OPEN-HOLE RESPONSE OF PSEUDO-DUCTILE THIN-PLY ANGLE-PLY LAMINATES

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Abstract

The aim of this study is to experimentally investigate the open-hole tensile response of pseudo-ductile thin-ply angle-ply laminates and to design laminates with reduced notch sensitivity. Thin-ply angle-ply laminates with $[(\pm 26)_5/0]_{s2}$ configuration were tested in both unnotched and open-hole tension and damage was characterized using ultrasonic C-scan. A pseudo-ductile stress-strain tensile response with pseudo-ductile to initial strain ratio of 1 has been achieved in unnotched tensile testing. In terms of open-hole performance, it is shown that 65% of the unnotched yield strength was retained and C-scan imaging revealed that no obvious damage was detected in a specimen interrupted at 95% of ultimate load. In addition, a finite element study suggests that a better performance could be achieved if the pseudo-ductile to initial strain ratio is increased.

1. Introduction

One of the main limitations of carbon fibre reinforced composites is the brittle and catastrophic failure. Recent research within the High Performance Ductile Composites Technologies (HiPerDuCT) programme has shown that pseudo-ductile carbon fibre reinforced plastics (CFRP) laminates can be achieved via several approaches. One of these approaches is using a hybrid concept, either using glass-carbon or carbon-carbon hybrids. Several novel configurations, consisting of low strain thin-ply uni-directional (UD) carbon in the middle and high strain standard glassfibre prepreg on both sides of the carbon have been tested under tensile loading by Czél et al [1]. A pseudo-ductile failure can be achieved but highly depends on the material properties, absolute and relative thickness of UD and glass plies.

In order to design hybrid laminates to fail under desired modes, Jalavand et al developed both analytical and numerical models for predicting stress-strain responses and damage modes of UD hybrid composites [2–4]. Three types of damage were introduced into this analytical model. The fracture in the low strain central UD-ply is considered as the first damage mode that occurrs when the overall strain is higher than the fragmentation strain of the UD fibre. Multiple fragmentations occur only if the local stress concentration generated at crack tip is lower than the strength in the high strain material. As these cracks can promote initiation of Mode II delamination, the second damage mode considered here is dispersed delamination at the interface of low and high strain materials on both sides of the fracture surface. The critical delamination onset stress is given in [2]. The last damage mode is fracture in the high strain material. Once the UD-ply is fully fragmented, the high strain material carries majority of the load until it reaches the material strength.

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Another approach suggested by Fuller et al [5–7] is via a fibre re-orientation concept. More specifically, it combines non-linearity of thin-ply angle-ply laminates with UD-ply fragmentation to achieve pseudo-ductility. An analytical model was developed to predict the tensile response of thin-ply angle-ply laminates with $[\pm\theta_m/0_n]_s$ configurations and to determine the failure modes. It is based on a similar damage modes analysis as the hybrid case, but uses pairs of thin angle plies instead of high strain glass materials. If either the absolute or relative thickness of the central UD plies is too large, the stress in the angle-ply can exceed its strength. Therefore, the thickness ratio between the UD and angle-ply needs to be smaller than a critical angle-ply thickness ratio "B_{max}" value which is defined in [7].

The tensile performance of pseudo-ductile thin-ply angle-ply laminates has been well studied. However, their performance under open-hole tensile loading is still unknown. Several studies have investigated open-hole performance of thin-ply laminate based on quasi-isotropic layups [8–12]. It is shown that the damage suppression nature of thin-ply materials improved the unnotched tensile response, but gave an increased notch-sensitivity in the open-hole performance. The concept of ply-level hybridisation has been developed by using a combination of thin-ply and thick-ply CFRP as sublaminates [8,12]. The experimental results revealed that these specimens presented a better open-hole performance compared with monotonic thin-ply or thick-ply because internal damage within thick-ply sublaminate reduced stress concentrations [8].

