Perforation of flexible laminates by projectiles of different geometry

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Abstract

This paper investigates the response of flexible laminates to ballistic impacts by projectiles of various geometries, namely, flat-ended, hemispherical, ogival (CRH 2.5) and conical (30° half-angle) projectiles. The laminate of interest is Spectra Shield® comprising [0°/90°] extended chain polyethylene filaments embedded in a thermoplastic resin. Ballistic tests show that flat-ended projectiles cut the laminate through a shearing action, effectively punching a circular hole in the laminate whereas hemispherical projectiles perforate the laminates by stretching the Spectra filaments to failure resulting in a rectangular hole in the laminates. While the manner in which they are perforated are different, many similarities are observed in specimens perforated by flat ended and hemispherical projectiles such as the formation of a generator strip, the extent of delamination, the creasing of the laminate, tearing of the laminate at the edges, etc. Ogival and conical projectiles, on the other hand, perforate the laminates with minimal delamination and tearing of the specimens. Interestingly, the region of the specimens affected by the projectiles appears to increase in size instead of becoming more localised at higher impact velocities as often reported for most ballistic impacts events, including the ballistic perforation of woven fabric. This suggests flexible laminates are more effective in dissipating energy than woven fabric in the application of flexible armour.

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1. Introduction

Flexible protective materials against ballistic impacts have made significant advances over the past few decades. Flexible armour is preferred for personnel protection because they offer less

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restriction to the mobility of users. Drapable armour was initiated by using high-strength materials instead of traditional yarns with established textile manufacturing techniques. Yarns made of nylon were the first generation of high-strength materials to replace natural threads in fabrics for ballistic protection applications. Following the introduction of nylon, research on flexible high impact resistant systems has largely focused on the search for stronger materials. The discovery of aramid marked another significant jump in the performance of fragment resistant flexible materials. Improvements in flexible armour are mainly a result of stronger materials. Fabric fabrication techniques have remained largely similar to traditional fabric weaving methods. Of the different woven architectures, it was recognized at a very early stage that the plain weave was the most efficient in dissipating impact energy because the simple weave introduces the most cross-yarn interactions. The yarn crossover points facilitate the dissipation of impact energy to yarns not in direct contact with the projectile.

Together with the search for stronger materials, the current trend in the research of ballistic-resistant materials is to look at novel ways to incorporate new materials into an armour system while maintaining drapability. However, it is no longer possible to make significant improvements merely through simple changes in processing techniques or in materials substitution. In yet another step towards higher levels of protection against ballistic impacts, flexible laminates were introduced. These comprise continuous high-strength filaments embedded in a thin film of flexible resin. Their advantage over woven fabrics is the absence of crimp in the filaments. Crimp is the undulation in each yarn as it runs over and under alternate crossover yarns. Crimped yarns need to straighten out before they start to stretch and become effective in resisting the projectiles. This gives rise to excessive deflection leading to blunt trauma. The straight filaments in flexible laminates extend immediately on impact and quickly spread the energy to the surrounding materials. By involving more material in the energy absorption process, it reduces blunt trauma and is able to defeat projectiles of higher energy than woven fabric. An armour system of flexible laminates will include multiple layers of unidirectional laminas at different directions because a unidirectional laminate is weak perpendicular to the filaments.

While literature on woven fabric material for ballistic resistance has grown substantially over the past few years, there is still much to be reported on the ballistic performance of flexible laminates. The results of ballistic tests on flexible laminates, namely, Spectra Shield® laminated composite roll (LCR) is presented in this article. The objectives are to understand how small projectiles perforate 2-ply flexible laminates and to study the effects of projectile geometry and impact velocity.

2. Spectra Shield® LCR

The material used in this study is Spectra Shield® LCR by Honeywell. It is a 0/90° flexible laminate of unidirectional Spectra-1000 fibre sandwiched between two thermoplastic films. Spectra-1000 is an organic fibre made of extended-chain polyethylene (ECPE). Spectra Shield® LCR has an areal density of 150 g/m² and is of 0.18 mm thickness. Reports of relevance are limited and focus on the characteristics of the individual constituent polyethylene fibre and hard Spectra Shield composite panels.
The mechanical strength of polyethylene fibres increases to a maximum with molecular weight and draw ratio of the fibre during processing. The relationships between fibre strength and molecular weight and draw ratio have been reported by Wang et al. [1]. Spectra 1000 fibre has an ultimate tensile strength of 3 GPa and elongation to breakage of about 3% strain. It has a tensile modulus of 100 GPa and a density of 0.97 g/cm³.

