An investigation into the ballistic response of stitched plain weaves

H Li and Y Zhou

Key Laboratory of Textile Fiber & Product (Wuhan Textile University), Ministry of Education, China

*Email: yi.zhou@wtu.edu.cn

Abstract. It has been widely accepted that yarn pull-out and windowing plays a vital role in absorbing impact energy in a protective fabric system. Stitching within the fabric has been devised to constrain the transverse and lateral displacement of the primary yarns, using conventional cotton sewing threads. This paper reports the experimental and numerical methods and results of an investigation on the mechanisms that enable higher impact energy absorption of woven fabrics with designed yarn stitching. Penetration tests were performed over a range of impact velocities from the ballistic limit up to 180 m/s. The experimental results showed that the energy absorption of the stitched fabric sample is over four times higher than that of unstitched one. For mass-normalized metrics, stitching the fabric on every other yarn yields a 146% improvement in energy absorption capacity when compared to unstitched samples. The numerical predictions suggested that yarn pull-out could be delayed or even eliminated on stitched samples, enabling the fabric to absorb more strain and kinetic energy.

1. Introduction

Modern soft body armour used in personal protection system consists of many layers of flexible materials, and it offers protection by absorbing and dissipating projectile kinetic energy. It has been reported that body armour used for ballistic protection is heavy, restrictive and can increase the thermo-physiological burden on the wear, and therefore efforts to identifying new materials or systems with improved performance and a lower mass penalty are the subject of many active types of research. Over the years, researchers have been on the lookout for innovative approaches to improve the performance of ballistic fabrics, among which increasing the frictional force between the fabric-forming-yarns has attracted many attentions.

The influence of inter-yarn friction on the energy absorption of woven fabric has been well-studied by many researchers. Duan et al. [1] found that increased inter-yarn friction enables more yarns to engage with the impacting projectile, which this significantly increases the amount of strain and kinetic energy deposited on the fabric target. In addition, friction helps to maintain the integrity of the weave pattern and reduce yarn slippage during ballistic impact. The reduced inter-yarn mobility in a reinforced woven fabric has a positive effect on energy absorption [2-3]. When the woven fabrics are
not compositied with matrix materials, fabric penetration is more often than not accommodated by yarn pull-out and “windowing”; this phenomenon hinders high-performance fibres from exhibiting their mechanical properties and consequently lowers the impact resistance [4-5]. If yarn mobility could be well-constrained to eliminate yarn pull-out and “widowing”, an improvement in ballistic performance is expected. 

Since the contribution of friction-sliding mechanism to fabric energy absorption could not be neglected, producing an appreciable component in the friction between the crossover-forming-yarns is believed to be beneficial. Numerous approaches have been investigated to constrain yarn mobility, among which the application of shear thickening fluid (STF) attracted great attentions. An STF is a non-Newtonian fluid whose viscosity increases discontinuously above a critical shear rate [6-7]. This response is due to the formation of particle clusters by shear force, resulting in a sudden increase in fluid viscosity [8]. It has been reported that the frictional effect on STF treated woven fabric is governed by many factors, such as particle size [9-10], suspension constituent [11], suspension concentration [12-13], fluid-phase [14-15], reinforcement construction [16] and temperature [17]. Apart from STF, other chemically related treatments have also been investigated, and some of the most recent works are listed as follows: Sun and Chen attempted to increase inter-yarn friction by using low-pressure plasma-enhanced chemical vapour deposition (PCVD) method [18]. Non-polymerizing reactive plasma N2 and polymerizing plasma (CH3)2ClSi were applied to Kevlar woven fabric, and the resultant fabrics showed enhanced resistance against yarn pull-out. Chu et al. simplified the process by using atmospheric-pressure PCVD technology [19]. Increase inter-yarn friction was found on samples with longer treatment time. Chu et al. also investigated the effect of different sized TiO2/ZnO hydrosols. It has been found that the yarns treated by sub-micro-sized hydrosol exhibit a nearly 50% increase in the coefficient of friction compared to neat yarn, while the increase of nano micro-sized coated yarns is only 10% [20]. Hwang et al. found that the application of ZnO nano-wire to fibre surface causes interlocking between the wire arrays, which results in a significant increase in yarn gripping [21]. In spite of the improved performance, fabric flexibility [22] and lightweight [23-24] are inevitably deteriorated, i.e., a trade-off must be made between ballistic performance and wearing comfort.