The aim of this research is to understand the mechanism of pseudo-ductile thin-ply angle-ply laminates under open-hole tensile loading and to reduce their notch-sensitivity. In this paper, laminates were designed with a $[(\pm26)_5/0]_{s2}$ layup using Skyflex USN020A thin-ply prepreg and tested under unnotched and open-hole tension. Damage analysis with ultrasonic C-scan is also presented. Lastly, finite element modelling suggests a possible way of improving the design.

2. Design and experimental procedures

The design of specimen configuration was according to the analytical methods developed by Fuller et al [7] and Jalavand et al [2]. They suggested that the elastic properties of UD and angle plies, the thickness of the central UD-ply and the relative thickness between central UD and angle plies are the governing parameters. The ideal damage modes are in the sequence: central UD plies fragmentations, dispersed delamination and final fracture in the angle-ply.

The materials used for design was the Skyflex USN020A with T300 fibres. Its mechanical properties are given in Table 1. A balanced and symmetric laminate $[(\pm26)_5/0]_{s2}$ with all plies in Skyflex USN020A (USN-USN $[(\pm26)_5/0]_{s2}$) was used. The reason for selecting this configuration was its high pseudo-ductile strain (2.3% pseudo-ductile strain achieved with a similar configuration has been presented in [7]).

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Table 1. Cured ply properties of UD laminate

Prepreg Type	E_1 (GPa)	E_2 (GPa)	σ_1 (MPa)	G_{12} (GPa)	ε_1 (%)	t (mm)	vf (%)
SkyflexUSN020A	121	5.4	1860	2.21	1.6	0.022	52

The definition of all the mechanical parameters for pseudo-ductility correspond to those used in the HiPerDuCT programme and are defined as follows and shown in Figure 1 [6]. The yield strength σ_Y is defined in terms of the 0.25% offset strain and the pseudo-ductile strain ε_d is defined as the difference between the failure strain and strain at the same stress level on the initial modulus.

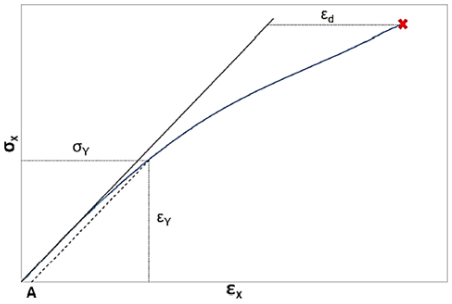

Figure 1. Defnition of parameters for pseudo-ductility [6]

The open-hole tensile testing specimen design was according to the ASTM 5766 standard [13]. A central drilled hole with diameter d = 3.175 mm was used and other details of specimen are specified in Figure 2. Unnotched tensile testing with same layup was also carried out for comparison purpose, with dimension 150 mm in gauge length by 15 mm in width. All tests performed under Instron 25kN universal hydraulic machine with crosshead speed 2 mm/min for unnotched tests and 0.5 mm/min for open-hole tests according to the ASTM standard. Overall longitudinal strain results were obtained from Imetrum Video Gauge.

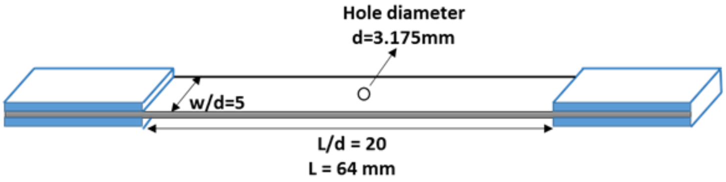

Figure 2. Specimen schematic for open-hole tensile testing

3. Results and Discussion

The typical stress-strain response of the above configuration under unnotched and open-hole tensile loading are presented in Figure 3 and all key results are given in Table 2 and Table 3. The blue line shows the unnotched behaviour and it can be seen that the specimens failed at a strain of 3% and gave a pseudo-ductile strain to initial (yield) strain ratio of close to 1. In terms of open-hole performance, it exhibited a linear stress-strain behaviour up to failure, followed by a brittle fracture. Due to the presence of stress concentrations, the net-section strength of open-hole specimen was only 527 MPa, which had a 35% reduction compared with the unnotched yield strength. As there is a significant strength reduction with the hole present, this configuration is notch-sensitive.

