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Reduced notch sensitivity in pseudo-ductile CFRP thin ply angle-ply laminates with central 0° plies

Xun Wu*, Jonathan D. Fuller, Marco L. Longana, Michael R. Wisnom

Bristol Composites Institute (ACCIS), University of Bristol, Bristol BS8 1TR, United Kingdom

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ABSTRACT

This paper presents an experimental investigation on the unnotched and open-hole tensile behaviour of pseudo-ductile thin ply angle-ply carbon fibre/epoxy laminates with central 0° plies. Laminates with two different configurations of $[\pm 26_5/0]_s$ and $[\pm 25_2/0]_s$ were designed and tested under unnotched and open-hole tensile loading. Metal-like tensile stress-strain curves with a plateau were observed in both unnotched configurations. The open-hole net-section strength of the $[\pm 25_2/0]_s$ laminate attained 96% of the unnotched "yield" strength. Digital image correlation and X-ray CT-scan images showed that the same damage mechanisms of central 0° ply fragmentation and local dispersed delamination observed in unnotched pseudo-ductile laminates were present in the open-hole specimens of the same configuration. These damage mechanisms caused stress redistribution around the hole and reduced the notch sensitivity in pseudo-ductile laminates under open-hole tensile loading. The main factors governing the open-hole performance are also discussed.

1. Introduction

One of the main limitations of high performance carbon fibre reinforced polymer composites (CFRP) is that they can fail catastrophically without any warning, so a greater safety margin needs to be considered when designing a structure from CFRP. Therefore, achieving "ductility" in carbon fibre composites is crucial and up to now, a number of different approaches have been developed, such as introducing ductile constituents [1–4] or by re-designing the architectures of carbon fibre laminates, for example using the extra strain generated by fibre reorientation [5–8] and making hybrid composites via either interlayer/ply-by-ply hybrids [9–12] or intermingled hybrids [13,14].

By using the fibre reorientation approach, Fuller et al. [7] showed that gradual failure can be achieved in a thin ply angle-ply laminate with central 0° plies. A high ultimate tensile strength and strain to failure have been found in $[\pm \theta_n]_s$ laminates using thin ply prepreg [5,6]. Subsequently, an analytical model was developed to predict the behaviour of $[\pm \theta_n/0_m]_s$ laminates, by incorporating the non-linear behaviour of angle plies and several possible failure modes such as 0° ply fragmentation, Mode II dispersed delamination at the $-\theta/0$ interface and fracture of the angle plies [7]. The predictions were then validated by experiment. A metal-like pseudo-ductile tensile stress-strain behaviour was experimentally demonstrated for a $[\pm 26_5/0]_s$ laminate with Skyflex USN020 prepreg (with fibre type TR30 and nominal ply thickness t = 0.03 mm) for all plies and the results showed a good agreement with the analytical model. A considerable strain to failure of 4.2% with a "yield" stress of 692 MPa was attained.

Pseudo-ductility and unique damage mechanisms have been found in these thin ply angle-ply laminates in tension. However, to progress these laminates towards real applications, their open-hole behaviour needs to be understood since the presence of stress concentrations can lead to catastrophic failure and significant strength reduction.

In previous research, notch sensitivity has been found to be related to the damage within the laminate prior to the final failure. In order to understand the relation between damage and notched strength, Kortschot and Beaumont [15] conducted a series of tensile tests on notched cross-ply laminates and employed an X-ray machine to monitor damage in the specimen. They concluded that the sub-critical damage in cross-ply laminates, such as 0° ply splitting, transverse ply cracking and delamination, can redistribute the stress and have a significant influence on the notched strength of the laminate.

The effect of sub-critical damage on notched strength has also been discussed in studies of laminate thickness and scaling effects in notched composites. Harris and Morris [16] tested a number of quasi-isotropic (QI) laminates with different numbers of sub-laminates in order to study the role of delamination and damage on notched strength. They found that the notched strength was reduced in thicker laminates, since delamination growth was limited in the through thickness direction. Green et al. [17] carried out a series of open-hole tensile tests with

* Corresponding author.
E-mail address: xunxun.wu@bristol.ac.uk (X. Wu).

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different hole diameters and ply thicknesses to investigate the scaling effects in notched composites. The results showed the trend that having less sub-critical damage in a laminate with less ply blocking, resulted in a larger strength reduction. This is due to the fact that sub-critical damage can redistribute the stress around the hole and delay the onset of final failure.

From the studies mentioned above, it is clear that the notch-sensitivity of a laminate is highly related to the damage development within the laminate prior to final fracture. Subcritical damage can redistribute the stress concentration at the notch-tip and therefore achieve a higher notched strength. However, this could be a concern with laminates using thin plies, since the damage suppression characteristic in thin plies has been shown to be sensitive to notches [18–21]. In all of these studies, the unnotched tensile strength increased considerably with a reduction in ply thickness, but the open-hole tensile strength can be at least 10% lower than the thicker one, whilst failing in a more brittle manner.

In order to improve the notched performance of thin-ply laminates and maintain the benefits of using thin ply prepreg, it is necessary to design the laminate with "built in" damage. Furtado et al. [19] developed a selective ply-level hybridisation concept, which combined off-axis thin plies with standard thickness 0° plies in a QI laminate. The splitting of the 0° plies was the main mechanism for reducing notch sensitivity and the thin off-axis plies delayed or suppressed further delamination within the gauge section. Jalalvand et al. [22] also suggested based on numerical modelling, that the notch sensitivity can be reduced in QI laminates made from pseudo-ductile thin-ply hybrid sub-laminates. The results showed that when the ratio of pseudo-ductile strain to "yield" strain is sufficiently high, the stress concentration can be reduced since damage of the pseudo-ductile thin-ply hybrid sub-laminate initiated and re-distributed the stress around the hole.

