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Dissipation of energy by bulletproof aramid fabric

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The bullet resistance of laminates comprised of several layers of aramid Armos fabric has been studied. The high bullet resistance of the fabric is caused by the pulling-out of yarns impacted by the bullet. The pull-out zone is cross-shaped, the centre being the impact point. The length and the width of the pull-out zone was determined for each fabric layer. Energy transferred to fibres increases with the volume of the pull-out zone. Water reduces the bullet resistance of laminates owing to reduction of the width of the zone. The length of the pull-out zone is shorter if the transverse displacement of layers is restricted. At a projectile velocity of 420 m s^{-1}, Armos yarns do not break immediately on impact, and the longitudinal wave propagates along the fibre. Friction of yarns in aramid fabric was studied by a yarn pull-out method.

1. Introduction

Jackets made from high-strength aramid Kevlar-49 and Armos fibres are used for bullet protection. A jacket must fulfil two major requirements. First, the jacket must stop a bullet. In addition, the height of a bullet bulge on the inside lining should not exceed some value. If the bulge height exceeds this value, the bullet may result in injury even if it is stopped. Light police jackets are comprised of a bulletproof laminate containing several (usually 10–40) aramid fabric layers. The height of the bulge is reduced by the second laminate made of some soft fibrous material.

On transverse impact, two waves, transverse and longitudinal, are generated in a fibre [1, 2]. The transverse wave results in triangular-shaped deformation of the fibre which spreads out from the point of impact. The longitudinal strain wave propagates at a much higher velocity along the fibre. For the magnitude of the tensile strain, four-thirds power dependence on the bullet velocity was obtained [3–5]. When the longitudinal wave reaches an unfixed end of the fibre, it is reflected and a "recoil" wave of unloading travels back to the impact point [6, 7].

Impact resistance of a laminate is usually characterized by a bullet velocity at which 50% of the bullets are stopped by the laminate [8]. Sometimes, the height of a bulge on the opposite to impact side of the laminate is measured. Both characteristics describe the integral bullet resistance of a laminate. The goals of the present work were to study the impact resistance of laminates based on aramid Armos fabrics. An additional objective was to determine characteristics related to energy dissipation in each fabric layer.

2. Experimental procedure

Friction of yarns in aramid fabric was studied by a yarn pull-out method illustrated in Fig. 1. A yarn was loaded with the upper grip. The lower edge of a rectangular fabric sample was fixed in the grip with a Π-shape plastic piece so that the pulled-out yarn was in the centre of the opening. The length of the test specimens varied from 100–700 mm.

Pull-out tests were performed for six different aramid fabrics with plane weaving. The number of 900 denier Armos yarns was 10 × 10, 12 × 12, 13 × 13, and 14 × 11 (warp/weft) per 10 mm × 10 mm fabric area (denier is weight (g) per 9000 m yarn). A 15 × 15 Armos fabric woven from 530 denier yarns was also tested. To change the friction, yarns were covered with size before weaving of the 12 × 12 Armos fabric.

Pull-out tests were conducted with an Instron model 1122 universal testing machine at 20 mm min^{-1} load rate. Four yarns were pulled-out and the results

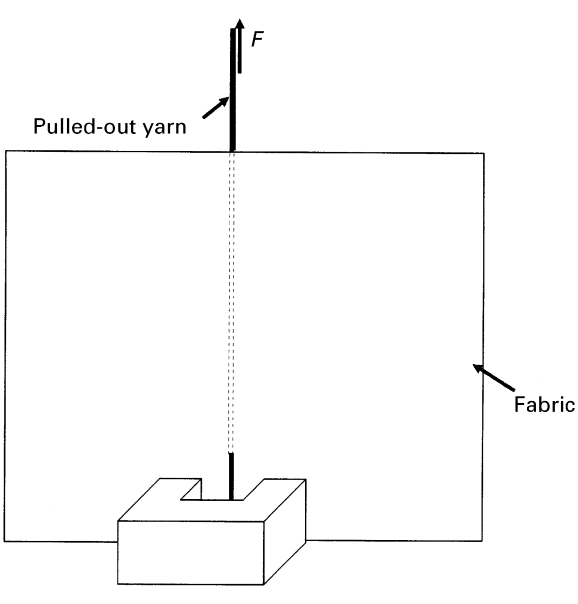


Figure 1 Yarn pull-out test.

of tests were averaged. Specimens were photographed with a Zenith TTL camera.

Bulletproof laminates comprised of 14 layers of 12×12 Armos fabric and 10 layers of fabric made of oriented polypropylene (PP) tape were tested. The bulletproof laminate was attached to a plasticine foundation and struck with a bullet fired from 9 mm Makarov's pistol at velocity of 315 m s^{-1}. The size of the laminate was 250 mm $\times$ 250 mm.

To study the effect of water, 14-layer and thicker 20-layer laminates were tested before and after immersion in water for 20 min. Before testing, water trickled down for 30 min. The size of the laminates was 150 mm $\times$ 200 mm.