An important characteristic of Spectra fibres as with other polymeric fibres is that they are strain rate sensitive. Prevorsek et al. [2] tested Spectra at strain rates from 10⁻² to 10² s⁻¹ and showed that the tensile modulus of the fibre is very strain rate sensitive. The quasi-static tensile modulus was found to be 12 N/denier while the tensile modulus increases to 32 N/denier at strain rates of 200 s⁻¹ as shown in Fig. 1. The higher tensile modulus at higher strain rates means that the fibre is able to dissipate impact energy from the impact point at a higher rate. However, this can be offset by the decrease in ductility of the fibres. Benloulo et al. [3] reported an increase in the maximum stress and decrease in the maximum strain of polyethylene fibre composites when strain rates are increased from 10⁻³ to 10³ s⁻¹ from dynamic tensile testing of the polyethylene composites. Hsieh et al. [4] showed that PE Spectra-900 composite plates of 10–30 plies of laminates absorb more energy at low-velocity impact of 10 m/s than for high-velocity impact of 360 m/s.

Although its ballistic mechanical properties are impressive, polyethylene has a low melting temperature. It is reported by Morye et al. [5] that the melting point of unidirectional Spectra 1000 fibre is about 147°C. Ballistic tests on materials constructed from polymeric fibres revealed the mode of material failure is strongly dependent on the glass transition temperature of the fibre. As temperatures increases, the strength of the polyethylene fibre shows a transition from brittle fracture to yielding. The effect of temperature rise on high-performance polyethylene fibres is also reported in [6] where it is reported a decrease in strength occurs with an

![Fig. 1. Tensile modulus of Spectra filaments as a function of strain rate [2].](image-url)
increase in temperature. However, Prevorsek et al. [7] measured the viscoelastic hysteresis (ratio of the strain energy of the fibre that is converted to heat) of high-performance polyethylene fibres and concluded that the temperature rise in spectra fibre caused by high-speed loading is negligible (not more than 1°C). Therefore, the amount of fibres that experience melting due to temperature rise is too small to have an influence on the ballistic performance of the polyethylene composite plates.

3. Experimental procedures and setup

The experiments were conducted on a ballistic impact tester using high-pressure helium to propel projectiles onto Spectra Shield specimens. The impact and residual velocities of the projectiles were captured during the impact tests. The tests were conducted using four types of projectiles over a range of impact velocities up to 400 m/s. The four projectiles used are shown in Fig. 2. All projectiles have a diameter of 12.6 mm and a mass of 15 g. The Spectra Shield specimens are clamped along the top and bottom edges while the other two edges are free. The target area of the specimens is 120 mm × 118 mm. The specimens were lightly pre-stretched before being fired upon. The filaments in the front ply (or impact ply) of the specimens run vertically and were therefore clamped at the ends. Filaments in the back ply are horizontal and were not clamped. The changes in the velocity of the projectiles after perforating the target specimens are shown in Fig. 3.

![Projectiles used in impact tests of Spectra Shield.](image1)

![Change in projectile velocity after perforation.](image2)
4. Results

This section presents the types of damage that were observed in the laminate specimens after impact tests. In general, specimens perforated by conical and ogival projectiles showed similar features and specimens perforated by flat and hemispherical projectiles showed another set of features. The mechanisms by which conical and ogival projectiles perforate the laminates were entirely different from those of the flat-ended and hemispherical projectiles. Although specimens perforated by the flat-ended and hemispherical projectiles showed many common features, there were a few characteristics that were unique to each projectile.

4.1. Flat-ended projectiles

Fig. 4 shows a schematic diagram of Spectra Shield specimens after they were perforated by flat cylindrical projectiles. Figs. 5 and 6 are photographs of laminates perforated by projectiles at velocities of 90, 160 and 340 m/s. The specimens deformed into a pyramidal shape after perforation. Material inside the pyramid is delaminated except within a vertical strip of the laminate directly in front of the projectile. This strip is referred to as the ‘generator strip’.

4.1.1. Shape of deflection

The pyramidal deflected shape is a consequence of the [0°/90°] laminate lay-up of Spectra Shield. Pyramid shape deflection is commonly reported for cross-woven fabrics subjected to ballistic impacts [8]. Numerical simulations taking into consideration the transversely orthotropic nature of such fabrics also predict pyramidal deformation [9,10], whereas conical deformation is predicted if the fabric is idealized as an isotropic membrane [11]. A conical deformation occurs in...
isotropic membranes because the transverse deflection front propagates radially away from the impact point at the same speed. In the case of Spectra Shield laminates, the filaments on the two plies are orthogonal to each other and hence, the deflection front travels faster along these two directions than any other direction resulting in a pyramidal deformation.

