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A numerical investigation into the influence of fabric construction on ballistic performance

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ABSTRACT

The use of high-performance fibres has made it possible to produce lightweight and strong personal body armour. Parallel to the creation and use of new fibres, fabric construction also plays an essential role for performance improvement. In this research, finite element (FE) models were built up and used to predict the response of woven fabrics with different structural parameters, including fabric structure, thread density of the fabric and yarn linear density. The research confirmed that the plain woven fabric exhibits superior energy absorption over other structures in a ballistic event by absorbing 34% more impact energy than the fabric made from 7-end satin weave. This could be explained that the maximum interlacing points in this fabric which help transmit stress to a larger fabric area, enabling more secondary yarns to be involved for energy dissipation. It was found that fabric energy absorption decreases as fabric is made denser, and this phenomenon becomes more pronounced in a multi-ply ballistic system than in a single-ply system. The research results also indicated that the level of yarn crimp in a woven fabric is an effective parameter in influencing the ballistic performance of the fabrics. A low level of yarn crimp would lead to the increase of the fabric tensile modulus and consequently influencing the propagation of the transverse wave. In addition, it was found that for fabrics with the same level of yarn crimp, low yarn linear density and high fabric tightness were desirable for ballistic performance improvement.

1. Introduction

Fabrics made from high performance fibres have been widely used for ballistic protection, leading to better performance and lighter weight of body armour. It has been well noted that the energy absorption of ballistic fabrics is influenced by many factors, among which fabric construction, including fabric structure, thread density and yarn linear density, play an important role. Cunniff [1] found that the ballistic performance efficiency of an assembly is always lower than its components in the woven fabric. For instance the potential of a fibre cannot be fully utilised in a yarn, and that of a yarn cannot be fully utilised in a fabric. Fibres can be assembled mainly into woven and knitted fabrics. The high level of yarn crimp of knitted structure would delay the fabric response to impact and transmit more force to the backing material, causing deep and narrow transverse deflection [2,3]. In this regard, knitted fabrics have been found not suitable to be used against high speed ballistic impact. For woven fabrics, the comparatively low level of crimp results in faster propagation of the stress wave than the knitted fabrics, making them a better structure for ballistic protection. Due to the yarn-interlacement in woven fabric, projectile is resisted by a network of fibre or yarns, which causes the fibre or yarns to be stretched, transmitting some projectile kinetic energy to the fabric. Among various weave patterns, the plain weave is the most commonly used pattern due to the maximum interlacing points it creates and the fabric dimensional stability, and hence attracted a lot of attentions [4–6]. Other structures, such as twill and satin, tend to deviate seriously upon the ballistic impact, failing to exhibit the high performance of fabric-forming yarns [7]. For multiaxial fabrics, as there has been a controversial over its performance upon ballistic impact [8,9], it is barely used in soft body armour design.

Many worked on the influence of the plain fabric thread density on ballistic performance. Chitrangad [10] reported that the cover factor should be in the range of 0.6–0.95. When the cover factor is greater than 0.9, yarn properties degrade in the process of weaving and when the cover factor falls below 0.65, the fabric will become

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too loose. Loose fabrics, according to Cunniff [1], result in inferior performance. Shockey [11] studied Zylon® fabrics with various fabric thread densities from 30 yarns per inch to 40 yarns per inch and observed that the increase in energy absorption is almost proportional to the increase in thread density. Abiru and Lizuka [12] tested upon Spectra® plain woven fabrics with a various diversity of thread density and yarn linear density. They found that the woven fabric gives highest ballistic performance when a balance is made between thread density and yarn linear density. In order to improve performance-to-weight ratio of single-layer fabric, Cork and Foster [13] explored the possibility of using narrow fabrics. They found that due to the extra gripping provided by the fringed selvedge, the narrow fabrics absorb more impact energy than the broad woven fabric. Sun et al. [14] and Zhou et al. [15] modified the plain woven fabrics by introducing a leno structure at given intervals, and this serves to increase inter-yarn friction, via improved yarn gripping, between the warp and weft yarns. It was established that such structurally modified fabrics led to better ballistic protection than the normal plain woven fabrics.

