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Ballistic-proof Effects of Various Woven Constructions

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Abstract
This research tested Para-aramid (Kevlar) fibrous products of equal specifications (material and density) with respect to the influence of the fabric construction on their bulletproof behaviour. Constant speed and constant deformation energy tests were performed based on the static methods of the Material Test System, in which Armour Piercing Bullets (AP), Full metal Jacket Rifle Bullets (RB), and Fragment Simulating Projectiles (FSP) were applied. Among the samples of Kevlar woven fabrics tested, namely plain, twill, basket, and satin constructions, the plain weave construction demonstrated the best proofing properties against AP and RB, especially during low-speed tests of single-layer materials. In the high-speed FSP bulletproof test of multilayer constructions, 2×2 Basket fabric had the highest ballistic resistance performance, followed by the plain weave construction; the ballistic qualities of both these materials appreciably exceed those of other fibre woven fabrics. Satin fabric exhibited the weakest bulletproof properties in all the tests, apparently because of the weak stability of its construction. The main conclusion that can be drawn from the investigations performed is that in order to withstand a projectile impact, fibre woven fabrics should have a strong enough stability of their construction.

Key words: *para-aramid fibre, plain weave, twill, satin, basket weave fabrics, bulletproof materials.*

Introduction

Kevlar fibre is one of the most widely-used impact-proof materials in many industries, finding different applications, particularly in the production of bulletproof and armour materials, wear resistant brakes, and aeronautical materials. Kevlar fibres have also found application in the production of high-performance materials due to their obvious very high strength, distinguishing them from ordinary industrial fibres.

To develop bulletproof materials, it is important to understand how they work and interact with a high-speed projectile. When a projectile impacts a fabric, the fibre of the yarn that mainly receives the impact force absorbs a great deal of energy and, thus, produces a counterforce to resist the high energy of the projectile. The impact energy is absorbed in the process of the complicated geometric strength and tensile deformation of Kevlar fibre. The theory predicts that any weaving point brings about a concentration of energy, thus weakening the material, which is the basis a very important rule: "the longer the fibre, the better the ballistic resistance". Hence the best conditions for impact energy dissipation are found in fibrous materials without weaving points. To solve this problem, a material of Uni-Direction construction (e.g. Honeywell Co. product) was developed and has been available on the market since 1990. These fabrics have been widely used over the past decades to improve the hardness, stiffness and weight of bulletproof material . However, improving the ballistic resistance of materials still remains an important task for researchers.

The ballistic resistance performance of fabrics does not exclusively depend on the features of the materials impacted but also on many projectile characteristics. Generally, the bullet protection might be affected by the following main factors: As concerns projectiles: (1) the mass and pattern, (2) the velocity, (3) the material it is made of, (4) the shape and size, and (5) the impact surface. As concerns fabrics: (6) the weave construction, (7) the weave density, (8) the strength, (9) the ultimate elongation, (10) the surface stiffness, and (11) the squeezing-through protection.

This research was devoted to the testing of para-aramid fabrics of equal specifications in terms of the raw material used