4.1.2. Delamination

Unlike conventional woven fabrics, Spectra Shield is a laminated system and is thus susceptible to delamination. Hsieh et al. [4] showed that the effects of delamination in polyethylene composite plates appeared to be minor in the impact energy absorption by PE Spectra-900 composite plates. This conclusion arises because the difference in the energy that is absorbed by layers of
impregnated sheets simply stack together to the energy absorbed by a PE Spectra-900 composite plate of the same thickness was small. However, it cannot be concluded if delamination is a governing mechanism for the energy absorption.

The delamination resulting from impact tests can be seen in Figs. 5 and 6. Primary filaments (filaments on the front ply in direct contact with the projectile) are pushed in during impact. These filaments will in turn push filaments in the back ply orthogonal to them. As the filaments in the back ply deflect, they tend to pull along other vertical filaments in the front ply not in contact with the projectile. The ability to pull the vertical filaments along depends on the strength of adhesion between the two plies. Because ballistic events involve high velocities, the interply adhesion must be strong enough to overcome the mass inertia of the front ply to keep the front ply adhered to the back ply. Spherical projectiles travelling at 100 m/s have been predicted to start perforating Spectra Shield specimens about 15 μs after impact [10]. Assuming constant acceleration and taking the areal density of Spectra Shield to be 150 g/m², the inertial force per unit area of the laminate is estimated to be of the order of

\[
\frac{1}{2} \left( \frac{150 \times 10^3 \times 100}{150 \times 10^{-6}} \right) = 50 \, \text{GPa}. \tag{1}
\]

Vertical filaments in the front ply are clamped at the ends, therefore, in addition to inertia, there is also a component of the tension in the filaments pulling them away from the back ply when they are deflected. In all cases, the interply adhesion is not strong enough to keep the two plies completely together. The front ply delaminates from the back ply while the primary filaments push filaments of the back ply along with it resulting in a ‘pyramid’. The generator strip comprising vertical filaments of the front ply in contact with the projectile remains bonded to the back ply even though all other regions within the pyramid are delaminated. There is an increase in the area of delamination as the impact velocity of the projectile increases up to 150 m/s, thereafter, the area of delamination remains fairly constant at higher impact velocity as shown in Fig. 7.

On the back-face of the laminate, a horizontal strip of the laminates is completely peeled off during the impact (Fig. 5). Since the filaments on the back ply are not clamped, they are able to completely separate from the laminate. It should be noted that this phenomenon occurs regardless of impact velocity. Numerical simulation reported in [10] predicted delamination
within a horizontal band of the laminate specimen extending to almost both free edges regardless of impact velocity. Once such delamination occurs, a horizontal strip of material is easily lifted off from the back ply when the projectile perforates the front ply. The simulation also showed that at high impact velocities, the horizontal strip of delamination occurs even though only the impact region is deflected. This is a strong indication that the delamination occurs as a result of large shearing forces between the plies when the filaments are pulled towards the projectile on impact.

Post-impact analyses of the specimens have shown that with the flat-ended projectile, the strip becomes wider as the projectile velocity increases but the width of the strip is always less than the projectile diameter for the range of impact velocities tested (Fig. 8). In almost all cases, the strip is completely torn off from the back face of the laminate. In a few instances, complete strips of material can be found still attached to the edge of the laminate. In all cases, there is no breakage of the strips lifted off by the projectile.

4.1.3. Generator strip

The term ‘generator strip’ was also referred to in [8], where such a feature is reported for crossply fiberglass–epoxy composite plates impacted by cylindrical penetrators. In ballistic impact tests of Spectra polyethylene composite plates, Lee et al. [12] compared plates of unidirectional plys stacked in different directions and plain-woven fabric-reinforced composite plates. Angled-

Fig. 8. Width of back strip in specimens perforated by flat and hemispherical ended projectile against impact velocity.

Fig. 9. Length of generator strip in specimens perforated by flat and hemispherical ended projectile against impact velocity.
plied polyethylene composites showed the presence of a generator strip while the plain-woven composites do not.

