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Investigation of Puncture Behaviour of Flexible Silk Fabric Composites for Soft Body Armour

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Abstract
In the field of protective clothing, many different materials are used to provide cut, tear and puncture resistance where high levels of stiffness and shear resistance are important. In this study, an analysis of the cutting phenomenon in protective material based on standard cut test methods was performed. In order to improve the puncher resistance of protective fabric, multi-layer pads, highly preformed woven nets and triaxial fabrics are used as supporting layers. The results indicate that the specific puncture load is highest when using a silk stuffed pad supported on a high tenacity polyester net. Multi-layer silk fabric over para-aramid triaxial weave fabric (TWF) is superior to para-aramid plain weave fabric.

Key words: *protective fabrics, cut resistance, traixial weave fabric, tear strength, comfort, para-aramid, composites.*

Introduction

It is important to point out that protective clothing is puncture resistant. Resistance to penetration is one of the most essential parameters considered for estimation of the usage properties of fabrics designed for protection against various types of mechanical impact; moreover, a soft vest should provide comfort for the user, as well as be of light weight, and cost-effective. Several researchers [1 – 12] have shown the puncture resistance of high strength fabrics as well as multi-layer stitching. The puncture resistance of the fabrics was determined by measuring the force needed to penetrate them using a knife probe. In their investigation there were either natural or synthetic fabrics of different weave structure types. These studies pursued a capability of increasing the energy absorption by using multi-layer compositions and optimising them for application in impact-resistant protective fabrics from natural fibres and their blends.

Jaime Lara [7] established knowledge about rupture mechanisms, giving new data that will help manufacturers improve the resistance of gloves to complicated mechanical risks and develop different as well as more versatile and comfortable materials.

Fnanr L. Scenprno and Frank K. Ko [8] stated that while the puncture resistance was not directly measured, the relative strength in a puncture is often calculated by taking an average value between the cutting and tearing or tensile. Nitinol fibres are used as reinforcement for fabrics made from cotton/nylon and cotton/polyester to give them increased cut, puncture and tear resistance without decreasing its flexibility or comfort. Material tear resistance depends on the fabric strength, elongation and packing density. More loosely packed fabric can be an advantage for tear resistance. Choi H. N. [10] pointed out that current stab resistant clothes have several weak points such as heavy weight, a bulky shape, and uncomfortable characteristics. Therefore one of the efforts to develop new stab resistant fibre composites is to use shear thickening fluids (STF) to overcome those problems. The stab resistance of untreated and STF treated fabrics was compared with 24 layers of para-aramid fabric. As was indicated, multi-layer fabric can be used, but it affects the comfort. Triaxial weave fabric (TWF) composites are of interest for future lightweight structures, both rigid and bendable. The fabric is made up of continuous, interlaced strips of composite material with longitudinal fibres (tows) in three directions, at 0 degrees and ±60 degrees [12]. Kueh A. and Pellegrino S. indicate that the behaviour of this material is more subtle than standard laminated composites, as in single-ply woven fabrics many of the three-dimensional degrees of freedom remain unconstrained. This results in some important differences between the behaviour of single-ply TWF composites and standard composites [12]. The aim of the study presented herein was to design a composite multilayer fabric that gives high stab resistance. In this work we suggested the usage of multi-layer silk fabric supported on a net of high performance material, either plain weave or triaxial fabric made of para-aramid or polyester. Thus it can be applied in protective materials that need to act against a mechanical impact.

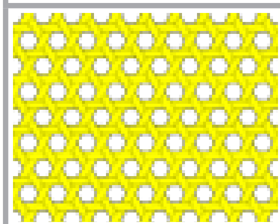
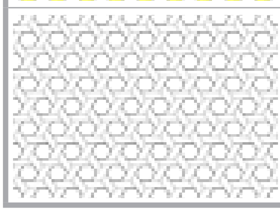
Materials and methods

Materials

Several samples were made of the following fabrics:

- Plain weave silk fabric with an areal density of 65 g/m^2, 50 picks/cm and 50 ends/cm, and a weft and warp count of 6.5 tex. The tenacity of the weft and warp yarns was 29.23 cN/tex and the elongation at break 13.5%.

