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Influence of yarn gripping on the ballistic performance of woven fabrics from ultra-high molecular weight polyethylene fibre

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ABSTRACT

It has been established that yarn–yarn friction plays an important role in absorbing impact energy in soft body armour. Yarn gripping within the fabric has been devised to increase the inter-yarn friction, using the lightweight ultra-high molecular weight polyethylene (UHMWPE) fibre. This paper reports the methods and results of an investigation on the mechanisms that enable higher impact energy absorption of woven fabrics with designed yarn gripping. Numerical and experimental models were used to study ballistic impact on soft textile panels. The numerical predictions suggested that the fabric is able to absorb more impact energy with enhanced yarn–yarn friction. It was also predicted from the FE simulation that further increases of the coefficient of friction beyond $\mu = 0.4$ reduces the fabric's capability to absorb impact energy. Three variations of the plain woven fabric were employed to increase the inter-yarn friction within the fabric, which are leno insertion, double weft and weft cramming. The yarn pull-out tests demonstrated increased resistance against the pull-out force for the fabrics with enhanced yarn gripping. This research illustrated the feasibility of creating novel fabric structures for effective enhancement of yarn–yarn friction.

1. Introduction

Modern soft body armour used in ballistic protection consists of many layers of woven or other forms of fabrics, and it serves to stop high-velocity projectiles by absorbing and dissipating projectile kinetic energy. The ballistic performance of fabric is influence by many factors, among which friction is considered to be of vital importance [1] and has been studied by many researchers. Duan et al. [2] investigated the role friction played in a ballistic event through finite element analysis. They found that projectile-fabric friction resists yarn slippage and enables more yarns to engage with the projectile, which significantly improves fabric energy absorption. yarn–yarn friction, however, restricts yarn movement and leads yarns to fail at an early stage. Lee et al. [3] and Cuong et al. [4] suggested that the reduced yarn–yarn mobility in a reinforced fabric has a positive effect on energy absorption. Friction helps to hinder yarn slippage and keeps fabric stability during ballistic impact. This is supported by Bazhenov's work [5], where tests were carried out on dry laminates and wet (water treated) laminates. The experimental results indicate that water reduces yarn–yarn and fabric-projectile friction, which cause wet laminates to have a narrower yarn pull-out zone and absorb less energy than the dry laminates. Zeng et al. [6] built a numerical model to study the yarn–yarn coefficient of friction. Their model showed that the increase in yarn–yarn friction for values of μ from 0 to 0.1 doubles the ballistic limit of ballistic fabric with further increases yielding little difference in ballistic limit. Nevertheless, the results obtained from their computational model appear contrary to Briscoe et al.'s experimental work. Briscoe [7] chemically-treated Kevlar®29 woven fabrics to achieve different levels of yarn–yarn friction. The soxhlet-extracted fabric ($\mu = 0.25 \pm 0.03$) gave better ballistic performance than as-received fabric ($\mu = 0.22 \pm 0.03$) and polydimethylsiloxane (PDMS) treated fabric ($\mu = 0.18 \pm 0.03$). As a result, further increase in yarn–yarn frictional coefficient above 0.1 appears to further improve the energy absorption of ballistic fabric.

The approaches developed so far to increase yarn–yarn friction are mainly based on surface treatment. One of the most popular methods is silica colloidal suspension impregnation [8,9]. Yarn pull-out tests showed that the highest force required to pull out a yarn is almost 650 N for 40 wt% particle impregnated fabric, which is 150 N greater than that of neat fabric [8]. It is also considered that the pull-out force was very sensitive to pull-out speed for

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treated fabrics [9]. The increase of speed from 100 mm/m to 1400 mm/m causes the highest pull-out force to increase from 6 N to almost 12 N, which means the yarn–yarn friction could be further increased at higher pull-out speed in ballistic events. Both of the aforementioned studies show the possibilities for improved ballistic performance of impregnated fabrics.

For ballistic fibres, a low coefficient of friction with processing equipment is desired to reduce fibre damage during weaving. This gives rise to a conflicting requirement as a high yarn–yarn friction is required in ballistic applications. Chitrangad and Rodriguez-Parada [10] developed a finish with certain fluorinated compounds containing polar nitrogen groups to achieve a higher yarn–yarn friction while not increasing yarn-equipment friction. Dischler [11] found that a deposition of 0.15–0.2 μm thick polypyrrole film on Kevlar fabrics increases the resistance to the impact projectile by about 19%. Apart from chemical-related methods, researchers also attempted to change yarn and fabric structure to increase yarn–yarn friction. Hogenboom and Bruinink [12] combined filaments of high strength and low frictional coefficient and filaments of low strength and high friction by core spinning. The combined yarns are considered to take the advantages of hybridization and be useful for bulletproof materials.

