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Textile Research Journal published online 7 March 2012
DOI: 10.1177/0040517512436826

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Original article

Textile Research Journal
0(00) 1–9

DOI: 10.1177/0040517512436826
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Protecting the extremities of military personnel: fragment protective performance of one- and two-layer ensembles

Sarah Sakaguchi[1], Debra Carr[2], Ian Horsfall[2] and Liz Girvan[3]

Abstract

In order to provide protection from fragmenting ballistic threats, combat body armour contains multiple layers of fabric. The garment covers the torso, but may provide (removable) protection to the upper arms, neck and groin. Such garments are thick, stiff, impede movement and increase the thermophysiological loading of the dismounted soldier. Examination of wound locations from recent conflicts has suggested it would be advantageous to provide protection to the extremities. Current modular systems can be expanded with strap-on coverings to the arms and legs, but this further exacerbates the mass, mobility and thermal problems already observed. Soldiers already wear coverings on their arms and legs in the form of a combat uniform, and the provision of a hierarchical protection system incorporated in the existing uniform has been discussed. Not all areas of the body would be protected to the same level. In the current work, the fragment protective capabilities of one or two layers of commercially available para-aramid woven fabric. Specifically, 1.1 g chisel-nosed fragment simulating projectile V_{50} data were obtained. The aim was to establish whether the incorporation of such one or two layers of para-aramid woven fabric into current combat clothing could provide a level of fragment protection with only a minimal associated increase in stiffness, mass and thermal resistance. Post-failure analysis was conducted to investigate inter-layer interaction and failure mechanisms. This work suggests that the use of one- and two-layer para-aramid woven fabric layers incorporated into clothing could offer some protection against wounding to the extremities from fragments.

Keywords

Para-aramid, ballistic testing, failure mechanisms, body armour, woven fabric

In the modern military context, the term *personal armour* includes body armour (waistcoat or vest-like garments covering the torso), helmets (covering the cranium), face and eye protection (primarily visors, glasses, goggles), Explosive Ordnance Disposal (EOD) suits, and ballistic shields.[1] The purpose of military body armour is to protect personnel from ballistic threats, primarily high-velocity fragments and high-velocity bullets. High-velocity fragments originating from, for example, artillery shells, mortar bombs, mines, grenades, improvised explosive devices (IEDs) and soil/sand are the major cause of injury in modern warfare.[2–6] These fragments typically have a mass of 0.1–0.25 g, a 'diameter' of 2–5 mm (they are rarely spherical, unless preformed) and an initial velocity of 1500–2000 m/s, however velocity declines rapidly with increasing distance from the origin of the detonation.[2,3,7,8] Velocities of small fragments are typically slower than 600 m/s over significant areas around the blast, and it is these fragments that are most likely responsible for many of the injuries observed.[2,8] Open source (i.e. unclassified) studies show that the use of

[1]Department of Defence, Defence Materiel Organisation, Australia
[2]Impact and Armour Group, Cranfield University, Shrivenham, UK
[3]University of Otago, New Zealand

Corresponding author:
Dr DJ Carr, Impact and Armour Group, Department of Engineering and Applied Science, Cranfield University, Defence Academy of the United Kingdom, Shrivenham, Wilts, SN6 8LA, UK
Email: d.j.carr@cranfield.ac.uk

body armour has reduced military casualty rates significantly, but has altered the pattern of injury resulting in a predominance of multiple wounds to the limbs,[3,4,7,9–12] and to the body segment located above the shoulder which is often referred to in the medical literature as the 'head, face and neck complex'.[2,3,7,13–15]

Body armour provides protection from fragments by using multiple layers of (primarily para-aramid plain woven) fabrics. The literature suggests that high sett, plain woven, balanced fabrics provide the best protection.[16–20] The design of military body armour varies among countries and manufacturers, and details are usually classified, however the literature suggests that the fragment protective element is typically constructed from between 10 and 50 layers of fabric and weighs up to 9 kg.[5,21,22] In modern military body armour the extremities and neck are often left exposed, however some modular designs allow for the addition of extra protection to the neck, arms, legs and groin. A typical example is the US Modular Tactical Vest (Protective Product Enterprises); modular components include cummerbund, side-armour plate pouches, collar, exterior plate pockets, adjustable throat protection, and increased coverage to the lower back and renal area, side, torso and shoulder. Modular components that provide protection from fragmentation usually offer a similar, if not the same, level of protection as the main garment, resulting in higher mass, bulk, and stiffness of the armour system which may negatively affect the performance of the person wearing it. Data suggests that an armour weighing less than 5 kg will provide a protective benefit while still allowing speed and mobility.[21] In an attacking role, a heavier armour encumbers soldiers leaving them exposed to hostile fire for longer.[21] Therefore, a compromise is usually made, especially for military armours, between protection and human performance.

