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Finite element analysis of effect of inter-yarn friction on ballistic impact response of woven fabrics

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ABSTRACT

Friction has shown to have a significant effect in determining the ballistic impact performance of woven fabrics. Many efforts were made to investigate how inter-yarn friction affects ballistic impact response of woven fabrics in the past decades. However, fundamental understanding of mechanics mechanisms of how inter-yarn friction works in woven fabric panels still needs to be established and improved. It is vitally important to understand for example how friction affects the distribution of stress and the magnitude of stress in yarns. This is necessary in determining the failure of the yarns and the energy absorption in a ballistic event. This paper presents a detailed analysis on ballistic impact behaviour of woven fabrics using the finite element method. It has been found that the magnitude of stresses on the yarn surface is sensitive to the frictional coefficient between the crossing yarns in the fabric. Increasing friction between the yarns reduces the stress at the edge of the projectile–fabric contact region. The fabric with higher inter-yarn friction between the yarns causes the impacting projectile longer time to penetrate the fabric compared to fabrics with lower friction between the yarns. The energy absorbed by the woven fabrics with higher inter-yarn friction is more than that by fabrics with lower inter-yarn friction. Increasing friction between the yarns decreases the longitudinal wave velocity whereas the transverse wave velocity is increased along with the increase of inter-yarn friction.

1. Introduction

Many investigations on the ballistic impact performance of woven fabrics have been carried out in the past decades [1–17]. Friction has been found to have a significant effect on ballistic impact resistance of the woven fabrics [1,2,7,18–21]. Briscoe and Motamedi [2] investigated the influence of interface friction on the ballistic impact characteristics of aramid fabrics. They studied various fabric weaves with three levels of inter-yarn frictional coefficients, and they found that higher projectile velocity is required to perforate fabrics with higher inter-yarn friction whereas the residual velocity of the projectile increases when reducing the inter-yarn friction. In other words, more energy was absorbed in the fabric with higher levels of inter-yarn friction. The researchers concluded that fabrics with high inter-yarn friction absorb and dissipate energy more effectively than fabrics with low friction between yarns during a ballistic event.

Friction between the projectile and the yarns is also responsible for energy absorption during an impact event. Lee and his colleagues [22] demonstrated that the energy-absorbing capacity of the fabric increases by restricting the ability of lateral movement out of the path of the projectile during an impact. Increasing friction between the projectile and the fabric hinders the mobility of the yarn and causes the projectile to engage with more yarns in the fabric, resulting in greater energy absorption.

Woven fabric tribology was investigated by Rebouillat [23], and he concluded that the yarn linear-density was observed to have the largest impact on friction, with fabrics made of higher linear-density yarns having a lower friction coefficient. Kirkwood and co-worker [24,25] developed a model to predict yarn pull-out force and energy as a function of pull-out distance. They concluded that the results of the quasi-static yarn pull-out tests can be quantitatively correlated with the yarn dynamic movement during a ballistic impact. Inter-yarn friction played a major role in the energy dissipation associated to yarn pull-out.

Duan et al. used a commercial FEA code, LS-DYNA, to model the ballistic impact of a rigid sphere into a square patch of single-layer plain-weave fabric [18,26]. Friction between the projectile and the fabric and between the yarns themselves was accounted for and its role during the impact process was investigated. Results from the modelling show that an increase in friction contributes to

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decreasing the projectile's residual velocity. The fabric with high friction absorbs more energy than the fabric with no friction. Zeng et al. [20] numerically studied the effect of inter-yarn friction on woven fabric armours. They concluded that the ballistic response of a woven fabric is very sensitive to the yarn friction for low frictional coefficients. Their results also showed that high inter-yarn friction beyond certain level can lead to premature yarn rupture, thus reducing the energy absorption capability of the fabric. This is echoed by Zhou et al. through a study in inter-yarn friction in fabrics intended for ballistic protection [27].

Research has shown that friction has a significant effect on ballistic impact resistance of woven fabrics and many attempts have been made to identify the role of friction in energy absorption and yarn fracture. Although the numerical analysis has been widely used in ballistic fabrics, the damage mechanics of the yarns in relation with inter-yarn friction in woven fabrics still calls for full understanding.

The purpose of the paper is to study numerically the way in which friction affects the impact behaviour of ballistic fabrics, and it is an effort to determine the stress distribution and magnitude of the stress that are crucially important for the engineering and development of ballistic fabrics with improved ballistic performance.

