International Journal of Impact Engineering 108 (2017) 389–401

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Perforation resistance of CFRP beams to quasi-static and ballistic loading: The role of matrix strength

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ARTICLE INFO

Article History:
Received 15 December 2016
Revised 1 April 2017
Accepted 1 April 2017
Available online 3 April 2017

Keywords:
Ballistics
Fibre composites
Perforation mechanisms
Shear plugging
Indirect tension

ABSTRACT

The effect of matrix shear strength on the ballistic response of simply-supported carbon fibre reinforced plastic (CFRP) beams was explored for a flat-ended projectile. To gain insight into the deformation and failure mechanisms, the following additional tests were performed on CFRP beams: (i) quasi-static indentation tests with rigid back support and, (ii) quasi-static cropping tests. In all 3 types of tests, CFRP [0°/90°] cross-ply laminates were tested in six states of cure, such that the matrix shear strength ranges from 0.1 MPa to 100 MPa. In the quasi-static cropping tests, the composite beams failed by shear plugging (involving transverse matrix cracks, ply delamination, and fibre fracture). In contrast, indirect tension (by ply tensile failure in the fibre direction) occurred in the back-supported quasi-static indentation tests. In the ballistic tests, the CFRP beams of high matrix shear strength (30 MPa–100 MPa) failed by a shear plugging mode. When the matrix shear strength was less than 30 MPa, the failure mode and the penetration velocity doubled and occurred by indirect tension. The optimal shear strength to give adequate static and ballistic strength is on the order of 20 MPa.

1. Introduction

Carbon fibre reinforced plastic (CFRP) composites offer high stiffness and strength but have a ballistic performance that is inferior to that of ultrahigh molecular weight polyethylene Dyneema® cross-ply laminates. This study explores whether the ballistic resistance of CFRP composites can be improved by altering the matrix shear strength, as motivated by the observation that Dyneema® possess a low shear strength.

Recent investigations have suggested that the high impact resistance of Dyneema® cross-ply composites is by the failure mechanism of indirect tension [1–5]. This indirect tension mechanism has also been observed in Dyneema® cross-ply composites under quasi-static out-of-plane uniaxial compression, see Attwood et al. [2]. The indirect tension mechanism is best understood by considering a stack of alternating 0° and 90° plies under out-of-plane compression in the z-direction, as shown in Fig. 1. Limit attention to the response of a unit cell comprising a single 0° ply (labelled A in the figure) adhered to an underlying 90° ply (labelled B). If the faces of the two plies were allowed to slip freely, then an out-of-plane compressive load will cause ply B to undergo a much larger Poisson expansion in the y-direction than ply A, due to the orientation-dependent Poisson ratio. Adhesion between the two layers implies that they share the same direct strain component in the y-direction; consequently, layer A is subjected to a tensile stress σ_{yy}^{A}, whereas layer B experiences a compressive stress $\sigma_{yy}^{B} = -\sigma_{yy}^{A}$ with no net traction on the section with unit normal in the y-direction. By symmetry, $\sigma_{xx}^{B} = \sigma_{yy}^{A}$ and $\sigma_{xx}^{A} = \sigma_{yy}^{B}$. We conclude that out-of-plane compression generates axial tension in the fibre direction for each ply: hence the description 'indirect tension'.

O'Masta et al. [4] observed that indirect tension is the active failure mechanism for Dyneema® cross-ply laminates due to impact by a projectile. In contrast, ballistic loading of a cross-ply CFRP composite induces shear plugging, as reported by Cantwell and Morton [6–8] for drop weight tests on CFRP layers. This mechanism has also been observed in quasi-static punch tests and in ballistic tests on carbon fibre and glass fibre composites [9–17]. The difference in dynamic failure mechanism for CFRP and Dyneema® may be due to the large difference in matrix shear strength. Whereas Dyneema® composites possess a shear strength on the order of 1–10 MPa, commercially available CFRP composites with fully cured epoxy matrix possess a shear strength in the range 50–100 MPa [18–22]. In support of the role played by the matrix shear strength on ballistic performance, Karthikeyan et al. [1] demonstrated that uncured CFRP laminate has a higher ballistic limit than that of the fully cured CFRP laminate. A strong dependence of ballistic limit on matrix properties is also deduced from the tests of de Ruijter et al. [23] on an aramid-based composite, although the penetration mechanism was not determined.

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http://dx.doi.org/10.1016/j.ijimpeng.2017.04.002
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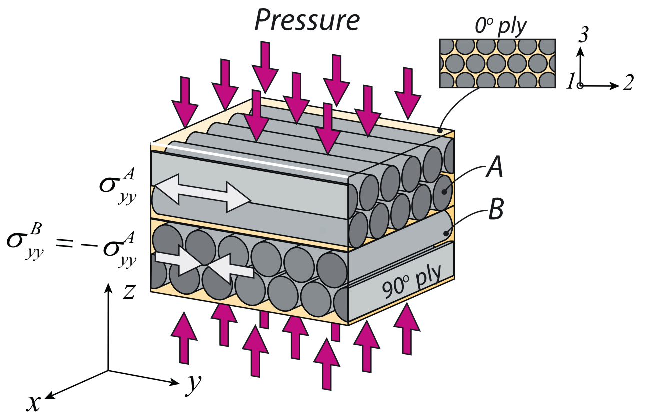

Fig. 1. Sketch of the indirect tension mechanism in a pair of 0° and 90° plies under out-of-plane pressure. Poisson lateral expansion in the 0° ply parallel to the fibre is less than in the 90° ply transverse to the fibre. Under out-of-plane compression, this mismatch in Poisson lateral expansion induces tensile stress in the fibre direction of both plies and compressive stress in the transverse direction.

