ARE PSEUDO-DUCTILE ALL-CARBON HYBRID LAMINATES NOTCH INSENSITIVE IN OPEN HOLE TENSION?

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Abstract: *The open hole tension response of multidirectional hybrid CFRP laminates with pseudo-ductile (PD) behaviour was investigated by using low- and high-elongation unidirectional (LE/HE UD) CFRP prepregs with conventional thickness. Two stacking sequences [0/45/90/-45]$_s$ (QI45) and [0/60/-60]$_s$ (QI60) were produced by the sub-laminate [HE/LE/HE] to achieve quasi-isotropy. PD sub-laminates were designed by combining Mitsubishi DIALEAD/ER450 (LE) and Toray T800/ER450 (HE) prepregs. The evolution of damage in the open hole laminates was monitored by digital image correlation (DIC) and acoustic emission (AE) recordings. For the considered laminates, with and without open hole, the pseudo-ductile plateau was clearly detected at almost the same stress level. Moreover, open hole QI60 laminates are notch-insensitive, and QI45 showed a limited notch sensitivity. These results can be helpful for the design of all-carbon hybrid composite components adopting small safety factors.*

Keywords: Carbon-carbon hybrid laminates; Pseudo-ductility; Quasi-isotropy; Notch insensitivity

1. Introduction

Hybrid effect and pseudo-ductile tensile behaviour in all-carbon hybrid composites is thoroughly investigated for laminates with thin prepreg plies [1,2] and (in previous publications of the present authors) for laminates with prepregs of conventional thickness [3,4]. Pseudo-ductile behaviour, with a well-developed plateau on the stress-strain diagram, creates post first failure safety, which is a desirable feature for applications where high loads can be present in design scenarios. In this context, the notch sensitivity is of considerable importance. The unnotched safety margin cannot be exploited if it is not preserved in the presence of a notch. The study presented in [2] has demonstrated that thin-ply all-carbon quasi-isotropic laminates preserve the pseudo-ductile behavior in an open hole tension test, and have very limited notch sensitivity. The behaviour has been motivated with the notch (un)sensitivity of ductile metals.

This paper investigates the strength sensitivity to open hole of all-carbon pseudo-ductile hybrid CFRPs made by standard thickness prepregs with a modified (toughened) matrix. The studied hybrids combine low elongation (LE) plies reinforced with high-modulus carbon fibres and high-elongation (HE) plies with intermediate-modulus carbon fibres.

2. Materials, specimens and test methods

Interlayer hybridisation of CFRPs has been realized using unidirectional prepregs with high-modulus DIALEAD fibres (MITSUBISHI) of thickness of about 220 µm and prepregs with high-strength fibres T800 (TORAY) of thickness of about 110 µm. Both prepregs had toughened ER450 epoxy resin [5, 6]. Everywhere below, prepregs with DIALEAD fibres are designated 'D', and T800 fibres are 'T'. During the production process, hybrid sublaminates were assembled, composed of three layers with parallel fibres [T/D/T]. Such sublaminates were laid according to the scheme $[0/45/90/-45]_s$ or $[0/60/-60]_s$ to obtain quasi-isotropic (QI) composites.

The laminates have been produced by hot pressing at a pressure of 5-6 bar and a temperature of 135°C for 2 hours. Heating and cooling rates were about 5°C/min. The same materials and processing techniques were used in a previous study on UD all-carbon hybrids [3, 4].

Specimens for mechanical tensile tests were cut from laminated plates with dimensions of 300x300 mm by a high-speed circular saw (water-cooled diamond disc). They had dimensions of 250x15 mm (prismatic specimens) and 200x25 mm with hole diameter of 6 mm (OH). Glass fibre composite tabs with dimensions of 50x15x2 mm were bonded to the specimen ends.

Loading was carried out on a universal electromechanical machine INSTRON 5978 with a 2 mm/min cross-head speed. A standard clip-on INSTRON 2620-829 extensometer with 50 mm gauge length was used to measure strain, alongside the registration of the grips displacement. Details of the damage process were monitored using the digital image correlation (DIC) [7], and acoustic emission (AE) signals by Vallen AMSY-5 system [8]. The main feature considered for AE analysis is the frequency at the maximum amplitude F_{max}, which has certain correlations with the damage mode at the signal origin.

3. Mechanical tests

Table 1 summarises the results of all tests (two UD, hybrid UD, two QI and two QI OH). The stress – cross-head displacement/strain diagrams were used to extract the characteristic values in Table 1, as illustrated in Figure 1: modulus of elasticity E_x, peak stress σ_p, pseudo-yield stress σ_{py}, ultimate stress X_T and OH strength sensitivity K_{py} and K_{max}.