Confronted by such a challenge, some researchers attempted to increase inter-yarn friction without using any chemically related treatment, among which modifying fabric structure seems to be a reasonable approach. Combining leno structure with plain weave demonstrated an increase in yarn pull-out force, but insufficient to provide a noticeable improvement in ballistic performance [25-27]. Our previous research showed that replacing leno structure with knitted single jersey structure yielded a junction rupture force (JRF) more than double that of the pure plain weave. The insertion of knitted rib structure within plain weave gives JRF ~15 times higher than pure plain weave. When withdrawing multiple yarns simultaneously, yarns are self-lock at the loop-intermeshing area, and failure occurs [28]. Bilisik and Korkmaz [29] used Nylon 6.6 and Kevlar 129® yarn to make stitching on plain weave. Ballistic testing results showed that stitched panels exhibit a lower depth of backface signature than the unstitched panel. This is because the structure becomes stiffer and more integrated into between the adjacent layers, providing sufficient resistance against a transverse impacting load. The contribution of increased inter-yarn friction has also been mentioned, but its mechanism has not been
fully realized. In this paper, investigations will be carried out to develop a comprehensive understanding of the working mechanism of stitching in resisting ballistic impact, aiming to provide alternatives for the engineering design of soft body armour.

2. Sample specifications

The plain fabrics are made of Kevlar®29 multi-filament yarns, which were provided by DuPont. All the fabrics share the same thread density and yarn linear density, which is 7 threads/cm and 1670 dtex, respectively. The plain weaves were stitched on both of the warp and weft directions using sewing thread. The sewing thread was manufactured by plying three cotton staple yarns, which have a yarn count of 40s Ne. The mechanical properties of Kevlar®49 multi-filament yarn and the sewing thread in use were shown in Table 1. Table 2 shows the specifications of different fabric samples. Stitched and unstitched fabric samples are shown in figure 1.

**Table 1. Yarn specifications.**

| Material       | Kevlar®29 | Sewing thread |
|----------------|-----------|---------------|
| Yarn type      | Aramid    | Cotton        |
| Yarn breaking strength (cN/ tex) | 203 | 32.7 |
| Yarn breaking elongation (%) | 3.6 | 20 |
| Yarn modulus (cN/ tex) | 4900 | 133 |
| Yarn count (dtex) | 1670 | 500 |
| Density (kg/m²) | 1440 | 1540 |

**Table 2. Fabric specifications.**

| Sample No. | Fabric type | No. of layers | Stitching direction | The density of stitching lines | Areal density (g/m²) |
|------------|-------------|---------------|---------------------|-------------------------------|----------------------|
| 1          | Plain weave | 1             | -                   | Stitching lines on every yarn | 240                  |
| 2          | Plain weave | 1             | Stitching lines on both of the warp and weft yarns | Stitching lines on every two yarns | 480                  |
| 3          | Plain weave | 1             | Stitching lines on every yarn | Stitching lines on every three yarns | 360                  |
| 4          | Plain weave | 1             | Stitching lines on every yarn | Stitching lines on every four yarns | 320                  |
| 5          | Plain weave | 1             | Stitching lines on every yarn | Stitching lines on every two yarns | 300                  |
| 6          | Plain weave | 1             | Stitching lines on every yarn | Stitching lines on every two yarns | 360                  |
| 7          | Plain weave | 1             | Stitching lines on every yarn | Stitching lines on every two yarns | 300                  |
Plain weave 1 Stitching lines on every three yarns 260

Plain weave 1 Stitching lines on every four yarns 250

Figure 1. Stitched and unstitched plain fabrics. (a) Sample 1; (b) Sample 2; (c) Sample 3; (d) Sample 4; (e) Sample 5; (f) Sample 6; (g) Sample 7; (h) Sample 8; (i) Sample 9.