Table 1. *Specifications of the triaxial weave fabric (TWF).*

Fabric type: triaxial basic weave	Material	Weave, yarns/cm	Yarn linear density, tex	Areal mass, g/m^2
	Para-aramid® 29	Open Basic 3.6 × 3.6 × 3.6	167	196.7
	Polyester		144	166

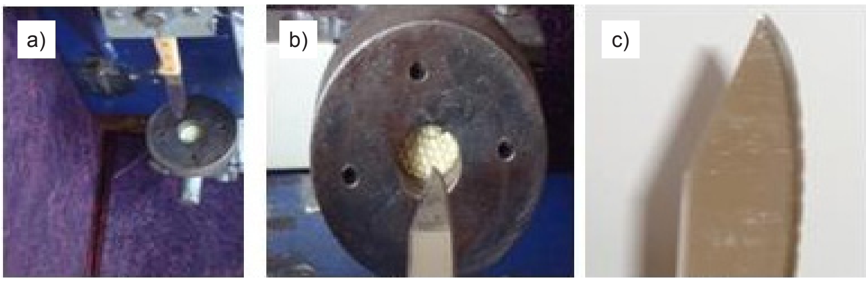


Figure 1. a) Penetration resistance test set-up, b) fabric sample clamp, and c) knife blade.

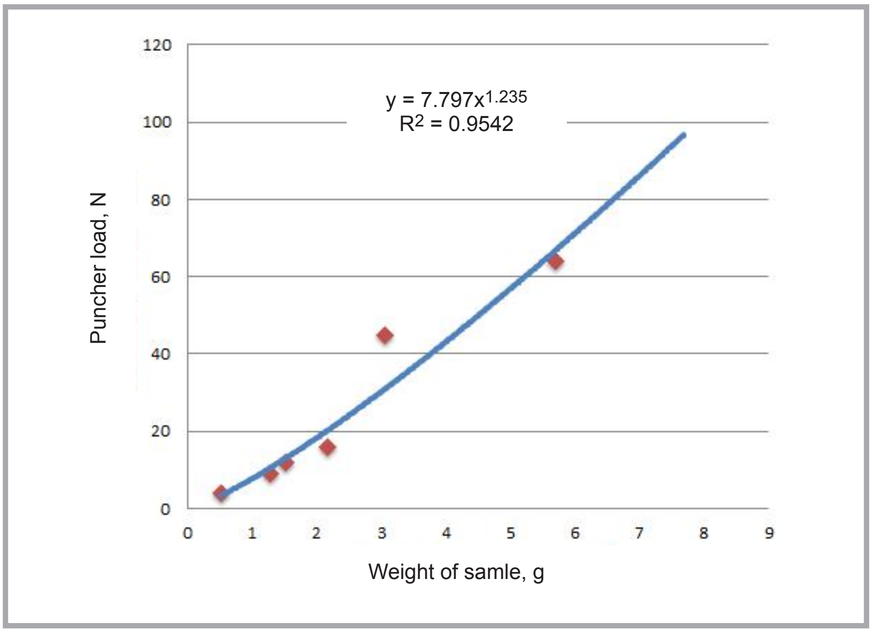


Figure 2. Puncher load of 100% silk versus the sample weight in grams.

