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Response of woven and laminated high-strength fabric to oblique impact

V.P.W. Shim*, Y.B. Guo, V.B.C. Tan

Impact Mechanics Laboratory, Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576, Singapore

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A B S T R A C T

An experimental investigation into the responses of a woven fabric and a pliable laminate – Twaron® CT 716 and Spectra Shield® LCR – subjected to oblique projectile impact is undertaken. Square specimens are clamped at their top and bottom edges and inclined at different angles to a gas gun which launches 13 mm-diameter steel spheres against them. High speed photography is employed to examine target deformation and failure, as well as post-perforation projectile velocity. The influence of impact obliquity on the ballistic limit and energy absorbed are analysed and discussed. For Twaron®, an increase in obliquity results in an initial decrease in the ballistic limit, followed by a slight increase. This arises from two competing mechanisms – asymmetric deformation of weft yarns and sliding of the projectile against the target. The variation for Spectra Shield® is different – the ballistic limit first increases then decreases, with values for oblique impact generally higher than those for normal impact. This possibly arises from competition between the weakening effect of asymmetric deformation and strengthening via sliding of the projectile against the fabric, and pulling out of horizontal yarns. With respect to energy absorption, results show that for both Twaron® and Spectra Shield®, the influence of impact obliquity on energy absorbed generally diminishes with an increase in impact velocity, and finally vanishes when the impact velocity is sufficiently high.

1. Introduction

Fabrics made from high-modulus, high-strength fibres possess the merits of low weight, high specific strength and high flexibility. They offer superior impact-resistance-to-weight properties and are widely used in protective systems against ballistic impact, such as bullet-proof vests, turbine engine fragment barriers, etc. The ballistic response of high-performance fabrics has been a topic of extensive research over the past three decades, which include analytical studies [1–6], experimental investigations [7–12] and numerical simulation [8,13–20]; comprehensive reviews have been presented by Cheeseman and Bogetti [21] and Tabiei and Nilakantan [22]. Results show that the impact resistance of these fabrics is influenced by a number of parameters, including material properties of the constituent fibre [13,22], fabric structure [7,12], projectile geometry [10,11], impact velocity [14,23], boundary conditions [7,8,24,25] and friction [12,26,27].

Although many studies on the ballistic behaviour of fabrics have been carried out, most of them focus on response to projectile impact at normal incidence; investigations into oblique impact appear relatively scarce. Yong et al. [28,29] applied both normal and oblique impact to single-plies of Twaron® fabric, and their results show that ballistic limit increases with impact obliquity, with the fabric generally absorbing more energy for a larger impact angle, especially for high speed impact. Cunniff [30] compiled ballistic test data for compliant fragmentation protection armour composed of multiple fabric plies (nylon, Kevlar®, Spectra®, etc) under normal and oblique impact by various types of projectiles (steel and tungsten spheres and cylinders, "chisel-nosed" steel fragment simulators and steel cubes). The results show that compared to normal impact, fabric armour generally absorbs more energy for oblique impact. In [30], Cunniff also proposed a semi-empirical model for estimation of the ballistic limit and residual velocity, using a dimensionless parameter $A_d A_p / m_p$ – the ratio of the mass of a plug of target material immediately in front of the projectile to that of the projectile. This was employed to describe the effects of fabric areal density and the size and mass of the projectile. The influence of obliquity was incorporated by use of an effective thickness t' ($= t/\cos\theta$, t is fabric thickness and θ the target inclination) for the target. The model provides a reasonable approximation of the experimental data for normal impact, but discrepancies appear for oblique impact. Tan et al. [31] undertook computational simulations of the response of a single-ply of woven fabric under oblique impact, whereby the fabric is modelled as a network of pin-

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* Corresponding author. Tel.: +65 6516 2228; fax: +65 6779 1459.
E-mail address: vshim.me@nus.edu.sg (V.P.W. Shim).

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jointed viscoelastic elements with lumped masses at the nodes. Yarn crimp and the influence of strain rate on yarn failure were incorporated to improve simulation accuracy. The results show that in low impact energy regime, energy absorbed by the fabric decreases with an increase in obliquity; however, for high speed impact, a larger target inclination tends to result in greater energy absorption. Chu et al. [32] studied the ballistic performance of fabric laminates comprising multiple plies (14, 22, 27 and 38) of Twaron® impregnated by epoxy, under oblique impact. They found that the ballistic limit changes little for small inclinations (less than 30°) but increases significantly when the obliquity exceeds 45°. This is attributed to the increase of penetration length through the laminate with impact obliquity. However, they noted that penetration length is not the only factor that affects ballistic performance; for a constant penetration length, a laminate subjected to oblique impact offers inferior ballistic resistance compared to one under normal impact.

