Experimental Study on Yarn Pullout Test of STF Modified Fabric

Yang Feng¹, Yu Ma¹, Zhenkun Lei¹,*, Saisai Cao², Qinghao Fang¹, Weikang Li¹, Ruixiang Bai¹ and Shouhu Xuan²

¹State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, China
²Department of Modern Mechanics, University of Science and Technology of China (USTC), Hefei 230027, China
Email: *leizk@163.com

Abstract. Shear thickening fluid (STF) solution with SiO₂ as dispersing phase and ethylene glycol as dispersing medium was prepared by ball milling, Kevlar49 plain woven fabrics impregnated with STF were prepared. The impact resistance and shear deformation of the STF modified fabrics were studied by single-yarn pull-out tests and digital image correlation (DIC). The experimental results show that a dynamic slippage of yarns makes the STF attached to the yarn surface appear shear thickening effect, so the sliding friction between the yarn is higher than the static friction due to the increased viscosity. Therefore, the bigger pull-out force of the STF-fabrics increases the energy absorption capacity of the fabrics. The DIC results show that the maximum shearing angle and the residual shearing angle of the STF modified fabrics are larger than those of the pure fabrics, indicating that the STF will increase the friction between the yarns without affecting the fabric flexibility.

1. Introduction
Aramid fibers produced by DuPont have the characteristics of high strength, high modulus and low density, improving the shortcomings of the heavy weight and inflexibility of traditional protective materials to a certain extent. In order to achieve the standard of bullet-proof protection, several layers of aramid fabrics need to be stacked, which will increase the relative weight and volume. In the process of ballistic penetration, the ability of the fabric to dissipate the impact energy of the bullet has a strong correlation with the friction between the fabric yarns [1]. Therefore, it is of great significance to find a suitable interface modification method for improving the friction between the yarns so as to improve the impact resistance of bullet-proof fabrics.

The STF is composed of disperse phase particles and dispersion medium. Since the phenomenon of shear thickening was first found in the hard-ball dispersion liquid, it was found that the STF is a non-Newtonian fluid and there is a non-linear relationship between the viscosity and the shear rate. Zhang [2] found that the viscosity increases abruptly and the increase is reversible when a critical dynamic shear rate is exceeded. Utilizing the above characteristics, the STF has great potential to the field of bullet-proof protection. Lee et al. [3] found that the fabric impregnated by the STF with a smaller dispersion phase size shows a greater interfacial friction under the critical shear strain rate. Cao [4] showed that the volume ratio of STF, the number of the fabric layers and the impact velocity all affect the mechanical properties and energy absorption capacity of Kevlar fabrics impregnated with the STF. Decker et al. [5] studied the better thorn proofing performance of Kevlar and nylon fiber cloth
impregnated with the STF under the same areal density. Gong et al. [6] studied the effect of different STFs on the stabbing and puncturing resistance.

In this paper, Kevlar49 aramid fiber fabric impregnated with STF was prepared. The yarn pullout tests of the STF modified fabric were performed to study the effect of the different STFs on the maximum drawing force, and then the mechanism of energy absorption was analyzed. Meanwhile, the DIC measurements were conducted to investigate the whole deformation of the fabrics.

2. Experimental procedure

2.1. Sample preparation

Experimental reagents and powder materials used in this paper are as follows: SiO$_2$ powder with a particle size of 1 micron (Rich Color Mineral Material Company, China), ethylene glycol analytical reagent (SINOPEC Chemical Reagent Co., Ltd., China), anhydrous glycol analytical reagent (SINOPEC Chemical Reagent Co. Ltd., China) and Kevlar 49 plain woven fabric (DuPont, USA).

The STF preparation process is as follows. Firstly, the SiO$_2$ powder was cleaned by anhydrous ethanol and in turn deionized water all three times. The washed SiO$_2$ powder and ethylene glycol was blended in a ball mill tank by a mass fraction of 70%, and then the ball mill tank was put into the ball mill to stirring for 24 hours. Finally, the stirred sample was put in a vacuum oven for 8 hours to remove air bubbles and sealed as shown in Figure 1.