3. Testing of fabric properties

3.1. Ballistic test
The ballistic tests were performed on a set-up shown in figure 2. In this set-up, the spherical projectile in use is 2 gram in weight and 8 mm in diameter. The projectile is propelled by compressed gas, and the impact velocity varies with the range of 0 m/s ~180m/s. The projectile can be captured by two sets of infra-red chronographs in front of and behind the sample target, and the impact and residual velocities could be obtained from velocity readers. Penetration tests were performed on both of the stitched and unstitched samples. The ballistic performance of sample target is measured by the energy loss of the projectile, determined by

\[ \Delta E = \frac{1}{2} m(v_1^2 - v_2^2) \]
Where, \( \Delta E \) is the kinetic energy loss of projectile, \( m \) is the mass of the projectile, \( v_1 \) and \( v_2 \) are impact and residual velocities of the projectile, respectively. In our research, energy loss due to air friction is neglected.

Conner-clamped (CC) frame was designed to clamp the sample target. In the CC frame, sample targets were gripped at their corners to allow yarn pull-out during the ballistic event. The fixing units were through-bolted with the back plate and fastened by four tightening nuts. In this case, the resistance against yarn pull-out comes solely from the frictional force at crossovers and the stitching lines; the influence of the stitching structures on ballistic performance could be better studied without any boundary constraint. In a ballistic penetration test, sample targets were cut into 25×25cm to fit the size of the frames.

![Schematic diagram of the ballistic range for the penetration test.](image)

**Figure 2.** A schematic diagram of the ballistic range for the penetration test.

![Corner-clamped frame.](image)

**Figure 3.** Corner-clamped frame.

### 3.2. Softness and yarn pull-out tests

Fabric softness test studies the influence of stitching on the flexibility of Kevlar plain woven fabrics. The tests were performed according to the European standard of EN ISO 17235:2015 for determination of leather softness. Yarn pull-out tests were performed to quantitatively characterise the influence of stitching on the constraint between the warp and weft yarns. The method was detailed in our previous papers [28]. Schematic diagrams of the yarn pull-out method are shown in figure 4. It can
be seen that a slot was retained for the yarn to be pulled out while the rest of yarn tails were clamped by a bottom jaw. The dashed red line indicates the stitching line. In this research, yarn pull-out tests were performed on both of stitched yarns and yarns perpendicular to the stitching lines.

![Figure 4. Schematic diagrams of the yarn pull-out test on (a) stitched yarn and (b) yarn perpendicular to the stitching line.](image)

### 4. Experimental Results

#### 4.1. Residual velocity comparison

Figure 5 reveals the impact velocities of the projectile against the residual velocity on both of the stitched and unstitched samples. Penetration tests were performed over a range of impact velocities from the ballistic limit up to 180m/s using CC frame. The black dashed line indicates the results obtained without the sample target. Since the effect of air drag on the projectile is neglected, there is no reduction on the impact velocities. It can be seen that the curves exhibit a non-linear increasing trend beyond the ballistic limit. The regression lines of each sample seem to be increasingly approaching the black dashed line as the impact velocity increases. This could be explained as follows: when the impact velocity is in the vicinity of the ballistic limit, projectile kinetic energy is mainly transformed to fabric strain energy; as the impact velocity increases beyond the ballistic limit, the fabric response inelastically and the residual velocity becomes nonlinearly with impact velocity. This indicates the reduced efficiency of energy absorption of the plain weave. It is evident in figure 5 that stitched fabric samples exhibit superior ballistic performance over unstitched one; the distance between two adjacent stitching lines varies inversely with the ballistic limit, with sample 2 being the most protective target.
4.2. Energy absorption capability