In actual situations, a bullet or fragment can strike a protective system at different angles; an understanding of the effect of impact obliquity on the ballistic resistance of fabrics is therefore important. In this study, oblique impact on two fabrics of different architectures – plain-woven Twaron® CT 716 and laminated Spectra Shield® LCR – is examined. Single layer specimens are inclined at different angles and subjected to impact by a spherical steel ball at various impact velocities; high speed photography is employed to observe the target deformation and failure. The effect of impact obliquity on the responses of the two fabrics is investigated, particularly with respect to the ballistic limit.

2. Experimental arrangement

The two fabrics studied are Twaron® CT 716, a plain-woven aramid fabric made of poly(p-phenylene-terephthalamide) (PPTA) and Spectra Shield® LCR, a laminated fabric constructed from two orthogonal plies of Spectra-1000 (extended-chain polyethylene) fibre tapes sandwiched between thermoplastic films. The fibres in each Spectra ply run parallel to each other and held together by a resin, and the plies are stacked in a 0°/90° sequence. Fig. 1 shows the structure of the two fabrics.

Single layer Twaron® and Spectra Shield® specimens were mounted within a fixture (Fig. 2) comprising two vertical side-plates and upper and lower horizontal clamps. Holes drilled around a circle in the side-plates facilitated positioning of the clamps to achieve the desired target inclination. Specimens were clamped along their upper and lower edges, with the left and right sides remaining free; this resulted in an exposed area of 120 mm × 120 mm. For woven Twaron® specimens, the weft yarns were clamped, while for Spectra Shield®, the 0° ply (horizontal fibres) corresponded to the impact (front) face and the 90° ply (vertical fibres) was at the exit (back) face; i.e. the 90° yarns were clamped. Projectile penetration tests on fabric specimens at 0°, 7.5°, 15°, 30° and 45° inclinations to normal incidence were undertaken to examine the effect of impact angle on ballistic performance. Fig. 3 illustrates the experimental arrangement. A gas gun was utilised to launch 13 mm-diameter steel spheres weighing 9 g at fabric targets. Two laser-photodiode pairs were sited in front of the specimen to measure the impact velocity, and a Photron APX high speed camera was employed to obtain visual images of the target deformation and failure. The camera was placed at different locations to capture the specimen side profile and exit face – at porthole I for the side profile, and at porthole II for the exit face, via reflection from a mirror with a 45° inclination. In tests where the specimen is perforated, the projectile residual velocity, required for calculation of the energy absorbed, was determined from the high speed images.

More recently, another high speed camera (Photron Fastcam) was employed to observe the deformation and failure of Twaron® under oblique impact, using a setup [23] that is able to capture simultaneous images of the specimen exit face and side profile. Some initial results are included in this paper for discussion of the deformation and failure of woven fabric samples (Figs. 4–6).

3. Experimental results and analysis

3.1. Twaron® CT 716 woven fabric

3.1.1. Influence of obliquity on ballistic limit

The ballistic limit is the minimum velocity required for perforation of a target and corresponds theoretically to zero residual velocity after perforation. Prior to analysing the experimental data relating to the ballistic limit for oblique impacts at various inclinations (0°, 7.5°, 15°, 30° and 45°), the deformation and failure of fabric specimens are first examined, based on high speed camera images, which provide a qualitative understanding and insights into the influence of obliquity.

Images showing the development of deformation and failure for normal and oblique impact are given in Figs. 4 and 5, respectively. When the projectile impinges a specimen at normal incidence, longitudinal and transverse waves propagate along the principal yarns (yarns in direct contact with the projectile). The longitudinal wave speed is determined by the yarn material properties ($c_0 = \sqrt{E/\rho}$, where E is the elastic modulus and ρ the density), while the transverse wave speed depends on both the yarn properties and the impact velocity, and increases with impact velocity

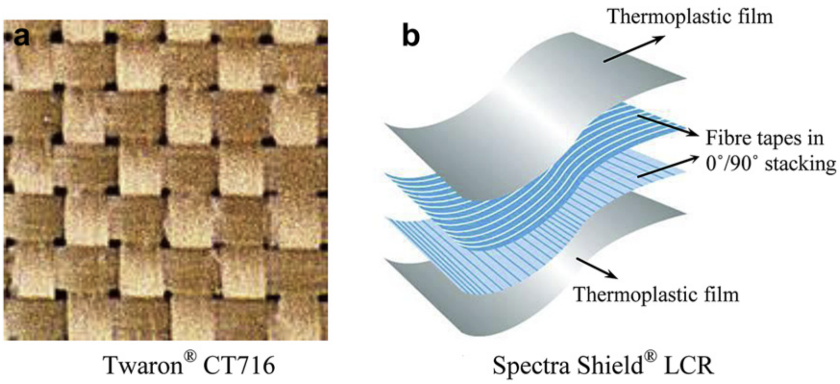

Fig. 1. Structure of Twaron® CT 716 and Spectra Shield® LCR.