Laminates comprising 45 layers of 15×15 Armos fabric (530 denier yarns) with 15 PP layers were struck with bullets fired from 7.62 mm TT (420 m s^{-1} velocity) and 9.0 mm parabellum pistols (410 m s^{-1}). The size of the laminate was 300 mm $\times$ 400 mm.

3. Results

3.1. Pull-out tests

Fig. 2 shows load–displacement curves for warp and weft yarns pulled-out of a 10×10 Armos fabric. The linear growth of the load is followed by the decrease in load due to pull-out of the yarn and shortening of the friction zone. The maximum pull-out force for the warp yarn is higher than that for the weft yarn. In contrast, the slope of the linear part of the curve is higher for the weft yarn.

Fig. 3 shows the initial part of the load–displacement curve for a warp yarn slowly pulled-out of the 14×11 fabric at 0.5 mm min^{-1} loading rate. The applied load is equal to the friction forces of neighbouring yarns. On the initial part of the curve, the load is roughly proportional to the grip displacement. The line is uneven, and small irregular fluctuations in load, caused by occasional shifts of the yarn, are observed. The slope of the quasistraight line corresponds to an effective Young's modulus of 13.5 GPa. This value is nine-fold lower than the Young's modulus of the Armos fibres (120 GPa). The difference, caused by sliding and straightening of the wavy warp yarn, is related to small load drops in Fig. 3. For the weft yarn in Fig. 2,

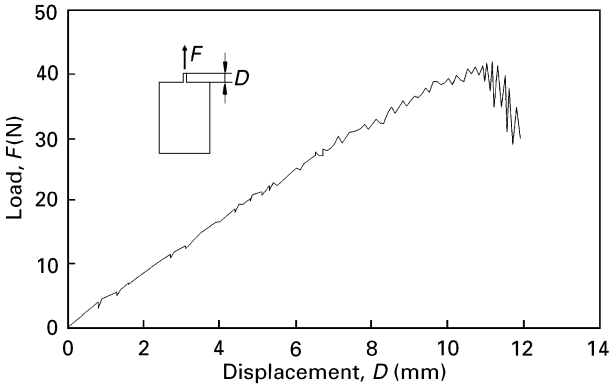


Figure 3 Initial part of a load–displacement curve of a warp yarn pulled-out from 14×11 fabric ($L = 130$ mm) at 0.5 mm min^{-1} loading rate.

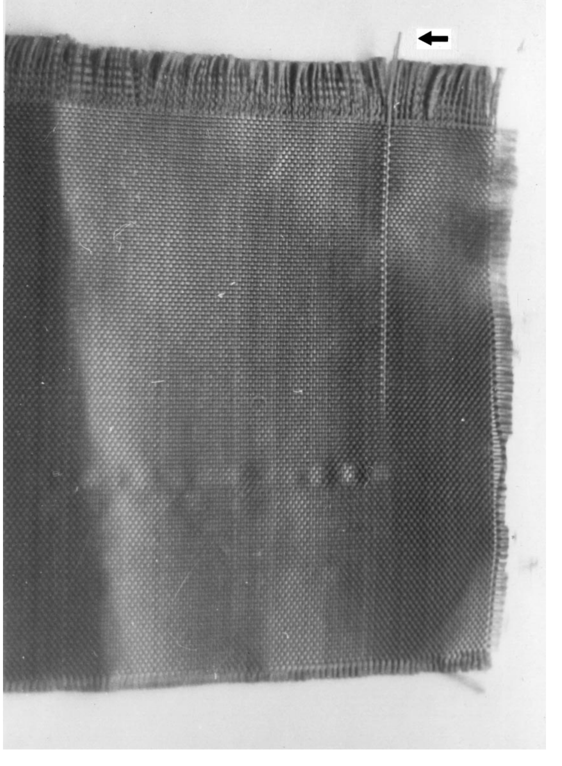


Figure 4 A photograph of 12×12 Armos layer unloaded before the maximum in load. The pull-out zone can be observed.

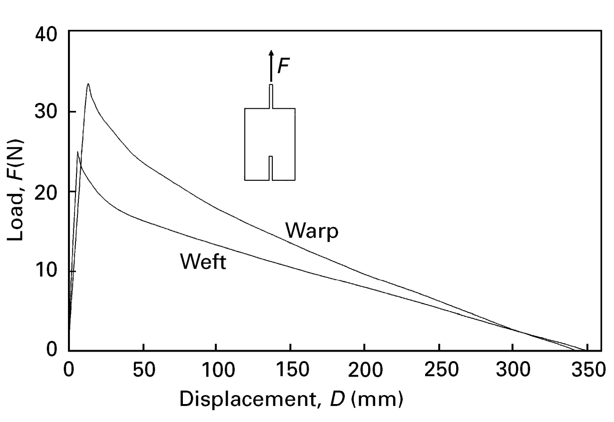


Figure 2 Pull-out load, F, plotted against grip displacement, D, for warp ($L = 340$ mm) and weft ($L = 352$ mm) yarns for 10×10 Armos fabric.

the slope of the straight line, equal to 110 GPa, is close to the Young's modulus of the fibres. The maximum pull-out force, 42 N, corresponds to tensile stress of 0.7 GPa. This value is 20%–25% of the ultimate fibre strength.