Figure 6 shows the energy absorption of different sample targets at the impact velocity of 180 m/s, aiming to minimise the impact of the variation of impact velocity on fabric performance. Also revealed is the ballistic performance of plain weaves stitched on the weft yarns only. It could be seen that sample 2 shows the greatest value of the average energy absorption, which is over four times higher than that of the plain weave. This is followed by sample 3, sample 4 and sample 5 successively. Samples stitched on both of the warp and weft directions consistently shows higher energy absorption than those stitched on the one direction only, indicating the reduced ballistic performance of the samples. The error bars in figure 6 represent the value of standard deviation (SD), and it is found that samples stitched on one direction shows greater variability or scatter in energy absorption than those stitched on both directions. For both types of fabric, the scatter in energy absorption increases with increasing distance between the two adjacent stitching lines. Plain weave seems to exhibit the least variability.
It should be noted that the added weight of the sewing thread could not be neglected. The application of stitching lines on every single yarn on both of the weft and warp directions results in 100% increase of the areal density on plain. Since the main purpose of most ballistic related studies is to improve material performance at a reduced weight, it is necessary to investigate further the energy absorption capability of stitched fabrics by taking into account fabric areal density. For mass-normalized metrics, total energy was divided by areal density to obtain normalised energy absorption, and the results are shown in figure 7. Among samples stitched on both of the weft and warp directions, sample 3 exhibits slightly higher normalized energy absorption and greater scatter than sample 2; the improvement in energy absorption capability is 146% when compared to unstitched plain weave; on samples stitched on the weft direction, error bars overlap to each other to a greater extent than samples stitched on two directions. The unstitched plain weave exhibits the least energy absorption.

![Figure 7](image)

**Figure 7.** Normalized energy absorption of stitched and non-stitched plain weaves at the impact velocity around 180m/s.

4.3. *Post-impacted images*

The ballistic results obtained from penetration tests provide a first-order estimate of the contribution of yarn stitching to fabric energy absorption. It is evident that stitching enables the fabric to absorb more kinetic energy from the projectile. Figure 8 displays the post-impacted images of stitched and unstitched samples. All of the samples were penetrated except sample 2. It could be seen from figure 8(a) that the primary yarns were pulled to a large extent on sample 1 where pull-out markers are clearly identified. Apart from the withdrawn yarns, the projectile was able to push aside other yarns, causing “windowing” [4]. Due to the existence of yarn pull-out and “windowing”, the primary yarns are not able to sustain the impact load, and therefore material failure was not observed on sample 1. On sample 2, where the stitching was applied on every single yarn, the projectile was completely stopped without yarn displacement and fibre failure. As the weft and warp yarns are constrained by the
sewing threads, yarn pull-out and “windowing” failed to occur. It can be seen from figure 4(c), (d), and (e) that fabric penetration was accommodated by dual mechanisms of filament failure and displacement as the distance between the stitching lines becomes widened. Also observed were filament flattening and spreading, which were probably caused by the transverse compression of the projectile [4]. Filament flattening and spreading is beneficial in preventing the projectile from “wedge through” the interstitial between the two neighbouring yarns. Figure (f)-(i) display post-impacted samples stitched on the weft direction only. On these samples, yarns are found to be pulled out to a greater extent than those stitched on both directions. Despite this, filament failure could still be noticed.

In figure 6 and figure 7, the value of energy absorption is found to exhibit variability, and the scatter increases with the distance between the two adjacent stitching lines. The variability of plain weave could be attributed to the number of yarns loaded by the projectile, which is essentially determined by the impact locations (directly on the yarn or in between the yarns). On stitched samples, the distribution of stitching lines needs to be taken into consideration when identifying the source of variability. When the projectile impacts the stitching lines, the probability of yarn failure increases and energy absorption is expected to be high; when the projectile impacts the gap between the stitching lines, the probability of filament failure decreases and the energy absorption is expected to be low. On densely-stitched samples, the impact site is more likely to be located on or in the vicinity of the stitching lines, and hence improved ballistic performance and lower scatter; on sparsely-stitched samples, the projectile is comparatively less likely to contact the stitching line, and hence reduced ballistic performance and greater scatter.
Figure 8. Post impact close-ups of different sample at the impact velocity of around 180m/s. (a) Sample 1; (b) Sample 2; (c) Sample 3; (d) Sample 4; (e) Sample 5; (f) Sample 6; (g) Sample 7; (h) Sample 8; (i) Sample 9.