- Para-aramid plain weave of 431 g/m^2 areal mass, 6 picks/cm, 6 ends/cm, and weft and warp yarn linear density of 347 tex. The tenacity of weft and warp yarns was 200 cN/tex and the elongation at break 3.3%.
- A woven net of high tenacity polyester from cord yarns of 2×246 tex, yarn tenacity of 38 cN/tex, 8 picks/cm, and 6.4 ends/cm, a fabric strength weft direction of 750 N and fabric strength in the warp direction of 530 N.
- Traixial fabrics were used as a supporting net with the specifications given in ***Table 1*** (see page 71). The basic pattern is the foundation of all traixial fabric patterns. The triaxial pattern is basic with a count of 9 yarns per inch and 3.6 yarns/cm in all three axes. The yarn used, with a linear density of 167 tex, was made of para-aramid Kevlar® 29 of 203 cN/tex tenacity and 3.6% elongation at break. The other traixial fabric was prepared from polyester yarns of 144 tex linear density, 80 cN/tex tenacity, and 14.5% elongation at break.
- Other composite silk fabric samples were prepared with a supporting net either from high tenacity woven polyester from cord or traixial fabrics.
- Also samples of pads were prepared from small pieces of silk fabric waste formed with different supporting nets.

Apparatus and procedures

Puncture resistance tests were conducted on a specially designed set-up for the penetration resistance test, as shown in ***Figure 1***. The primary objective of the test is to identify the maximum loads needed to perforate fabrics. The samples were placed in a circular clamp with a diameter of 25 mm and tightly gripped by a 90 mm clamp to prevent slippage during the test, as shown in ***Figure 1.b***. A load cell of 0.6 kN was used. To cut through material, it is necessary to slide a cutting probe (knife), ***Figure 1.c***, applying a given force to cross the material at a direct speed of 100 mm/min. The blade is stopped after the blade penetration reaches 20 mm.

A paired t-test statistical analysis was done in order to see whether there was any significant difference between the various fabric designs produced from different materials.

Results and discussion

Mechanism of fabric punching

During cutting through a material, fibre in contact with the knife edge has high stress and tends to be stretched, and the yarns will move in the direction of weft and warp, allowing the edge of the knife to pass through. The fabric will be deformed under the build-up force, and the edge of the knife will start to cut the yarn. The resistance to cutting depends on the material, the cross-section of the threads, their strength and the support points in the base fabric [6]. The puncture resistance will be increased also by the friction between yarns and the sliding blade. The total energy required to penetrate strongly depends on the energy lost cutting the yarns around the edge of the blade and that overcoming the friction between the blade surface and surrounding surface of

Figure 3. Cut behaviour in silk fabric and para-aramid samples.

the fabric. In the case of using multi-layer fabric, the penetration force should be increased by the value of friction between the successive layers that will move under the puncture force, increasing the total punching force; consequently the total punching force will be;

$$P_t = \sum_{i=1}^{i=n} Pi + \sum_{i=1}^{i=n} \mu P'i \qquad (1)$$

where, ***Pi*** is the punching force for a single layer, ***P'i*** the component of the punching force in a direction perpendicular to the fabric layers, and μ is the coefficient of friction between the layers of fabrics.

Effect of the number of layers

Significant differences are expected for materials with high coefficients of friction. ***Figure 2*** shows the effect of the fabric sample weight on the punching resistance force, indicating that an increase in the puncher resistance force is not linearly proportional to that in the sample weight when using multi-layer fabric, which confirms ***Equation 1***. The puncher load of the five layer silk fabric, each with an areal mass of 65 g/m^2, can reach the puncher resistance of para-aramid plain woven fabric, with an areal mass of 431 g/m^2.

The cut behaviour of the pure silk fabric shows dissimilar shapes to that of para-aramid fabric, as illustrated in ***Figure 3***, which indicates that the tip of the blade will cut one yarn while pushing the others away; hence the shear modulus plays a substantial role in resisting the penetration of the blade through the fabric.

