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Experimental study of yarn friction slip and fabric shear deformation in yarn pull-out test

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ABSTRACT

Single yarn pull-out test is a model experiment method to research the mechanical properties of fabric under impact. This study aims to understand the yarn pull-out mechanism and fabric shear deformation behavior of Kevlar 49 plain fabric by using the single yarn pull-out test combined with the digital image correlation method. The load-displacement curve contains typical physical phenomena such as crimp extension, crimp swap, frictional slip of yarn, and fabric deformation behavior. In the static friction stage, the pull-out load increased nonlinearly with the displacement, and the crimp extension of the pulled warp yarn occurred gradually. In the kinetic friction stage, the load decreased undulately until the warp was pulled out. Moreover, the fabric shear deformation sharply increased in the static friction stage, then decreased slowly during the kinetic friction stage. It was found that fabric shear deformation was still apparent after the yarn was completely pulled out.

1. Introduction

Currently, there are three types of body armor: hard body, soft body, and hard-soft composite. Composite body armor is the focus of research, because it can prevent the secondary damage of shrapnel, and it is soft and lightweight [1]. High-quality body armor material must have good energy absorbing capacity, and fast and efficient energy transfer capability [2]. Kevlar fiber is a type of aramid composite developed by DuPont in the 1960s; it has high specific strength and modulus, good toughness, high temperature resistance, and high energy storage capacity and energy transfer efficiency. Kevlar fabric is woven with Kevlar yarn, and each yarn consists of hundreds or thousands of fibers. Thus, it is an ideal composite fiber for manufacturing bullet-proof clothing [3]. The evaluation of the impact resistance of bullet-proof fabrics not only depends on the energy absorption capacity but also on the degree of deformation of the fabrics after impact. In terms of ballistic protective materials, the conventional warp and weft knitted fabric structures are not used at all due to large transverse deformation the produce when receiving impacting load. Due to the special structure of knitted fabric, the phenomenon of yarn pull-out does not exist in the ballistic impact process, and the energy dissipation caused by the relative sliding between the yarn compared with the strain energy and kinetic energy of the yarn can be neglected [4]. According to the United States NIJ standard [5], it allows maximum 44 mm backface signature (BFS), but the BSF of knitted fabrics will exceed that easily. The plain woven structure not only has sufficient flexibility to meet the requirements of soft bullet-proof equipment, but also has certain resistance to deformation relative to the knitted fabric.

In the impact process, there are three types of transfers of the kinetic energy of a bullet: the kinetic energy of yarn, strain energy of yarn, and friction dissipation caused by frictional slip [6]. Of the three, friction force has an important role in the impact process. Some studies have shown that the fabric will absorb more energy with the increase of friction force; but when the friction force is too large, a premature rupture of the yarns may occur and reduce the energy absorbing ability of the fabric [6–9]. The main role of friction force during impact is to strengthen the interaction of yarns, and remote yarns can contribute to energy absorption. The moderate friction can improve energy absorption as well as delay fabric failure through increasing fabric deformation during impact [6]. In a low-speed impact, there are three main failure modes of fabric: yarn pull-out, local yarn fracture, and remote yarn failure [9]. Multi-ply fabric impact tests and numerical simulation showed that the front layers of fabric are more likely to be sheared out by a bullet, and the rear layers tend to be broken and have a larger deflection [10].

Owing to the high speed of a bullet at impact, fabric properties were studied by comparing the change in fabric state and bullet speed before and after impact, as it is difficult to monitor the deformation process of

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fabric during impact, and it is impossible to fully understand the friction mechanism. Lower length scale experiments are necessary to better understand these mechanisms and the associated energy absorption [11]. Some researchers developed the yarn pull-out test to simulate the process of yarn pulled out from fabric during impact [12]. The yarn pull-out test is a quasi-static test whereas the ballistic impact is a dynamic process. However, it is found by many that the yarn pull-out test results correlates reasonably well with the dynamic behavior of the materials. This method provides good insight into the fabric deformation process under impact, and is helpful in understanding friction and energy absorbing mechanisms.

Some research showed that yarn pull-out load is positively related to impact resistance, and that fabric with a high yarn pull-out load behaves better in an impact test [9,13]. Zhu et al. [14] regarded the yarn pull-out process as the process of fiber pulled out from the matrix, and an analysis solution of load-displacement was established by considering the variations of yarn crimp extension and contact area. Bilisik et al. [15] studied the influence of fabric size and pull-out yarn amount as follows: the maximum yarn pull-out load is proportional to the longitudinal dimension of the fabric, while the transverse size has little effect on the maximum pull-out load. Moreover, when multiple yarns were pulled out at one time, the maximum load was larger than in the case of single yarn pull-out. Nilakantan et al. [16] found that the transverse preload is proportional to the maximum pull-out load. Dolatabadi et al. [17] studied fabric deformation under bias extension with the two-dimensional fast Fourier transform method, and the results showed that there is a critical shear angle during bias extension, which may be related to the geometric parameters of the fabric. Zhu et al. [18] discussed the deformation behavior of Kevlar 49 under bias extension; the results showed that fabric nonlinear properties and orthogonal behavior occurred under bias extension, and deformation reached 20% before fabric failure. Moreover, shear response has four distinct regions: linear elastic rotation, dissipative rotation, yarn compression, and shear locking. Bilisik et al. [19] studied the effects of yarn amount and width/length ratio on shear strength using the yarn pull-out test. However, the above works are statistical research on the relationships between load and displacement, and load and fabric geometric size. There is little research focusing on the distribution of friction force and the energy absorption mechanism at the mesoscopic level.