Fig. 4 shows a photograph of the 14×11 fabric unloaded before reaching a maximum load. The arrow indicates the warp yarn that was pulled-out from the fabric. The arrowed white line shows the zone where the yarn was loaded. The length of this zone, L_l, increases with pull-out displacement as illustrated by Fig. 5. When the length of the zone reaches the bottom edge of the specimen, the entire yarn is pulled-out, and the maximum in load is observed (Fig. 2). Similar zones were observed after impact tests. In these zones, bullet energy is transferred to fibres, and they will be called "pull-out zones". Obviously, energy transferred

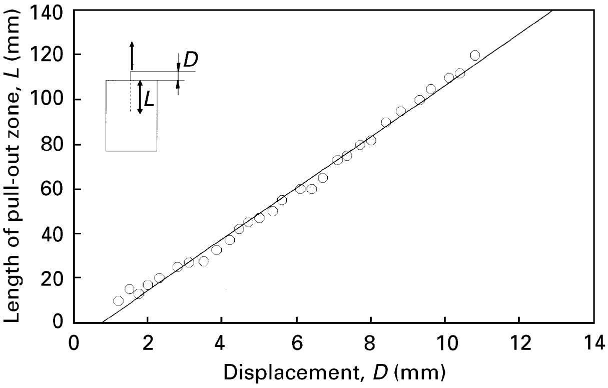


Figure 5 Length of the pull-out (friction) zone, L, plotted against grip displacement, D, for a warp yarn pulled out from 14×11 fabric. $L = 130$ mm.

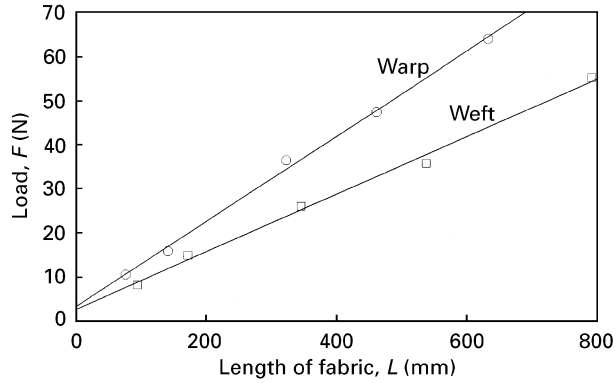


Figure 7 Maximum pull-out force, F, plotted against the length of 10×10 fabric, L.

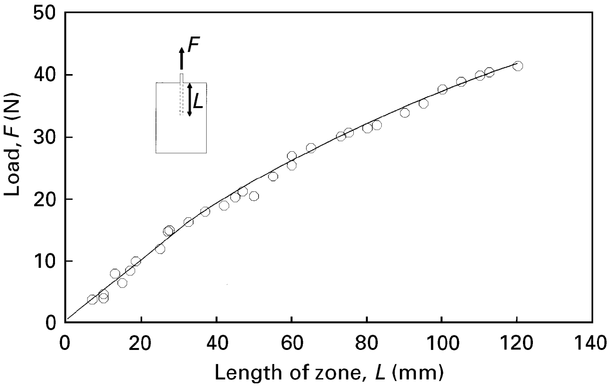


Figure 6 Pull-out force, F, plotted against the length of the pull-out zone, L, for the warp yarn in 14×11 fabric, $L = 130$ mm.

TABLE I Pull-out characteristics

Fabric	Modulus (GPa)		Pull-out strength ($\mathrm{N\,m^{-1}}$)	
	Warp	Weft	Warp	Weft
10×10	53.4	110	98	47
12×12	14.2	71	243	155
12×12, sized	25	38	410	129
13×13	24	31	248	170
14×11	13.5	124	300	169
14×11, wet			330	191
15×15			248	82
530 denier				

to a fabric layer increases with an increase in the length and the width of the pull-out zone (bullet is decelerated).

Fig. 6 shows the pull-out force, F, plotted against the length of growing pull-out zone, L, for the 14×11 sample. The pull-out force increases with the length of the zone. The initial part of the curve may be approximated by the linear function

$$F = KL \tag{1}$$

where K is the coefficient related to friction stresses.

Fig. 7 shows the maximum pull-out force, F, plotted against the length of 10×10 Armos specimens. The relationship may be described by Equation 1. K is equal to $105\ \mathrm{N\,m^{-1}}$ for warp and $65\ \mathrm{N\,m^{-1}}$ for weft yarns. Hence, the pull-out force for warp is higher than for weft yarns. For the warp yarn, the strength limit is reached at length of 1.8 m.

