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Effect of pre-tension on energy absorbed by fabric during projectile penetration

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ABSTRACT

High-strength woven fabrics made of polymeric yarns are widely used for protection against projectile impact, because of their strength, low density and high toughness. Their response to projectile impact is complex, because of the woven architecture and rate-dependent behaviour of constituent yarns. This work is directed at understanding the influence of applying pre-tension to a woven fabric, on the energy absorbed during impact by a spherical projectile. An experimental arrangement that facilitates the application of pre-tension to fabric specimens, is used to investigate fabric performance in terms of the variation of energy absorbed with impact velocity, and how pre-tension affects this. The results show that the relationship between energy absorbed during projectile penetration and impact velocity, displays an increasing-decreasing parabolic-type profile. Below the ballistic limit, fabrics subjected to a higher pre-tension perform better, but for higher impact velocities, fabric subjected to lower pre-tensions absorb more energy. To explain the results, projectile impact is simulated using a numerical model that includes the geometrical features of the fabric and incorporates rate dependence of the yarn material. The model exhibits relatively good correlation with experiments, and yields a fuller understanding of the mechanisms governing fabric behaviour. Results show that the initial increase in energy absorbed by the fabric is mainly due to the transfer of projectile kinetic energy to fabric kinetic energy; pre-tension restrains yarn movement and thus decreases energy absorption. Analysis of the variation of transverse wave speed with impact velocity shows that it increases approximately linearly with impact velocity, and that a higher pre-tension also elevates transverse wave speed. The fabric studied fails rapidly when the impact velocity is sufficiently high; this is caused by stress concentration at the impact point and insufficient time for the transverse wave to propagate through the fabric; failure is aggravated by a higher pre-tension and accounts for the resulting poorer performance for impact velocities significantly higher than the ballistic limit.

1. Introduction

The drive towards enhancing the mechanical properties of materials – e.g. durability, relative energy absorption capacity, strength and stiffness – has led to the formulation of advanced polymeric materials. Lightweight, high strength, high stiffness aramid fibres such as Kevlar® and Twaron®, woven into fabric, are used for reinforcing components like armour and aircraft engine containment shells, due to their favourable energy absorption capacity when subjected to impact by objects such as debris from an explosion, fragments, etc.

The performance of woven fabric subjected to projectile impact encompasses various aspects which require specific characterisation. The ballistic limit – maximum impact velocity at which a projectile is arrested by a fabric – is of primary importance, and has been the focus of many investigations [1–3]. For impact velocities above the ballistic limit, whereby the projectile perforates the fabric and exits with a residual velocity, the energy absorbed by the fabric is usually employed to quantify its ability to retard a projectile. This energy varies with impact velocity, and an increasing-decreasing trend has been identified in previous reports [1,4] – i.e. the energy absorbed beyond the ballistic limit first increases with impact velocity up to a point, beyond which it decreases, resulting in a parabolic profile.

Many studies on the ballistic resistance of high-strength fabrics have been undertaken, and the results indicate that the ballistic limit and energy absorption capacity of the fabric are influenced by various fabric parameters – e.g. inter-yarn friction [3,5–7], fabric density, yarn material properties [2] – as well as external factors, such as environment (moisture, light) [8,9], angle of impact [10] and projectile nose-shape [11,12]. In the large majority of published literature, the fabric specimen is free from any loading before the projectile makes contact with

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it. However, when high-strength fabrics are incorporated into components and devices that sustain internal pressure, such as in pressure vessels, inflatable boats, hovercraft, etc., they could already be subjected to in-plane tension before a projectile, fragment, shrapnel, etc., strikes. Therefore, it is instructive to investigate the ballistic resistance of fabrics under in-plane pre-tension. The influence of pre-tension on the ballistic performance of metal or composite plates has been studied by several researchers [13–16]; however, such investigations on flexible material like fabric, appears limited.

In a previous study by the authors [17], an in-depth investigation was performed to examine the effect of applying an in-plane pre-tension to T717 Twaron® fabric specimens, on the resulting ballistic limit. The present study focuses on the energy absorption capacity of the fabric for impact velocities above the ballistic limit, and how this varies when a pre-tension is applied. Projectile impact tests were first performed to identify the effect of applying an initial pre-tension on the resulting energy absorption capacity. Subsequently, finite element simulation, whereby the fabric is modelled as a plain weave of yarns comprising three-dimensional solid elements, was undertaken to gain an understanding of the mechanisms accounting for the influence of pre-tension. This influence for various impact velocity ranges was identified and explained, based on the experimental and numerical results. A quantitative analysis of the effect of pre-tension on stress wave propagation in the fabric was also undertaken.

