Study on Single-yarn Pullout Test of Ballistic Resistant Fabric under Different Preloads

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Abstract. During bullet penetrating fabric, the pull-out force of yarn in fabric is related to the impact resistance of fabric when the yarn is pulled out from the fabric. The complex uncrimping and friction slip behavior occur during the yarn pullout process, which is critical to learn the impact resistance of fabric. Based on digital image correlation technique, the deformation behavior of Kevlar 49 fabric subjected to preload during the single-yarn pullout process was studied in this paper. The pullout force and displacement curve shows a straight rise and an oscillated decrease. In the linear rise stage, the yarn uncrimping causes a static friction effect. The maximum of the pullout force is not linearly increased with the preload. In the oscillating descending stage, the local descent of the pull out force indicates that the yarn end is gradually withdrawn from the fabric, and the local rise indicates that the yarn end moves to the next weft/warp interaction until the yarn is completely pulled out. The shear deformation of fabric corresponds to the single-yarn pullout process.

1. Introduction
Aramid fiber Kevlar made by DuPont company can be used as a kind of bulletproof textile fiber with excellent performance, such as low fiber density, high crystalline, high temperature resistance, chemical stability, high tensile modulus, good energy absorption and anti-shearing ability. In recent years, many scholars have studied the behavior of fabric by combining experiment with finite element method [1, 2], Bilisik et al. [3] aimed to study the pullout properties by changing the yarn linear density, demonstrating that the pullout force increased with the yarn linear density. Chen et al. [4] reported on an analytical model of ballistic impact of multi-layer woven fabrics, finding that during the ballistic impact of multi-layer woven fabrics, shear failure occurs before tensile failure for the front layers, preventing the high strength polymer fibers reaching full energy absorption potential.

In the process of bullet penetrating fabric, the yarns are pulled out from fabric under the action of friction, so the pullout force of the yarns is related to the impact resistance. As a complex process of fabric impact, the impacting damage is not only related to fabric weaving ways, yarn material properties, yarn friction coefficient, shearing contact area, but also bullet shape and speed [5]. Yarn tensile fracture and shear tearing are two common failure forms. The crimp yarns are stretched up to fracture and the adjacent yarns are squeezed each other to produce a frictional shear effect. The single-yarn pullout test is used to study the energy-absorption behavior of fabric under impact. Tapie et al. [6] studied the response of plain weaving fabric during in-plane and out-of-plane pullouts and the energy dissipation in yarns was mainly caused by frictional force. Duan et al. [7, 8] studied the role of the friction on the ballistic impact behavior of fabric with the method of experiment and simulation, and
the results showed that the friction contributed to increasing the fabric energy absorption not only through frictional sliding dissipated energy but also by increasing yarn strain energy and yarn kinetic energy, which indicated an indirect effect on the fabric energy absorption. Zhou et al. [9] introduced yarn gripping as a key parameter to learn the mechanisms of the energy absorption, concluding that resistance against the pullout force of fabric increased with the enhanced yarn gripping.

The uncrimping and frictional slipping behavior is complex during the yarn pullout, which is important to investigate the energy absorption behavior. Many methods have been proposed to investigate the interactions. King et al. [10] established a continuum constitutive model to characterize the process of the yarn pullout with the introduction of the anisotropic shell; they also extended the model to three dimensions. Bazhenov [11] intended to learn the friction of yarns during pullout, characterizing energy transferred to different fabric layers and noting that the friction improved energy dissipation.

In this paper, the deformation behavior of Kevlar 49 fabric subjected to preload during the single-yarn pullout process was studied by digital image correlation (DIC) technique. The influence of preloads on the maximum pullout force and the shear deformation was studied. The study is helpful to understand the energy absorption mechanism of fabric under impact.

2. Testing process

2.1. Kevlar 49 plain fabric parameters

The basic properties of the Kevlar 49 plain fabric are shown in Table 1.

| Name     | Density (g/cm³) | Fiber diameter (μm) | Fiber number per yarn |
|----------|----------------|---------------------|-----------------------|
| Kevlar 49| 1.44           | 12                  | 1000                  |

3. Experiments

The fabric specimen has 65 pairs of intersections in the warp and weft direction, as shown in Figure 1(a). Before the testing, both sides of the specimen are clamped in a stress-free state by the fixture. The preload can be applied through adjusting the slider on the rail.