![Figure 1. The prepared STF samples.](image)

The prepared STF was diluted with absolute ethanol at a ratio of 1: 8, and then the Kevlar 49 plain woven fabrics (Figure 2a) were immersed in the diluted solution for 5 minutes. The STF modified fabrics were taken out and placed in a drying oven to remove the ethanol until a unchanged weight.

![Figure 2. SEM of (a) Kevlar 49 fabric and (b) STF modified Kevlar 49 fabric.](image)

It can be seen from Figure 2(b) that the modified Kevlar49 fabric with STF adsorbed a large amount of SiO$_2$ particles, which uniformly distributed into the fabric.
2.2. Yarn pullout test
The yarn pullout test is a simplified modeling of the process of bullet striking fabrics into the process of pulling a yarn out of the fabrics. As shown in Figure 3(a), the prepared specimen was placed in the fixture and the middle single-yarn was drawing out from the fabric using a tester. The Kevlar 49 plain fabrics and the STF modified Kevlar 49 were used in these experiments.

Figure 3. Single yarn pullout test, (a) experimental setup and (b) markers on fabric for DIC measurement.

An Instron 3345 test machine with a loading rate of 100 mm/min was used in the experiment. As shown in Figure 3 (b), black spots were marked at every 3 warp/weft intersections on the right side of the specimen. The fabric deformation process was recorded by a camera (Guppy F080b) with an image grabbing rate of 5 fps. The distorted fabric image has a resolution of 1024 × 768 pixels. The DIC technique is used to measure the in-plane displacement of each marker of the fabrics to characterize the overall deformation. Typical load–displacement curves of single yarn pull-out test of Kevlar49 fabric and STF-Kevlar49 fabric are shown in Figure 4.

Figure 4. Load–displacement curves of (a) Kevlar 49 fabric (b) STF modified Kevlar 49 fabric during yarn pullout test.

3. Results and discussion

3.1. Load–displacement curves
As shown in Figure 4(a), the load–displacement curve of Kevlar fabric is obviously composed of two parts. In the linear ascending stage, the tensioned single yarn is in the static friction state, and the uncrimping elongation occurs. After reaching a limit load (8.4N), it enters the dynamic friction stage, which is a non-linear oscillation descending stage and the tensioned single yarn begins to slip. The yarn pullout process from a warp/weft intersection will produce a similar sinusoidal waveform.
As shown in Figure 4(b), the load-displacement curve for the STF modified Kevlar 49 fabric is similar to Figure 4(a). The most obvious difference is that the linear limit load (68.1N) is significantly increased, about 8 times as much as Kevlar49 fabric. This is mainly due to the increase of the roughness of the yarn surface by the attachment of STF to the surface of the yarn, which makes the friction between the yarns increased.

It is noted that the second wave after the linear limit load is significantly higher than the first wave in the dynamic friction stage, as shown in Figure 4(b), which is different to the load–displacement curve of the Kevlar fabric in Figure 4(a). This is due to the rheological properties of the STF itself. During the yarn pulling out from the fabric, the yarn dynamic slip causes the shear thickening effect on the STF attached to the yarn surface. The increase of the viscosity makes the sliding friction between the yarns higher than the static friction.

3.2. Energy absorption

The protective ability of the fabric is related to the energy absorption. Integrating the area under the load-displacement curve of Figure 4 yields the total work done by the drawing force on the fabric. Each pull-out wave in the dynamic friction stage corresponds to a warp/fill intersection. Therefore, the relationship between the absorption energy and the wavenumber can be obtained, as shown in Figure 5.

![Figure 5](image-url)

**Figure 5.** The absorption energy changes with the wave number of the drawn yarn during the dynamic friction stage.

It can be seen that the absorbed energy trends are similar for the Kevlar 49 fabric and the STF modified Kevlar 49 fabric. With the yarn pulling away from the intersection position, the number of fabric intersections gradually reduces. The ability of the absorbing energy of the fabrics decays. At the dynamic friction, the absorbed energy decreases greatly and then reduces slowly.

Moreover, the fabric impregnated with STF shows stronger energy absorption than the pure fabric. It indicates that STF can increase the friction between the yarns so that the performance of the impact resistance is greatly improved.