The fibres in the generator strip are strained in tension due to the pushing of the projectile on the laminate. The vertical boundaries of the generator strip are marked by split lines running vertically along both sides of the strip showing where the strip has torn off from the rest of the front ply. The length of the strip is taken to be the length of these split lines. The length of the generator strip is dependent on the projectile impact velocity as shown in Fig. 9. At low impact velocities, the generator strips are short. The length of the strip increases with impact velocity until about 150 m/s at which it extends to the top and bottom of the specimens. At even higher impact velocities, the generator strips tend to become shorter again.

For the flat cylindrical projectile, the width of the generator strip is always equal to the projectile diameter as shown in Fig. 10. This is because of the combination of high stresses within the target specimens at the angled edge of the projectile and the preferential tearing of the plies in the direction of the filaments causes the generator strip to propagate from point A as indicated in Fig. 4.

4.1.4. Tearing at the clamps

The stresses that propagate to the clamped edges are significant enough to cause some tearing as shown in Fig. 11. The tear occurs on the back ply along the edges within the band of the primary filaments. The tear occurs only for impact velocities from 150 to 340 m/s. At higher velocities, the laminate is perforated before stresses of significant magnitude build up at the edges.

4.1.5. Creasing

In addition to the generator strip and delamination, another obvious feature is creasing of the specimens. Laminates perforated by flat projectiles display creases that run vertically from top to bottom. The creases do not diminish at high impact velocities. In fact, the creasing is more pronounced for flat projectiles at an impact velocity of 340 m/s than at lower velocities. The extensive creasing suggests that a large part of the laminates is still affected even for high velocity impacts. This is unlike the observations reported in [9] for woven aramid yarns where damage
becomes more localised at the impact point as velocities increase. Interestingly, there is no visible delamination between the laminate within the creases.

4.1.6. Mode of perforation

As evident from Fig. 12 the flat-ended projectile perforates the laminate by a shearing action. A hole of similar diameter to the projectile is cleanly punched out from the laminate. This shearing off of the plug is caused by the sharp circumferential edge of the projectile. This phenomenon occurs regardless of projectile velocity.
4.1.7. Quasi-static punch tests

Quasi-static perforation of Spectra Shield specimens where a cylindrical rod is pushed through the specimen at less than $10^{-3}\text{m/s}$ reproduces the features observed in specimens subjected to impact of less than 150 m/s. Under such low loading velocities, the entire laminate is fully deflected between the top and bottom clamps before it is perforated. There is minimal delamination as both plies are deflected together. Delamination only starts at an advanced stage of the loading resulting in a small rhombic region of delamination just before the specimen is perforated.

Short generator strips are also observed in the quasi-static tests. Generator strips form following the splitting of the thermoplastic film (at point A of Fig. 4) on the front ply. The generator strip becomes longer and delamination propagates from the split lines when the front ply separates from the generator strip as the strip is pushed further in (and away from the front ply) by the cylindrical rod. Since the laminate does not deflect much further by the time the split lines are formed, the generator strip is short and delamination is minimal.

It is postulated that when impact velocity is increased, the thermoplastic film start to split earlier because of higher stresses resulting in longer generator strips by the time the laminate is fully deflected. However, at impact velocities above 150 m/s, the generator strips become short again (Fig. 9) because the laminate does not have time to fully deflect before the laminate is perforated.

4.2. Hemispherical projectiles

Specimens perforated by hemispherical and flat-ended projectiles display many similar features as shown in Figs. 13 and 14. The generator strip is also present in specimens and similarly, the generator strip is short at low impact velocities and increases with impact velocity up to 150 m/s at which the strip extends to the clamped edges. At higher velocities the length of the generator strip drops quite sharply (Fig. 9). While the effects of impact velocity on the length of the

![Fig. 13. Back view of specimens perforated by hemispherical ended projectiles at (a) 90 m/s, (b) 160 m/s and (c) 340 m/s.](image-url)
generator strip are similar for both flat and hemispherical projectiles, the width of the generator strip is different for both. This is illustrated in Fig. 10 where the width of the generator strip normalized by the projectile diameter is plotted against the impact velocity. Two obvious differences between the width of the generator strips in specimens perforated by the flat and hemispherical projectiles are:

- the width of the generator strip is equal to the projectile diameter for the flat projectile whereas the width is smaller than the projectile diameter for the hemispherical projectile regardless of impact velocity,
- the width of the generator strip shows a drop at about 150 m/s for the hemispherical projectile.

