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Effects of pre-tension and impact angle on penetration resistance of woven fabric

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ABSTRACT

High-strength woven fabrics made of polymeric yarns are widely used because of their low density and high toughness, as well as good resistance to high speed loading, particularly ballistic impact. However, their response to impact is complex, due to the woven architecture and rate-dependent behavior of their constituent yarns. This work aims at understanding the effect of applying pre-tension to a woven fabric subjected to normal and oblique impact. A new experimental setup is designed to facilitate application of pre-tension and prescription of specimen inclination. The fabric performance in terms of its ballistic limit is examined, and the variation of the in-plane force experienced by the fabric during impact is also measured. The fabric response for different pre-tensions and impact angles in terms of the ballistic limit is analyzed. In parallel, a numerical model that includes the geometrical features of woven fabric and incorporates the rate-dependent behavior of the yarns, is established. Results generated by the model correlate well with experiments, and yield useful insights into the mechanisms governing fabric behavior, and how pre-tension and impact obliquity influence them. The findings indicate that the fabric response is determined by four primary factors, all of which are affected differently by pre-tension and impact angle: (i) number of yarns involved in the deformation process (increases with pre-tension); (ii) degree of yarn mobility (reduces with pre-tension); (iii) yarn strain energy absorption capacity (decreases with pre-tension and impact obliquity); (iv) sliding of the projectile against the fabric (increases with impact angle). These combine such that the ballistic limit increases with pre-tension up to a critical value, after which it drops. In terms of impact obliquity, the ballistic limit increases with impact obliquity; this is because there is greater sliding of the projectile against the fabric as the impact angle increases, which offsets the decrease in strain energy absorption capacity associated with asymmetric deformation for oblique impact.

1. Introduction

Over the past 50 years, the requirement for materials to accommodate extreme applications (e.g. blast, high temperatures, high speed impact, etc.) has generated a demand for high performance materials. Strong and flexible aramid fibers, such as Kevlar® or Twaron®, are now used as reinforcement layers in a wide range of components, like bulletproof vests and aircraft engines, because of their light weight and high strength.

The performance of an impact-resistant woven fabric is generally defined by its ability to arrest incoming projectiles. Consequently, its ballistic limit – which denotes the critical speed at which a projectile perforates a fabric, and hence its maximum energy absorption capacity before failure – is of prime interest, and has been the focus of numerous investigations – for example [1–3]. The ballistic limit and energy absorption capacity of a fabric are influenced by many fabric parameters – e.g. inter-yarn friction [3–6], fabric density, yarn properties [2] – as well as external factors – e.g. projectile geometry [7,8], environment (moisture, U.V. exposure) [9,10], impact angle of incidence [11]. For designers of personal protection systems however, another critical aspect of fabric performance is its ability to prevent excessive deflection, as a large deflection may lead to severe damage of the protected structure [12], even when the energy is absorbed. To assess such information, experiments involving high speed photography must be conducted to observe the fabric deformation and projectile residual velocity [5,13]. Such experiments are complex to undertake, and only provide partial information on the deformation mechanisms which the fabric experiences during impact.

To address such issues, researchers have capitalized on the progress in computer performance and improvements in finite element codes. Simulations of ballistic impact on woven fabric have facilitated new insights into the dynamic behavior of woven fabrics. Lim et al. [14] proposed a model whereby the fabric was homogenized, and incorporated rate dependency of the material. However,

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homogenized continuum models cannot simulate yarn level interactions, inter-yarn friction, unraveling, influence of weave pattern, or yarn movement. A simple way to address this is to model the fabric yarns as trusses [6,15,16]; with such models, the yarn is only characterized by its tensile properties, and the computational cost is relatively low. However, oversimplification of the yarn structure leads to poor approximation of contact interaction between yarns, and therefore fabric transverse deformation. Related issues are projectile-surface interaction (sliding) and inter-yarn friction. Moreover, the volume of the yarn is not considered. To address this, models employing 2-D elements in the form of membranes [17] and shells [18] have been used to simulate fabric and yarns. Although they are able to approximate a fabric, shell elements introduce unrealistic significant flexural stiffness to the fabric, which results in overestimation of the flexural rigidity. Since yarns are made of fibers with essentially negligible flexural stiffness, membranes elements, which do not have any bending resistance, are a better choice. However, their flat geometry limits good approximation of the actual geometrical characteristics of a fabric. Features such as volume changes or inter-yarn friction lack precision because the contact area is oversimplified.