3.3. Fabric deformation

As shown in Figure 6, the overall deformation of the fabric occurs in the yarn pullout process. A shear angle $\theta$ is defined as the angle between the fill yarn and the horizontal direction, as shown in Figure 6(b). The shear angle is positive in the counterclockwise direction. The initial shear angle is $0^\circ$ (Figure 6a).
Figure 6. (a) Initial fabric state without load, (b) deformed fabric state at maximum pullout force.

The markers were identified by the DIC method before and after deformation so that the shear deformation of the fabric can be measured during the yarn pullout process. Since the geometry and boundary conditions of the fabrics are symmetrical with respect to the drawing yarn, it is necessary to study the shear deformation on the right side of the fabric. There are 10 markers in each row and a total of 22 rows with a total of 220 markers on the fabric.

Figure 7. Curves of tangent shear angle with time for different lines of (a) Kevlar 49 fabric and (b) STF modified Kevlar 49 fabric.

Using the DIC analysis, the curves of the tangent shear-angle (Tan(θ)) of each row with time are obtained as shown in Figure 7. It can been seen that the Tan(θ) for different rows has a similar trends. Firstly, the shearing angle rapidly increases in the static friction stage, and reaches the maximum value when the yarn is about to slip. It indicates that the shearing deformation reaches the maximum at the maximum static friction force. Next, in the dynamic friction stage, the shear angle gradually decreases until the drawn yarn is completely pulled out. Finally, there still exists a large residual shear angle. It means that the whole fabric remains largely deformation after the yarn pulled out.

Table 1. Shear angles for two kind specimens.

| Specimen    | Range of max shear-angle tangents | Range of residual shear-angle tangents |
|-------------|----------------------------------|---------------------------------------|
| Kevlar      | [-0.10401, -0.10174]             | [-0.07275, -0.06903]                  |
| STF- Kevlar | [-0.18878, -0.17939]             | [-0.13018, -0.11951]                  |
The maximum and residual values of the tangent values of the shearing angles per row extracted and listed in Table 1. It can be seen that the maximum shearing angle and the residual shearing angle for the STF modified fabric are larger than those of pure fabric. It is because the drawing force for the STF modified fabric is large so that the corresponding shear deformation is also large. In addition, the stiffness of the STF modified fabric changes a little. It indicates that the STF increases the friction between the yarns but does not affect the fabric flexibility.

4. Conclusions
The effects of STF on the deformation parameters of Kevlar 49 fabrics such as drawing force, absorption energy and shear angle were studied by the yarn pullout test and the DIC method. The experimental results show that the single yarn drawing is divided into two stages. In the stage of yarn uncrimping elongation, the static friction plays a major role. In the stage of yarn slipping out, the sliding friction in yarns plays a major role. The maximum pullout force of the STF modified fabric increases significantly. It is due to the shear thickening effect of the STF between the yarns as the yarn is drawn, so the energy absorption properties have greatly improved. Moreover, the STF modified fabric has larger deformation, indicating that the STF increases the protective performance of the fabrics, but do not affect the flexibility of the fabrics.

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6. References
[1] Wang Y, Chen X, Young R, Kinloch I. Finite element analysis of effect of inter-yarn friction on ballistic impact response of woven fabrics. Composite Structures. 2016, 135: 8-16.
[2] Zhang XZ, Li WH, Gong XL. The rheology of shear thickening fluid (STF) and the dynamic performance of an STF-filled damper. Smart Materials and Structures. 2008, 17 (3): 035027.
[3] Lee BW, Kim IJ, Kim CG. The influence of the particle size of silica on the ballistic performance of fabrics impregnated with silica colloidal suspension. Journal of Composite Materials. 2009, 43(23): 2679-2698.
[4] Cao S, Chen Q, Wang Y, Xuan S, Jiang W, Gong X. High strain-rate dynamic mechanical properties of Kevlar fabrics impregnated with shear thickening fluid. Composites Part A: Applied Science and Manufacturing. 2017, 100: 161-169.
[5] Decker MJ, Halbach CJ, Nam CH, Wagner NJ, Wetzel ED. Stab resistance of shear thickening fluid (STF)-treated fabrics. Composites Science and Technology. 2007, 67(3): 565-578.
[6] Gong X, Xu Y, Zhu W, Xuan S, Jiang W, Jiang W. Study of the knife stab and puncture-resistant performance for shear thickening fluid enhanced fabric. Journal of Composite Materials. 2014, 48(6): 641-657.