Composites Part B 90 (2016) 30–36

Contents lists available at ScienceDirect

Composites Part B

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

Effect of reinforcement continuity on the ballistic performance of composites reinforced with multiply plain weave fabric

Shengnan Min [a], Xiaogang Chen [a, *], Yuan Chai [a], Tristan Lowe [a, b]

[a] School of Materials, University of Manchester, Sackville Street, Manchester M13 9PL, UK
[b] Henry Moseley X-Ray Imaging Facility, School of Materials, University of Manchester, Manchester M13 9PL, UK

ARTICLE INFO

Article history:
Received 29 September 2015
Received in revised form
12 November 2015
Accepted 4 December 2015
Available online 18 December 2015

Keywords:
A. Discontinuous reinforcement
B. Impact behaviour
B. Delamination
D. Non-destructive testing

ABSTRACT

Structural composites with doubly curved surfaces, including ballistic helmet shells, require the use of discontinuous reinforcements due to their limited mouldability. This paper reports on the effect of reinforcement continuity on the ballistic performance of composites made from multiply plain weave fabric. Composites reinforced by 20-ply Twaron® plain weave fabrics, both continuous and discontinuous (with 20 mm and 45 mm overlapping respectively), were produced using the vacuum-bagging method. The composites were subjected to perforation ballistic tests for performance evaluation. The damage morphology after impact was examined and characterised using through-transmission ultrasonic C-scan and X-ray computed tomography (CT). The ballistic results confirmed the superiority of the continuously reinforced composites as they absorbed up to 19.30% more impact energy, caused wider delamination, and exhibited more than twice the damage volume when compared to their discontinuously counterparts. Both ballistic test and X-ray CT results suggested that for the discontinuously reinforced composites, longer reinforcement overlapping length are associated to more effective ballistic protection. The findings are indicative for the engineering design of lightweight ballistic helmet.

1. Introduction

Woven fabrics made from high-performance fibres have been intensively used as reinforcements for composites in ballistic protective and aerospace applications [1]. Limited by the mouldability of the conventional two-dimensional fabric reinforcements, cutting and darting according to designed patterns are the commonly employed methods for the forming of structural parts with doubly curved shapes, such as the construction of military helmet shells [2,3]. Consequently, discontinuity in reinforcement becomes inevitable. It was reported that discontinuity in composite reinforcements is the source for out-of-plane stress concentrations from the interlaminar fracture view point [4,5] and from the compressive strength perspective [6]. The 3D woven through-the-thickness angle-interlock fabrics are capable of conforming onto doubly curved surfaces without forming wrinkles and were prototyped into reinforcing riot police helmet shells using the vacuum-bagging method [7,8], which showed improved protective performance against low velocity impact. For the same concept to be used for engineering military helmet, which is designed to protect against high-velocity low-mass impacts, it is imperative to study the effects of reinforcement discontinuity on the ballistic performance of woven fabric reinforced composites and to confirm the effectiveness of multiply continuous reinforcement against ballistic impact [9].

Improvement of protection performance and reduction of weight are the two most important considerations in engineering design of ballistic helmet. The ballistic test standards, including NIJ-STD-0106.01 [10] by U.S. National Institute of Justice and MIL-H-44099A [11] by U.S. Department of Defence, set out the performance requirements and give details of test methods for ballistic helmets intended to offer protection against different levels of ballistic impact. Between these two test standards, the NIJ standard qualifies the usefulness of a helmet part if it can sustain a required number of fair hits by standardised weapons and ammunition, and the MIL-H-099A standard requires a PASGT helmet to satisfy a V50 ballistic limit of 610 m/s under hits by the 1.1 g 0.22 calibre fragment simulating projectile (FSP). The V50 ballistic limit is defined as the impact velocity at which the projectile stands a 50% chance of complete penetration of the target [11].

---

* Corresponding author. School of Materials, University of Manchester, Sackville Street, Manchester M13 9PL, UK. Tel.: +44 (0)774 016 7749.
E-mail address: xiaogang.chen@manchester.ac.uk (X. Chen).

http://dx.doi.org/10.1016/j.compositesb.2015.12.001
1359-8368/

The failure mechanisms of woven fabric reinforced composites under ballistic impacts have been extensively studied [12–15]. Upon ballistic impacts, damage often occurs locally at the impact location [14], associated with damage are fibre breakage, matrix cracking, and delamination [12]. The ballistic performance of composites depends largely on their ability to absorb impact energy [12,15] through the aforementioned damages as well as heat and frictional dissipation. Gellert et al. [13] characterised the process of projectile penetrating a composite target into two distinctive stages, i.e. the damage initiation stage and the penetration stage. Acceleration of target material, compression on the target material by the projectile and material shear are the predominant damage mechanisms at the impact initiation stage, whereas stretching of fibres, delamination and dishing continue during the second stage until target penetration. One obvious route of engineering composites with improved ballistic performance is to develop and use better materials for matrices and reinforcements. It is also possible to take advantages of the currently available matrix and fibre materials by arranging them in a manner that allows for more effective impact kinetic energy absorption.