The response of a single layer of fabric during a ballistic impact event was described by Cunniff.[16] During a ballistic impact, transverse and longitudinal waves develop in a single layer of fabric armour propagating away from the impact point in the impacted (principal) yarns. Orthogonal yarns (those that intersect the principal yarns), are pulled out of the original fabric plane by the principal yarns, forming a 'pyramid' in the fabric (Figure 1). The transverse deflection proceeds until the strain at the impact point reaches a breaking strain. There is some evidence in the open literature that the relationship between the number of fabric layers used in a pack and the measured ballistic protective performance of the pack is not linear.[16,23] However, if fabric layers are spaced, so that no two layers are in contact *during the impact event*, the ballistic performance of the system would be exactly equivalent to the sum of the individual layers i.e. the layers do not interact with each other.[16] Conversely, if the fabric layers are in contact with each other they interact, resulting in poorer performance than if spaced.[16] Energy absorption occurs via: in- and out-of-plane yarn and fabric movement; strain energy accumulated in the fibre, yarns and fabrics; fibre fracture; and energy dissipated as heat by friction and melting.[16,24–27]

While one or two layers of fabric would clearly not offer the same level of protection as a typical military body armour, even the use of a few layers of fabric to cover the extremities may offer some additional protection without significant mass, stiffness and thermal loading penalties. There is some evidence that stiffer body armour, as measured in a laboratory, can be related to user perceptions of comfort and flexibility.[28] However, data available in the open literature regarding the fragment protective performance of one or two layers of fabrics is sparse, because i) the need for specialised test facilities (i.e. a ballistic test range), ii) conducting ballistic testing at low velocities (100–200 m/s) is relatively difficult and iii) combat body armour is designed to provide protection at higher velocities (typically >450 m/s). Studies investigating the interaction of layers of fabrics typically used in military body armour are also rare. Even in the general textile science literature, the effect of the interaction of layers of fabric on their properties are not commonly discussed, exceptions include House et al.,[29] Ren and Ruckman[30] and Laing et al.[31]

The aim of the work summarised in this article was to identify the fragment protective performance and

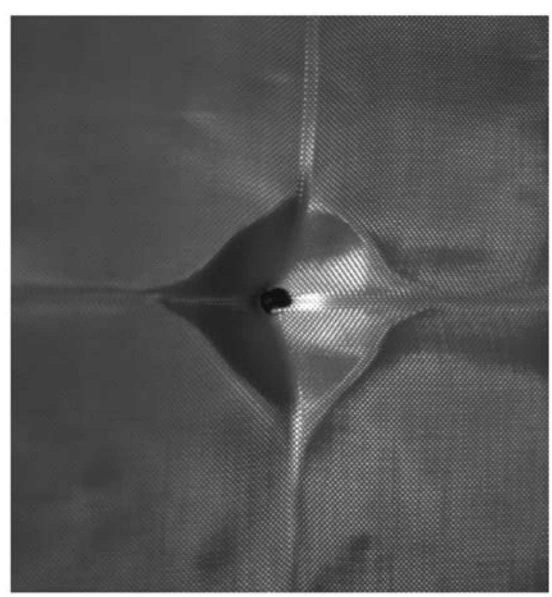


Figure 1. Deformation of a single layer of fabric impacted by a fragment simulating projectile (image by: Sakaguchi, 2010).

failure mechanisms of one- and two-layer fabric packs of two commercially available para-aramid fabrics suitable for use in military body armour.