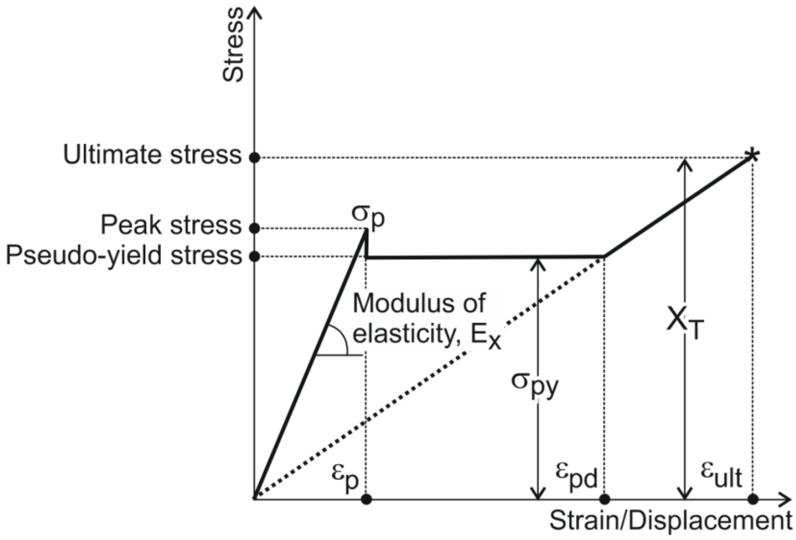

Figure 1. Schematics of the stress-strain/displacement diagram

Table 1: Mechanical properties of all-carbon hybrids, 4 – 6 specimens tested for each test type, ± means standard deviation.

Layup	Modulus of elasticity, E_X [GPa]	Peak stress, σ_p [MPa]	Pseudo-yield stress σ_{py} [MPa]	Ultimate stress, X_T [MPa]	OH peak stress sensitivity, K_{py} [-]	OH strength sensitivity, K_{max} [-]
UD [D_4]	382±36	1410±42	-	1410±32	-	-
UD [T_8]	148±10	2505±58	-	2505±58	-	-
UD [T/D/T]$_3$	255±16	960±12	810±15	1203±51	-	-
QI45	82.1±4.3	300±16	260±8.5	339±5	-	-
QI60	84.3±3.8	330±11	315±8.2	462±12	-	-
OH QI45	75.0±3.62(1,2)	285±13(1)	240±17(1)	295±13(1)	1.08±0.09	1.15±0.07
OH QI60	76.5±3.8(1,2)	340±18(1)	340±18(1)	444±29(1)	0.96±0.08	1.04±0.10

(1) net section of the specimens.
(2) with a hole at the base of the extensometer

The clip-on extensometer readings ("extensometer strain") increased monotonically up to the first peak at a strain of 0.38 ± 0.01%, corresponding to the breakage of the D-layer. Beyond the first peak, failure of the D-layers, the clip-on extensometer had sliding of the legs along the specimen surface . In this case, the extensometer readings became questionable, and, therefore, the tensile behaviour of unnotched and notched QI specimens are compared in Figure 2 in terms of "stress – displacement" curves.

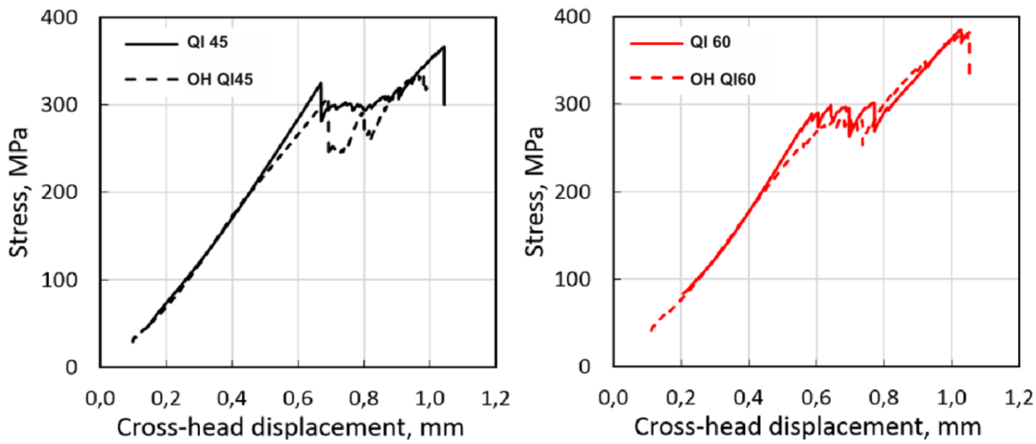

Figure 2. Typical 'stress – cross-head displacement' diagrams of unnotched specimens (solid lines) and 'net stress – cross-head displacement' diagrams of open hole QI45 and QI60 specimens (dot lines).