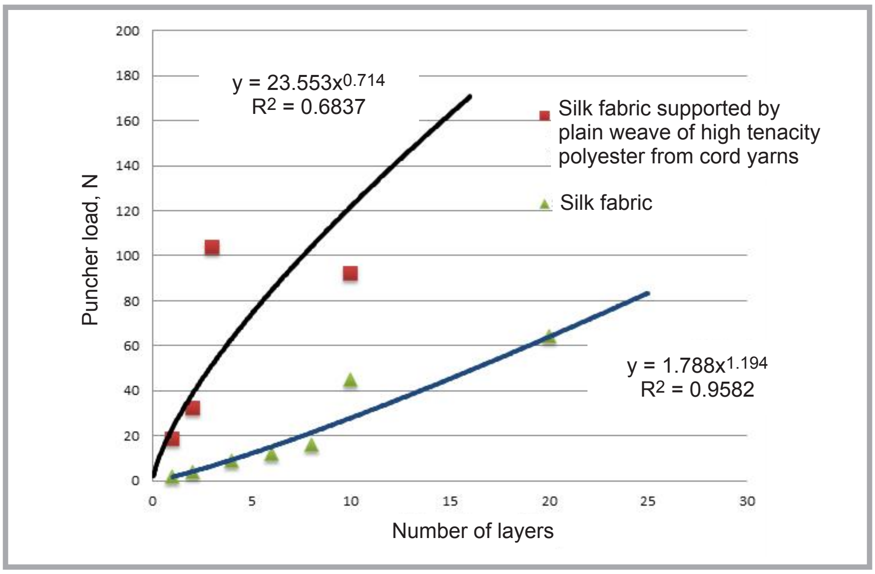


Figure 4. *Puncher load versus the number of fabric layers.*

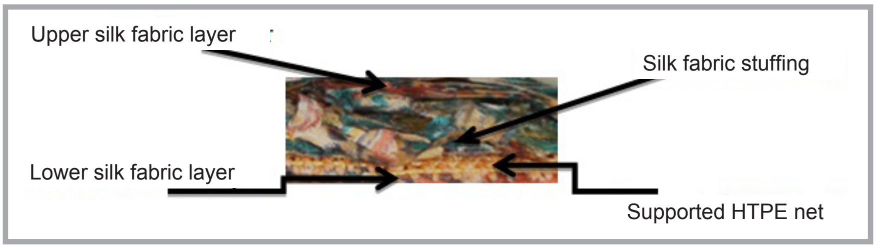


Figure 5. *Cross-section of pad specimen.*

Improving fabric puncher resistance

Using a high tenacity polyester net

For the purpose of increasing the puncher load, plain weave of high tenacity polyester from cord yarns with an areal mass of 385 g/m^2 is used to support the layers of silk fabric. Correlation analyses of the factors affecting the puncher force ***P*** and the expected value of P_t indicates that;

1. Both P_i & P_t are highly correlated with the number of layers (r=0.95).
2. In the case of using a polyester net, the value of P_t expected depends on the type of material and number of layers.
3. Usage of light multi-layer fabric creates a significant increase in (P_t), contrary to one thick fabric.