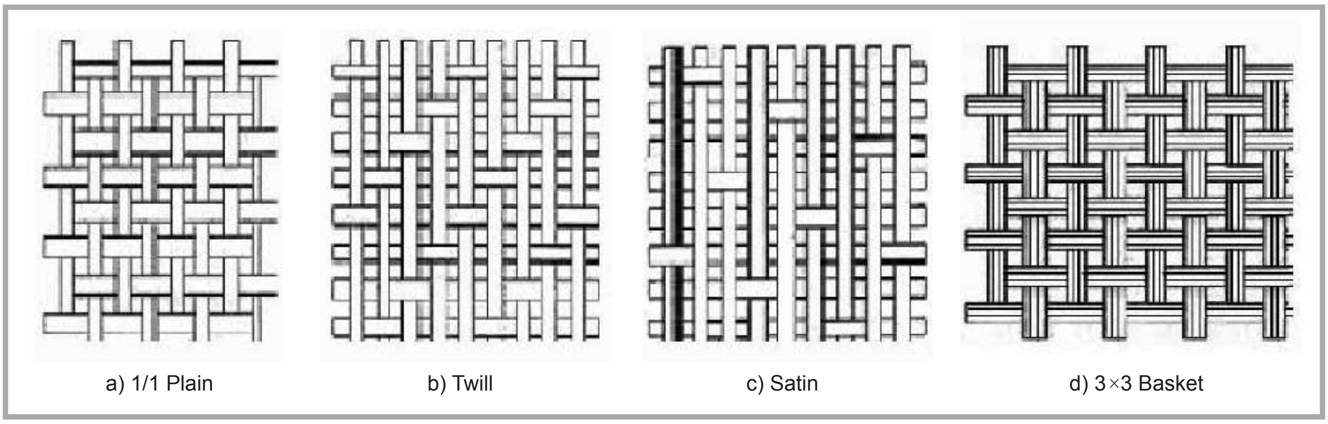

***Figure 1.** Fabric construction diagram; a) Plain weave is the commonest weaving method of producing tough fabrics with the shortest inter-weave fibre length and easy-creasing characteristics; b) Twill woven fabric has fewer warp-weft interweaves than plain weave for the same unit area. The fibre is long enough to allow the design of different float yarns; c) Satin woven fabric has the fewest warp-weft interweaves with the longest inter-weave fibre length and high softness in every single unit area; d) Basket weave is a variation of plain weave, in which a few warps cross alternately side-by-side with a few weft yarns. Basket weave fabrics are more pliable and stronger but less stable than 1/1 Plain weave. Basket weave is typically used in the composite industry.*

and density. However, different woven constructions were tested to study their influence on the impact-proof behaviour of fabrics subjected to impact by projectiles of various types.

Experimental

Materials

A SUZUKI loom was used to weave Kevlar 29 1000d/666f, making fabrics with the same density but of different fabric construction. The density of the fabric construction was 28 roots/per inch. Four popular weave constructions (***Figure 1*** see page 63) were investigated in this study:

Methods

Mechanical test

A tensile test was performed using the material strength tester MTS Test Star IIs (Taiwan Textile Research Institute) to investigate the strain-stress behaviour of the materials developed. With the MTS Test Star IIs, (5×15) cm^2 samples of each material were tested dynamically for their tensile-strength behaviour based on Standard ASTM D 638 .

Estimation of bulletproof properties

Ballistic Impact Test. Ballistic impact tests were performed with various Kevlar woven fabrics in order to determine the limit velocity (V50), which is one of the important bulletproof characteristics of this type of material. To project the projectile at a low speed (below 250 m/s), a firearm with a shortened barrel or reduced explosive charge was used in this study. The low-speed projectiles produced were impacted against Kevlar fabrics of various constructions, and the test results were analysed based on the Ballistic limit Criteria V50 mode (BLC) [4].

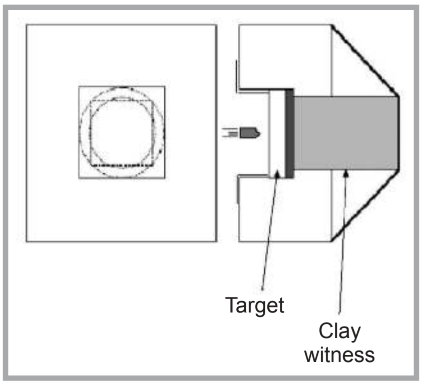

Figure 2. *Schematic diagram of the ballistic experiment.*

Ballistic Resistance Energy Methods. Two Energy Methods were used in this research to estimate the bulletproof properties of the materials, namely the constant speed and MIL-STD-662F methods [5]. In both of these the fibre woven fabrics tested are impacted at a constant speed and in a controlled manner. A thick block of Roma Plastilina clay was placed behind the fabric. When the projectile impacted the target, its impact force was transmitted to the plastilina clay through the dispersion of the stress from the fabric, making an indentation on the surface of the plastilina clay (***Figure 2***). The shape and depth of each indentation can serve for estimation of the bulletproof quality of the product.

Constant speed method. The fabric tested was impacted at a constant projectile velocity of 100 m/s, and the indentation was measured after the impact. Then the capability of the fabric construction to resist the projectile was analysed based on this indentation. The constant speed test method used in this study is demonstrated in ***Figure 3 a***. 10 cm diameter width. The test sample was impacted by one bullet, and a clamp was used to prevent the movement of the sample (***Figure 3 b***). An indentation was clearly observed on the surface of plastilina clay of 4.5 cm diameter width (***Figure 3 c***) after the test, which was then measured as shown in ***Figure 3 d***.