The diagrams in Figure 2 show that the notched specimens have similar pseudo-ductile behaviour to the unnotched specimens, with comparable levels of pseudo-yield stress (see Table 1). QI45 specimens fail at the end of the pseudo-ductile plateau without developing resistance of the HE plies. Correspondingly, the net ultimate stress of the notched specimens (295±13 MPa) is 13% lower than the unnotched one (339±5 MPa). This can be attributed to more intensive damage around the notch in the QI45 laminate, which led to the failure of the load-carrying 0° HE plies. The post-plateau behaviour of the notched QI60 specimens is similar to the unnotched ones, with well-developed linear resistance of the HE plies and with the net ultimate stress (444±29 MPa) close to the one of the unnotched counterpart (462±12 MPa).

The OH strength sensitivity can be characterised as the ratio of the strength of unnotched and notched specimens, which is higher than 1 for a notch-sensitive material and close to 1 for a notch-insensitive one [9]. For pseudo-ductile QI laminates, two notch sensitivity ratios can be introduced:

$$K_{py} = \frac{\sigma_{py}}{\sigma_{py}^{OH}}, \quad K_{max} = \frac{X_T}{X_T^{OH}} .$$

The first, K_{py}, assesses the change of the pseudo-yield limit in the presence of the notch. It can be considered a helpful design limit when the (pseudo)-ductile deformation is unknown. The second, K_{max}, assesses the change in the ultimate load-carrying capability and is useful if post-yield safety is of concern. In both cases, the net stresses in the OH specimen are used.

Table 1 shows the notch sensitivity ratios for QI45 and QI60. Both types of QI laminates exhibit low notch sensitivity, especially compared to experimental data of QI carbon/epoxy laminates with comparable hole size [9], where values K_{max}~2 were measured. The low K_{py} can be explained by the failure of 0° LE plies, which is controlled by the failure strain of the LE fibres. A similar low K_{max} notch sensitivity was measured in thin QI all-carbon hybrids [2]. It was explained by analogy to the reduced notch sensitivity in ductile metals, which is related to the release of the stress concentration due to localised progressive damage.

4. Localised damage around the notch

Figure 3 shows the localisation of the AE events in a typical OH test. It reveals the location of the events X_{loc} in relation to the frequency at the maximum amplitude F_{max} of the signal. The centre of the notch corresponds to X_{loc} = 6 cm. The distribution shows the localisation of the damage near the notch. As discussed in [3], the frequency of the events can be interpreted as follows: the high-frequency events, with F_{max} ~ 1400...1500 kHz for LE and F_{max} ~ 700 kHz for HE fibres, can be associated to fibre breakage; the bands with F_{max} ~ 500 kHz and F_{max} ~ 200 kHz can be associated to off-axis cracking, including matrix cracks and interface damage.

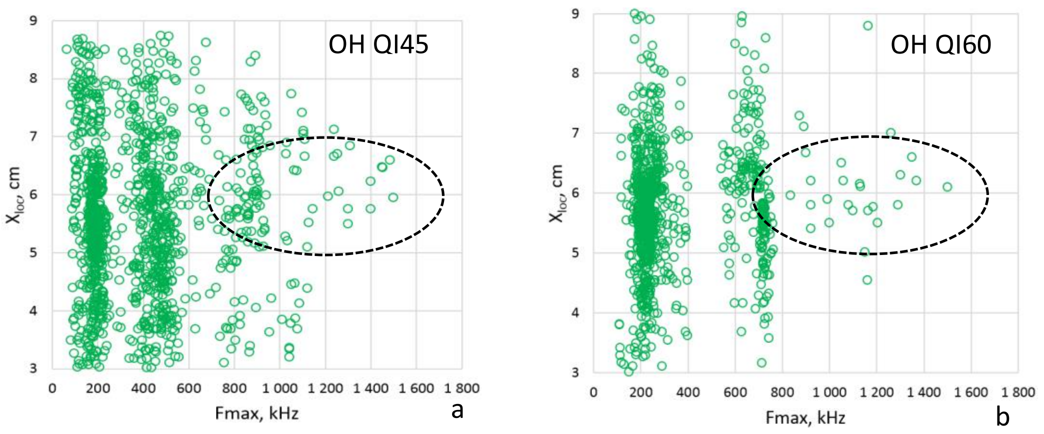

Figure 3. The relationships between the X_{loc} coordinate of the AE source and the frequency F_{max} for notched specimens OH QI45 (a) and OH QI60 (b). The ellipses show the position of high frequency (fibre breakage) events near the notch.