2. Finite element modelling of woven fabrics

2.1. Fabric geometry model

Finite element (FE) analysis offers a convenient approach to study the stress distributions within a fabric panel upon ballistic impact. In this research, the FE model is created using ABAQUS to simulate the transverse impact of a projectile onto woven fabric panels. The fabric model is created at the yarn-level. For the warp and weft yarns involved in the woven fabrics, the lenticular shape is assumed for the cross-section, consisting of two identical arcs facing each other. In the geometrical model, the yarn cross-sectional shape remains constant along the yarn length.

The fabric model used in the present research is plain woven. The fabric thread density is 7.5 per centimetre for both warp and weft. The linear density of the yarn is 158 tex. Accordingly, the yarn crimp wavelength and fabric thickness are 2.8 mm and 0.345 mm, respectively.

Two geometrical aspects, i.e. the cross-sectional shape and path of yarn, are used to describe the yarn geometry. The cross-section of the yarn is composed of two identical arcs facing each other, and the path of the yarn is the curve that represents the yarn waviness through the yarns in the other direction. The cross-sectional view of the fabric model is shown in Fig. 1. All geometrical parameters can be calculated using the following expressions:

$$L = 2/\text{thread density} \tag{1}$$

$$x = L/4 \tag{2}$$

$$b = \text{Fabric thickness}/4 \tag{3}$$

$$R_m = (x^2 + b^2)/2b \tag{4}$$

$$R_i = R_m - b \tag{5}$$

$$a = \left(2bR_i - b^2\right)^{1/2} \tag{6}$$

where L is the wavelength of the yarn path, R_i is the radius of the arc for the yarn cross-section, R_m is the radius of the arc for the yarn path, and a and b are half of the width and half of the height of the yarn cross-section, respectively.

The yarns are assumed to be made from a continuous material and the yarn material is considered to be isotropic although the yarns are made of bundled fibres. The reason for this is that there is a very small difference in the energy absorption whether the isotropic material mode or orthotropic material mode is applied, according to our research. In the case that the fibre material is aramid, the volumetric density of the yarn is then 1440 kg/m^3 and the Poisson ratio is 0.35. The elongation and Young's modulus of the aramid yarn are 4% and 93.5 GPa, respectively. The tensile strength of the yarn is 3.5 GPa.

2.2. Description of the finite element model

It was found appropriate that the cross-section a yarn was meshed using 10 elements and the yarn wavelength using 24 elements. Typically, the FE fabric model involves 143,520 eight-node solid brick elements. The projectile is a cylinder with a diameter of 5.5 mm and height of 5.5 mm. The projectile is modelled as a rigid body. The simple Coulomb friction is introduced between the projectile and the fabric, and between the yarns themselves. Yarn–yarn and projectile–fabric contact are modelled using a hard contact-penalty algorithm provided by the ABQUS/Explicit finite element program [28]. Different frictional coefficients are selected to investigate their influences and are applied for all the contact scenarios.

A fixed edge boundary condition is applied for all models. A typical three-dimensional finite model of the plain-woven fabrics is shown in Fig. 2(a), where a rigid projectile transversely impacts at the centre of the circular patch of the plain-woven panel. The projectile only moves in the direction perpendicular to the fabric plane, and the impact velocity of the projectile is assumed to be 500 m/s, the same as the impact velocity practically measured. The diameter of the circular patch is 148 mm, following the aperture size of the clamp used for holding the fabric panels in experiment. Fig. 2 (b) shows the detailed view of projectile–fabric system after meshing.

The ballistic impact performance of the fabrics was assessed by measuring the energy absorbed by the fabric panel on penetration. The energy dissipation due to projectile deformation, fibre intermolecular friction, air resistance and acoustic losses are all assumed to be negligible. Thus, it is taken that the loss of kinetic of the projectile equals to the energy absorption by the fabric. The FE simulations involved calculating the projectile velocity change during the impact event. The loss in kinetic energy (ΔE) of the projectile is determined using the expression below.

$$\Delta E = \frac{1}{2} m \left(V_s^2 - V_r^2\right), \tag{7}$$

where m is the mass of the projectile, V_s and V_r are the striking and residual velocities of the projectile, respectively.

3. Analysis of calculated results

3.1. Effect of friction on energy absorption

Fig. 3(a) shows a plot of projectile velocities against acting time with various frictional coefficients when impacting at a single layer fabric. It can be seen from Fig. 3(a) that the residual velocity of the projectile decreases when the inter-yarn frictional coefficient goes higher. The time taken to penetrate the panel is also increased generally along with the increase of frictional coefficient. In other words, the fabric with higher friction between the yarns has a tendency to delays the time of fabric failure, and consequently the amount of materials involved in impact deformation is increased. Therefore, the energy absorbing capacity of the fabrics can be