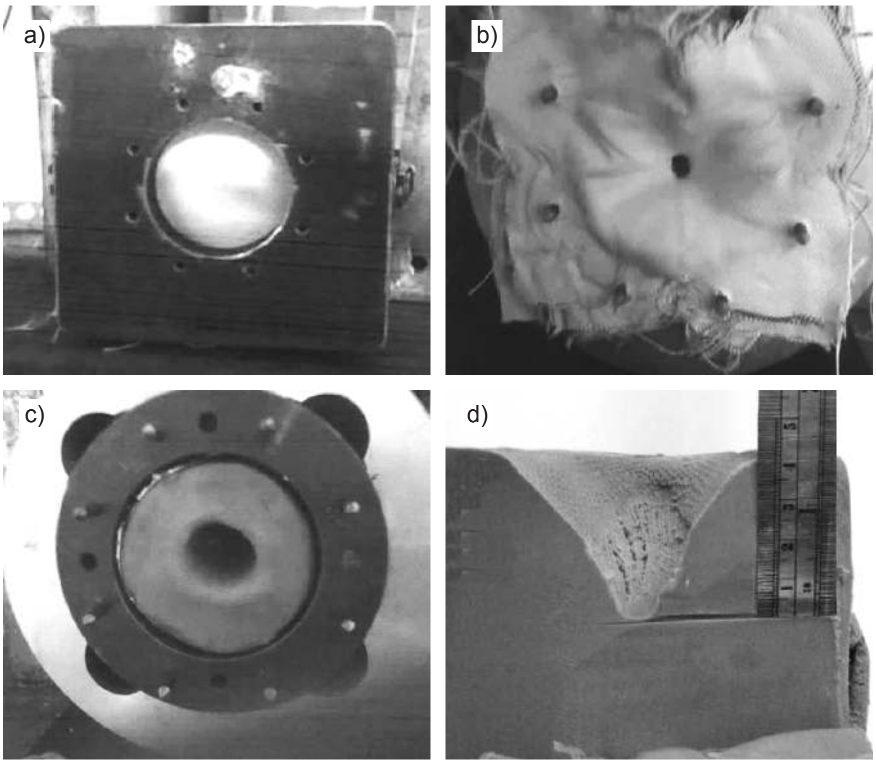

Figure 3. *a) fabric clamp, b) fabric impacted at high speed, c) indentation on the plasticine clay surface behind the fabric after a high speed impact, d) cross section of an indentation appearing on plasticine clay after a high speed impact.*

MIL-STD-662F is another energy method commonly used to test bulletproof materials. The fabric to be tested is impacted at different speeds due to different powder dosages, and the speed at which the impact brings about a 44 mm indentation on the surface of the plasticine clay behind the fabric assessed is accepted for the limit velocity of a V50 projectile. The bullets used in this study were MIL-P-46593 7.62 mm 44 grain (2.8 g) Fragment Simulating Projectiles (FSP) as specified in MIL-STD-662F, and Roma Plastilina No. 1 clay was applied as witness clay. The speed was adjusted during the test to produce a 44 mm indentation on the surface of the plasticine clay behind the fabric assessed. This controlled speed is accepted as the limit velocity of the fabric.

Calculations of the Ballistic Impact

A complete and strict set of test regulations, especially the V50 value, was available for the testing and verification of the ballistic resistance performance. The ballistic limit criteria – NIJ 0101.04 [1] usually used for the ballistic resistance of personal body armour contains backface signature (BFS) criteria, the maximum indentation of the plasticina clay.

The depth of the depression created by the impact force of a non-penetrating projectile in the backing material is measured from the plane defined by the front edge of the backing material fixture. ***Figure 2*** shows more information. The BFS criteria are widely recognised and applicable to appraise different materials [1]. In this study it was adopted by the National Institute of Justice (NIJ) to determine the quality of bulletproof vests and materials.

The limit velocity is taken as the basis for determining the ballistic quality of the product.

In order to normalise results with respect to variations in impact velocities, the results of ballistic tests are also presented in terms of the projectile kinetic energy dissipated (*E*), expressed in Joules [2]:

$$E = \frac{1}{2} m (V_i^2 - V_r^2) \qquad (1)$$

where: *m* is the projectile mass (kg), V_i – the initial bullet velocity (m/s), and V_r is the residual velocity of the bullet after target penetration (m/s).