The results of testing of different fabrics are presented in Table I. Friction in 12×12 fabric is higher than in 10×10 fabric. Further increase in fabric density leads to moderate increase in friction. The friction of weft yarns remained the same or even decreased, whereas the friction of yarns in wet 14×11 fabric is 10%–15% higher than that in dry fabric. In addition, water changes the mechanism of pull-out, and the wet yarn is pulled-out by a "stop–jump" mechanism with a number of regular abrupt peaks on the load–displacement curve.

3.2. Impact tests

3.2.1. Hollow

Fig. 8a shows a photograph of a 14-layer laminate tested with Makarov pistol. The face layer is not perforated. However, at some impacts, up to four face layers were perforated. A rectangular hollow with arrowed uneven boundaries is observed in the photograph. The hollow resembles a tray. A schematic drawing of the hollow is presented in Fig. 8b. The length of the hollows varied from 25–80 mm. After some impacts, hollows were not observed, especially if a laminate was perforated.

Usually the impact point was not in the centre of the hollow (Fig. 8a). Fig. 9 shows the distance between the impact point and the boundary of the hollow, S, plotted against a distance between the impact point and the edge of the laminate, D. The dependence is described by a straight line passing close to the zero point. No difference between warp and weft directions was noticed. Although hollows are larger in larger laminates, S does not depend on the size of a laminate, and depends only on the distance to the edge of the laminate, D. This indicates that the size of hollow, S, is determined by the time for which the longitudinal wave travels to the edge of the laminate. Evidently, the hollow is formed by the transverse wave. In an isolated fabric layer this wave has a conical shape [9]. In a laminate, the transverse displacement is restricted and the transverse wave is tray-like in shape, as depicted in Fig. 8b.

The linear relation between S and D in Fig. 9 may be explained assuming that the size of the hollow is

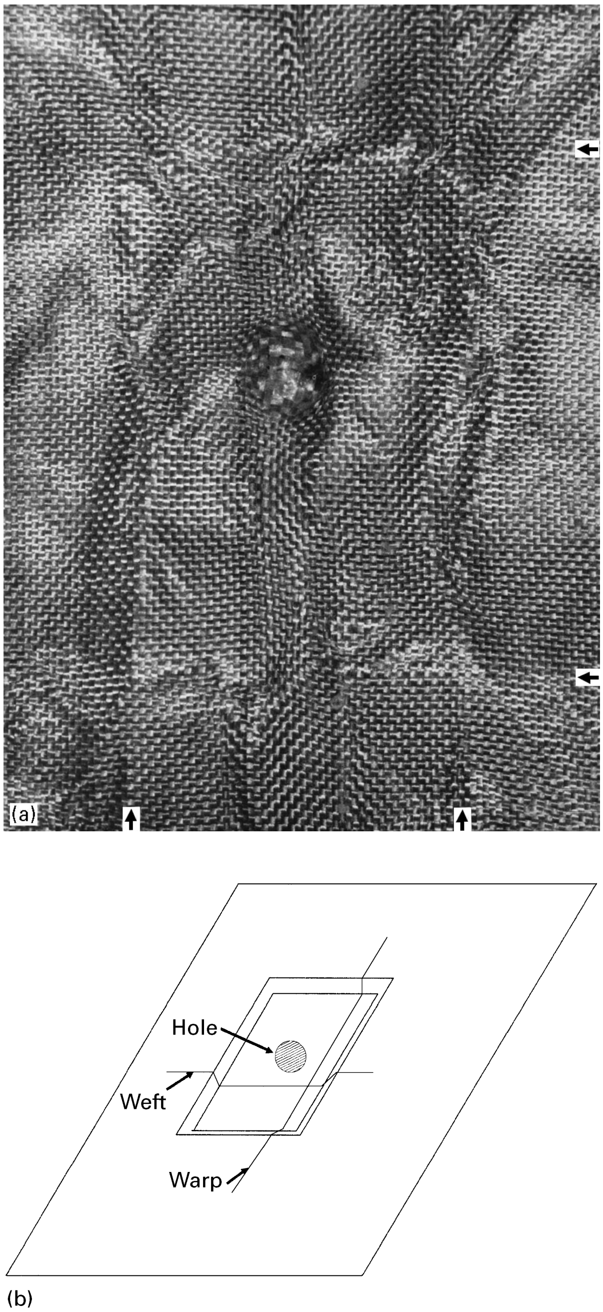


Figure 8 (a) Photograph of a rectangular tray-like hollow after an impact. Arrows show the borders of the hollow. (b) Schematic drawing of the hollow.