4.4. Yarn pull-out test and fabric softness test results
Since the ballistic penetration tests indicate that thread stitching improves the ballistic performance by effectively prevents yarns from being pulled out and pushed aside, it is interesting to investigate the
constraint on the stitched fabric-forming-yarns quantitatively. This was done by measuring the resistance of stitched samples against pull-out force.

Figure 9 displays the force-displacement curve of yarn pull-out test performed according to the method stated in figure 4 (a). In this method, sewing threads were stitched on neighbouring yarns perpendicular to the pulled yarn. It was found that stitching lines increase the pull-out force considerably. The peak load force of one-yarn-stitched sample is over eight times higher than that of the plain weave. The maximum pull-out force increases with the number of yarns stitched. Samples with four and five yarns stitched exhibit similar peak load force of around 50 N. The results indicate that the constraint provided by stitching lines greatly increases the frictional force between the weft and warp yarns. It must be pointed out that the load-displacement curves share similar force values at the initial stage of yarn pull-out. The difference starts to become pronounced beyond the displacement of 6 mm, indicating that the constraint mechanism of stitching is activated at the stage of “stick-slip” [30]. If the projectile impacts the plain weave region, stitching plays a limited role in resisting yarn pull-out until the primary yarns are pulled to a certain extent. This is supported by the fact that yarn pull-out is still noticeable in figure 8 (c), (d) and (e). In this regards, the pulled yarns provide extra length for the projectile to push the yarns aside and consequently increases the probability of “windowing”.

![Figure 9](image)

**Figure 9.** Pull-out force as a function of displacement on the weft direction.

Figure 10 displays the load-displacement curve of yarn pull-out test performed according to the method stated in figure 4 (b). In this case, the withdrawn yarn is entirely stitched by the sewing thread. It could be seen in the figure that the curve representing the stitched sample increases sharply at the initial stage of the process, reaches a peak value of around 45 N and drops thereafter. The result indicates that the stitched yarn exhibits a swifter response upon pull-out force in comparison with those shown in figure 9. This provides insight into the superior energy absorption capability of sample 2 over other samples in figure 6. The fact that every individual yarn is stitched by the sewing thread on sample 2 eliminates the probability of yarn pull-out and “windowing”, enabling the constraint
provided by stitching to take effect at the very beginning of the ballistic event and making sure that the sample target resists projectile penetration more effectively than other samples. It is reasonable that the ballistic performance of other samples may decrease under the condition that the projectile impacts the unstitched yarns. Therefore, the scatter of energy absorption becomes greater on the rest of the samples.

![Graph](image)

**Figure 10.** Pull-out force as a function of displacement on the warp direction.

Figure 11 displays the results obtained from the fabric softness test according to the European Standard of EN ISO 17235:2015. The value of distension on the vertical axis is the depth of fabric when pressed an indenter. It could be seen that the unstitched sample exhibits greater distension value, and hence highest flexibility. It seems that stitching stiffens the originally soft plain weave and the magnitude of flexibility varies inversely with the density of stitching lines. The constraint provided by the stitching lines increases the friction between the warp and weft yarns, restricts yarn displacement and impedes the inter-fiber and inter-yarn motion. This mechanism inevitably increases the stiffness of the plain weave. A detail explanation of the relationship between friction and stiffness was given by McNeil and Standard, who investigated the bending rigidity of sol-gel coated wool fabrics [22].
5. Conclusions
The focus of this research was to investigate the ballistic performance of stitched plain fabrics and to develop a method to constrain the mobility of the fabric-forming yarns based on textile technologies. The ballistic performance of both stitched and unstitched fabrics was characterised using a gas gun. The experimental results show that stitched fabric samples exhibit superior ballistic performance over unstitched ones, and samples stitched on one direction shows greater variability or scatter in performance than those stitched on both directions. For mass-normalized metrics, stitching the fabric on every other yarn yields a 146% improvement in energy absorption capacity when compared to unstitched samples. Fibre failure is more evident on the stitched sample than on unstitched samples. This is because that the stitching lines impede yarn displacement without pull-out or windowing and enable Kevlar yarns to sustain projectile impacting load. The constraining effect of the stitching line was verified by yarn pull-out test. The results confirmed the increase in frictional force between the weft and warp yarns due to yarn stitching. It was also found that stitching line stiffens the plain weave, and consequently decreases the magnitude of flexibility.