Materials and methods

Two plain woven fabrics each containing a different para-aramid fibre were obtained from the two fibre manufacturers (Table 1). Bending length was measured and flexural rigidity, which is related to a wearer's perception of stiffness, was calculated for the fabrics using BS3356:1990 Determination of bending length and flexural rigidity.[32] Specimens for ballistic testing (405 mm × 405 mm; one or two layers; n = 3) were cut 50 mm from the selvedge using aramid shears, where possible containing different warp and weft yarns; folds and flaws were avoided.[33] The specimen edges were not finished. Specimens were stored in an opaque plastic container to avoid degradation by ultraviolet radiation and visible light. Prior to each test, the specimens were conditioned for 24 hours (20 ± 5°C and 65 ± 10% R.H.).[34]

The fragment protective performance of each specimen was measured using 1.1 g chisel-nosed fragment simulating projectiles (FSPs).[35] Each FSP was mounted in a split polymeric sabot and inserted into a 7.62 mm × 39 mm cartridge case (WOLF Hunting) (Figure 2a). Velocity was manipulated by altering the amount of gunpowder (Vihta Vuori N310) used in the cartridge case. The hand-loaded cases were fired from a Number 3 proof housing fitted with a 7.62 mm × 39 mm barrel, fixed onto a range firing mount (Figure 2b). The barrel muzzle was located 1500 mm from the specimen. Fabric specimens were mounted on a plywood support (10 mm × 400 mm × 400 mm; 300 mm × 300 mm cut-out) which was clamped to a steel frame using six G-clamps (finger tight). Whilst the clamping method used was a potential source of variability and difficult to reproduce, and testing was conducted by an experienced Range Officer. Specimens were mounted taut, the technical face was the strike face. A 0.5 mm thick AlCuMg alloy witness sheet (ISO/R209) was mounted 150 mm behind the fabric specimen.[35] Projectile velocity was measured using a Weibel fixed head Doppler radar (model W700). In between shots the specimen was adjusted, if required, and the G-clamps re-adjusted. Impacts were >50 mm from the inner edge of the fabric support frame, other impact points, any discontinuities, or damage on the fabric. Yarns that had been previously impacted were avoided,[34,35] and 16 impacts were typically possible on each specimen. A barrel-mounted laser aiming device was used to ensure the accuracy of the impact point. Temperature and relative humidity were monitored during testing using a hand-held digital thermometer and a hygrometer.

Table 1. Description of test fabrics

	Fabric A	Fabric B
linear density (dtex)[1]	440[3]	930[3]
sett (yarns/10 mm)[1]	12 × 12	8.5 × 8.5
mass per unit area (g/m^2)[1]	105 ± 4	160 ± 5
finishing treatment[1]	loomstate	WRT[2]
bending length (cm)		
warp	5.7 ± 0.5	7.5 ± 0.5
weft	6.8 ± 0.1	6.2 ± 0.4
flexural rigidity (mg·cm)[4]		
warp	2174.2 ± 584.2	6832.7 ± 1496.6
weft	3692.2 ± 103.0	3989.3 ± 771.0

[1]manufacturer's data.
[2]water repellent treatment (further details not available, manufacturer's proprietary information).
[3]44 tex and 93 tex respectively.
[4]calculated using actual mass per unit area not manufacturer's information.

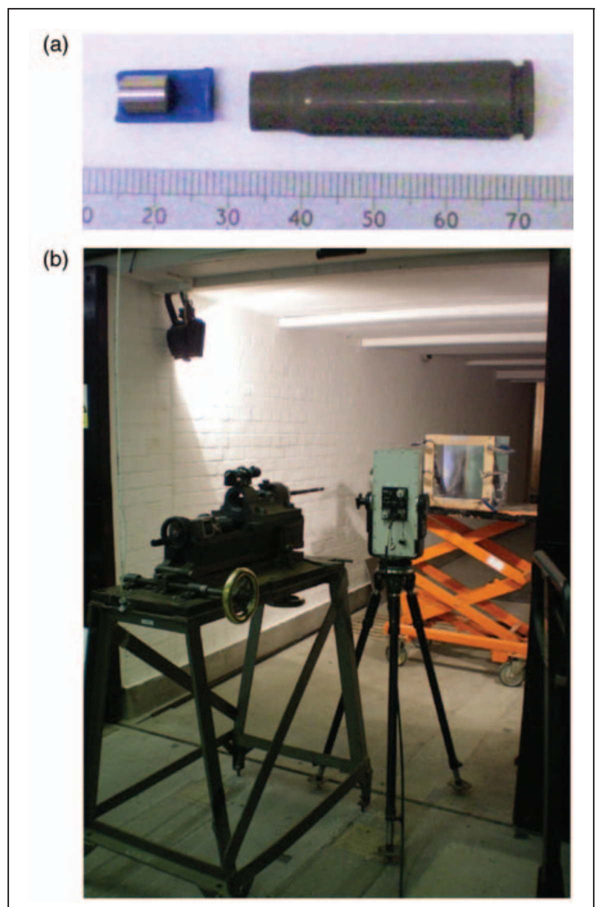


Figure 2. (a) 1.1 g FSP shown with split sabot and 7.62 mm cartridge case (b) Experimental apparatus (left to right: assembly on mount, Doppler radar, target frame and witness screen).