determined by the time for which the longitudinal wave travels to the edge of the laminate and back to the impact point. The transverse wave is moved by the axial tensile load. When the recoil wave arrives, tensile stress vanishes, and the transverse wave stops. Assuming that a hollow is formed when the recoil wave meets the transverse wave the size of the hollow is

$$S = u\tau \quad (2)$$

where u is the velocity of the transverse wave, and τ is the time of wave propagation. The longitudinal wave travels to the edge of a laminate and back to the front of the transverse wave. The total length passed by the longitudinal wave is

$$2D - S = c\tau \quad (3)$$

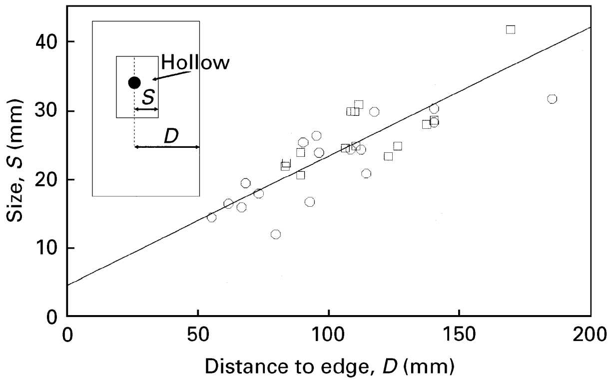


Figure 9 The distance between the impact point and the boundary of a hollow, S, plotted against the distance between the impact point and the edge of the laminate, L. (○) weft, (□) warp.

where c is velocity of the longitudinal wave. Substitution of Equation 2 into Equation 3 gives

$$D/S = \frac{c}{2u} + 0.5 \quad (4)$$

The velocity of the longitudinal wave is [10]

$$c = (E/\rho)^{1/2} \quad (5)$$

where ρ is the density, and E is the Young's modulus of the fibre. Assuming that the velocity of the transverse wave in a laminate is equal to that in an isolated fibre, u is [3, 4]

$$u = (v^2 c/2)^{1/3} \quad (6)$$

where v is the velocity of a bullet.

The velocities of the longitudinal and the transverse waves were calculated assuming that at impact the Young's modulus of the fibres is equal to that at static loading, 120 GPa. For $v = 315\ \mathrm{m\,s^{-1}}$, the calculated L/D ratio, equal to 6.4, is slightly higher than the slope of the line in Fig. 9, equal to 5.5. Probably, the velocity of the transverse wave in the laminate is higher than the value calculated from Equation 6. Similarly, the velocity of the longitudinal ultrasonic waves in aramid fibres is higher than expected from Equation 5 due to an increase in the Young's modulus under strain [11–13].

3.2.2. *Pull-out zone*

Fig. 10a shows a photograph of a third layer taken out of a laminate. The edges are not straight, and both warp and weft yarns are partially pulled-out by the bullet. Fig 10b shows magnification of the edge with pulled-out weft yarns. The number of pulled-out yarns is 14–16, and the width of the pull-out zone is higher than the bullet calibre, 9 mm.

The arrow in Fig. 10a indicates the pull-out zone where warp yarns were loaded by the bullet. The pull-out zone is 100–110 mm in length, shorter than the distance to the edge of the fabric. The pull-out length and width may be determined for each fabric layer. These parameters characterize energy transferred to different fabric layers. The larger the pull-out zone, the higher was the energy dissipated by a layer.