2. Experimental testing and numerical modelling of fabric subjected to projectile impact

2.1. Experimental arrangement for projectile impact tests

The experimental setup is similar to that described in an earlier work by the authors [17], and is illustrated schematically in Fig. 1. A fixture is used to clamp the T717 Twaron® fabric specimens, which measure 400 mm in the warp direction and 140mm in the weft direction before clamping. The upper and lower portions in the warp direction are wrapped around clamping rods, which are rotated by a gear system, leaving a final exposed area measuring 140 × 140 mm, corresponding approximately to 116 × 116 yarns. The gear system also enables the application of pre-tension to specimens in the warp direction, and the tension force is measured via strain gauges mounted on the four columns that support the fabric clamps; the sides corresponding to the ends of the weft yarns are left unclamped. A 12 mm diameter 6.95 g spherical steel projectile is launched from a gas gun, and the impact velocity is measured using two laser photodiodes. A high-speed camera operating at 43,200 frames/s, is employed to observe specimen deformation during projectile impact, and the side profile and exit face of the fabric specimen are simultaneously captured by the camera, through an arrangement of mirrors inclined at 45°, as shown in Fig. 1. Since the impact velocity exceeds the ballistic limit, the projectile perforates the specimen and exits with a residual velocity – this is determined from images recorded by the high-speed camera, depicting projectile movement after it exits the specimen.

Two levels of initial pre-tension are applied in the warp yarn direction – 500 N, and 4,000 N. To examine the variation of energy absorbed with impact velocity, the projectiles are launched at velocities ranging from 100 m/s to 350 m/s, at intervals of ~25 m/s; 20 impact velocity data values are used to establish the variation of energy absorbed with impact velocity, and two specimens are subjected to each impact velocity, to see if the results are consistent. To calculate the energy absorbed by the fabric, the projectile initial and final kinetic energies are measured and compared, and the difference is assumed to be absorbed entirely by the fabric.

2.2. Numerical model of fabric

Numerical simulation is valuable in helping identify mechanisms accounting for phenomena observed experimentally. Early models of fabric have idealised them as continuum plates or membranes [18]; these have been superseded by models that incorporate fabric internal features – e.g. yarn interactions, weave pattern, yarn movement [4,6]. In these yarn-level fabric models, constituent yarns of the fabric are first modelled using simplified one-dimensional (1D) elements (e.g. pin-jointed fibre elements [19] or truss elements [20]) or 2D elements [21,22] (e.g. shell or membrane elements) to reduce computational costs; however, over-simplification of a yarn structure inevitably results in approximation, in terms of contact interactions between yarns, and this can significantly affect the accuracy of the simulation. To enhance accuracy, a 3D yarn-level model using solid brick elements, was

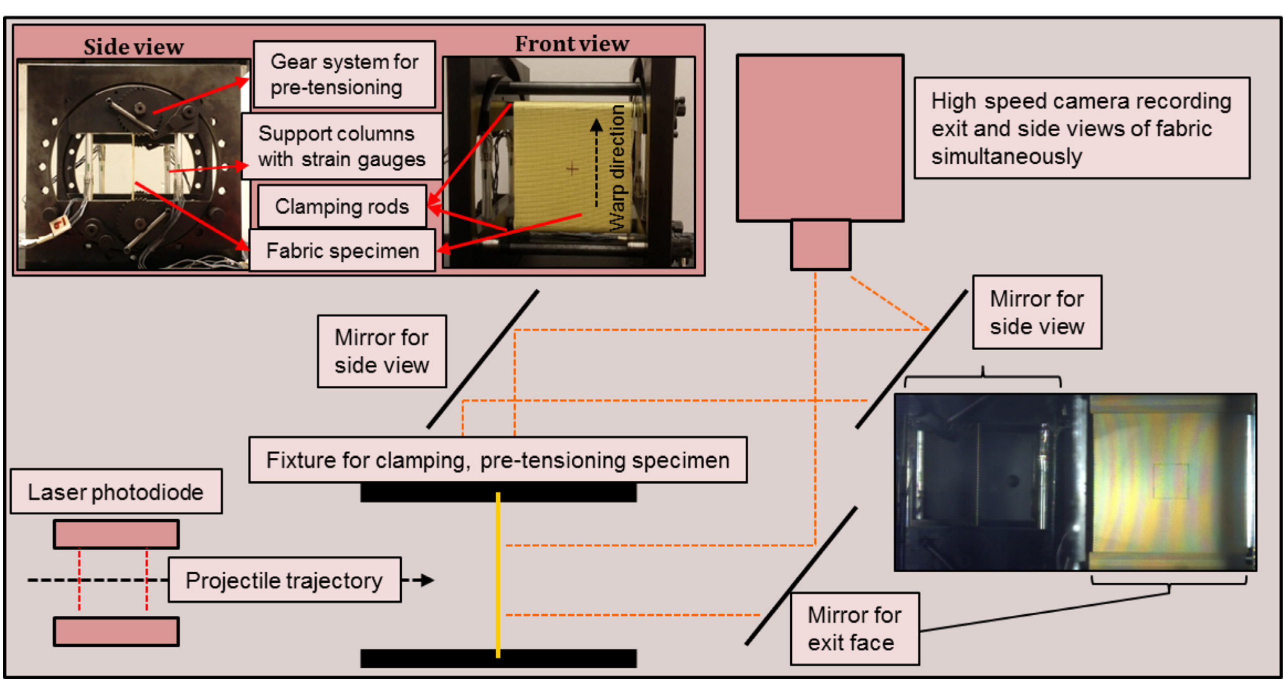

Fig. 1. Experimental arrangement for projectile impact tests.