For the flat-ended projectile, the width of the generator strip is equivalent to the projectile diameter because stresses in the laminate specimens are highest under the right-angled edge of the projectile as evidenced by the imprints of the projectile face often seen on the generator strip (Fig. 12). In the case of the hemispherical projectiles, the impact face is smooth and hence it is not intuitive where a tear will initiate on the front ply. Once a tear is initiated, it propagates vertically to form the generator strip. The rounded surface of the projectile allows the projectile to slip through a narrower generator strip to perforate the front ply. Hence, the width of the generator strip is smaller for hemispherical projectile compared to the flat projectile.

The decrease in the width of the generator strip at impact velocities above 150 m/s is a strong indication that the generator strip is initiated by different mechanisms at the low- and high-velocity regimes. Quasi-static perforations of Spectra Shield specimens were conducted using the hemispherical projectile to determine how the generator strip is formed. The tests resulted in specimens bearing similar features to the specimens perforated at low impact velocities. As with quasi-static perforation tests using flat projectiles, delamination commences only after
the indenter has pushed significantly into the specimens by which time, a large region of the hemispherical projectile face is in contact with the specimen. When delamination occurs, tensile forces in the laminate in the horizontal direction initiate a tear in the front ply on either side of the projectile, which propagates vertically to form the generator strip. At high impact velocities, it is believed that tensile stresses propagating from the impact point are large enough to cause the tears in the front ply on impact. The tears then grow vertically to form the generator strip. The points where the tears initiate are closer to the centre of the impact point than in the cases of quasi-static and low-velocity impacts resulting in a sudden drop in the width of the generator strip at about 150 m/s.

Similar to laminates perforated by flat cylindrical projectiles, a tear can be found in the back ply along the clamped edges (Fig. 11). However, for the hemispherical projectile the tear is not only restricted to the intermediate impact velocity regime like for the flat-ended projectile but also occurs for the high-velocity regime. Therefore, stresses of significant magnitudes propagate to the edges before the laminates are perforated by hemispherical projectiles even at high impact velocities. Such tearing at the edges for high-velocity impacts were not reported in [9], where similar ballistic tests were conducted on woven aramid fabric. This suggests that crimp free laminates may be better at dissipating impact energy than woven fabrics.

There are distinct differences in how delamination of Spectra Shield® LCR laminates is affected by impact velocity between the flat-ended and hemispherical projectiles. Specimens perforated by the hemispherical projectile shows two regimes in the delamination trend. At low impact velocities the area of delamination is between 0.0025 and 0.003 m², but at velocities above 105 m/s the area of delamination drops sharply to 0.002 m² (Fig. 7). This trend is exactly similar to the trend observed for the width of the generator strip as shown in Fig. 10. This indicates a strong relationship between delamination and the formation of the generator strip. The delamination area due to the flat-ended projectile has a mean value of 0.002 m² which is smaller than the mean value of 0.0026 m² for hemispherical projectiles.

Creasing in laminates perforated by hemispherical projectiles also follow the same characteristics as laminates perforated by flat projectiles. These creases are also vertical and most pronounced at the centre of the specimens. The creasing is also more extensive at higher impact velocities.

In contrast to flat-ended projectiles, hemispherical projectiles perforate the laminate specimens by straining the primary fibres to failure at the impact region (Fig. 15). There is no formation of a plug due to shearing of the primary fibres. In all cases, the perforation is formed when primary filaments in the front ply are strained to failure and a strip of material is lifted off from the back ply. The result is a rectangular perforation instead of a circular one as seen in specimens perforated by flat-ended projectiles. It can also be seen that fraying of the ruptured filaments is less pronounced at high impact velocities. A possible explanation for this is that they could have been strained to a shorter elongation to break. Peijs et al. [6], among others, has reported that high-performance polyethylene fibres fail from a transition of yielding to brittle fracture as strain rate increases.

Hemispherical projectiles also cause a horizontal strip of material from the back ply to peel off from the laminate as with flat cylindrical projectiles. Similarly, the peeling off of the horizontal strip occurs at all velocities. The only difference between the hemispherical and flat-ended projectiles in this aspect is that the width of the horizontal strip does not show a clear increase for
specimens perforated by the hemispherical projectile as impact velocity increases. This is shown in Fig. 8. The width of the strip is always less for the hemispherical projectile than for the flat projectile because the rounded profile allows the hemispherical projectile to push material aside more easily than the flat projectile.