Y. S. Lee [2] proposed the following linear relation between the depth of the bullet penetration and its residual velocity:

$$V_r = 38.9 + 3720\,L \qquad (2)$$

where: *L* is the penetration depth into the clay witness (m).

Equations (1) and (2) are used throughout this paper to correlate the penetration depth with the residual kinetic energy of the projectile. The deformation rate of a fluid during a ballistic event is estimated to be of the order of 10^4 ... 10^5 s^{-1} (deformation rate = V_i/penetration depth). These data are an excellent indication of protective capability.

As shown in ***Figure 4*** (on top) [3, 4], when a projectile impacts the fabric construction, and a shock wave is transmitted to the weaving point, a counterforce is brought about by this impact [7]. The impact force distribution is different for different fibre constructions (***Figure 4 a-c***). Only in the case of continuous fibre without weaving points is the stress distributed along the fibre quite evenly (***Figure 4 c***). The appearance of weaving points brings about local overstress (***Figure 4 a*** and ***b***), being the reason for various fibre damage. This verifies a very important rule: “the longer the fibre, the better the ballistic resistance”, which is used by several manufacturers to produce bulletproof items.

Equations for the ballistic impact on fibres and Newton’s second law of motion can be expressed as follows:

$$\Delta y = V \cdot \Delta t - \frac{1}{2} a_1 (\Delta t)^2 \qquad (3)$$

where: Δy is the length relative to direction Y, Δt is the time required to stop the projectile, and a_1 is the deceleration.

When the fibre is impacted at speed V_i, the force transmission in the fibre of the fabric produces an indentation behind the sample. The fibre length can affect the transmission rate of the shock wave and impact force. The longer the fibre, the higher the impact force that can be sustained, as the relative elongation decreases in this case. On the other hand, to resist projectile movement (Δy = 0), the Δt should be as short as possible ($\Delta t \rightarrow 0$). Consequently, the lower the Δy and Δt, the better. Hence, reducing the Δy of the indentation is currently the goal of all manufacturers.

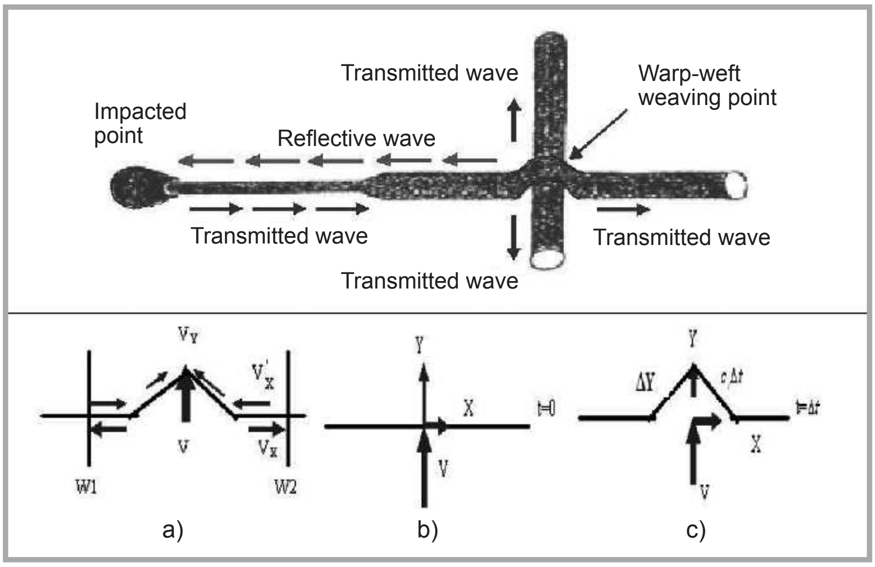

Figure 4. Stress transmission from the fibre impacted: general view (above) and the impact force distribution for different fibre constructions (below): a) impacted interweave fibre, b) impacted weaving point, c) impacted straight fibre.

Results and discussion

Fabric tensile test

The strength and elongation of the fibre woven fabrics tested are summarised in ***Table 1***. These data evidence both the strength and rigidity or pliability of the fabrics with different weave constructions. Among the fabrics tested, 3×3 basket, 1/1 plain, and 1/3 twill weaves provide the highest strength values ; at the same time these materials demonstrate quite good pliability with tensile elongation ≥ 10%. The weakest material is 8H satin.