Despite the large amount of experimental work by researchers, effort to study the influence of fabric construction on ballistic performance through numerical simulation has been quite limited. Since the numerical simulation is able to provide more in-depth information to reflect the nature of a ballistic impact event, this paper endeavours to study, through finite element simulation, the influence of the fabric construction on the impact energy absorption capabilities of ballistic fabrics, aiming to develop guidance for the engineering design of ballistic fabrics.

2. Finite element simulation

The initial fabric model is built according to the UHMWPE plain woven fabric used in Chen et al. [16]'s work. The experimental results will be used to validate the FE model. Fabric models with other structure parameters will be built based on this model, which will be shown later.

2.1. The initial FE model

Commercial FE software ABAQUS® is used to simulate the ballistic event. In our research, the projectile in use is assumed to be made of a rigid material. 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 for the yarn cross section in the fabric model, as proposed by Shanahan and Hearle [17]. The width and height of the yarn cross section are set to be 1.35 mm and 0.19 mm respectively, according to the measurement of the real fabric. Hearle et al. [18] developed two types of yarn path, i.e. non-constant elliptic curvature (for fabrics with different yarn linear densities) and constant elliptic curvature (for those with the same linear densities). The latter is used for the yarn path in this fabric model.

The woven fabric is simulated at the yarn level and has a thread density of 6.75 threads/cm in both of the warp and weft directions and a yarn linear density of 174 Tex. The fabrics are assumed to be made of an UHMWPE fibre. The areal density of a single-ply fabric is 240 g/m^2. Limited by computer sources, this woven fabric model is created into 10 cm by 10 cm. As the model is symmetric about the X and Z axes, quarter of the model is used for simulation. In the simulation, the projectile impacts the fabric panel at a velocity of 500 m/s, corresponding to the projectile velocity measured in practical experiments. The coefficient of friction between UHMWPE yarns is found to be 0.14 [19], and that between the projectile and fabric is obtained from KES FB-4 surface tester, which is 0.175.

The warp and weft yarns are assumed to be a continuum respectively in the fabric geometric model. Because of the tensile properties of UHMWPE fibre, 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, modulus in this direction, E_{11}, has the highest value, 130 GPa [20]. For the impact simulation, 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} following other researchers [21]. Transverse shear modulus G_{12} and G_{13} are taken from the work by Grujucic and his colleagues [22]. The Poisson's ratio ν for the all three directions is assumed to be a value of 0.2 following Lin et al. [23]. The transverse shear modulus G_{23} is calculated using

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

where ν_{23} is the Poisson's ratio for plane 2 and 3. The values for mechanical properties of the yarn are summerised into Table 1.

Yarn failure is strain-controlled in the FE model. According to the DSM data sheet [20], the tensile strength and failure strain are 3.9 GPa and 0.04 respectively.

2.2. Initial model validation

Validation of the plain woven fabric described in section 2.1 model was performed using experimental data obtained from the ballistic impact tests reported by Zhou et al. [15]. The impacting projectile is manipulated to produce velocities ranging from 400 m/s to 500 m/s. The residual velocities of the projectile from experimental tests and the same rang of impact velocities from FE simulation were used. Fig. 1 shows the correlation between the FE predictions and the experimental results, where the gradient of the regression line is 1.056, indicating validity of the model.

3. Effect of fabric structures

The influence of fabric structure on fabric ballistic performance and energy absorption mechanisms is important for understanding the impact event and for engineering design of ballistic fabrics. Five models of woven fabrics, using plain, 2/1 twill, 3/1 twill, 5-end satin, and 7-end satin, were created to investigate the stress distribution and the energy absorption. The yarns in the models have a same linear density, which is 174 Tex. The fabrics have a thread density of 6.75 threads/cm.

3.1. Stress distribution

Fig. 2 shows the schematic diagram of stress distribution (greyed area) on a woven fabric subjected to ballistic impact. The four “legs” are formed by the propagation of the longitudinal wave on the primary yarns. The secondary yarns are influenced by the transverse wave and the coupling effect of the crossovers, forming a diamond-shaped area in the vicinity of the impact point. The shape

Table 1
Material parameters (GPa) of UHMWPE yarn.

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