the laminates failed in the desired pseudo ductile manner, with consistent stress-strain curves, without any catastrophic delamination and with obvious plateau. This failure behaviour is in good agreement with that expected from the design considerations. The carbon fibres started to fragment near the knee-point which was then followed by a plateau due to stable progressive carbon plies fragmentation and local delamination of the carbon fragments. After the plateau, the stress started to increase as fragmentation was fully saturated, the contribution of the carbon plies to the specimen stiffness was diminished and the glass plies carried most of the increase in load.

Table 3 gives some of the important features of the stress–strain graphs such as the initial elastic modulus, pseudo-yield strain, and pseudo-ductile strain of these hybrid configurations. The pseudo-yield strain is the strain level at which the tensile response deviates from the initial linear elastic behaviour and the final failure strain is the point that the high strain material cannot carry any more load and 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. Pseudo-yield strain values were defined as the intersection of two lines fitted to the stress-strain graph before and after the fragmentation initiation point. From Table 3 and Figure 4, the elastic response of the layups is identical; however, the average pseudo-yield strains and the average pseudo-yield stresses are slightly different. This enhancement in strain and stress to failure of the low strain fibres in the ±60QI/0° laminate (1.8%), compared to the other laminates (1.6%), is called hybrid effect.

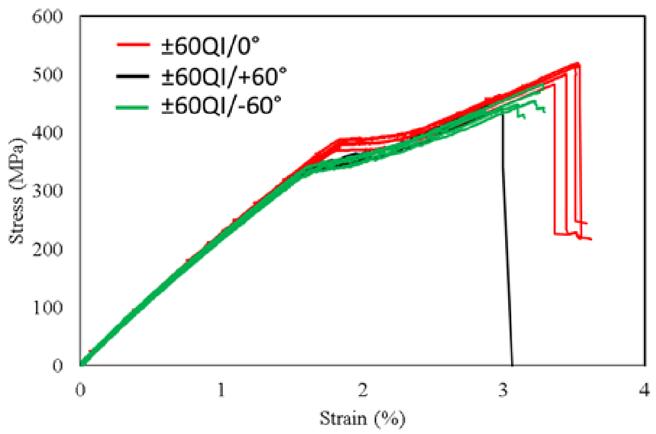

Figure 3: Results of the tensile tests for the investigated laminates.

Table 3: Summary of the test results for the hybrid specimens.

Specimen type	Initial in-plane elastic modulus (GPa)	Pseudo-yield stress (MPa)	Pseudo-yield strain (%)	Pseudo - ductile strain (%)	Final failure strain (%)	Final failure stress (MPa)
±60QI/0°	23.5±0.1	379±6	1.80±0.02	1.30±0.05	3.5±0.10	504±18
±60QI/+60°	23.1±0.2	334±3	1.60±0.04	1.15±0.10	2.95±0.15	436±14
±60QI/-60°	23.2±0.1	335±7	1.60±0.02	1.20±0.06	3.2±0.10	464±16

3-2- MICROSCOPIC OBSERVATIONS

Microscope images taken through the laminates thickness by polishing the laminates, interrupted before the final failure, ply by ply, showed that the fragmentations were only in the 0° carbon plies. As an instance, Figure 4 shows microscopy pictures from the polished surface of the ±60QI/-60° laminate at different depths through the thickness. Fragmentations were observed only in the 0° carbon plies. Similar results were obtained for all the investigated specimens. Figure 5 shows the fragmentation pattern in the 0° carbon layer over the width of the investigated layups after removing the top layers. The highest fragmentation crack density and the smallest average fragmentation spacing is observed in the ±60QI/0° which is believed to be due to the highest hybrid effect in this configuration. The other laminates have significantly lower fragmentation cracks densities, compared with the ±60QI/0°. For the ±60QI/0° laminate, the nearby 0° glass ply has a significantly higher stiffness compared to the off-axis glass layers. So, when it is next to the fragmenting 0° carbon layer, the stress concentration at a single carbon fibre break would be lower as the glass ply can significantly contribute to carrying load around a subcritical cluster of broken fibres [5]. This explains the highest average pseudo-yield strain (1.80%) and the highest fragmentation crack density in the ±60QI/0° laminate. More details regarding the hybrid effect can be found in [6-7].