Comparing 1/3 and 2/2 twill weave materials, one can see that despite the low

Table 1. *Strength and elongation of various fabric constructions.*

No	Fabric construction	Thickness, mm	Tensile elongation, mm	Maximum strength, kN	Max. strength normalised*, kN
1	1/1 Plain weave	0.47	17.6	9,5	20,2
2	8H Satin weave	0.52	7.9	7,9	15,1
3	1/3 Twill weave	0.46	14.3	9,1	19,8
4	2/2 Twill weave	0.45	7.6	8,6	19,2
5	2×2 Basket weave	0.45	9.9	8,7	19,3
6	3×3 Basket weave	0.70	20.8	15,0	21,4

** – The value of the maximal strength is normalised to a fabric thickness of 1.0 mm.*

Table 2. Single layer limit velocity for various fabric constructions and projectile types.

No	Fabric construction	Fabric thickness, mm	AP steel-cored 5.1g Bullet		AK 47 M43 8g FMJ Bullet	
			Limit velocity, m/s	Limit velocity normalised *, m/s	Limit velocity, m/s	Limit velocity normalised*, m/s
1	1/1 Plain weave	0.47	58	123	79	168
2	8H Satin weave	0.52	20	38	25	48
3	1/3 Twill weave	0.46	31	67	41	89
4	2/2 Twill weave	0.45	41	91	55	122
5	2×2 Basket weave	0.45	53	118	67	149
6	3×3 Basket weave	0.70	53	76	56	80

** – The value of the limit velocity is normalised to a 1.0 mm fabric thickness.*

Table 3. FSP 100m/s indentation & dissipative energy after impacting single-layer fabrics of different construction.

No	Fabric construction	Sample thickness, mm	Specific weight of samle, g/m^2	Penetration depth, mm	Deformation rate×10^4, mm	Limit velocity V_r, m/s	Dissipated energy, J	Dissipated energy normalised *, J
1	1/1 Plain weave	0.47	268	6	1.67	61.2	138	513
2	8H Satin weave	0.52	328	5	2.00	57.5	147	449
3	1/3 Twill weave	0.46	256	7	1.43	64.9	127	497
4	2/2 Twill weave	0.45	276	7	1.43	64.9	127	461
5	2×2 Basket weave	0.45	316	6	1.67	61.2	138	435
6	3×3 Basket weave	0.70	506	5	2.00	57.5	147	291

** – The value of dissipated energy is normalised to a fabric specific weight of 1000 g.*

Table 4. FSP limit velocity & dissipative energy after impacting 7-layer fabrics of different construction.

No	Fabric construction	Sample thickness mm	Specific weight of sample, g/m^2	Apparent density, g/cm^3	Deformation depth, mm	Limit velocity V_r, m/s	Dissipated energy, J	Dissipated energy normalised*, J
1	1/1 Plain weave	3.29	1,876	0.570	44	365	2028	1081
2	8H Satin weave	3.64	2,296	0.631	44	289	935	407
3	1/3 Twill weave	3.22	1,792	0.557	44	310	1211	676
4	2/2 Twill weave	3.15	1,932	0.613	44	325	1421	735
5	2×2 Basket weave	3.15	2,212	0.702	44	389	2426	1097
6	3×3 Basket weave	4.90	3,542	0.723	44	400	2617	739

** – The value of dissipated energy is normalised to a fabric specific weight of 1000 g.*

difference in their strength, they differ appreciably in their rigidity. Moreover, 1/3 Twill is rather pliable, whereas 2/2 Twill is rather rigid. A similar situation was observed for 2×2 and 3×3 Basket weave materials: the latter is much more pliable than the former.

Ballistic Impact Test

Table 2 shows the limit velocity determined in a low-speed impact test of various constructions of 1000D Kevlar fabric.

After conducting a normalisation analysis, it was found that the Plain weave construction has the best ballistic resistance performance. It is worth noting that samples 5 (2×2) and 6 (3×3), both of Basket weave construction, differ from each other significantly. The fabric damage model might be the reason for this difference. When a projectile impacts a fabric, its fibres are damaged in various ways: drawn out, broken (torn), or a combination of both. Additionally the piercing of the projectile might be the cause of fibres being pushed from the projectile path, especially in the case of pointed bullets, as is seen in ***Figs. 5 a*** and ***b***. Among the fibre woven fabrics tested, Plane weave obviously provides the most stable fabric construction, which must inhibit the projectile from pushing fibres and squeezing through the fabric. In our opinion this is the main reason why Plane weave shows the best bulletproof properties in these tests (***Table 2***) compared with other weave constructions.