A discrete 3D yarn-level model was introduced by Shockey et al. [19] to study impact on fragment barriers in commercial aircrafts. Several authors have since used such models to simulate fabrics [17,20,21], but in most cases, the large number of elements limited the size of the model. To overcome this, Nilakantan et al. [22] and later Jia et al. [23] proposed an option whereby only the center of the fabric is modeled using solid elements, and the edges are modeled using shell elements. However, solid elements also have the tendency to exaggerate fabric flexural rigidity since the yarn is homogenized as continuum, compared to actual yarns, which are made of parallel fibres, giving them exceptional flexibility to bend. As highlighted by Shim et al. [15], an important aspect in simulations is accurate representation of material behavior. The viscoelasticity of aramid fibers was first observed by Roylance et al. [24], and later confirmed by others [25–27]. However, although some fabric models have incorporated viscoelasticity [25,28], most models disregard it. Yarns are often modeled as elastic or transversely isotropic material [17,29], and hence may not reflect the actual behavior of the fabric, as wave propagation is governed by yarn stiffness.

The present work is directed at two aspects: (i) an experimental and numerical study of the influence of pre-tension on the ballistic limit of fabric subjected to both normal and oblique impact, and (ii) establishment of a numerical model that incorporates the viscoelastic behavior of yarns and captures the unique flexibility of fabric materials.

2. Experimental and numerical framework

2.1. Experiments

2.1.1. Experimental setup

The experimental setup followed the work of Shim et al. [11] and is shown in Fig. 1. A fixture is designed so that a fabric specimen can be pre-tensioned and inclined at different angles. Strain gauges are mounted on four high strength aluminum support columns to measure the amount of pre-tension applied to the fabric specimen, as well as the dynamic in-plane force experienced during impact.

The fabric specimens measured 140 × 140 mm, which corresponds approximately to 116 × 116 yarns. They were pre-tensioned in the warp direction, and impacted at various speeds by a spherical steel projectile, 12 mm in diameter and weighting 6.95 g, launched from a gas gun. In this study, penetration resistance is quantified in terms of the ballistic limit with regard to a spherical projectile, because a sphere has a simple geometry, which facilitates experimental tests and computational simulation. A spherical projectile was chosen also because it has been used in the majority of investigations reported; this provides a basis for comparison. It is noted that actual projectiles can come with various nose profiles, and that this will affect their penetration ability; naturally, a sharper projectile nose is expected to have an enhanced penetration ability and thus decrease the resistance of the fabric. In such cases, the effect of fabric pre-tension on its ballistic resistance may not necessarily follow the trends for the spherical projectile observed in this study, and the resistance may decrease with initial tension. The effect of projectile nose geometry on penetration of pre-tensioned fabric has yet to be examined, and is a potentially worthwhile topic for a subsequent investigation. A system of mirrors facilitates observation of both the side profile and exit face of the fabric specimen during impact, using a single high-speed camera (Fig. 2). The side view is obtained indirectly by the conjugation of two mirrors, whereas the exit view is observed directly using a mirror inclined at 45° and placed behind the target specimen. A high speed camera operating at a framing rate of 43,200 frames/s and a shutter speed of 1/95,000 s records optical images of the deformation. Given the very high framing rate, a lighting system has to be used to illuminate the specimen during impact. The projectile impact velocity was measured using laser photodiodes placed in front of the

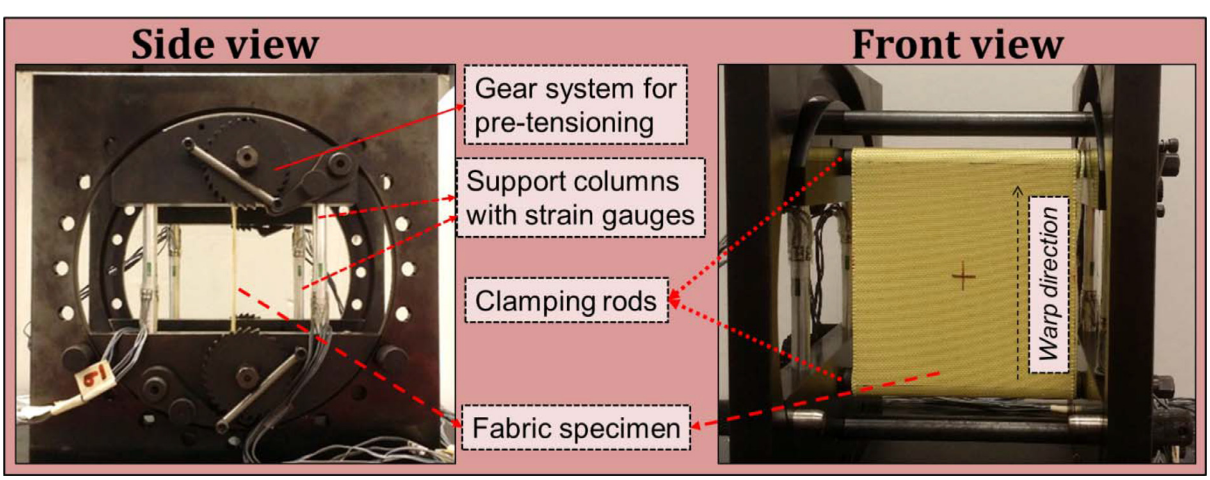

Fig. 1. Side and front view of the test fixture.