Although there is no shortage of literature on the working mechanisms of yarn–yarn friction, little attention has been paid to the relationship between friction and strain distribution. This paper will examine the influence of yarn–yarn friction on fabric strain distribution. In addition, as the majority of the approaches employed to increase yarn–yarn friction are based on the chemical treatment technologies, there is little work focused on employing textile based technologies. In the present research, novel weaving techniques will be used to create real woven fabrics with increased inter-yarn friction on power looms, aiming to explore the possibility of improving the ballistic performance of soft body armours.

2. Methodologies

This paper concerns the investigation of the effect of yarn–yarn friction on woven fabric energy absorption. The research has been carried out with two approaches. Firstly, the finite element method has been used to analyse the response of fabric, with different levels of friction, upon ballistic impact. As the strain directly reflects the fabric's ability to dissipate and transfer projectile kinetic energy, fabric strain distribution is also studied by carrying out FE simulations. Parallel work undertaken includes those by Duan et al. [2,13,14] and Zeng et al. [6]. The results obtained from the FE modelling in this research will be compared with their data for validation. Secondly, yarn pull-out test and ballistic penetration test will be undertaken to determine fabric inter-yarn friction and ballistic performance, respectively. In this paper, fabrics with increased yarn–yarn friction will be termed as gripping fabric.

3. Finite element simulation

3.1. Finite element model for the woven fabric

Commercial FE software ABAQUS® is used to simulate the ballistic event. In these high velocity impacts, a projectile of a more rigid material collides with a panel of fabric which is flexible. The projectile model is of a cylindrical shape with the diameter and height both being 5.5 mm, and the mass of the projectile being 1 g, identical to the projectile used for practical ballistic tests. The lenticular cross-sectional shape is used as the yarn cross section in the fabric model, as proposed by Shanahan and Hearle [15]. The length and height of the yarn cross section are set to be 1.42 mm and 0.225 mm respectively, according to the measurement of the real fabric. Hearle et al. [16] developed two types of yarn path, i.e. non-constant elliptic curvature and constant elliptic curvature. The latter is used for the yarn path in this fabric model. The length and the height of yarn crimp are set to be 0.13 mm and 1.48 mm respectively.

The woven fabric is simulated at the yarn level and has a yarn density of 6.73 threads per cm in both warp and weft directions. The areal density of a single layer fabric is 240 g/m^2. The woven fabric model is 10 cm by 10 cm. As the model is symmetric about the *X* and *Z* axes, only a quarter of the fabric is simulated. In this simulation, the projectile impacts the fabric panel at a velocity of 500 m/s, corresponding to the highest projectile velocity measured in practical experiments. Higher impact velocities can be achieved using other existing firing equipments. The coefficient of friction between yarns is found to be 0.14 [17]. The coefficient between projectile and fabric is obtained from KES FB-4 surface tester, which is 0.175.

Warp and weft yarns are assumed to be a continuum. That is, the inter-fibre movement within a yarn is not taken into consideration. The material is assumed to be transversely isotropic and linear-elastic up to the point of fracture. Since the fibres are oriented along the yarn path, this direction is has the highest of modulus, taken as 130 GPa [18]. For impact simulation, the values of E_{22}, E_{33}, G_{12} and G_{13} must be high enough to make the model stable. As it is not appropriate to use the transverse compression modulus of a yarn in ABAQUS, the values of a fibre are employed to define E_{22}, E_{33} [19]. Transverse shear modulus G_{12} and G_{13} are taken from the literature [20]. As it is not correct to consider the Poisson's ratio v to be 0 for the all three directions, a value of 0.2 is selected according to Lin et al. [21]. The transverse shear modulus G_{23} is calculated by

$$G_{23} = \frac{E_{33}}{2(1 + v_{23})} \tag{1}$$

where v_{23} is the Poisson's ratio of direction 2 and 3. The values for yarn mechanical properties are shown in Table 1.

Yarn failure is defined as strain controlled in the FE model. The tensile strength and failure strain are obtained from the DSM data sheet [18], determined as 3.9 GPa and 0.04 respectively (see Table 2).

3.2. Initial model validation

Validation of the plain woven fabric model was performed using experimental data. The ballistic range employed to carry out the test will be described in Section 4.4. The impact velocity

Table 1
Material parameters (GPa) for UHMWPE yarn.

E_{11}	E_{22}	E_{33}	G_{12}	G_{13}	G_{23}	v_{12}	v_{13}	v_{23}
130	1.21	1.21	3.28	3.28	0.504	0.2	0.2	0.2

Table 2
Fabric specifications.

Fabric structure	Distance of the intervals (cm)	Abbreviation
Plain weave	N/A	PW
Plain weave with leno insertions	2	PWL02
Plain weave with leno insertions	3	PWL03
Plain weave with leno insertions and double weft insertions	3	PWL03DW
Plain weave with leno insertions and weft cramming	2	PWL02WC