Ballistic Resistance Test

When different single-layer fabric constructions are subjected to a high-speed FSP impact at fixed energy, a clear bullet mark is left on the surface of the fabric impacted, and an indentation is clearly seen on the surface of the plastilina clay behind the fabric (***Figure 3 a*** and ***b***). The results of the single-layer test for both the indentation and limit velocity are given in ***Table 3***.

The cross-section of the FSP is U-shaped, hence it is not easy for it to damage the fabric, indicating a smaller indentation on the surface of the plastilina clay and the better ballistic resistance performance of fabrics against FSP compared with both AP steel-cored or AK-47 Metal bullets. As a result, single-layer indentations brought about by an FSP impact at afixed energy bring about rather few changes in different fabrics varying in the range from 5 to 7 mm (***Table 3***), making it difficult to establish the ballistic resistance performance of fabrics precisely . However, comparing the dissipated energy normalised (***Table 3***), it can be concluded that the best results are demonstrated by 1/1 Plain weave (1st line) and 1/3 Twill weave (3rd line).

To overcome the problems in the more precise estimation of FSP bullet proof properties, the impact must be carried out at high speed with increased energy, and the difference shall be indicated using the limit velocity.

Table 4 shows the FSP limit velocity of a 44mm indentation acquired by impacting 7-layer fabrics of different construction in accordance with the MIL-STD-662F test.

Basket 2×2 and 3×3 materials differ from each other significantly with respect to the FSP limit velocity (lines 5 and 6 in ***Table 4***), despite both being of a Basket weave construction. When laminated fabric samples were tested, however, 2×2 had the highest limit velocity against the FSP because it contains a larger quantity of fibres in a unit area, hence the bullet is completely blocked in the material by its fibres under their tensile strength, similar to the situation shown in ***Figure 5 a***.

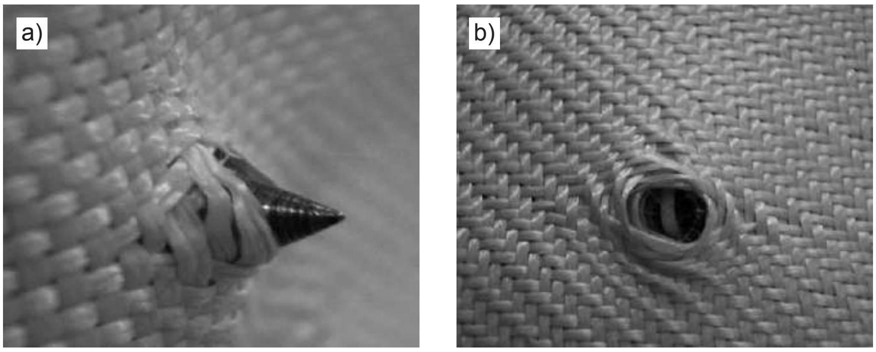

Figure 5. Basket fabrics after impact: a) Steel-cored bullet test of 2x2 Basket fabrics, b) Twill fabrics with a steel-cored bullet removed.