In this study, the yarn pull-out process was measured by the digital image correlation (DIC) method, and the load-displacement curve and fabric shear deformation were obtained. Combined with the mesoscopic geometry of fabric structure, the pull-out load, frictional force distribution, and energy absorption were investigated, and yarn crimp extension, crimp swap, frictional slip, and shear deformation were discussed.

2. Geometric properties of fabric

Kevlar 49 plain fabric (DuPont) was used in this study, and the basic properties are listed in Table 1.

The micrograph of Kevlar 49 plain fabric is shown in Fig. 1(a); the fabric is woven alternately by warp yarn in the vertical direction and fill (weft) yarn in the horizontal direction. The figure shows a period cell structure consisting of 2 × 2 intersections of warp and fill yarns. Owing to the interaction of warp and fill yarns formed during the process of weaving, wavy crimp exists in the fabric under a relaxation condition. As shown in Fig. 1(b) and (c), fill and warp yarns have different weave lengths and widths of f_a, w_a and f_b, w_b, respectively. A period size of a cell is $(f_a + w_b) \times (f_b + w_a)$ in the vertical and horizontal directions, respectively.

The abridged view of warp yarn trajectory with cross fill yarns and the fill yarn trajectory with cross warp yarns are shown in Fig. 1(d) and (e), respectively. The cross-sectional height of warp and fill yarns is f_c and w_c, respectively. There is an overlapping region of warp and fill yarns, which is called the intersections of warp and fill yarns, and the intersection area is $S = f_b \times w_b$. In addition, there is a gap between the intersections, and the area of the gap is $s = (w_b - f_a) \times (w_a - f_b)/2$. The geometric dimensions of warp and fill yarns are listed in Table 2.

Table 1
Material properties of fabric.

Type	Dtex	Density (g/cm^3)	Number of fibers	Fiber diameter (μm)
Kevlar 49	1420	1.44	1000	12

3. Single yarn pull-out test

3.1. Sample and experiment process

The test equipment used to conduct the experiment is shown in Fig. 2(a); two clamps are placed on a sliding rail to clip the two sides of fabric. Each clamp comprises three parts: front u-shaped groove, back u-shaped groove, and the board between the two. Before the test, the fabric was placed between the board and the back groove, and secured by the bolts installed in the front groove. Hence, the fabric was clamped tightly between the board and the back groove. This design reduces boundary stress concentration and improves the accuracy of the experiment.

Before the experiment, the direction of the warp yarn is along the tension direction and the upper end of the warp yarn is loaded. The width and length of the sample are both 15 cm. There are a total of 65 cells (130 intersections) along the warp direction and the same number of cells along the fill direction. There is no preload in the sample before the experiment. The middle warp yarn is pulled out using a universal testing machine (Instron 3345) and the pull-out speed is 100 mm/min.

Before the experiment, black markers were placed on the intersections of the pulled warp yarn and the 14 fill yarns in order to measure fabric deformation by DIC, as shown in Fig. 2(b). There were a total of 112 markers on the sample. During the experiment, a camera (AVT, F080b) was used to take photos with a frame rate of 5 fps, and the image size was 1024 × 768 pixels.

3.2. Pull-out load and displacement curve

The load-displacement curve of the yarn pull-out test is shown in Fig. 3(a). There are two distinct regions: static friction and kinetic friction. In the static friction region, the pulled yarn had crimp extension and produced the static friction force among the intersections, which led to the fabric deformation. When the pull-out load reached the maximum, the pulled yarn began to slip in the kinetic friction region in Fig. 3(b).

In the kinetic friction region, the load-displacement curve shows a classic sine-wave feature corresponding to a yarn crimp swap, where the pull-out load first increased and then decreased. The increase of pull-out load indicates that the bottom end of the pulled warp yarn is slipping into the adjacent intersection, while the decrease of pull-out load indicates the bottom end is slipping out of the current intersection. A sine wave corresponds to two intersections. When the pulled warp yarn slips through two intersections, it is a “slip in-out” process corresponding to the production of a sine wave in the load-displacement curve, shown as a dashed rectangle in Fig. 3(b). Therefore, the load-displacement curve comprises fabric shear deformation at a macroscopic scale and yarn deformation at a mesoscopic scale, which reflects a coupled physical phenomenon of yarn crimp extension, crimp swap, and friction slip.

At the beginning, the fabric sample produced overall deformation and the pull-out load varied linearly with displacement, owing to the structural adjustment of warp and fill yarns, as shown in Fig. 4(a). Next, the pulled warp yarn produced crimp extension, as shown in Fig. 4(b);