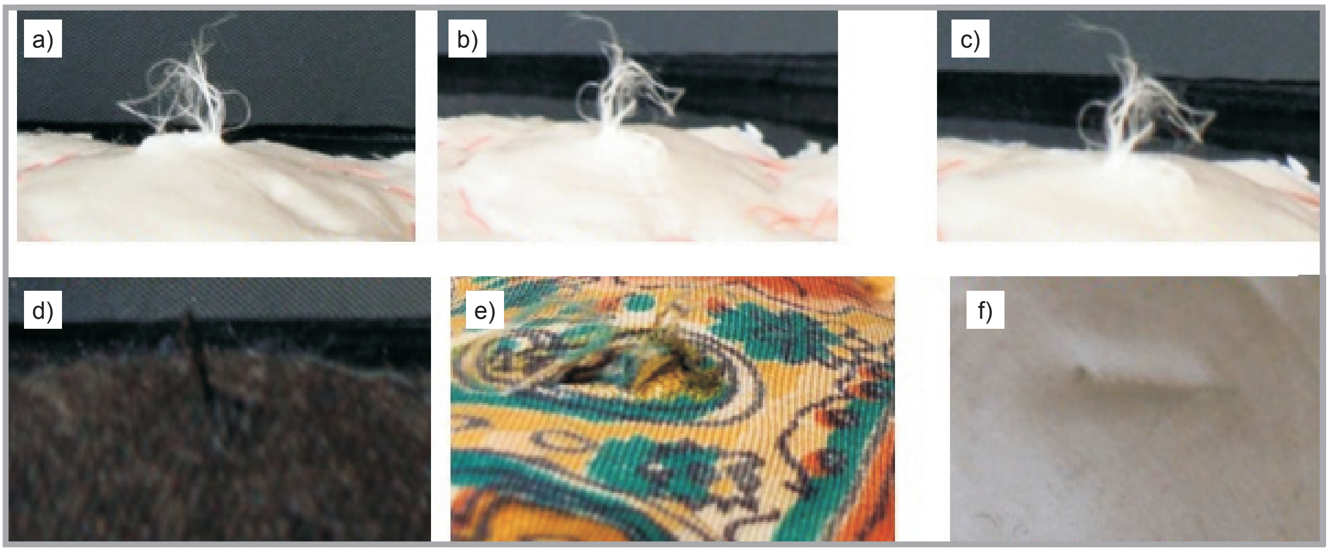


Figure 6. *Cut behaviour in the case of a pad made of different materials; a) multi-layer 100% silk pad, b) multi-layer 100% silk pad, c) multi-layer 100% silk pad, d) multi-layer 100% wool pad, e) multi-layer 100% silk pad, f) multi-layer 100% silk fabric.*

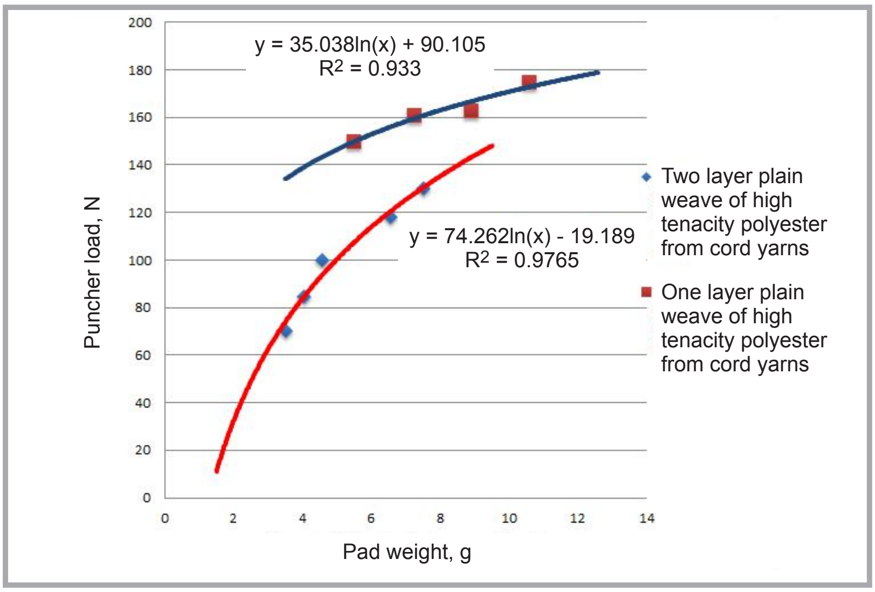


Figure 7. *Puncture load of a 100% silk pad supported by one or two high tenacity polyester nets versus the pad weight.*

Figure 4 (see page 73) illustrates that the use of a supporting high tenacity net with silk multi-layer fabric gives a substantial increase in the puncher load.