4.3. Conical and ogival projectiles

Tests conducted with conical and ogival projectiles showed that they perforate Spectra Shield laminates through very different mechanisms compared to the flat-ended and hemispherical projectiles. The pointed projectiles do not give rise to generator strips, do not cause material to peel off from the back ply of the specimen, leave minimal crease marks and the specimens do not experience tearing at the clamps.

Conical and ogival projectiles perforate the specimens mainly by pushing apart the filaments in each ply. Therefore, the perforation resembles a slit as shown in Figs. 16 and 17. The perforations by conical and ogival projectiles are much smaller for Spectra Shield® LCR laminates than those in woven fabric armour reported in [13]. This is because the Spectra filaments are not held in place by any weaving and hence it is possible for the projectile to push the filaments apart and perforate the laminate without breaking many filaments. The mean of the width of the slit-like perforation is 1.45 mm with a standard deviation of 0.78 mm for conical projectiles and the width of the perforation on the laminate by the ogival projectile has a mean of 0.89 mm and standard deviation of 0.7 mm (Fig. 18).

Specimens are delaminated near the impact point. The delamination takes the shape of a ‘star’ for conical and ogival projectiles as shown in the schematic drawing in Fig. 19. The star-shape delamination is caused by two effects. The first is similar to the flat-ended and hemispherical projectiles where the back ply is pulled away from the front ply when the projectile has past the front ply. This gives rise to a rhombic shaped delamination as with the flat and hemispherical projectiles but on a much smaller scale. The second effect is due to the pushing apart of the
filaments. In order for the filaments on the front ply to be pushed apart they must debond from the back ply first. Similarly, horizontal filaments on the back ply will debond from the front ply when they are pushed apart. This results in a pointed cross superposed onto a diamond-shaped delamination, leading to the star shape. The star-shaped delamination as seen from the back face of the specimens is shown in Figs. 16 and 17.
The delamination generally increases as the impact velocity increases as shown in Figs. 16 and 17. However, this increase is small when compared to the flat-ended and hemispherical projectiles. On the average, the conical projectile results in 33% larger delamination compared to the ogival projectile (Fig. 20).

Although no generator strip is formed, it can be seen from Figs. 16 and 17 that the primary filaments in the vertical direction are pushed out during the impact. This vertical strip differs from the generator strips observed for hemispherical and flat projectile in that they are separated from the front ply of the laminate, i.e. there is no split in the front ply. This vertical deflection increases in extent, reaching the clamped edges as the projectile velocity increases. This deflection is similar for both the conical and ogival projectiles.
5. Conclusions

The ballistic impact and perforation of flexible Spectra Shield laminates by small projectiles of four different geometries were studied in this paper. Spectra Shield laminates perforated by hemispherical and flat-ended projectiles showed many similarities. In both cases, the formation of a generator strip was observed for the range of impact velocities reported. The generator strip manifests itself as a band of material within which there is no delamination. Outside of the generator strip, the laminates showed a region of delamination that is rhombic in shape centred at the impact point. In addition to the generator strip, a strip of material is always pushed away and completely detaches from the material from the exit face of the laminate. It is also noted that the size of the delamination, length of the generator strip and amount of creasing observed on the laminate are dependent on the impact velocity. Although ballistic impact by hemispherical and flat ended projectiles result in many similar observations, it is also clear that hemispherical projectiles perforate the laminates by stretching the Spectra filaments to failure whereas flat ended projectiles tend to shear the filaments. This is observed from the cleaner edges of the perforation for laminates impacted by flat-ended projectiles compared to the hemispherical projectiles. As a result of its angled edge, flat-ended projectiles leave a circular perforation instead of a rectangular perforation as with hemispherical projectiles. Since the flat-ended projectiles shear the laminates, the width of the generator strips and the strips of material detached from the back of the laminate is smaller for hemispherical projectiles. It was also found that with flat-ended and hemispherical projectiles, the amount of material that is affected during impact increases with impact velocity instead of becoming more localized.

Laminates perforated by conical and ogival projectiles showed localized damaged but the region affected by the impact also increases with impact velocity. There is no generator strip and no material is stripped off from the back when the projectile perforates the laminate. Delamination within the laminate is also minimal. Instead of a diamond-shaped delamination, the delaminated area forms a star shape because the delamination is caused by the filaments being pushed aside laterally as the sharp projectiles perforate rather than the back ply being pushed away from the front ply.

Fig. 20. Area of delamination in specimens perforated by conical and ogival projectiles against impact velocity.
References