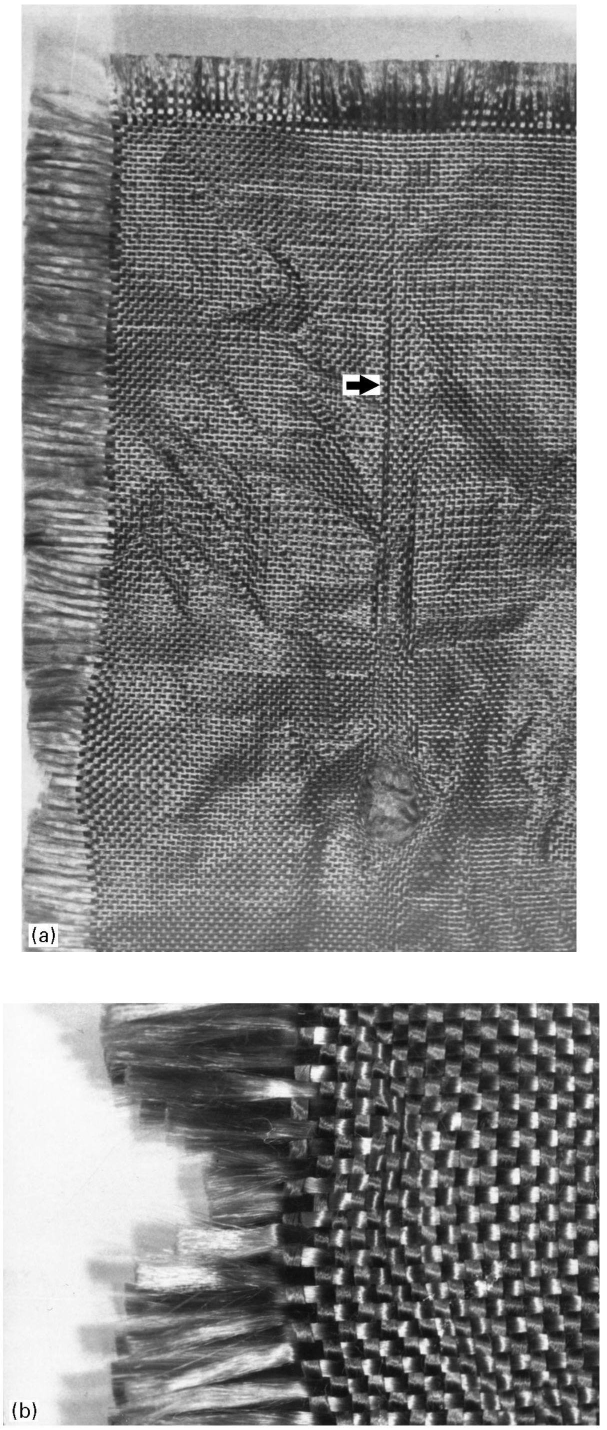


Figure 10 (a) Photograph of the face fabric layer taken out of the laminate. The arrow indicates the pull-out zone in the weft direction. (b) Magnified edge of the layer with pulled-out weft yarns.

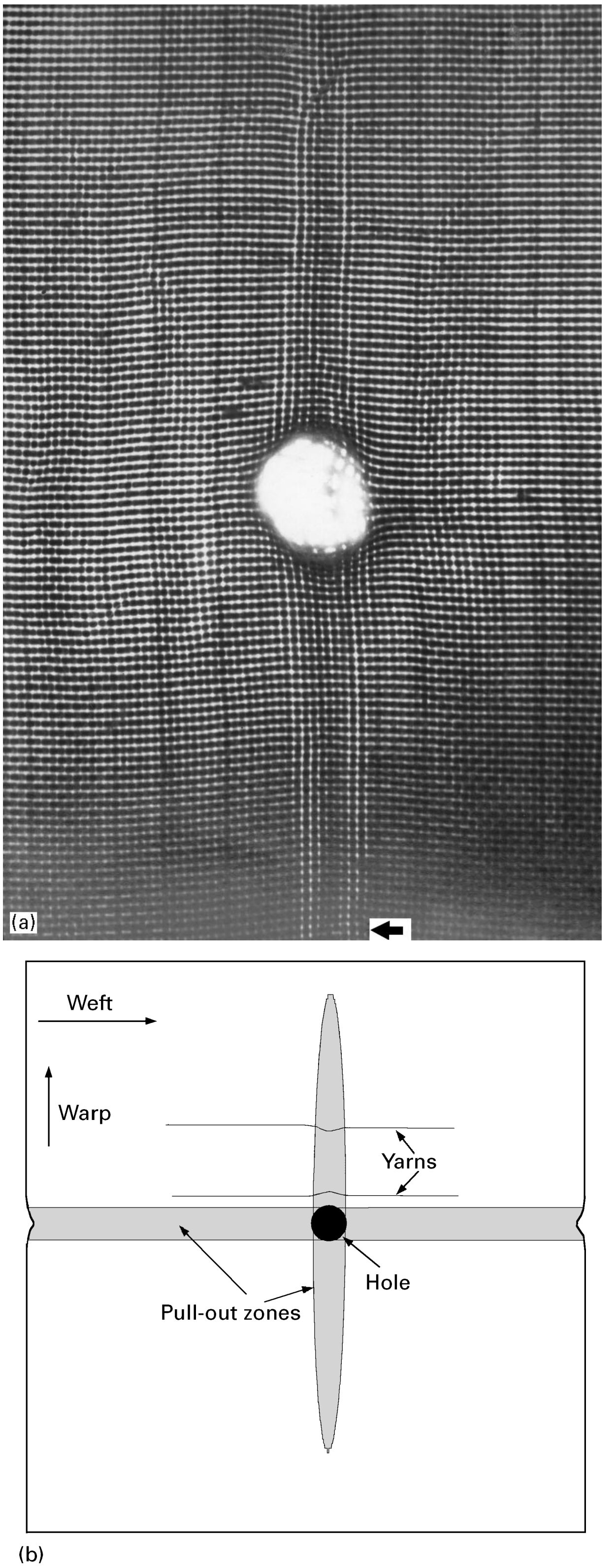
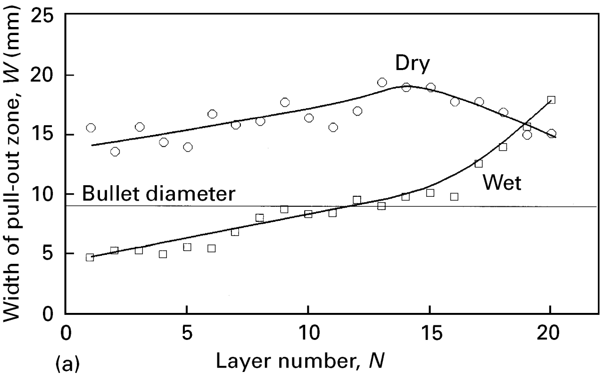


Figure 11 (a) Photograph of a fabric layer in transmissive light. (b) Schematic drawing of a pull-out zone.