Silk fabric pad

For increasing the puncher force, pads were made from small pieces of silk fabric waste formed with a supporting net woven of high tenacity polyester from cord yarns with an areal density of 385 g/m^2 and covered with silk fabric. Samples of different weight silk pads were prepared using one or two supporting polyester nets. ***Figure 5*** (see page 73) illustrates the cross-section of a pad specimen with one layer of net woven of high tenacity polyester from cord yarns.

Several investigators [5, 9] indicate that the total energy required to cut through a pad material is a result of the involvement of two components: lost energy dissipated by the lateral force exerted by the sample material on the blade sides and the cutting energy at the tip edge of the blade. These energies have opposite effects on the cut resistance measured; the lateral force contributes to the increase in the material cut resistance while that at the tip of the blade corresponds to the energy necessary to cut through the material. ***Figure 6*** (see page 73) shows the samples after testing, which demonstrates that the blade is entangled with the fabric pieces resisting the knife motion and increases the value of the puncher force. Usage of the pads designed will increase the resisting puncher force, which is intensely controlled by the friction distribution between the silk stuffing materials. The tip of the knife will be resisted by several fabric pieces that are able to move when the force applied overcomes the friction between fabric pieces. Further movement of the knife will push yarns and even fabric through the cut, increasing the lost energy dissipated by the lateral force exerted by the sample material on the blade sides as well as the cutting energy at the tip edge of the blade. ***Figures 6.a - 6.e*** show the cut shape in the case of pads made of several materials, which demonstrates that a lot of yarns are coming through the cut at the back of the pad, opposite to the clear cut on the upper face of the silk fabric, as shown in ***Figure 6.f***.

Table 2. *Specific puncture load for fabric multi-layered design.*

Fabric multi-layered design	Specific puncture load, N·m^2/g
Silk multi-layer fabric	0.0303
Para-aramid woven fabric	0. 041
Para-aramid triaxial fabric	0.007
Polyester triaxial fabric	0.007
Silk fabric on supporting net of para-aramid triaxial fabric	0.06
Silk fabric on supporting net of polyester triaxial fabric	0.04
Silk pad on supporting net of high tenacity polyester fabric	0.122
Silk fabric on supporting net of high tenacity polyester fabric	0.100

Figure 7 illustrates the puncture load of a 100% silk pad verses the pad weight in the case of using one or two supporting polyester nets. Test results are rated according to EN 388 score 4.

Multi-layered design of silk traixial para-aramid fabric

The main points of triaxial weaving are light weight, low material cost, isotropy, and shear-resistance. Militiky [5] indicates that there is no correlation between the bursting strength of biaxial structures and the cutting force. In general, under burst-deformation, triaxial weave fabrics (TWF) are strained more uniformly than biaxial structures because loads are distributed more evenly throughout the plane of the fabric [8]. With triaxial fabric, tearing is always opposed by two yarn sets instead of one; hence overall improved tear resistance results. Shear resistance is found to be over 5 times more than that of woven fabrics. Triaxial fabric shows tear resistance four times higher than that of conventional fabric of equal weight. In ball burst tests, triaxial fabric, because of its isotropic nature, had far superior load distribution characteristics than conventional fabric [11]. However, triaxial fabric under a force will redistribute the strain better than conventional woven fabric. During the loading of the samples using traixial fabric as a supporting net for silk fabric, the sample deforms under the axial load changing from an uniaxial to a biaxial strain. More yarns of the triaxial fabric are involved in resisting the deformation. Consequently more energy is required for the blade to pass through the protective fabric, in our case about 20%. ***Figure 8*** shows the blade penetration through triaxial fabric when it is used as a single layer, while ***Figure 9*** illustrates shapes of the blade penetration in the case of putting the triaxial fabric between layers of silk fabric. It is clear from ***Figures 8*** and ***9***, that the triaxial fabric is deformed in all directions before the blade can pass through, increasing the energy required to punch the fabric structure. Moreover some of the filaments are entangled with the blade and are protruded through the upper silk fabric layers. This mostly happens for polyester and para-aramid triaxial fabric, but in the case of woven fabric, the blade will be able to cut the fabric before it passes through. A clear cut is shown in ***Figure 10***.