The aim of this paper is to investigate the open-hole tensile performance of pseudo-ductile thin ply angle-ply laminates based on a single hole size, to understand the role of the damage mechanisms of these pseudo-ductile laminates on their notch sensitivity and compare the open-hole performance of two different layups. The damage within the laminates was studied using Digital Image Correlation (DIC) during testing and X-ray CT-scan techniques for post-failure analysis. The factors that govern open-hole performance are also discussed.

2. Methods/experimental testing

As mentioned in the work of Javalvand et al. [22], in a pseudo-ductile thin ply glass-carbon hybrid QI laminate, notch sensitivity is expected to decrease with increasing ratio of pseudo-ductile strain to "yield" strain (termed strain ratio) and it can potentially be eliminated when the strain ratio is greater than 3. The definition of pseudo-ductile strain, the "yield" strain and other key measures used in pseudo-ductile laminates are presented in Fig. 1.

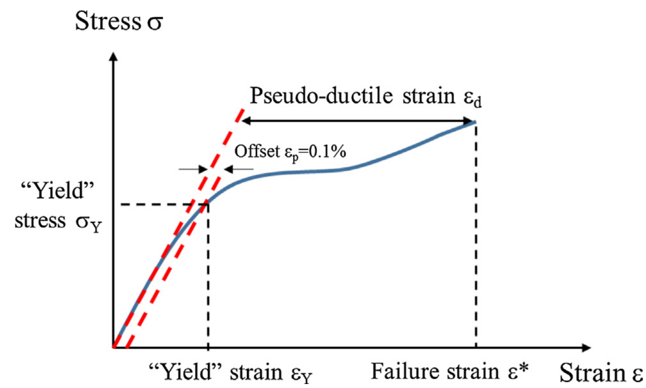

Fig. 1. Definition of pseudo-ductile strain and other key parameters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Inspired by this, in the current paper, two different pseudo-ductile thin ply angle-ply laminate configurations are presented: one is a laminate with a strain ratio higher than 3 and the other one has a low strain ratio for a contrasting study. The design of the unnotched specimens follows an analytical method developed by Fuller et al. [7].

2.1. Design concepts for unnotched specimen

The criteria used in the design of a pseudo-ductile $[\pm\theta_m/0_n]_s$ laminate follow the analytical method presented by Fuller et al. [7] and is briefly summarised here. Two types of design considerations are made in order to promote the failure in a pseudo-ductile manner:

(1) Once the fibre failure strain of the 0° plies has been reached, the central 0° plies start to fracture and ± θ° plies have to be sufficiently strong to withstand the increased stress at the tip of the crack through the thickness of the adjacent 0° plies (σ_{crack}) to avoid angle-ply failure and ensure the multiple fractures in the central 0° plies (termed fragmentation) that leads to gradual failure. σ_{crack} is calculated as:

$$\sigma_{crack} = K_t\sigma_x\left(\frac{t}{t_{AP}}\right) \tag{1}$$

where σ_x is the laminate applied stress, t_{AP} is the thickness of angle plies, t is the total laminate thickness and K_t is an assumed stress concentration factor (SCF). An approximate value of 1.08 predicted from a finite element analysis, was used for all of the laminates [11].

(2) The stress concentration at the crack tip promotes a Mode-II delamination at the 0/θ interface. The second design criterion is to assess the delamination stress, ensuring it is higher than the fragmentation stress to avoid the complete delamination of the specimen after the first fracture. The delamination stress σ_{del} is governed by:

$$\sigma_{del} = \frac{1}{t_{AP}+t_{UD}}\sqrt{\frac{2G_{IIc}E_x^{AP}t_{AP}(E_x^{AP}t_{AP}+E_{11}t_{UD})}{E_{11}t_{UD}}} \tag{2}$$

In this equation, G_{IIc} denotes the critical Model II fracture energy, subscripts "UD" and "AP" denote the properties of the 0° plies and angle plies respectively, and E_x^{AP} and E_{11} represent the stiffness of the angle plies and 0° plies respectively.

To achieve the required strain ratio, two approaches can be used, either by increasing the final failure strain or reducing the "yield" strain. Standard modulus fibres normally have a relatively high fracture strain, for example 1.6% for the T300 carbon fibre [23], and a high failure strain of 6% is required for the laminate, which is difficult to achieve in angle-ply laminates whilst retaining good strength and stiffness. Therefore, high modulus fibre prepreg has been used to replace the standard modulus fibre prepreg in the central 0° plies, since the high modulus fibres have a lower fracture strain, for example 0.5% for the TORAYCA YSH70A carbon fibre [24]. Finally, two different laminates were selected in the present study: SM-SM $[\pm 26_5/0]_s$ laminate, where "SM" stands for standard modulus fibre prepreg, and IM-HM $[\pm 25_2/0]_s$, where IM and HM denote intermediate and high modulus fibre prepreg respectively. The SM-SM laminate was based on a similar configuration presented in [7]. In the IM-HM laminate, since the central 0° plies were replaced by high modulus fibre prepreg, the angle plies were adjusted to ± 25° to ensure that they would be strong enough to carry the stress redistribution after the fracture in the 0° plies.

2.2. Materials and laminate specifications

The materials used in each of the tests are commercially available