![Figure 1](image1.png)

**Figure 1.** (a) Plain fabric specimen, (b) schematic of single yarn pullout test and (c) schematic of black markers

A single warp yarn in the middle of the specimen was clamped into the upper fixture of the tensile machine (Instron 3345) and was pulled out, as shown in Figure 1(b). The preloads of 25N, 65N and 100N were applied, respectively. A displacement loading rate was 100 mm/min.

In order to identify the fabric deformation, the black markers (Fig. 1c) with equal intervals were made and identified by the DIC method which used the local matching algorithm to reveal the full-
field deformations with accuracy. The deformed images were captured by a camera (Guppy F080b) with a image resolution of $1024 \times 768$ pixels and the sampling frequency was 5 fps.

4. Results and discussion

4.1. Pullout force - displacement curve
The curves of pullout force and displacement in single-yarn pullout tests under different preloads are shown in Figure 2. There are two parts: a linear ascending phase and an oscillating descending phase, which correspond to an uncrimping process and a sliding process of the pulled yarn, respectively.

![Figure 2](image)

Figure 2. Typical curves of pullout force and displacement in single-yarn pullout test under different transverse preloads

(1) Linear ascending phase
At the beginning of the experiment, the pullout force increases linearly with the displacement and the pulled warp yarn is gradually stretched from the initial crimping state, and the pullout load is transferred by the friction between the yarns. Due to the uncrimping of the pulled yarn end, the cross-section of the yarn is reduced and the contact surface of the warp and weft yarns decreased. The uncrimping portion of the drawn warp yarn has begun to slide before reaching the maximum pullout force. In contrast, the remaining crimp part of the warp is still in the static friction stage, at this time the pullout force is shared together by the dynamic friction and the static friction. It can be seen that the linear ascending phase is not only the process of uncrimping of the pulled yarn, but also the transformation process from the static friction to the dynamic friction.

(2) Oscillating descending phase
When the maximum pullout force is reached, the pulled warp yarn has been completely uncrimped and then slipped; the pullout force is entirely shared by the dynamic friction in the oscillating descending stage. The decrease in pullout force indicates that the end of the warp is pulled out from the last intersection, and the rise in pullout force indicates that the warp end moves to the next intersection. It results in a drop of the pullout force in the sliding friction phase. Thus, the "slip-out and slip-in" process at the end of the pulled yarn means a pair of warp/ weft intersections is crossed, producing a "wave" of pullout force. As the yarn is gradually pulled out, the intersections gradually decrease until the yarn is completely pulled out, and the load is reduced to zero.

4.2. The effects of the preloads
In order to analyze the effects of different transverse preloads, the maximum pullout force and its displacement data are extracted from Figure 2, as listed in Table 2. Obviously, the maximum pullout force is increased with the increase in preload and the spent time is shorter, because the weft yarn deformation under preload expands the contact area between the weft and warp yarns. It is noted that
the contact pressure at the intersection of the warp and weft yarns is increased as the weft yarn under preload, so the frictional force at the intersections is also increased.

Table 2. Effects of preload on pullout parameters

| Preload (N) | Time (s) | Max load (N) | Displacement (mm) | Slope (N/mm) |
|------------|----------|--------------|-------------------|--------------|
| 0          | 7.6      | 8.933        | 12.985            | 0.688        |
| 25         | 6.9      | 9.533        | 11.475            | 0.724        |
| 65         | 5.4      | 10.539       | 8.967             | 1.175        |
| 100        | 5.0      | 11.905       | 8.333             | 1.429        |

It can also be seen from Table 2 that the maximum pullout force increases nonlinearly with the preload. The preload of 25N is taken as an example, when the preload force increased to 260% and 400%, the corresponding maximum pullout force increased by about 110.6% and 124.9% respectively. It indicates that the increase in preload will inhibit the fabric shear deformation. According to time data of the maximum pullout force in Table 2, it can be seen that the presence of the preload causes the single-yarn to be pulled early into the oscillating descent stage. The increased preload changed the initial buckling state of the weft yarns and increased the contact pressure. According to the curves in Figure 2, the slopes of the linear ascending phase are listed in Table 2, it can be seen that the slope also increases with the preload, indicating that the yarn is more difficult to be pulled out.