Fig. 11a shows a photograph of a fabric layer in transmitted light. Dark points are intersections of warp and weft yarns. Near the hole, transverse weft yarns are bent by the bullet from its centre as illustrated schematically in Fig. 11b. In contrast, far from the hole, weft yarns are bent (pulled-out) towards the hole. Evidently, weft yarns are bent due to friction with the pulled-out warp yarns.

3.2.3. Effect of water

14-layer Armos laminate stops a bullet fired from a Makarov pistol. However, the same laminate in the wet state is perforated. Wet laminates were perforated even when the number of aramid layers was increased to 20. Fig. 12 illustrates the effect of water on a 20-layer laminate tested without PP fabric layers. In this figure, the width of the pull-out zone in the weft direction, W, is plotted against the ordinal number of layer N in the laminate. W was determined at the edge of the laminate, at a distance of ≈ 50 mm from the impact point.



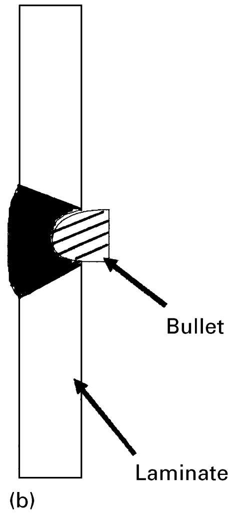


Figure 12 (a) Width of the pull-out zone, W, plotted against the ordinal number of layer, N, after testing with a Makarov's pistol (weft direction); 20 layers of 12×12 fabric. (b) Schematic drawing illustrating the broadening of the pull-out zone with an increase in N.

For a dry laminate at $N = 1$, the width of the pull-out zone is ≈ 14 mm, higher than the bullet calibre of 9.0 mm. Hence, the energy is transferred to yarns that were not impacted immediately by the bullet. Further widening of the pull-out zone is observed with an increase in N. This is explained schematically by Fig. 12b. At $N = 15$, the zone is ≈ 5 mm broader that at $N = 1$. This value is close to the laminate thickness of 4–5 mm. In the back layers, the pull-out zone is reduced, owing to stopping the bullet and reduction of the pull-out displacement.

At $N = 1$, in a wet laminate, the width of the pull-out zone is more than three-fold narrower than in a dry laminate, and equal to one-half of the bullet diameter. Hence, dissipation of energy is much lower than in the dry state. This explains the cause of perforation. Impacted yarns were not broken, and perforation was caused by sliding of a bullet between slightly pulled-out yarns. Hence, water does not reduce the strength of the fibres. The tip of the Makarov's bullet is spherical, and a yarn may slide over it if friction with the bullet is lower than some critical value determined by the angle between the surface of a bullet and the direction of the bullet propagation. Possibly, water leads to a reduction of friction between the bullet and the yarn. The width of the zone, W, increases with N (Fig. 12a), and at $N = 19$ W approaches that in the dry laminate.

3.2.4. *TT*

The 45-layer laminate tested with a TT pistol was perforated. Fig. 13 shows the width of the pull-out zone in the warp direction, W, plotted against the layer number, N. The width of the pull-out zone initially increases linearly with N, and at $N = 25$ it levels up. In the first layer, W is equal to 4 mm. This value is less than the bullet diameter (calibre) of 7.62 mm and equal to the diameter of the bullet tip. The sharpened conical shape of the TT bullet reduces the number of pulled-out yarns and leads to perforation of the laminate.

The second cause of perforation is illustrated by Fig. 14 where the length of the pull-out zone in the warp direction, L, is plotted against the number of layers, N. The pull-out length is short, just 20–40 mm for all layers except for the last ten, $N > 35$. Hence, energy is dissipated by a short part of the fibres near the impact point.

The pull-out length is not constant, and a broad minimum is observed at $N = 7$–32. Face layers were occasionally more wavy than the central layers. The pull-out length in these layers was longer than in the following layers. The same is true for the last layers adjacent to soft PP layers. The pull-out zone was longer for layers in which transverse displacement was

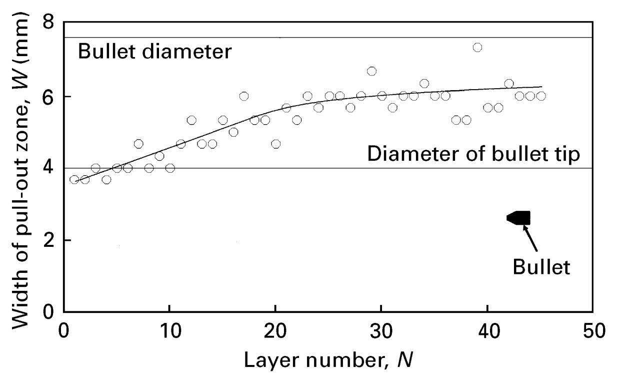


Figure 13 The width of the pull-out zone, W, plotted against the ordinal number of layers, N, after testing with a TT pistol.