Table 2. Key results from USN-USN $[(\pm26)_5/0]_{s2}$ unnotched tensile testing

Unnotched	E_x (GPa)	σ_Y (MPa)	σ_x* (MPa)	ε_Y (%)	ε_x* (%)	ε_d (%)
USN-USN $[(\pm26)_5/0]_{s2}$	57	793	830	1.62	3.00	1.38

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Table 3. Key results from USN-USN $[(\pm 26)_5/0]_{s2}$ open-hole tensile testing

Open-hole	E_x (GPa)	σ_x^* Net-section (MPa)	$\sigma^*_{\text{Unnotched}} / \sigma^*_{\text{Notched}}$	ε^* (%)
USN-USN $[(\pm 26)_5/0]_{s2}$	58	527	1.52	0.78

Note: in all the tables, “ Y ” denotes to properties at the yield point, “ * ”denotes properties at ultimate load and “d” defines the pseudo-ductile strain. Ultimate strength in the open-hole case is net-section strength, based on the width minus the hole diameter.

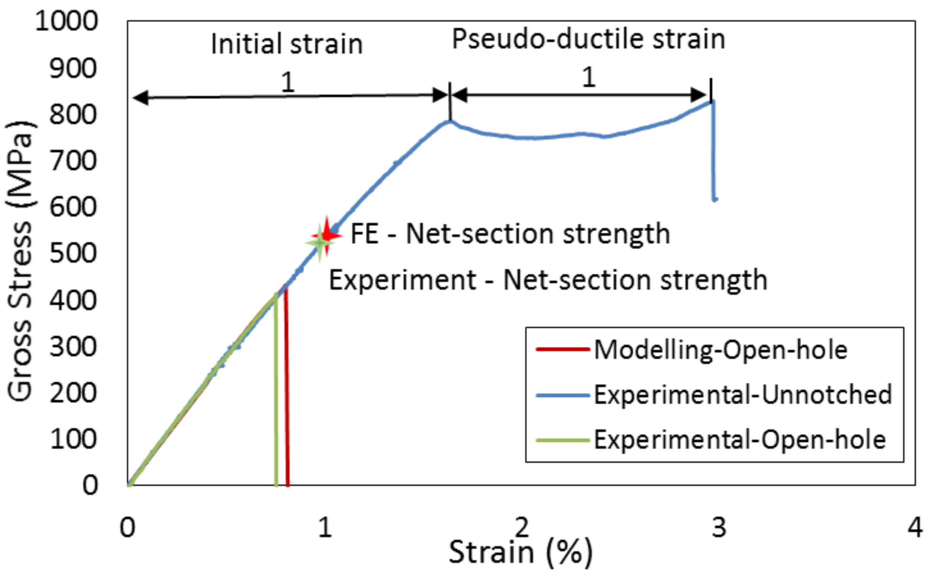

Figure 3. Stress-strain behaviour of USN-USN $[(\pm 26)_5/0]_{s2}$ under open-hole and unnotched tension.

In order to understand the damage development within the specimen with the USN-USN $[(\pm 26)_5/0]_{s2}$ configuration, one of the specimens was interrupted at 95% failure load and then was further characterized using a ultrasonic C-scan with 5MHz probe. As suggested in [2,7], as long as the local strain reaches the UD fibre fragmentation strain, fragmentation in the UD-ply and dispersed delamination are the main damage mechanisms for generating pseudo-ductile behaviour. However, as shown in the C-scan image (Figure 4), no significant damage was observed in the open-hole specimen. It indicates that the previous damage mechanisms in pseudo-ductile thin-ply angle-ply laminates under unnotched tensile loading were not ireproduced in the USN-USN $[(\pm 26)_5/0]_{s2}$ design under open-hole tensile loading.