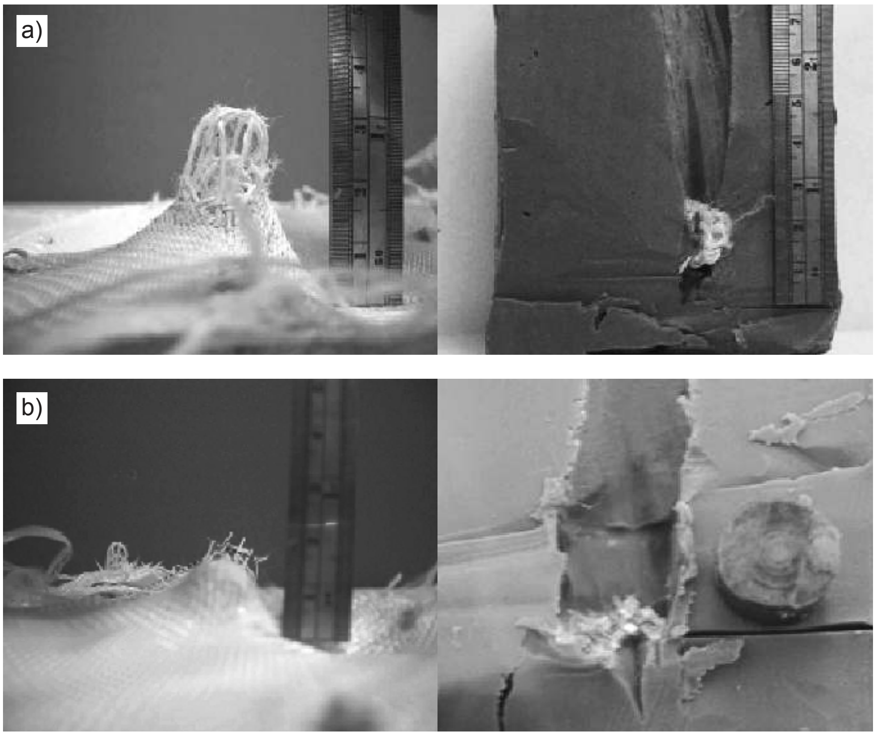

Figure 6. a) Satin fabrics with fibres drawn out: general view of the material damaged (left image) and view of fibres drawn out, visible on the section surface of the clay witness (right image); b) Plain fabrics with torn fibres : general view of the material damaged (left image) and view of torn fibres, visible on the section surface of the clay witness (right image).

For other fabric constructions, ***Figure 6 a*** shows that the bullet perforates fabrics of Satin weave construction under their squeezing force, results in a decreased ballistic resistance performance. However, the advantage of "the longer the fibre, the better the ballistic resistance performance" might manifest under conditions of few weaving points with long fibres if the number of fibres were large enough to block the bullet. In fact, the Satin weave construction has long fibres of inadequate density, hence the fibres are drawnout by the bullet, as shown in ***Figure 6 a***, losing their ballistic resistance capability. On the other hand, Plain and Twill weave constructions have a higher density of warp-weft interweaves, thus they can effectively resist the impact of the projectile (***Figure 6 b***) and bring the ballistic resistance capability of the fibres into full play. The lamination effect of the fabric also contributes to the ballistic resistance performance by improving the stability of the fabric construction.

Conclusions

Analysing the experimental data obtained, it follows that diverse woven constructions behave in various ways under different conditions. However, comparing these data, the following main conclusions can be drawn: Among the samples of Kevlar woven fabrics tested, the 1/1 Plain weave construction demonstrates the best proofing properties against armour-piercing and rifle bullets, particularly at low speeds (low energy). In the high-speed FSP bullet test of multilayer constructions, the 2×2 Basket fabric had a higher ballistic resistance performance, followed by the 1/1 Plain weave construction; the ballistic qualities of both these weave constructions appreciably exceed those of other fibre woven fabrics. The Satin woven fabric exhibited the weakest bulletproof properties in all the tests, apparently because of the weak stability of its construction. In our opinion, to withstand a projectile impact, fibre woven fabrics should have as strong a stability of their construction as possible. Whereas previous studies showed that 1/1 plain fabrics present the highest V50, our research reveals that basket 2×2 fabrics have the highest energy absorbing capacity under low speed impact.

In all probability, to obtain bulletproof materials that work well enough under different conditions, one should design a multilayer system with several weave constructions of various types, e.g. via a combination of 1/1 Plain and 2×2 Basket fabrics. This is the topic of our next investigation.

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References

1. *National Law Enforcement and Corrections Technology Center, Ballistic Resistance of Personal Body Armour NIJ Standard-0101.04 Revision Washington DC, USA, June, 2001, p. 35.*
2. *Lee Y. S., Wetzel E. D., Egres Jr. R. G., Wagne. N. J.; J. Mater. Sci., 38, 2003, pp. 2825-2833.*
3. *Young H. H.; Kevlar Aramid Fibre. DE: USA, 1993, Chapters 5, 138.*
4. *Laible R. C.; Ballistics Materials and Penetration Mechanics. MA: USA, 1980, Chapters 3, p. 58.*
5. *Army Research Laboratory. Weapons and Materials Research Directorate. V50 Ballistic Test for Armor. Test Method Standard. USA Department of Defence. 1997.*
6. *Bohong Gu. Analytical modelling for the ballistic perforation of planar plain-woven fabric target by projectile. Composites: Part B, 34, 2003, pp. 361-371.*
7. *US Patent No 5,935,678. (1999).*

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