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Notch insensitive orientation-dispersed pseudo-ductile thin-ply carbon/glass hybrid laminates

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ABSTRACT

Notch sensitivity, free edge delamination and brittle failure are limiting factors for the wider use of conventional composite laminates. In our previous study, a hybrid layup concept with the different materials blocked together but with dispersed orientations was successfully used to design pseudo-ductile hybrid composites with no free-edge delamination. This study introduces a comprehensive set of designed and characterised orientation-dispersed pseudo-ductile thin-ply hybrid composites to address notch sensitivity, another important limiting factor in conventional composite laminates. Un-notched, open-hole and sharp notched tension tests were performed on three different thin-ply carbon/glass hybrid configurations. The investigated laminates showed a successful pseudo-ductile un-notched behaviour with improved notch-insensitivity and suppression of free-edge delamination that was an undesirable damage mode in previously investigated hybrids with plies of the same orientation blocked together. This notch insensitivity results from subcritical damage in the laminates due to the pseudo-ductile damage mechanisms, i.e. dispersed delamination and fragmentation. These damage mechanisms can eliminate stress concentrations near the notch and suppress the conventional damage mechanisms that govern the notched response of the laminates.

1. Introduction

Composite materials have high specific stiffness and strength and their use has been increasing in engineering applications. However, cutouts and holes are necessary for the geometry and assembly of composite sub-components and they weaken the laminate. Due to the importance of the notched strength in the design of composite structures, considerable research has been undertaken to investigate the notched behaviour of these materials [1–5].

Many parameters such as notch size and geometry, laminate size and thickness, machining quality, ply orientation and thickness, and material constituents affect the complex failure mechanisms during the loading of notched laminates [6–14]. These parameters change the damage mechanisms during loading and have a profound effect on laminate strength and notch sensitivity. In some cases [8,9,15] a positive effect on specimen ultimate strength was reported due to the damage growth prior to catastrophic failure, but conventional laminates always show some degree of notch sensitivity.

Thin-ply composites have been reported to show enhanced un-notched strength in tension, potential for improved compressive unnotched and notched strength and higher fatigue resistance [16–21]. However, due to the lower local stress redistribution in the vicinity of the notch, thin-ply laminates have a negative impact in notched structures loaded in tension that results in earlier brittle failure of the composites [20]. Early work on pseudo-ductile composites [22–28] reported that by combining different types of thin-ply carbon fibres and standard glass fibres, an optimised gradual failure process can be achieved in tension that can avoid catastrophic failure. In these studies, unidirectional hybrids were used to generate pseudo-ductile behaviour, with the concept then applied on quasi-isotropic (QI) laminates [29–31]. It was found that by changing the relative and absolute thickness of the carbon layer as well as the material properties, three damage mechanisms, i.e. low strain material failure/fragmentation, delamination, high strain material failure, or a combination of these damage modes may occur before the final failure.

Un-notched and notched tensile response and damage accumulation of multi-directional carbon/epoxy hybrid laminates made from ultra-high modulus and high strength have been studied [29]. Locally active fragmentation in the notched QI specimens demonstrated a notch-insensitive behaviour, but a significant free edge delamination occurred

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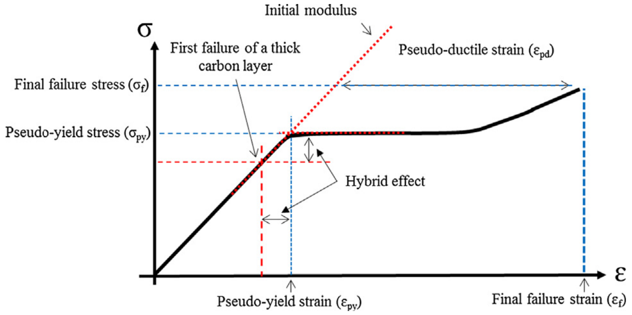

Fig. 1. Schematic of the stress–strain graph of a thin-ply hybrid with Pseudo-ductility.

due to the choice of the UD hybrid sublaminates that were used as the building blocks of the hybrid laminates. This is due to high thickness of each sub laminate in this orientation-blocked concept, resulting in high-energy release rates for free-edge delamination. A different orientation-dispersed concept was recently introduced [30] in which non-hybrid multi-directional sublaminates with different fibre types are stacked up to solve the free edge delamination by reducing the thickness of material of the same orientation. It was shown that the orientation-dispersed concept significantly reduces the energy release rate associated with stresses at the free edges of the tensile samples and therefore suppresses free-edge delamination.

This paper presents a comprehensive set of designed and characterised orientation-dispersed pseudo-ductile thin-ply hybrid laminates to improve notch insensitivity and to avoid free edge delamination in tension. The introduced thin-ply hybrid configurations show pseudo-ductile damage mechanisms that suppress the mechanisms that govern the notched response of conventional laminates.