A perforation of the specimen was defined as a perforation of the witness sheet. Impacts which were not identified as perforations using this definition were recorded as non-perforations.[35] Thus the impact velocity and whether or not the FSP perforated the witness plate were recorded and used to determine an estimated V_{50} for each specimen i.e. the estimated velocity at which the probability of perforation (using the named projectile and target) is 0.5. Use of the word 'estimated' is deliberate, Tobin[36] stated 'If enough V_{50}s are recorded *[for a single mode of failure]* it becomes obvious that that the figures form a normal distribution... For this reason it is not sensible to talk about "the" V_{50}...'. For woven fabrics, it is generally accepted that the standard deviation associated with V_{50} data will be 1–2% of the mean within a batch and 5% of the mean among batches.[36] In the current work, estimated V_{50} data were determined using an even number of shots (minimum six), of which half the shots perforated the specimen and half did not.[34] NATO STANAG 2920 (edition 2) and UK/SC/5449 both set a maximum allowable velocity range of 40 m/s between the lowest and highest velocities used in V_{50} calculations.[34,35] Due to variability of gunpowder and the (fabric) specimen, it may take a large number of shots to calculate the estimated V_{50}. Therefore, for specimens of a limited physical size, a four shot estimated V_{50} can be determined, but it is recognised that this is less accurate. The effect of fabric type and number of layers on fabric protective performance was determined by analysis of variance using SPSS Statistics 17.[37]

Impacts were filmed with a high speed camera (Phantom V12). Once testing was completed, fabric specimens representative of typical impacts were selected. The technical face and technical rear of each impact were photographed thus recording impact size, weave distortion, yarn and fibre failure mechanisms.

Yarns from selected specimens were mounted on aluminium stubs with double-sided carbon tape, sputter coated with gold palladium using an Emitech K575X Peltier-cooled high resolution sputter coater and examined using a JEOL 6700F field emission scanning electron microscope (FESEM) (LEI detector; 3 kV; 10–12 mm working distance).

Results and discussion

Data obtained are summarised in Tables 1 and 2. Mass per unit area and flexural rigidity (in the warp direction) of Fabric B were higher than for Fabric A, in particular, the flexural rigidity of Fabric B in the warp direction i.e. the garment length direction, was over three times higher than for Fabric A (Table 1). Thus Fabric B would probably feel heavier and stiffer to a user.[28]

Fragment protective performance

Environmental conditions during ballistic testing met the requirements of UK/SC/5449 (20 ± 5°C and 65 ± 10% R.H.).[34] Estimated V_{50} was not affected by the type of fabric tested, but was affected by the

Table 2. Results from ballistic testing

fabric	number of layers	estimated V_{50} (m/s)	s.d. (m/s)	CV (%)	spread[2] (m/s)	E_{abs}[3]
A	1	117[1]			9	
		107			32	
		112			33	
mean		112	5	4		59
B	1	126			35	
		111			25	
		99			40	
mean		112	13	12		42
A	2	119			40	
		134			29	
		122			35	
mean		125	8	6		37
B	2	141			35	
		134			33	
		146			25	
mean		140	6	4		33

[1]4-shot V_{50}.
[2]maximum impact velocity – minimum impact velocity.
[3]calculated using actual mass per unit area not manufacturer's information.

number of layers ($F_{1,8} = 2.29$, $p = NS$; $F_{1,8} = 16.68$, $p \leq 0.05$). For both fabrics, two-layer specimens had higher estimated V_{50} compared to one-layer specimens. The higher estimated V_{50} offered by two-layer specimens was not additive when compared to one-layer specimens, supporting observations by Cunniff.[16] Relative energy absorbed data (E_{abs}) were calculated i.e. normalising the kinetic energy equivalent to the estimated V_{50} by mass per unit area. Normalising data with respect to mass is of interest because of the effect on the burden carried by the dismounted soldier. E_{abs} data for Fabric B was lower than for Fabric A, particularly for one-layer specimens. E_{abs} values for two-layer specimens were approximately 63% and 79% of the E_{abs} for one-layer specimens for Fabrics A and B, respectively (Table 2). Therefore, the efficiency of two-layer specimens with respect to an associated mass and stiffness penalty was lower than for one-layer specimens.