Funding
This work was supported by the National Natural Science Foundation of China (11502179).

References
[1] Duan Y, Keefe M, Bogetti T A, Cheeseman B A and Powers B 2006 Int. J. Impact Eng. 32 1299-312
[2] Lee B L, Walsh T F, Won S T, Patt H M, Song J W and Mayer A H 2001 Penetration Failure Mechanisms of Armour-Grade Fibre Composite Under Impact J. Compos.Mater. 35 1605-33
[3] Cuong H., Boussf F, Kanit T, Crépin D and Imad A 2012 Effect of Frictions on the Ballistic Performance of a 3D Warp Interlock Fabric: Numerical Analysis Appl Composit Mater 19 333-47

[4] Nilakantan G, Merrill R L, Keefe M, Gillespie J W and Wetzel E D 2015 Compos. Part. B Eng. 68 215 – 29

[5] Wang Y, Miao Y, Huang L, Swenson D, Yen C-F and Yu J 2016 Int. J. Impact. Eng. 97 66 – 78

[6] Hoffman R L 1998 Explanations for the cause of shear thickening in concentrated colloidal suspensions J. Rheol. (N Y N Y) 42 111 – 23

[7] Barnes H A 1989 Shear - thickening (“Dilatancy”) in suspensions of nonaggregating solid particles dispersed in Newtonian liquids J. Rheol. (N Y N Y) 33 329 – 66

[8] Brady J F and Bossis G 1985 J. Fluid. Mech. 155 105 – 29

[9] Lee B W, Kim I J and Kim C G 2009 J.Compos.Mater. 43 2679 – 98

[10] Feng XY, Li S K, Wang Y, Wang Y C and Liu J X 2014 Mater. Desian. 64 456 – 61

[11] Hasanzadeh M, Mottaghiatalab V, Babaei H, Rezaei M Part A-Appl. S. 88 263 – 71

[12] Tan V B C, Tay T E, Teo W K 2005 Int. J. Solids. Struct. 42 1561 – 76

[13] Fahool M, Sabet A R. 2016 Int. J. Impact. Eng. 90 61 – 71

[14] Ávila A F, Oliveira A M, Leão S G, Martins M G 2018 Compos. Part A-Appl S. 112 468 – 74

[15] Gürgen S and Kushan M C 2017 Polym. Test. 64 296 – 306

[16] Laha A and Majumdar A 2016 Materials&Design 89 286 – 93

[17] Wang Q S and Feng Y 2019 Part A-Appl S. 116 46 – 53

[18] Sun D and Chen X 2012 Res. J. 82 1928 – 34

[19] Chu Y, Chen X, Sheel D W and Hodgkinson J L 2014 Text. Res. J. 84 1288 – 97

[20] Chu Y, Chen X, Wang Q and Cui S 2014 Appl. Surf. Sci. 320 710 – 17

[21] Hwang H S, Malakooti M H, Patterson B A and Sodano H A 2015 Compos. Sci. Technol. 107 75 – 81

[22] McNeil S J and Standard O C 2017 Text. Res. J. 87 607 – 16

[23] Tan V B C, Tay T E and Teo W K 2005 Int. J. Solids. Struct. 42 1561 – 76

[24] Lee Y S, Wetzel E D and Wagner N J 2003 J. Mater. Sci. 38 2825 – 33

[25] Zhou Y, Chen X and Wells G 2014 Part B. Eng. 62 198 – 204

[26] Sun D, Chen X and Mrango M 2013 Fibers. Polym. 14 1184 – 89

[27] Sun D, Chen X and Wells G 2014 J. Compos. Mater. 48 1355 – 64

[28] Zhou Y, Muhammad A and Deng Z 2019 Text. Res. J. 89 4717-31

[29] Bilisik K and Korkmaz M 2010 Test Text. Res. J. 80 1697 – 720

[30] Sebastian S, Bailey A I., Briscoe B J and Tabor D 1987 J. Phys D. Appl. Phys. 20 130