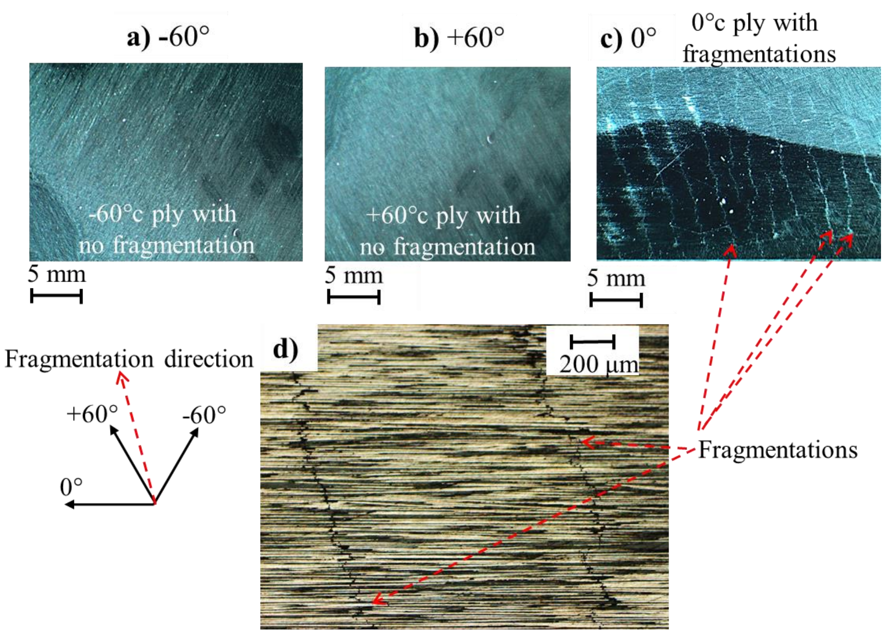

Figure 4: Microscopy pictures from the polished surface of the ±60QI/-60° laminate at different depths through the thickness a) the -60° carbon ply with no fragmentation, b) the +60° carbon ply with no fragmentation, c) the 0° carbon ply with fragmentation and d) the 0° carbon ply, microscopy picture with higher zoom.

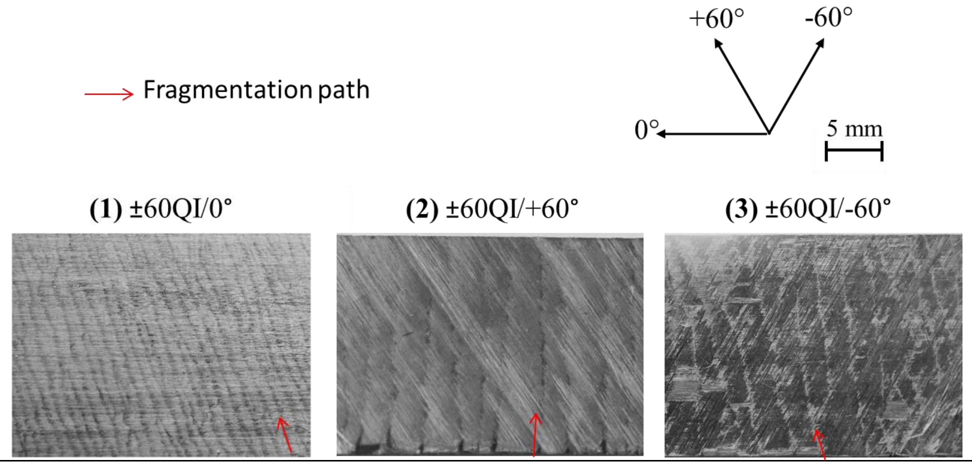

Figure 5: Fragmentation pattern in the 0° carbon layer over the whole width of the investigated layups after removing the top layers.

4- CONCLUSIONS

This aim of this work was to generate high performance QI composite laminates that show pseudo-ductility in all the fibres orientations under tensile loading. Novel QI thin-ply carbon/glass hybrid laminates made from non-hybrid multi-directional sub-laminates with different fibre types were put together to build the hybrid laminate. The investigated QI laminates showed the desired pseudo-ductility in all the fibre directions, with an obvious plateau and without any catastrophic delamination before the final failure. Microscopic observation showed carbon ply fragmentations just in the 0° carbon plies. It was observed that altering the stacking sequence influences the stiffness of the plies adjacent to the 0° fragmenting carbon plies, therefore, leads to changes in the pseudo-yield strain. A significant hybrid effect was observed for the ±60QI/-60° laminate where the 0° carbon plies were adjacent to the 0° glass plies that have the highest stiffness in the loading direction, compared with the other configurations.

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