Specific puncture load for fabric multi-layered design

Table 2 gives the specific puncture load: N.m^2/g for a multi-layered fabric design with different material combinations. The composite of silk fabric supported by a net of traixial para-aramid fabric

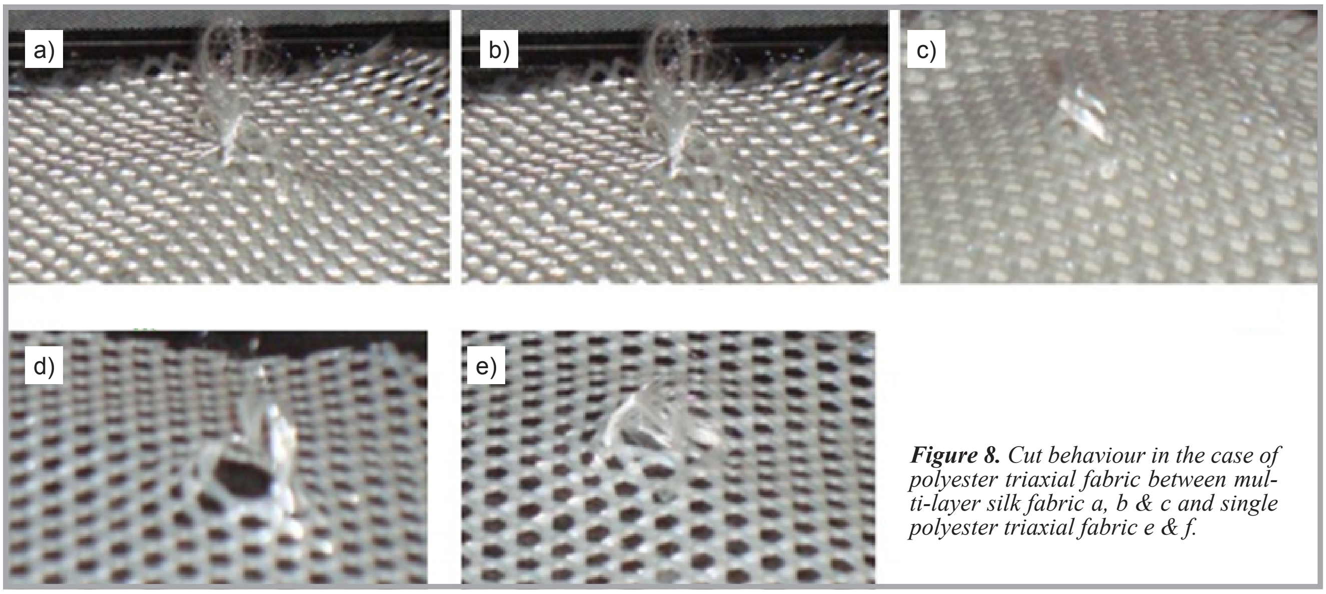


***Figure 8.** Cut behaviour in the case of polyester triaxial fabric between multi-layer silk fabric a, b & c and single polyester triaxial fabric e & f.*

gives a higher specific puncture load than plain woven para-aramid fabric as well as less weight, and it is expected to be more comfortable due to the net shape of traixial fabric.

The highest values of the specific puncture load were obtained when constructing fabric using silk pads or plain silk fabric supported by a high tenacity polyester net. This comparison shows that even though the fabric's multi-layered design can give a high value of a specific puncture load, the best resistance to a puncher load was recorded using a silk fabric pad supported by a high tenacity polyester net of 0.122 N·m^2/g, which reduced the linear density by 50% while maintaining the same puncture load (***Table 2***), thus making it lighter and more comfortable to wear. Silk fabric on a supporting net of para-aramid triaxial fabric increases the specific puncture load by 50% more than para-aramid woven fabric. Furthermore the fabric porosity allows water vapour transmission, hence fabric of such a composite design is more comfortable in use.