Post-test morphology

Strain rate effects were observed in all specimens, and these are illustrated in this discussion by a comparison

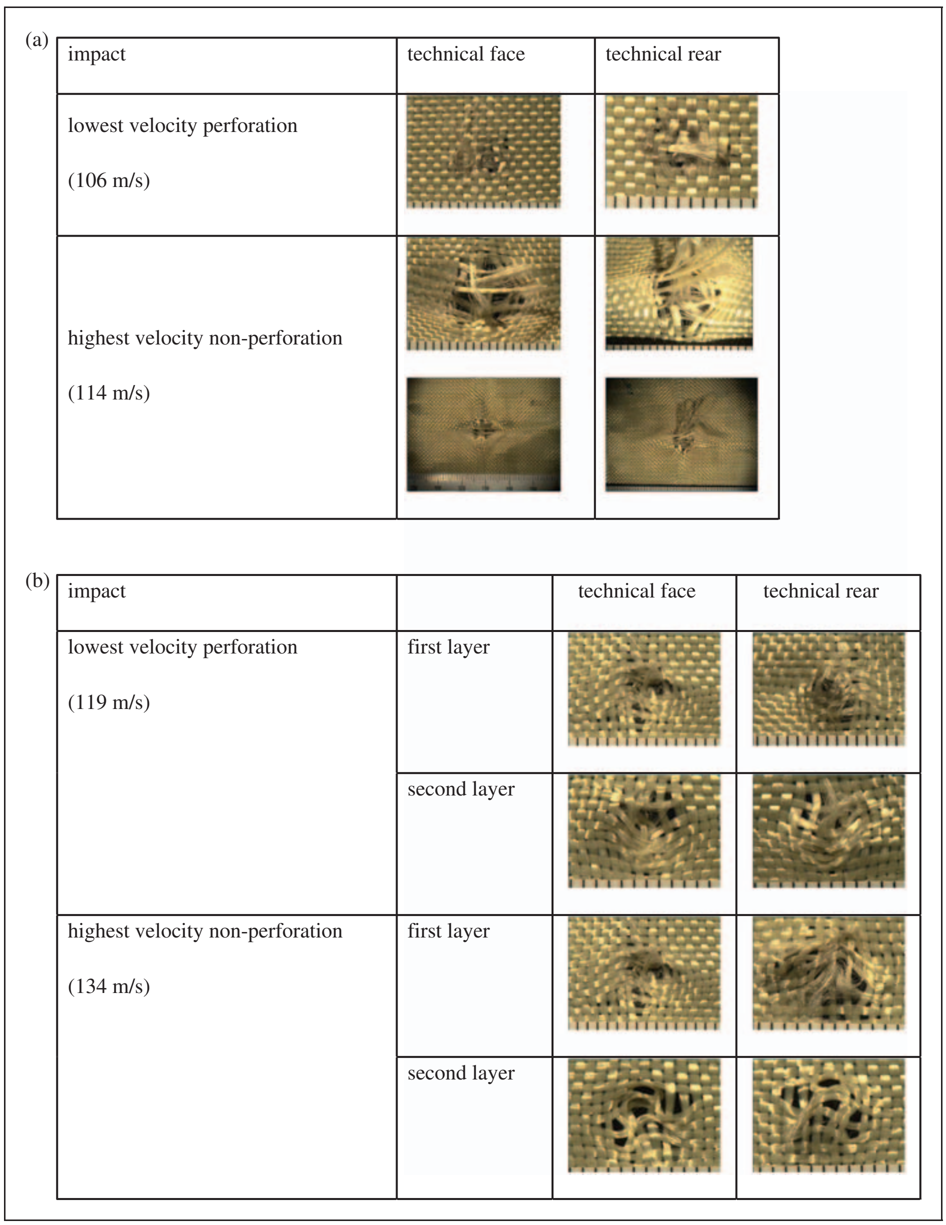


Figure 3. Typical impacts on Fabric A (a) one-layer specimens, (b) two-layer specimens.