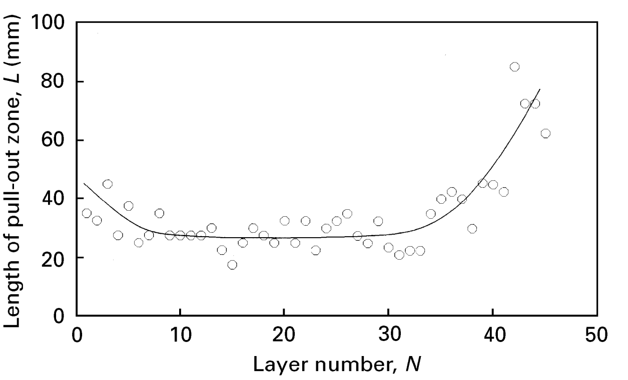


Figure 14 The length of the pull-out zone in the warp direction, L, plotted against the number of layers, N, after testing with a TT pistol.

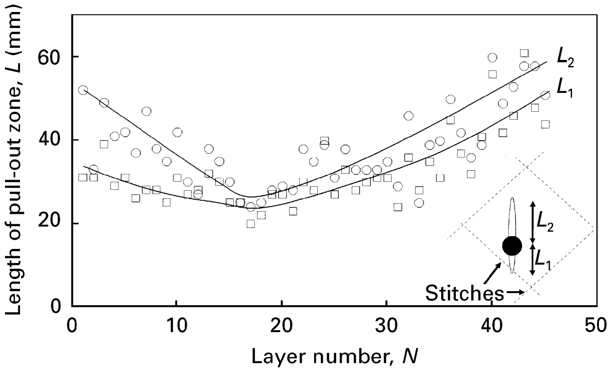


Figure 15 The length of the pull-out zone, L, in the warp direction plotted against the number of layers, N, after testing with a parabellum pistol.

less restricted than in the central layers placed close to each other.

This conclusion is confirmed by Fig. 15 which illustrates the results of testing of the 45-layer laminate with 9.0 mm parabellum pistol. The laminate was perforated. The impact point was at a distance 15 mm from a stitch line (oriented at 45° to warp/weft direction). The pull-out zone is not symmetrical, being shorter in the direction of the stitch line where the layers are closer to each other ($L_1 < L_2$). Thus, the pull-out zone is shorter in all cases when the laminate is occasionally too tough and does not have enough space for transverse displacement. It is worth mentioning that the pull-out zone in the weft direction is much longer and reaches 150 mm. However, the number of pulled-out yarns is only 1–4 depending on the distance from the impact point.

4. Discussion

A study of the pull-out zone qualitatively estimates the energy transferred to fibres in each fabric layer. It gives additional characteristics of energy dissipation, and may reveal the cause of perforation. This method resembles fractographic analysis used for study of failure in metals and polymers.

Energy transferred to a fabric layer may be estimated by the equation

$$U = u_0 N L \tag{7}$$

where u_0 is energy of both waves per unit length of a yarn [14], N is the number of pulled-out yarns, L is the pull-out length. Equation 7 reflects the dependence of the bullet resistance on the length and the width of the pull-out zone.

The presented results indicate that key parameters determining bullet resistance are the shape of the bullet, friction between the yarns and the bullet, and friction between the yarns. In a dry laminate, the pull-out zone may be wider than the bullet calibre. Hence, friction between the yarns improves energy dissipation. Bullet resistance depends also on restriction of transverse displacement and density of the laminate.

The magnitude of the tensile strain increases with an increase in the projectile velocity [3–5]. When tensile stress reaches the ultimate fibre strength it breaks, and the longitudinal wave does not propagate along the fibre. As a result, fabric effectively dissipates energy only if the projectile velocity is lower than some critical value. For a single aramid SVM yarn the critical velocity at transverse impact was found to be $670\ \mathrm{m\,s^{-1}}$ [15]. At a TT bullet velocity of $420\ \mathrm{m\,s^{-1}}$, Armos yarns in laminates do not break at the moment of impact despite the restriction of the transverse displacement and growth of the tensile stress. Hence, the decrease of the critical velocity in the laminate is less than 1.6-fold (if any).

5. Conclusions

1. The length and the width of the pull-out zone are related to the energy transferred to fibres in each fabric layer.
2. Water leads to a reduction of the width of the pull-out zone.
3. Rectangular hollows were observed near impact points. The size of the hollow is proportional to the distance from the edge of the laminate. The hollow is caused by a transverse wave that stops when the longitudinal recoil wave meets the transverse wave spreading from the impact point.
4. Friction between yarns leads to broadening of the pull-out zone.
5. At a projectile velocity of $420\ \mathrm{m\,s^{-1}}$, Armos yarns in the laminate do not break right at the moment of impact.
6. To measure the friction of yarns, a yarn pull-out method was developed.

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