4.3. Fabric energy absorption

![Figure 3. Absorbed energy curves with wave number under different preloads](image)

In the yarn pullout force and displacement curve, the area under the curve is regarded as the total work of the pullout force. The area under the pullout peaks was integrated and the relationship between the wave number and the absorption energy was obtained, as is shown in Figure 3. It can be seen that the yarn intersections is decreased in the yarn pullout process, and the overall energy absorption capacity of the fabric is also decreased. In the initial dynamic friction stage, the fabric energy absorption ability was exponentially decayed; after the yarn was pulled out to half of the intersections, the yarn energy absorption rate decreased and the energy absorption capacity was weakened. It indicates that the effect of preload on the fabric deformation is mainly reflected in the forward stage in single-yarn pullout test. Comparing the energy absorption characteristics under different preloads, it can be found that the stronger the preloads, the stronger the energy absorption effect of the fabric, which indicates that the preload expanded the energy absorption potential of the fabric and improved the ability of the fabric to resist the deformation. Moreover, the energy absorption efficiency is not the same, which was better under the preload of 25N or 65N. At last, four curves in Figure 3 tended to coincide after the half intersections pulled out, then the preload no longer played a major role of limiting the fabric deformation.
4.4. Fabric shear deformation

Displacement measurement of markers on the fabric surface (Figure 1c) was achieved by using the DIC method. A correlation function was used to measure the similarity of the markers before and after the deformation, and the displacements generated by the markers were obtained. In order to obtain subpixel accuracy, a bilinear interpolation method was used to the image before and after the deformation.

Since the pulled yarn is located in the middle of the fabric, which is symmetrical in both geometric and boundary conditions, thus only the right side of the fabric is used to study on the shear deformation. The horizontal angle of the weft yarn on the right side of the fabric is defined as the shear angle $\theta$ (Figure 1b), and the shear angle without fabric deformation is $0^\circ$. The markers on the top weft line of the fabric are regarded as the row 1, then the row 2 is followed and so on (Figure 1c).

![Figure 4](image)

**Figure 4.** Tan($\theta$) with time curve for different weft lines under preload of (a) 0N, (b) 25N, (c) 65N and (d) 100N.

The yarn pullout process is accompanied by the overall deformation of the fabric, which can be analyzed by the DIC method. The tangential value of the shear angle for each weft row with time is shown in Figure 4. It can be seen that there are similar changes of shear angles for different weft lines. In the initial stage, the absolute shear angle increased linearly and rapidly and reached the maximum at the moment of the largest static friction. After entering the dynamic friction stage, the absolute shear angle was gradually reduced until the yarn was completely pulled out. The shear angle was remained at last, which indicates that the fabric remains larger deformation when the yarn was pulled out completely. In the dynamic friction stage, the absolute shear angle decreases oscillatingly, which corresponds to the oscillation of the curve of pullout force and displacement. It shows that the decrease of the shear angle of the fabric is closely related to the pullout force.
Table 3. Shear angles under different preloads

| Preloads (N) | Range of shear-angle tangents          | Range of residual shear-angle tangents          |
|-------------|----------------------------------------|-----------------------------------------------|
| 0           | [-0.10401, -0.10174]                   | [-0.07275, -0.06903]                          |
| 25          | [-0.08879, -0.08698]                   | [-0.02057, -0.01897]                          |
| 65          | [-0.06196, -0.05994]                   | [-0.02016, -0.01843]                          |
| 100         | [-0.04865, -0.04834]                   | [-0.01222, -0.01037]                          |

The minimum shear angle tangent is used to characterize the maximum deformation of the weft yarns, meanwhile, the residual shear angle is used to characterize the residual deformation after the weft is fully pulled out, which are summarized in Table 3. It can be seen that these tangent values increase with the preload, which indicates that the increase of the preload not only restrains the fabric shear deformation, but also increases the ability of the fabric to restore deformation. The greater the preload, the better the effect of fabric deformation recovery, which is due to the warp pullout causing the vertical deformation of the weft yarns.

5. Conclusions
By conducting the single-yarn pullout test under different preloads, the influence of preload on the deformation parameters such as the pullout force, absorbing energy and shear angle was studied. The static friction plays a major role in the yarn uncrimping elongation stage. Then, the sliding friction takes the main role in the yarn slip stage. The maximum pullout force increases non-linearly with the preload so that the pulled warp enters the dynamic friction stage early. The fabric energy absorption decays exponentially, and the effect of preload on the fabric deformation is mainly reflected in the stage of the first half intersections of the yarn. The fabric shear deformation corresponds to the yarn pullout process. The absolute shear angle of the fabric increases linearly in the yarn uncrimping stage. In the dynamic friction stage, the absolute shear angle oscillates down to the residual value, which indicates that the fabric still remains residual deformation after the warp pulled out. The greater the preload, the smaller the fabric residual deformation.

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