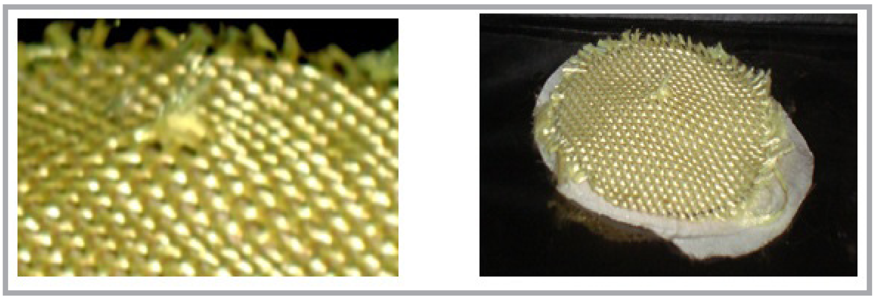


***Figure 9.** Cut behaviour in the case of triaxial fabric between multi-layer silk fabrics.*

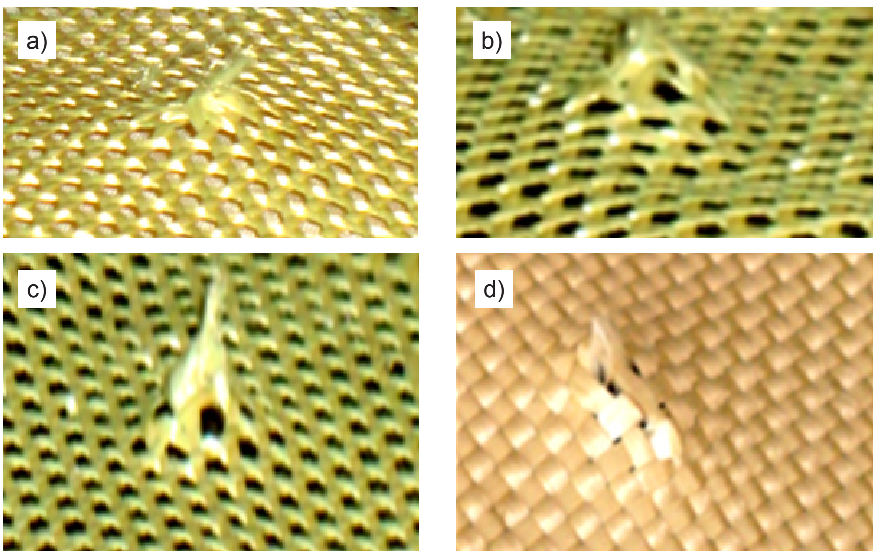


***Figure 10.** Cut behaviour in the case of; a) triaxial fabric between multi-layer silk fabric, b, c) single para-aramid triaxial fabric, d) para-aramid woven fabric with an areal density of 431 g/m^2.*

Conclusion

The demand for protective garments has been ever increasing during the last decade.

An analysis of the fabric tests and properties of the fabrics led to the following conclusions:

- For protective fabric, spun silk multilayer woven fabrics have a higher penetration resistance force and provide more comfort in use.
- Additional fabric layers contributed to the increment of puncture resistance. The number of layers can be selected according to the degree of protection required.
- The puncher resistance force of a multi-layered designed unit made of multi-layer fabric formed from five layers of silk above and five others below supporting a triaxial para-aramid fabric net can reach a puncher resistance force of 50 N.
- A silk stuffed protective pad on a supporting net of high tenacity polyester fabric covered by silk fabric can increase the specific puncture resistance up to 0.122 N·m^2/g.

In the future, research should be performed in order to analyse the influence of the para-aramid triaxial fabric structure in protective clothing on its puncher resistance.

Acknowledgement

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