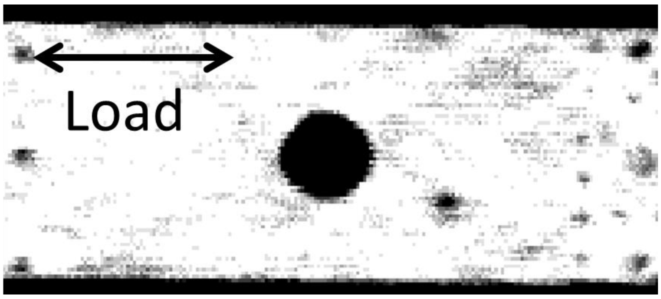

Figure 4. Ulatrasonic C-scan images of specimen under 95% ultimate loading USN-USN $[(\pm 26)_5/0]_{s2}$,

4. Finite element analysis

A finite element analysis (FE) was performed for estimating the overall open-hole stress-strain response of pseudo-ductile thin-ply angle-ply laminates. The FE model used 2D shell elements and was based on a material model in an explicit user subroutine. The FE predicted stress-strain response of USN-USN $[(\pm 26)_5/0]_{s2}$ is presented as the red-line in Figure 3. It can be seen that with unnotched pseudo-ductile to initial strain ratio of 1, the predicted FE net-section strength under open-hole tension is 538 MPa, which is more than a 30% reduction of reduction compared with unnotched yield strength As identified from the stress-strain response and C-scan results, the pseudo-ductile strain margin was not large enough for demage development as the damage initiation strain was close to the failure strain. Therefore, by lowering the damage initation strain, FE suggests that a better performance in open-hole strength can be obtained as shown in Figure 5.

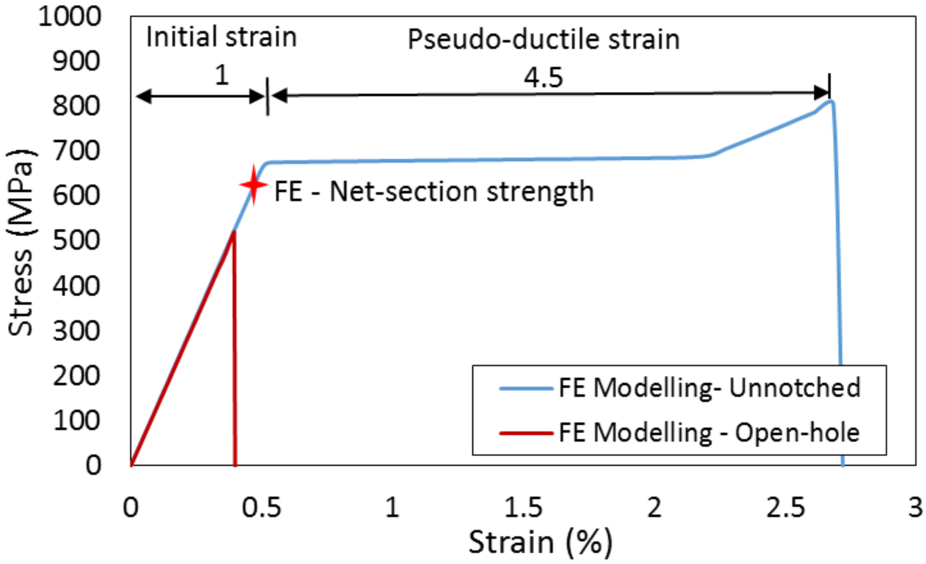

Figure 5. Finite Element predicted open-hole stress-strain response with increased pseudo-ductile strain to initial strain ratio of 4.5

5. Conclusions

Pseudo-ductile thin-ply angle-ply laminates were tested under open-hole tension loading. It was found that layup USN-USN $[(\pm 26)_5/0]_{s2}$ gave a linear stress-strain response with a brittle failure. In terms of strength, only 65% of the unnotched yield strength was retained due to the appearance of stress concentrations. Ultrasonic C-scan was employed to characterize the specimen after testing to 95% of ultimate load. C-scan imaging indicates that no obvious damage was detected, which means that the damage mechanisms of fragmentation and dispersed delamination in unnotched tensile pseudo-ductile laminates were not active in open-hole performance with this layup. In addition, FE model predicted the possibility of reducing notch sensitivity by increasing the pseudo-ductile to initial strain ratio.

Acknowledgments

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