2. Pseudo-ductility features

Fig. 1 shows a schematic of the stress–strain graph for a thin-ply hybrid with pseudo-ductile behaviour. The five important features of the nonlinear stress–strain curve are as follows:

(i) Pseudo-ductile strain (ε_{pd}) which is the extra strain obtained due to gradual failure. The ε_{pd} is defined here as the extra strain between the final failure point and the initial slope line at the failure stress level as shown in Fig. 1.
(ii) Pseudo-yield stress (σ_{py}) which is the stress level at which the tensile response has a significant deviation from the initial linear elastic behaviour.
(iii) Pseudo-yield strain (ε_{py}) which is the strain level at which the tensile response deviates significantly from the initial linear elastic behaviour. Pseudo-yield strain values are defined as the intersection of two lines fitted to the stress-strain graph before and after the knee point that marks the establishment of the fragmentation process.
(iv) ε_f and σ_f are the final failure strain and stress values at which fibre failure of the high strain material occurs, respectively.
(v) The hybrid effect is defined here 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 [26].

3. Experimental procedures

3.1. Materials and specimen design

Properties of the 4 types of prepregs that were used in the experimental design are listed in Table 1. Some of these are estimates, but they are sufficient to enable appropriate combinations of materials to be selected. Unidirectional (UD) Xstrand-glass/513 epoxy prepreg manufactured by North Thin-ply Technology and UD S-glass/913 epoxy prepreg supplied by Hexcel were used as the high strain materials of the hybrid laminates. The low strain materials were thin UD carbon prepregs, M46JB-carbon/120EP-513 epoxy from North Thin-ply Technology and T300/epoxy (SkyFlex USN020A) from SK Chemicals (South Korea).

The investigated layups are schematically illustrated in Fig. 2 and listed in Table 2, where, in the layup column, the first numbers show the orientations of the sub-laminates in degrees. AP is the abbreviation of Angle Ply. The non-zero degree layers in the ± 60QI/Hexcel, ± 60 QI/North and ± 30AP/North laminates are ± 60°, ± 60° and ± 30°, respectively. The (1) and (2) refer to the number of separate blocks of carbon in the North layups, i.e. (1) has a single block of 6 carbon plies, whereas (2) has two blocks of 3 plies each.

The layups were designed in a similar way as the previously investigated pseudo-ductile QI laminates [30], using damage mode maps and choosing appropriate values of absolute and relative thicknesses of the carbon fibre plies. Choosing the appropriate values suppresses catastrophic fibre failure and delamination and results in pseudo-ductile damage mechanisms (i) fragmentation in the carbon plies and (ii) local delamination. The calculations were done by homogenising the multi-directional glass and carbon sub-laminates, using Classical Laminate Theory. The failure strain of the homogenised materials was assumed to be equal to the fibre failure strain of the 0° layers. This is an acceptable assumption as the stiffness reduction in the deterioration process of the homogenised QI laminate is mainly due to 0° carbon layer fragmentation and the final failure of the QI glass is because of 0° glass failure. Although this assumption may not be completely accurate due to possible hybrid effects, it is a reasonable basis to design the configurations. Most of the strength and stiffness of each layer is coming from the 0° layers and fragmentation/failure of this layer means a big drop in the stiffness of the remaining parts or failure of the whole laminate. Although the fracture toughness of the investigated hybrid interfaces was not characterised directly, our previous experiments, on similar UD hybrid materials comprising the same combinations of epoxy matrix systems as those of this study [24,29,36], indicated that the Hexcel and Sky Flex prepregs have higher mode II toughness ($G_{IIc} \sim 1$N/mm) than those of the North Thin-ply Technology prepregs ($G_{IIc} \sim 0.7$ N/mm). Therefore, interfacial fracture toughness values between the glass and carbon layers, G_{IIc}, were assumed to be 1 N/mm and 0.7 N/mm for the Hexcel and North configurations, respectively.

The resulting damage mode maps with the calculated boundaries between the different regions are illustrated in Fig. 3. The terms “Relative carbon thickness” and “Carbon thickness” are referring to the thickness of the carbon layers divided to the total thickness of the laminate, and the absolute thickness of the carbon layers that are sandwiched between the glass layers, respectively. The colours represent the expected amount of pseudo-ductile strain. The thickness and proportion of carbon plies in the ± 30AP/North (2), ± 60QI/North (1) and ± 60 QI/Hexcel configurations are in the Fragmentation and Dispersed Delamination (Frag. & Del.) regions. Therefore, the damage scenarios in these laminates are expected to be fragmentation in the low strain material followed by dispersed delamination and then high strain material failure. For the ± 60QI/North (2), multiple fractures in the low strain material and then high strain material failure are predicted by the damage mode map. The ± 30AP/North (1) laminate is in the Catastrophic Del. region and a premature failure of the high strain material is expected. Even though the designed ± 30AP/North (1) and ± 60QI/North (2) laminates did not look promising regarding the desirable pseudo-ductility, they were selected to have a good set of experimental data and to compare their behaviour with the other notched and un-notched designed configurations. Please note that the damage mode maps are obtained for the un-notched samples and damage mechanisms in the notched configurations might be slightly different.