2D DIC was used to measure full-field strain on the surface of the samples near the hole during tension. The ε_{yy} strain maps are shown in Figure 4 just before and after the first load peak.

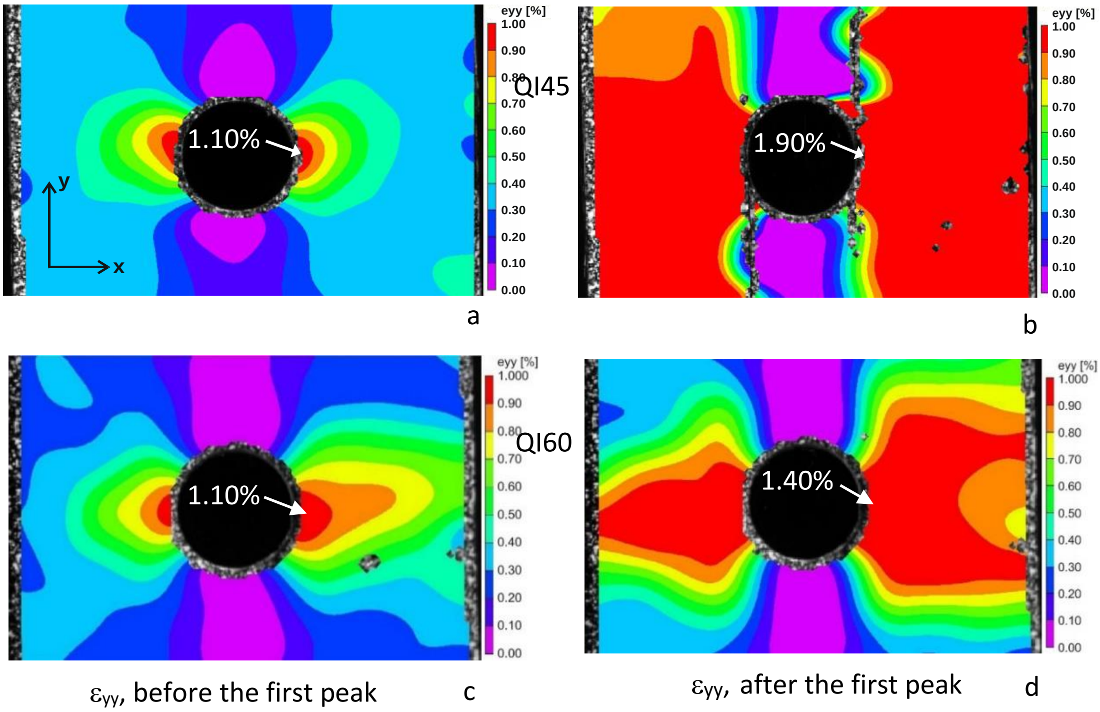

Figure 4. Strain maps ε_{yy} on the OH specimens surface, transition to unstable deformation after first peak failure, QI45 (a,b) and QI60 (c,d; (a,c) just before and (b,d) just after the first load peak.

The strain maps of QI45 just before the load peak (**Ошибка! Источник ссылки не найден.**a,c) are similar to the maps detailed in [9] for non-hybrid carbon/epoxy OH laminates with the layup $[0/45/90/-45]_s$. Failure of the LE ply drastically changes the strain field pattern, especially for QI45. Splitting of the 0° plies, seen in Figure 4b,d as non-correlated zones originating from the hole edge, separates the strain pattern into two parts. In the central part, the strain ε_{yy} is almost constant, as before the 0° LE failure. These maps are the witnesses of [0°] LE-ply failure near the hole, limited internal delamination (smearing of ε_{yy} in the net section) and shear splitting of outer HE-ply.

Conclusions

The paper reports an investigation of notch sensitivity of open-hole pseudo-ductile quasi-isotropic all-carbon hybrid laminates, combining low-elongation and high-elongation carbon fibre/epoxy plies of conventional thickness. Two types of QI laminates have been studied: QI45 - $[0/45/90/-45]_s$ and QI60 - $[0/60/-60]_s$. The results can be summarised as follows:

1. The OH QI hybrid laminates are almost notch-insensitive, with the notch sensitivity factors for pseudo-yield and ultimate stress below 1.15 (Table 1);
2. The notched specimens have similar pseudo-ductile behaviour to the unnotched specimens, with the same stress level (Figure 2);

3. The post-plateau linear resistance and the ultimate stress of HE plies are preserved in the notched specimens only for the QI60 case. Notched QI45 lose the post-plateau resistance of HE plies, and their ultimate stress decreases (Figure 2).

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