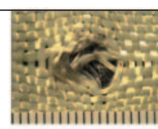
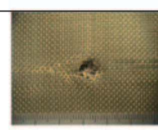
of impact sites associated with the highest velocity non-perforations and lowest velocity perforations for one- and two-layer specimens (Figures 3 and 4; Fabrics A and B). For both one- and two-layer specimens, more yarn pull-out was observed for Fabric B than Fabric A. However, for non-perforation events more evidence of fabric distortion was observed for Fabric A than Fabric B. During testing more weave distortion and slip between the clamped section of the fabric occurred in specimens made from Fabric B compared to those made from Fabric A. These observations are likely to be due to the lower sett of Fabric B i.e. the inter-yarn friction in Fabric A would be higher, and the fibres and yarns more tightly held in place. However, it should be noted that the finishing treatments for the two fabrics was different and this may have affected the inter-yarn friction.

One-layer specimens

For one-layer specimens, irrespective of the fabric type investigated, larger distorted areas of fabric post-impact were observed for non-perforating impacts compared to perforations (e.g. Figures 3a and 4a). This is similar to the response previously reported for single yarns impacted transversely at ballistic rates.[25] Larger impact areas indicated the involvement of a greater number of principal yarns in the impact event and thus higher energy absorption via fabric distortion and yarn pull-out.

High-velocity non-perforations all exhibited yarn pull-out on the technical rear of the fabric. The higher the velocity of the non-perforation, the more yarn was pulled out from the fabric structure. The involvement of a greater number of yarns and the

(a)

impact	technical face	technical rear
lowest velocity perforation (90 m/s)		
highest velocity non-perforation (119 m/s)		

(b)

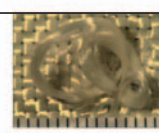
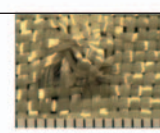
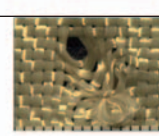
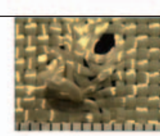
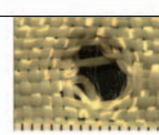
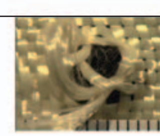
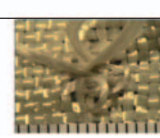
impact		technical face	technical rear
lowest velocity perforation (134 m/s)	first layer		
	second layer		
highest velocity non-perforation (145 m/s)	first layer		
	second layer		

Figure 4. Typical impacts on Fabric B (a) one-layer specimens, (b) two-layer specimens.

pull-out of these yarns indicated that work was done on the fabric by the projectile and consequently, the impact energy of the projectile was absorbed by the fabric via these mechanisms.

For perforations, holes were observed at the impact site in both fabrics. The area of fabric distorted was smaller, some yarns were displaced within the fabric structure indicating that fragments had perforated the fabric in either an inter- or intra-yarn mode, and fibre fractures were noted. In comparison to non--perforations, relatively little of the projectile's kinetic energy was absorbed by fabric distortion.