The aim of this study is to analyses the effect of reinforcement discontinuity on the ballistic performance of woven fabric reinforced composites. Flat composites are selected for research to avoid the influence on ballistic performance by composite curvature. Composite samples with continuous and discontinuous aramid reinforcements are prepared using epoxy resin. Perforation ballistic impact tests will be used to evaluation the performance of the composite samples, and non-destructive test (NDT), including ultrasonic C-scan and X-ray Computed Tomography (CT), are planned to examine the damage morphology of the composite samples.

2. Experimental

2.1. Materials

Plain weave reinforcements were fabricated from a Twaron® yarn of 93tex (provided by Teijin® Ltd.) with the fabric thread density being 11.5 threads per cm in both warp and weft directions. The areal density of the reinforcing fabric is 202 g/m2 per ply and the mechanical properties of the Twaron® yarn [16,17] are listed in Table 1. For all composites involved in this research, the plain weave fabrics were laid up in aligned orientation.

In order to create evenly distributed discontinuity in fabric reinforcements, the plain weave fabrics were cut into pattern strips with the width of Lp prior to lay-up. Fig. 1 is a schematic cross-sectional view of a discontinuously reinforced composite panel. Resin gaps with the size of Lm were created in each reinforcement ply, and its width is arranged to be about 2.5 mm in these composites. The distance between the neighbouring resin gaps on the adjacent plies is noted as the overlapping length Lo. The pattern strip width Lp is twice the size of overlapping length plus the resin gap. In order to receive perforated results while having detectable delamination after impact for damage morphology analyses, the decision of using 20 plies of reinforcement for all the testing samples in the present study was made. This decision was based on an experiment where composite panel P10C reinforced by 10 plies of the same plain weave fabric absorbed an average of 34.84 J impact energy, but the delamination damage was rather localised. Details of the 10-ply composite panel are listed Table 2. A trial of doubling the number of plies also led to a total perforation of the composite panel. In this 20-ply composite, the amount of delamination damage accumulated was more obvious and more widely distributed. In making helmet shells, the discontinuities resulted from the patterning of reinforcing fabrics need to be staggered away from each other to achieve even thickness of the helmet shell. Considering that the length of each petal of a four-legged pinwheel fabric preform is 20 cm in respect to the size of an actual helmet, an even distribution of 30 plies of the fabric preform around the helmet circumference would lead to an average overlapping length of around 15 mm–20 mm. In order to be more representative in evaluating the ballistic performance of the discontinuously reinforced composites, the overlapping lengths of 20 mm and 45 mm were chosen for the spliced panels.

Epoxy resin is a commonly used matrix material for aerospace and impact resistance applications. A warm-curing epoxy system based on Araldite® LY564 and formulated amine hardener XB3486 from Huntsman® mixing at the weight ratio of 100:34 [18] was chosen as the matrix for manufacturing composite panels in this research. Because of its low viscosity and excellent mechanical properties, as listed in Table 1, this epoxy matrix system allows the use of vacuum bagging method for composite making. The vacuum bagging setup is illustrated in Fig. 2. Instead of using the infusion mesh only on the top surface of the fabric reinforcements, a continuous piece of mesh wrapping around the spiral tube is used to facilitate double meshing. The mesh on the bottom surface is expected to promote an additional channel below the reinforcing fabrics for the resin flow to advance, leading to more uniform impregnation of the resin in the composite panel.

After infusing the degassed resin into the reinforcement assembly at room temperature, curing was conducted under the prescribed curing cycle in an oven as recommended by the resin manufacturer. The temperature rising time is 1 h before reaching 80 °C from the room temperature. After maintaining this temperature for 8 h the composite was then left to cool following the switch-off of the heating system until it reaches the ambient temperature. Each type of composite was produced according to the specifications tabulated in Table 2. The fibre volume fractions of all samples were determined using the acid digestion method. Based on the rule of mixture, the Young's modulus of the continuously reinforced specimens was estimated to be 24.8 GPa and the fracture strain is taken to be 3.23% based on previous research [19].

2.2. Ballistic impact tests

A ballistic test was arranged for the projectile to perforate the composite panels, where the energy absorbed by composite panels (*EA*) is considered the same as the kinetic energy loss of the projectile despite the existence of friction between the projectile and air. *EA* is employed in this research to quantify the ballistic performance of the composite targets. A schematic of the ballistic

Table 1
Properties of Twaron® yarn [16,17] and epoxy resin [18].

Materials	Specific density (g/cm^3)	Tensile strength (GPa)	Young's modulus (GPa)	Compressive strength (GPa)	Elongation at break (%)	Decomposition temperature (°C)
Twaron® yarn	1.44	2.40–3.60	60–80	0.58	3.00–4.40	500
Epoxy resin	1.25	70–74	2.86–3.00	–	4.60–5.00	80–84