The objective of the current study is to provide a comprehensive experimental investigation to understand: (i) the effect of matrix cure on the failure mechanism and ballistic resistance of CFRP composites, (ii) the difference in quasi-static and dynamic response of CFRP composites, and (iii) the potential to improve the ballistic resistance of CFRP composites by suppressing the shear plugging mechanism. To achieve this objective, composite beams were manufactured with various states of cure and then subjected to three types of tests: (i) a quasi-static indentation test with rigid back support, (ii) a quasi-static cropping test, and a (iii) ballistic impact test using a flat-ended projectile.

2. Specimen manufacture

Cross-ply laminates $[0°/90°]_{16}$ were assembled from Hexply® 8552/35 % 134/IM7 carbon fibre/epoxy prepregs (with a ply thickness of 0.131 mm). Six states of cure were considered, with the following labelling procedure employed throughout this study: (A) uncured, (B) partially cured at 100 °C for 2 h, (C) partially cured at 120 °C for 2 h, (D) partially cured at 120 °C for 2 h and 15 min, (E) partially cured at 180 °C for 24 h, and (F) autoclaved fully cured specimens.

The laminates were laid-up by hand, and then cut using a band saw into rectangular beams dimensions of height $H = 4$ mm (32 plies), breadth $B = 11$ mm, length $L = 300$ mm, and areal density $\rho_A = 6.28$ kg/m^2. A portion of these uncured beams were tested in this state (A). The partially cured composites of types (B) to (E) were prepared by placing most of the uncured beams in an air-oven using the above-mentioned cure cycles and were compressed in-situ at 0.1 MPa in the out-of-plane direction by spring-loaded platens. The fully cured specimens (F) were autoclaved following the procedure recommended by Hexcel Ltd. [24]. The matrix shear strength of the laminates was then measured by performing short beam shear test at a quasi-static loading rate (following the recommendation in ASTM standard D2344). The shear tests are given in Appendix A. Table 1 summarises the curing process and the matrix shear strength and the shear modulua of laminates type (A)–(F). With the exception of the fully cured material (F), all laminates were stored at −15 °C to avoid further curing and slowly re-elevated to room temperature over a period of 5 h prior to testing. With the exception of the fully cured material (F), all laminates were stored at −15 °C for a duration of less than 30 days (a duration well below the expiry date of the prepregs) to avoid further curing and slowly re-elevated to room temperature over a period of 5 h prior to testing.

3. Test methods

3.1. Quasi-static indentation tests

CFRP composite beams with rectangular dimensions of height $H = 4$ mm (32 plies), breadth $B = 11$ mm, and the reduced length $L = 75$ mm were sectioned from the cross-ply laminates $[0°/90°]_{16}$ (32 plies) in six states of cure, as described in the previous section. Specimens were subjected to an out-of-plane indentation test by placing them between a flat back support and a hardened steel indenter with a square bottom of plan dimension $l_1 = l_2 = 12.5$ mm in the x-y plane, as illustrated in Fig. 2a. A small edge radius $R = 0.3$ mm was introduced to reduce the stress concentration of the indenter. Both the back support and the indenter were made from hardened silver steel (700 Vickers) and were lubricated with a low viscosity mineral oil in order to reduce the role of friction.

Materials (A) and (B) were tested using a screw-driven test machine with a 150 kN load cell, whereas materials (D)–(F) were tested using a servo hydraulic test machine with a 1 MN load cell. For consistency, all specimens were tested with the fibres of the top ply lying parallel to the x-direction in the figure. The indenter was then displaced along the z-direction such that it contacted the central point of the top face of the specimens. Indentation tests were performed at a constant displacement rate of $\dot{u}_z = 4 \times 10^{-3}$ mm/s. The indentation load $F$was recorded by the machine load cell and the displacement between the steel plate and the indenter u_z was measured using a laser extensometer. During the indentation test, high-speed images were recorded from the side-view of the specimens using a Phantom® V1610[1] camera with an inter-frame time of 100 μs and an exposure time of 90 μs in order to identify the failure mechanism.

3.2. Quasi-static cropping tests

CFRP composite beams with same rectangular dimensions as for the indentation test were subjected to a cropping test at a quasi-static loading rate using a screw-driven test machine with a 150 kN load cell. Specimens were placed between a hardened steel indenter (with a square bottom of $l_1 = l_2 = 12.5$ mm in the x-y plane) and two back supports of spacing 18.5 mm, thereby creating a clearance $c = 3$ mm (with $c/H = 0.75$) between the steel supports and the indenter (see Fig. 2b). Again, a radius $R = 0.3$ mm was introduced into the edges of the indenter and the steel support in order to reduce the stress concentration. Both the supports and the indenter were made from hardened silver steel (700 Vickers) and were lubricated with a low viscosity mineral oil. As for the indentation tests, the specimens were placed so that the fibres in the top ply were parallel to the x-direction in the figure. The average shear strain in the specimen $\overline{\gamma}$ exists within the clearance c between indenter and back support; this shear strain scales with the indenter displacement u_z according to $\overline{\gamma} = u_z/c$.

The cropping test was performed at an out-of-plane displacement rate of $\dot{u}_z = 3 \times 10^{-3}$ mms^{-1} (to generate an average shear strain rate of 10^{-3}s^{-1}). The compressive load $F$was recorded by the machine load cell and the displacement u_z between the steel plate and the indenter was measured using a laser extensometer. Side-view optical images of the specimen were recorded during the cropping test using a digital camera with a resolution of 2048 × 1536 (3.1 megapixel), and a flame rate of 12 FPS at full resolution. For maximum resolution, only a 9 × 9 mm window of one side of the punched regions was filmed. The preliminary tests revealed that

[1] Vision Research Inc., 100 Dey Road, Wayne, New Jersey 07470, USA.