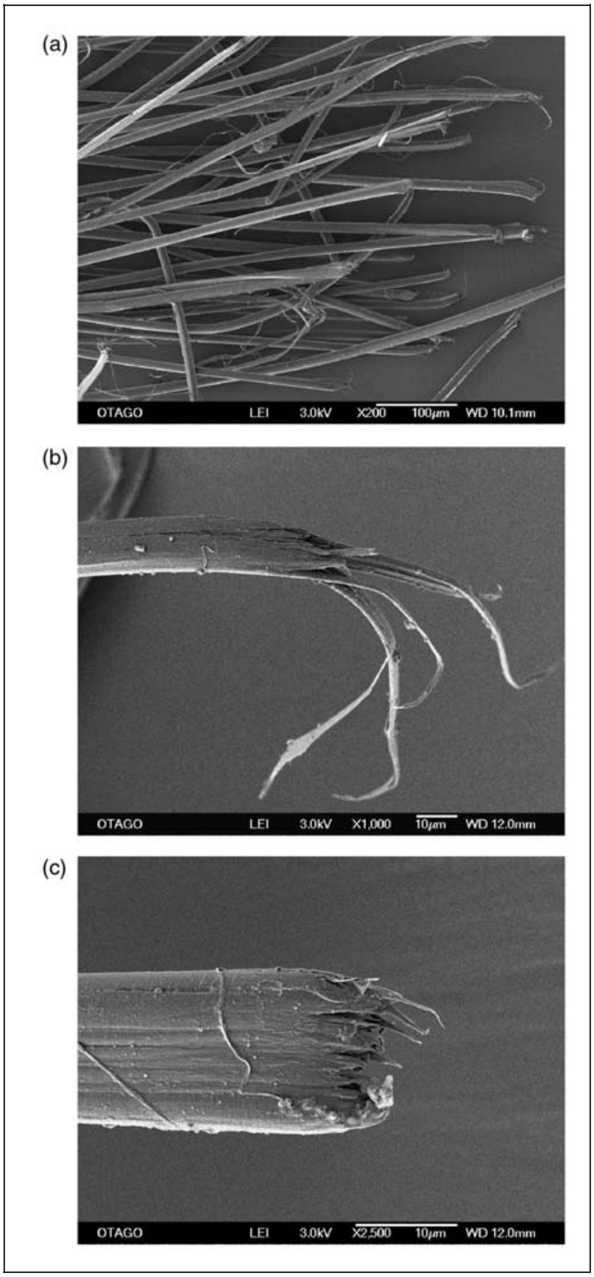


Figure 5. Typical failure mechanisms of yarns and fibres (a) within yarn planar array – evidence of variation in fibre failure mechanisms e.g. different fibrillation length, brittle failures and mixed-mode failures, (b) fibre failure – typical example of longitudinal splitting and fibrillation, some evidence of mixed-mode failure, (c) fibre failure – typical example of short length fibrillation (more brittle failure).

Two-layer specimens

The two-layer impacts were more complex than one-layer impacts due to the interaction of the fabric layers. For high-velocity non-perforations, yarn pull-out was observed in both layers of Fabric B, but not in Fabric A. This is possibly due to the tighter weave structure minimising out-of-plane fabric deformation.

For low-velocity perforations, holes were observed at the impact site more obviously in specimens made from Fabric B. However, the area distorted was minimal for both fabrics, although some yarns were displaced within the fabric structure indicating that fragments had perforated the fabric in inter- or intra-yarn modes, and fibre fractures were noted. Little of the kinetic energy of the projectile was absorbed by fabric distortion.

Yarn and fibre failure mechanisms

Yarn and fibre fracture morphologies varied little between the two fabrics and specimen types i.e. one and two layers and different shot types (slow, fast, fast edge). Yarn failure was broadly characterised by a planar array irrespective of experiment variables (e.g. Figure 5a). Individual fibres generally failed by longitudinal splitting and fibrillation, with varying degrees of brittle and mixed-mode mechanisms i.e. the length of fibrillation within a fibre varied considerably among fibres within a yarn (e.g. Figures 5b and 5c). Fibrillation of para-aramid fibres after impact at ballistic rates has been previously reported, although not with the same level of variation as observed in the current work.[25]

Conclusions

Estimated V_{50} data were higher for specimens containing two layers of fabric compared to one-layer packs, although the increase was not additive. Both fabrics offered a similar level of fragment protective performance for one- and two-layer systems. However, in terms of a normalised comparison between the two fabrics, E_{abs} for Fabric A was higher than Fabric B for one- and two- layer specimens when tested with 1.1 g chisel-nosed FSP. Fabric A was lighter, and had a lower flexural rigidity than Fabric B. Thus of the two fabrics assessed, Fabric A would be the more desirable fabric to use for reinforcing combat uniforms with one or two layers of fragment protective layers. Fibre failure was characterised by longitudinal splitting and fibrillation of varying lengths, although brittle and mixed-mode failures were also observed. Yarn failure had a planar array appearance.

This work suggests that the use of one- and two-layer para-aramid woven fabrics as clothing layers could offer some protection against wounding to the extremities from low kinetic energy fragments. Increases in garment stiffness, mass and thermal resistance should be minimised by the use of only one or two layers of para-aramid fabric in combat uniforms, and should not impede user mobility to any great extent.[21,28] Clearly, such garments would require user acceptability trials to assess any impacts on user performance. It must be noted that how much protection would be offered is hard to quantify. How such protection would be affected by operational and environmental conditions is not known.

Acknowledgements

The authors would like to thank Mr M Teagle, Mr D Miller, and Mrs C Lankester for ballistic testing; and Dr J Painter for assistance with optical microscopy (all at Cranfield University). SMS acknowledges funding for post-graduate study at Cranfield University from Land Engineering Agency, Defence Materiel Organisation, Department of Defence, Australia.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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